Comparison of calcium ameliorants and coal ash in alleviating the effects of subsoil acidity on maize root development near Middelburg, Mpumalanga

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Declaration

I, the undersigned, hereby declare that the work contained in this 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.

Signature

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24 February 2010

Date

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Abstract

Acidic soils are a major limitation to agriculture worldwide. The Highveld in South Africa has many acidic soils and several coal burning power stations. These coal burning power stations generate alkaline fly ash as a waste material and it can thus serve as an ameliorant to the surrounding acidic soils.

A two year field trial was undertaken to compare fly ash and other calcium ameliorants to alleviate the effects of subsoil acidity on maize root development. The field trail was established on Beestepan Farm in Middelburg, Mpumalanga. It consisted of 24 treatments, each done in triplicate, rendering a total of 72 plots.

The materials used were unweathered fly ash (CCE 10%), calcitic lime (CCE 77%) and Calmasil (a calcium silicate slag, CCE 99%). Calmasil and lime were applied at rates of 0-, 1-, 2-, and 4t/ha, while fly ash was applied at 0-, 7-, 14- and 28t/ha. These treatments were applied to an acidic sandy loam soils in the presence or absence of 4t/ha gypsum.

Beans were harvested after the first season following the application of amendments and maize was harvested in the second season. Yield, root length, leaf and soil analysis was undertaken to evaluate the effectiveness of the different liming materials. The effect of the treatments on fertility indicators such as pH, exchangeable acidity, Ca and Mg was investigated.

Results indicated that all liming materials increased topsoil pH, soil nutrient and base status and crop yield in both seasons. Calmasil was the superior liming material in all respects.

Fly ash increased pH minimally but reduced exchangeable acidity by 12% and 24% in the first and second seasons, respectively. Fly ash increased topsoil Ca levels from 74 to 102mg/kg and subsoil Ca from 61 to 114mg/kg. Topsoil Mg levels were increased from 7.3 to 16mg/kg and subsoil Mg was increased from 9.4 to 13mg/kg. The consequence of these increased nutrients was the subsequent increased foliar uptake of Ca and Mg. The substantial increase in bean yield from 958 to 1724kg/ha and maize yield from 5569 to 7553kg/ha following ash application compared well with results obtained from lime and Calmasil application. This may partly be due to the presence of additional plant nutrients such as P and K in the fly ash. Dissolution behaviour of fly ash indicates that upon exposure to acidity the release of

micronutrients like B, Co, Cu, Fe, Mo, Mn and Zn occurs, and preliminary data shows that there is comparatively little concern regarding heavy metal accumulation in crops.

The application of 4t/ha gypsum had no effect on pH and decreased subsoil acidity only minimally however, subsoil Ca status and acid saturation levels were considerably improved which would possibly account for the overall beneficial effect on maize yield, increasing by an average of 1071kg/ha.

It was not possible to make any conclusions relating treatment application and maize root length.

This field trial has confirmed that fly ash can be used as an efficient liming material and that it compares well with traditional liming materials.

Uittreksel

Suurgronde is ‘n groot beperking tot landbou wêreldwyd. Die Suid Afrikaanse Hoëveld het menigte suurgronde en verskeie steenkool-aangedrewe kragstasies. Hiedie kragstasies produseer alkaliese vliegas as ‘n afvalproduk. Hierdie vliegas kan dus dien as ‘n grondverbeteringsmiddel vir die aangrensende suurgronde.

‘n Tweejarige veldproef was onderneem om vliegas met ander kalsium-bevattende grondverbetereringsmiddels te vergelyk om die effek van ondergrondse suurheid op mielies op te hef. Hierdie veldproef was opgeset te Beestepan plaas in Middelburg, Mpumalanga. Dit het bestaan uit 24 behandelings wat drie keer herhaal was en lewer dus ‘n totaal van 72 persele.

Die kalkmateriale wat gebruik was, is onverweerde vliegas (KKE 10%), kalsitiese kalk (KKE 77%) en Calmasil (‘n kalsium silikaat slak, KKE 99%). Calmasil en kalk was toegedien teen 0-, 1-, 2-, en 4t/ha, en vliegas teen 0-, 7-, 14- en 28t/ha. Hierdie behandelinge was toegedien tot ‘n suur leemsand met of sonder gips. Gips was toegedien teen 4t/ha.

Een jaar nadat behandelinge toegedien was, is boontjies geoes en mieles was die daaropvolgende jaar geoes. Opbrengs, wortel lengte blaar- en grondontledings was uitgevoer om effektiwiteit te evalueer. Die effek van die behandelinge op indikatore van grondvrugbaarheid soos pH, uitruilbare suurheid, Ca en Mg was ondersoek. Resultate dui daarop dat alle kalkmateriale die grond se voedingstof- en basisstatus, bogrond pH asook gewasopbreng verhoog het. Calmasil was die beste kalkmateriaal in alle opsigte.

Vliegas het die pH minimaal verhoog, terwyl dit die uitruilbare suurheid verminder het met 12% en 24% in die eerste en tweede jaar onderskeidelik. Vliegas het bogrond Ca vlakke vanaf 74 tot 102mg/kg vermeer, sowel as ondergrond Ca vanaf 61 tot 114mg/kg. Bogrond Mg was vermeer vanaf 7.3 tot 16mg/kg, asook ondergrond Mg vanaf 9.4 tot 13 mg/kg. Die gevolg van hierdie verhoogde voedingstowwe was die toename van Ca en Mg in die blare van die gewasse.

Die beduidende toename in opbrengste van boontjies vanaf 958 tot 1724mg/kg en mielies vanaf 5569 tot 7553kg/ha na die toediening van vliegas vergelyk goed met die resultate van kalk en Calmasil. Dit is gedeeltelik toe te skryf aan die teenwoordigheid van addisionele plantvoedingstowwe soos P en K in vliegas. Oplossingstudies van vliegas dui op die teenwoordigheid van mikrovoedingstowwe soos B, Co, Cu, Fe, Mo,

Mn en Zn. Aanvanklike data wys dat daar relatief min kommer oor swaarmetaal akkumulasie in gewasse is.

Alhoewel 4t/ha gips geen effek op pH gehad het nie, en ondergondrondse suurheid minimaal verminder het, het ondergrondse Ca en gevolglik suurversadiging heelwat verbeter. Dit mag moontlik as verduideliking dien vir die oorhoofse voordelige effek van gips op mielie opbrengste, wat verhoog het met ‘n gemiddelde 1071kg/ha.

Oorvleuende omstandighede het daartoe gelei dat geen konkrete afleidings gemaak kon word oor die wortel lengte van die mielies nie.

Hierdie veldproef bevestig dat vliegas as ‘n effektiewe kalkmateriaal gebruik kan word en goed vergelyk met tradisionele kalkmateriale.

List of Abbreviations

CCE	Calcium Carbonate Equivalence
KKE	Kalsium Karbonaat Ekwivalent
ESKOM	Electricity Supply Commision
CCB	Coal Combustion Byproducts
FGD	Flue Gas Desulphurization
UK	United Kingdom
USA	United States of America
ASTM	American Society for Testing and Materials
EC	Electrical conductivity
IC	Ion Chromotography
AAS	Atomic Adsorption Spectroscopy
SEM	Scanning Electron Microscope
EDX	Energy Dispersive X-ray Spectroscopy
XRFS	X-ray Fluorescence Spectrometry
XRD	X-ray Diffraction
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
SEM-EDX	Scanning Electron Microscope – Energy Dispersive X-ray Spectroscopy
LOI	Loss On Ignition

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Chapter 1

Introduction

Depletion of soil fertility is one of the fundamental biophysical limitations for the declining per capita food production on the African continent (Sanchez and Leakey, 1997). It is intrinsically linked with soil acidification and it is a major problem worldwide (Santoceto *et al*., 2002). Acidic soils that limit crop production are found throughout the world and approximately 30-40% of the world's arable soils have a pH below 5.5 in water (Samac and Tesfaye, 2003).

In South Africa 16 million hectares of soils are naturally acidic (Laker, 2005). A further complication to acidity is the phenomena of acidic subsoils. These often occur in the developing world, South Africa included, and it is here that sustainable increases in food production are urgently needed (Farina and Channon, 1988a). Acidification is escalated by human-induced activities and the consequences are serious because it affects high yield-potential lands. The amelioration of these soils requires regular liming or rather alternatives thereof as the cost of lime application is expensive (Noble *et al*., 1996).

Eskom (Electricity Supply Commission), the South African electricity public utility, generates, transmits and distributes 95% of the electricity in South Africa. The generation of electricity is largely from the combustion of coal and with this Eskom annually produce approximately 30 million tons of fly ash (Potgieter, 2004). Only 5% of this material is currently utilised while the rest of this alkaline waste material is disposed of as a slurry in a landfill close to the coal power stations (Fatoba, 2007). Researchers have been encouraged to explore ways to increase the productive use of fly ash as it is increasingly an environmental concern. The fly ash generated by Eskom contains alkalinity and so it has been suggested that it could serve as a liming material for acidic soils.

The coalfields and power stations of Eskom are mainly situated in the Mpumalanga Province of the Eastern Highveld region in South Africa. These coalfields underlie one of the most important agricultural areas in the country as it is one of the key grain

producing provinces in South Africa (Jovanovic *et al*., 1998). Most farms surrounding the coal stations in Mpumalanga have naturally acidic soils that require liming.
The power stations are often located adjacent to farms, therefore the two problems of alkaline fly ash accumulation and the costly amelioration of acidic soils in the area, could potentially be solved simultaneously by using fly ash as an alternative agricultural liming material. This is the essence of the research questions on which this thesis is based. Due to the proximity of the ash to the farms, transportation costs would be decreased in comparison to other liming material transport costs and therefore needs investigating. A further advantage in the utilization of fly ash is the small particle size that ranges between 20-80 microns (Mattigod *et al*., 1990, Bezuidenhout, 1995) as the degree of fineness is widely recognised as the major factor in the selection of a liming material (Tisdale *et al*., 1990) and a finer material means that no crushing is needed, thus further reducing cost and increasing the efficiency of the material.

Fly ash has similar properties to agricultural lime and has been researched for approximately seven years under South African conditions (Truter and Rethman, 2005) and for more extensive periods in other countries. Kumar *et al*. (2000) and Basu *et al*. (2009) undertook reviews of previous work done on the agricultural applications of fly ash. They concluded that the amount of fly ash and the method of application vary with soil type, crop grown, fly ash source and existing agro-climatic conditions. In order to test whether Eskom fly ash is a viable alternative liming material on the South African Highveld, it is essential to evaluate the effects of the Eskom fly ash under the prevailing conditions. Several industrial slags are used annually as liming materials in the Higveld due to the close proximity of slag producing steel plants (Van der Waals and Claassens, 2002). An example is Calmasil, which is a stainless steel slag that is dominantly comprised of approximately 35% Ca and 15% Si.

This project seeks to examine the suitability of fly ash as a substitute calcium ameliorant instead of calcitic lime and Calmasil. In this study the effect of fly ash on alleviating the effects of subsoil acidity on maize root development was studied.
A factorial study was undertaken on Beestepan farm, near Middelburg, Mpumalanga (25° 46' 60S, 29° 28' 0E). According to the soil classification system of South Africa the soil is a clay loam soil of the Bainsvlei and Avalon forms (MacVicar *et al*., 1977).

Nomenclature under the IUSS Working Group WRB (2006) would classify the soil as a plinthic Acrisol (dystric, rhodic). Saprolite is found approximately 1m below the soil surface and the site has an average topsoil pH_{KCl} of 4.0.

Three alkaline materials (fly ash, Calmasil and calcitic lime) are compared in the field trial, both with and without the addition of gypsum. These ameliorants were applied at four different levels. Gypsum (phosphogypsum) was included in the trial as previous research by Farina *et al*. (2000(a, b)) and Shainberg *et al*. (1989) showed encouraging results in combating subsoil acidity due to the promotion of calcium movement down the soil profile. Therefore it was deemed necessary to compare the effectiveness of the liming materials with this highly soluble material. The fly ash that was used in this trial was obtained from the Duvha coal power station in Mpumalanga. Calcitic lime was obtained from Immerpan lime and Calmasil is a blast furnace calcium silicate slag that is locally available and utilised as a liming material.

This research study has the following objectives:

1. To determine if fly ash serves as an effective and practical source of alkalinity to reduce acidity in soils on the South African Highveld.

2. To study the dissolution behaviour of fly ash to understand the liming efficiency and effect on nutrient movement.

3. To determine if fly ash can compete with other calcium ameliorants in relation to soil nutrient movement, root development and yield.

4. To evaluate the effect of the gypsum application on nutrient movement and crop yield and study the interactions with the different liming materials used.

To address the aforementioned issues, this thesis consists of three sections. The first section (Chapter 2) is an overview of the literature on soil acidity, the effect of acidity on maize growth, the global use of fly ash with a focus on ameliorating soil acidity, and results obtained from several previous field trials with gypsum, lime and fly ash. The second section (Chapter 3) deals with the dissolution behaviour of fly ash and the possible effects on nutrient movement in soil. Section 3 (Chapter 4) is assigned to the results obtained from the field trial where different treatments will be compared on the subjects of pH and acidity, exchangeable and water soluble cations, nutrient movement down the soil profile, foliar nutrient concentration, yield and root density.

Chapter 2

A review of the alleviation of soil acidity with calcium containing liming materials and its effect on maize root development with a special focus on fly ash

2.1 Introduction

Acidic soils and their occurrence is a well researched and documented area. Subsoil acidity is a major factor that limits crop yield in vast areas of the world and it is particularly prevalent in the humid tropics and subtropics and climatic zones that include many of the world's countries struggling to achieve self-sufficiency in food production (Farina *et al*., 2000b).

South Africa's electricity is mostly derived from coal fired power stations and a result of this is the production of approximately 30 million tonnes of fly ash per annum (Potgieter, 2004). It is likely that the volume of coal combustion byproducts (CCB) produced will increase with increasing population as there tends to be increasing electricity demands. CCB's include a number of residues, namely bottom ash, boiler slag, fly ash, flue gas desulphurization sludge and non captured particles (Mattigod *et al*., 1990; Fytianos *et al*., 1998). The amount of each residue depends on the power plant configuration and emission control devices (Fytianos *et al*., 1998; Jala and Goyal, 2006; Fatoba, 2007). Typical percentages of materials in CCB are 70% fly ash, 10-12% bottom ash, 4-6% boiler slag and 10-12% flue gas desulphurization (FGD) material (Jala and Goyal, 2006). Bottom ash is the large ash particles that accumulate at the bottom of the boiler and boiler slag is the molten inorganic material that is collected at the bottom of the boilers and discharged into a water-filled pit. Fly ash is the fine fraction of the coal combustion products, which is carried out of the boilers by the flue gases (Fatoba, 2007). Fly ash and bottom ash are the predominantly inorganic fraction of the coal that has undergone heating (Bezuidenhout, 1995).

In South Africa fly ash is currently disposed of in landfills and ash dams or settling ponds (O' Brien, 2000; Fatoba, 2007). In countries like Denmark, France, UK and the

Netherlands more than 85% of the fly ash is used. USA and Germany use 50-85% of fly ash and China 25-45% (Basu *et al*., 2009; Pandey *et al*., 2009). Fly ash utilization in India was 35% in 2005 due to the unavailability of affordable effective technologies (Basu *et al*., 2009). Up to 70% of fly ash in Denmark, Germany, France, UK and the Netherlands is used for building materials, ceramics and other civil construction purposes, while only 15% is used in India for that purpose (Sharma and Kalra, 2006). Fly ash is used in road base construction and mineral filler in asphaltic mix (Dutta at al., 2009). Fly ash is also used for agricultural and wasteland reclamation in these countries. South Africa utilizes 5% of the produced fly ash (O'Brien, 2000) and with the storage of ash in dams, it is important that ash is carefully sealed and monitored as otherwise it can have potentially negative impacts on the environment (Pandey *et al*., 2009). A need to re-evaluate the potential uses of fly ash in South Africa, especially in an agronomic perspective, therefore exists.

This review looks at the causes and effects of soil acidity, the use of liming materials including fly ash and their effectiveness in the amelioration of acidic soils. The dissolution behaviour of the liming materials, with the focus on fly ash is also reviewed. The main purpose of this review is to evaluate the studies done on the use of fly ash as an acidic soil ameliorant for improvement of crop yield and quality. This review also aims to show how this study fits in with other field trials that have been done around the world, and highlight the positive and negative effects of fly ash use.

2.2 The causes of soil acidity

Soil acidification is a natural process and occurs in many soil environments, and is accelerated by agricultural practices, pollution from industrial mining and other human activities (McBride, 1994). An acid soil is defined as a soil with a soil solution pH of less than 7, but excessive soil acidity is indicated by a soil solution pH of less than 5.0-5.5 in water and is a concern from an environmental and agronomic perspective (Essington, 2003).

2.2.1 Natural acidification

Leaching or hydrolytic dissociation of exchangeable bases

Hydrolytic displacement of cations is an inevitable natural process that takes place due to the reaction of water with parent material as shown below (Fey *et al*., 1990):

$$\text{Na-colloid} + H_2O \rightarrow \text{H-colloid} + NaOH$$

Water reacts with the CO_2 in the soil it and forms carbonic acid. Carbonic acid assists in the dissociation of the basic cations and subsequent replacement by protons. Acidification only occurs when the soluble base is removed by leaching or plant uptake (Fey *et al*., 1990). After prolonged intense weathering of the parent material only oxides and hydroxides of aluminium and iron remain. This effect is greater in the humid tropics than in the moderate cooler climatic regions (Fey *et al*., 1990).

2.2.1.1 Carbon dioxide

Atmospheric CO_2 dissolves in water to form carbonic acid and react with parent material and the soil (FSSA Fertilizer handbook, 2003). Metabolic activity of roots, micro organisms and other living organisms contribute to the acidification of soils by generating CO_2, soluble organic acids and acidic organic acids during respiration (McBride, 1994).

2.2.1.2 Plant uptake of nutrients

The form of nitrogen used by plants determines if an excess cation or anion is taken up. To maintain electroneutrality, NH_4^+ uptake by plants results in exudation of H^+ and NO_3^- uptake will release OH^- or HCO_3^-(McBride, 1994). Since cation uptake generally exceeds anion uptake in natural plants, the exudation of acidity exceeds the generation of alkalinity by plants (Essington, 2003).

2.2.1.3 Nitrogen and sulfur oxidation

Oxidation of reduced forms of S and N can acidify soils (McBride, 1994). If sulfide particles which are initially insoluble are present in the soil, oxidation can be rapid once soils are aerated (McBride, 1994).

The mechanism is as follows:

$$FeS_2 \text{ (pyrite)} + O_2 \rightarrow 4H^+ + 2SO_4^{2-} + 1/2Fe_2O_3$$

A significant extension of this mechanism is the genesis of acid sulfate soils. Dent and Pons (1995) considered these soils to be the nastiest in the world because they generate sulfuric acid and cause the soil pH to plummet as low as 2. The acid can leak into drainage and floodwater (Dent and Pons, 1995). Acid sulphate soils occur in coastal regions, freshwater wetlands and sulfate-rich groundwater agricultural areas. They can also occur at mining sites due to the acidic drainage waters.

2.2.1.4 Nitrification

Nitrification is mainly influenced by pH, temperature, moisture and O_2 supply and is a key process in the humid tropics because high nitrate leaching after heavy tropical rainfall results in greater acidification (Sierra *et al*., 2006).

Nitrification is acidifying once NO_3^- is leached from soils (McBride, 1994):

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

2.2.1.5 Acid rain

Acid rain (with a pH_{water} in the region of 4) contains nitric acid and sulphuric acid. When it rains they act as a source of hydrogen and increase the rate of soil acidification (Samac and Tesfaye, 2003). Acid rain is mainly of anthropogenic origin due to the strong presence of SO_2 and NO_x gases and the formation of acid rain takes place as follows (Calace *et al*., 2001):

$$NO_2 + 1/4O_2 + 1/2H_2O \rightarrow HNO_3$$

$$SO_2 + 1/2O_2 + H_2O \rightarrow H_2SO_4$$

If acid rain continues over a long period, the natural buffer capacity of the soil can be fully exhausted and soil can be further acidified (Zhuang *et al*., 2006).

2.2.2 Anthropogenic causes

Most soils with pH_{KCl} values of less than 4.0-4.5 or greater than 8.5 have been impacted by human activities (Essington, 2003). Certain agricultural practices, accelerated climatic change and acid rain due to industrial activity, are all causes induced by human activities.

2.2.2.1 Crop removal

Harvesting removes plant matter, thereby preventing bases taken up by plants from the soil being returned to the soil. Without any external input of bases by fertilizer for example, this can lead to permanent soil acidification (FSSA Fertilizer Handbook, 2003). Essentially soil acidification can be attributed to two processes: the addition of acids and the removal of bases by leaching or biomass accumulation (Vlek *et al*., 1997). Vlek *et al*. (1997) estimated that a minimum of 4 million tons of nutrients are harvested annually in Sub Saharan Africa and only one-fourth are returned in the form of fertilizer. This removal of bases and nutrients causes acidification if it is not replenished by the use of fertilizers or other base sources.

2.2.2.2 Use of fertilizers

Fertilizer that contains ammonium compounds is the largest anthropogenic contributor to soil acidification. The acidifying effect of these fertilizers is based on the nitrification process, whereby nitrate and protons are released into the soil (Samac and Tesfaye, 2003). The rate of acidification is influenced by the form and amount of N fertilizer applied (Mahler and Harder, 1984; Brown *et al*., 2008).

Work done by Mahler and Harder (1984) indicated that after the introduction of ammonium fertilizers in the 1960s, the average pH in the first 30cm of agricultural soils in the region declined from a pH_{water} of 6.5–7.2 to less than 5.7 in 1984.

Phosphate-containing fertilizers, when added as phosphate salts, may cause acidification when used over a long period of time. Superphosphate releases $H_2PO_4^-$ in the soil, which only dissociates at a neutral pH of 7. But a less soluble phosphate mineral eventually precipitates in alkaline or acidic soils to produce acidity in soils. The other benefit of this is that the phosphate fertilizers can decrease phytotoxic Al^{3+} in acidic soils by precipitating Al^{3+} at the current pH (McBride, 1994).

2.3 The causes of subsoil acidity

Subsoil acidity is characterized by low Ca^{2+} and high Al^{3+} levels at depths below the plow layer (Liu and Hue, 2001, Farina and Channon, 1988a). It is an important crop yield-limiting factor in areas that suffer from water stress (Tang *et al* 2002). The causes of subsoil acidity are not fully understood, but the acid release by plant roots due to excess cation uptake is a major cause (Tang, 2004). This is especially true for plant uptake of NH_4^+ and the amount of acid generated is comparative to the root length distribution. Legumes cause more soil acidification than non-leguminous species (McLay *et al*., 1994a; Tang *et al*., 2000) and Tang *et al*.' s work shows that the acidification by nitrification and nitrate leaching does not contribute to subsoil acidity (Tang *et al*., 2000, Tang 2004). The movement of H^+, Al^{3+}, and NH_4^+ may contribute negligibly to subsoil acidification (Hue and Licudine, 1999; Tang 2004).

2.4 The effects of acidity on plant nutrient availability

Soil pH is important for nutrient availability to plants and extreme pH conditions encourage mineral stress. Plants grown on acid soils (pH_{water} <5.5) have deficiencies

of P, N, Ca^{2+}, K^{+} and Mg^{2+} or toxicities of H^{+}, Al^{3+} and Mn^{2+} (Marschner, 1991; Sumner and Yamada, 2002).

As the pH_{KCl} falls below 4.5 the aluminium concentration increases rapidly. Aluminium is solubilized into the toxic Al^{3+} and it proves to be a great limitation to plant productivity (Ma *et al*., 2001). Aluminium toxicity is regarded as the universal factor of acid-soil infertility and the concentration in the solution is dependent on the soil pH, organic matter content and the solubility of minerals that contain Al^{3+}.(Adams and Lund, 1966; Adams, 1981). Soil pH cannot predict the toxicity levels of Al^{3+}. pH and soil solution Al^{3+} is therefore not a convenient measure but rather exchangeable Al^{3+} (Adams, 1981).

The plant availability of Mn is sensitive to changes in soil acidity and reducing conditions (Kogelmann and Sharpe, 2006). Low pH conditions induce reduction of Mn^{4+} to $Mn^{2+}$and when plants absorb an excess Mn^{2+} it leads to toxicity. Manganese can be a toxic agent to plants by decreasing photosynthesis and therefore reducing yield (Kogelmann and Sharpe, 2006).

In acidic soils that are high in Fe, Mo deficiency in legumes occurs (Marschner, 1991), but it is especially prone to occur in soils where the pH is less than 5.6. This could be explained by the role Mo plays in the nitrogen–fixation by *rhizobia* (Adams, 1981). A decrease in $Ca^{2+,}$ K^{+} and Mg^{2+} occurs in acidic soils and plant uptake of these nutrients is severely lowered.

In highly weathered and acidic soils, P is not readily available for crop use, because Al and Fe hydrous oxides can also absorb P onto their surfaces (Haynes and Mokolobate, 2001). Phosphorous also forms complexes with soluble Al in acidic ranges.

2.5 Soil acidity in Mpumalanga, South Africa

In South Africa there is very little arable land and only one third (4.5million ha) is regarded as high potential (Jovanovic *et al*., 1998). Further, on average the country has a low and inconsistent rainfall with 66% of the country being classified as semi-arid to arid (Jovanovic *et al*., 1998). Such agricultural limitations demand careful

management of the arable soils in the country, for both production and environmental reasons.

Most soils in the Mpumalanga province (67%) fall within a pH_{water} band of 5.2- 6.5. Approximately 24% of land is considered neutral (pH_{water} of 6.5-7.3) while only 2% is considered alkaline (pH_{water} of 7.3-8.4). The area of greatest acidity (pH_{water} less than 5.2) includes 8% of the province and compares with the areas afforested under commercial species (Mpumalanga state of the environment report, 2003).

Much of the soils in Mpumalanga are naturally acidic and Mpumalanga has a fairly high average rainfall of greater than 800 mm per annum (Van der Waals and Claassens, 2002). This rain can be highly acidic from the sulphur released by the large number of coal burning power stations, and there are concerns that rain on the Mpumalanga escarpment may increase the leaching potential of cations (Dames et. al., 2002).

2.6 Soil acidity and maize root development

Maize (*Zea mays*) is an important part of the sub Saharan African diet and produced throughout South Africa under diverse environments (Du Plessis, 2003). For any crop to grow it requires certain climatic and soil nutrient requirements. Given the same management system, these requirements greatly influence the production potential of any crop.

Maize growth is limited by soil acidity only if toxic levels of elements like Al are reached. This is reached at $pH_{KCl} < 4.4$ or at $pH_{water} < 5.4$, but this does not necessarily mean that Al toxicity will occur at these hydrogen activities (Du Toit, 1999). It is only when the acid saturation reaches 20% and above that toxic Al levels are reached. Al toxicity is usually demonstrated by short and thick roots without any fine root hairs (Farina and Channon, 1991).

Aluminium toxicity primarily affects root elongation and functioning as a result of root apex disruption (Jorge and Menossi, 2005; Sierra *et al*., 2006). It has a restrictive influence on the calcium and magnesium uptake of plants (Tisdale *et al*., 1990). Inhibition of plant growth is proportional to the exchangeable Al or the Al saturation

level. These levels are extremely soil dependant. Root apical aluminum exclusion *via* Al-activated root citrate exudation is widely accepted as the main Al-resistance mechanism operating in maize roots (Pineros *et al*., 2005). Other mechanisms to overcome toxicity and increase resistance of maize to Al toxicity have been widely studied (Jorge and Menossi, 2005).

The relationship between exchangeable and soluble Al and pH depends upon the soil mineralogy and clay content (McLean, 1982; Sierra *et al*., 2006). The sensitivity of maize roots to acidity is due to two indirect effects which are the increased solubility of Al ions and the decrease in available P. When the maize experiences soil P stress it develops mechanisms, such as mycorrhizal symbioses and release of exudates, to make water more available (Sierra *et al*., 2006). It also changes its root morphology and physiology by producing root hairs that can accumulate P (Sierra *et al*., 2006). In affecting the root length and therefore the distribution, the plant's ability to take up water and nutrients decreases and it leads to poor growth (Sierra *et al*., 2006).

2.7 Ameliorants used for soil acidity

For maize to adapt to the ever-changing exterior conditions, maize hybrid technology is relentlessly improving to overcome these inadequacies. Some maize hybrids can tolerate acidity but no hybrid is resistant to it and soil acidity should therefore be ameliorated with a suitable alkaline material.

Agricultural liming is an age old practice and a liming material is defined as any compound that increases soil pH by combining with hydrogen ions in the soil. Liming materials can therefore include oxides, hydroxides, carbonates and silicates of Ca^{2+} and Mg^{2+}. In addition to this criteria the anion must reduce the hydrogen activity and hence the Al in the soil solution (Tisdale *et al*., 1990).

The reactions of these materials with the acid soils are complex. Common liming material are calcium oxide (quicklime), calcium hydroxide (slaked lime), calcium carbonate (calcitic lime), calcium-magnesium carbonates (dolomitic lime), marl and slags (Tisdale *et al*., 1990, Materechera and Mkhabela, 2002; Van der Waals and Claassens, 2002). Slags include basic slag, furnace-electric slag and blast-furnace slag

and sundry liming materials include fly ash and sludge from industrial water treatment plants (Tisdale *et al*., 1990).

Literature shows that there are a variety of alternative materials to agricultural lime that are used in an attempt to alleviate acidity. These materials could potentially be economically beneficial for poor farmers and it can aid in areas where lime is not readily available (Mokolobate and Haynes, 2002). The use of plant residues as ameliorants of soil acidity for the highly weathered soils of the sub-humid tropics has been reported, as the high alkalinity of these residues makes it possible ameliorants (Sakala *et al*., 2004). Experimental work has also been done to evaluate the effects of water soluble plant extracts on soil acidity (Meda *et al*, 2001). A variety of organic materials can be used, such as manure, plant residues (Shen and Shen, 2001) and guano. Mokolabate and Haynes (2002) compared the liming effect of poultry manure, filter cakes, household compost and grass residues on maize in an acidic Oxisol. These materials were added at a rate of 20 t/ha and incubated for six weeks. All materials increased pH, decreased exchangeable Al and raised the levels of exchangeable cations and extractable P relative to the control.

In Korea crushed oyster shells were evaluated as a liming material for Chinese cabbage (*Brassica campestris L*.) (Lee *et al*., 2008), while pulp mill inorganic wastes such as wood ash, residue and grits were evaluated in a laboratory experiment and found to be efficient at raising pH (Cabral *et al*., 2008).

Noble *et al*. (1996) evaluated the neutralizing ability of leaf litter ash alkalinity on acid soils. It was illustrated that the increase in pH was proportional to the ash alkalinity and Al levels were lowered by direct treatment with leaf litter.

Liming increases the pH and these increases are explained by (i) proton consumption of the organic material's functional groups, (ii) proton consumption during decarboxylation of organic acids during decomposition (Noble *et al*., 1996), (iii) OH^- release during ligand exchange (Hue *et al*,. 1986) or (iv) reduction reactions (Mokolobate and Haynes, 2002). They explain the Al decrease with the formation of soluble organic matter- Al complexes.

The greatest direct benefit of liming is the decrease in Al and Mn solubility. Liming improves root development, nutrient uptake and it supplies necessary elements like Ca and Mg (Tisdale *et al*., 1990; Mokolobate and Haynes, 2002). The indirect benefits include increased P availability, micronutrient availability, nitrification and nitrogen fixation and it indirectly improves the physical conditions of the soil and reduces certain plant pathogens that thrive in acidic soils (Tisdale *et al*., 1990).

The quality of any liming material depends on the neutralizing value, Mg content, moisture content, fineness and reactivity. The liming ability of other materials compared to calcitic lime is measured by their calcium carbonate equivalence (CCE) (McLean, 1982; Tisdale *et al*., 1990).

Calcitic lime reacts with soil in the following manner to form Ca bicarbonate:

$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$$

This Ca bicarbonate then further results in the formation of OH^- which can react with H^+ to form water or hydroxyl groups:

$$Ca(HCO_3)_2 \rightarrow Ca^{2+} + 2OH^- + CO_2$$

These released OH^- can react with exchangeable Al^{3+} and other partially hydrolysed Al^{3+} to form insoluble $Al(OH)_3$, hence decreasing Al^{3+} activity in the following manner:

$$Al^{3+} + 3OH^- \rightarrow Al(OH)_3$$

Lime therefore increases pH by decreasing H^+ and Al^{3+} activity (Rechcigl, 1995).

Liming soils normally decreases the SO_4^{2-} availability to plants as sulfate adsorption is decreased with increased pH. The solubility of other plant micronutrients such as B, Mn, Cu, Zn and Fe become less soluble with increasing pH and therefore less toxic to plants (Rechcigl, 1995). Liming only affects the topsoil and does not remove Al in the subsoil where it poses as a severe problem (Toma *et al*., 1999; Sierra *et al*., 2006). Liming of the soil to a pH_{water} of 5.6 can reduce soil Mn^{2+} to acceptable levels, (Baligar *et al*., 1997), but liming subsoils is also usually prohibitively expensive (Tang *et al*., 2002), while negative plant responses to liming have been reported to occur on highly weathered and acidic soils of the tropics (Carran, 1991). For maize in South Africa the amount of lime needed should neutralize both active and reserve

acidity to 15% or below so that there is some buffer against re-acidification and Al-toxicity (Du Toit, 1999).

Amelioration of subsoil acidity with surface application of lime, albeit heavy applications or deep application, is often ineffective due to the low solubility of lime and the subsequent limited movement down the soil profile (Oates and Caldwell, 1985; Farina and Channon, 1988b; Sumner, 1990; Smith *et al*., 1994; Tang, 2004). Common practices used for this purpose include deep application of lime (Sumner, 1990; Farina *et al*., 2000b), the use of more soluble liming materials and the use of gypsum or phosphogypsum (Pavan *et al*., 1984; Sumner, 1990; Smith *et al*., 1994, Toma *et al*., 1999; Wang *et al*., 1999; Farina *et al*., 2000b).

2.8 Fly ash

2.8.1 Origin and production

Fly ash is a product of coal combustion at high temperatures. The four types of coal are anthracite, bituminous coal, sub-bituminous coal and lignite (Cunningham and Saigo, 1990, Mattigod *et al*., 1990). These four types of coal vary with regard to their heating value, chemical composition, ash content, geological origin and age. Coal is a complex material that contains organic matter, water, oils, gases (such as methane), waxes, and inorganic matter (Fatoba, 2007; Love *et al*., 2009).

Eskom generates approximately 30 million tons of fly ash annually (Potgieter, 2004) while the USA is generating 118 million tons of CCPs each year and India follows with 100 million tons per annum (Jala and Goyal, 2006, Pandey *et al*., 2009). Fly ash can be disposed of by wet or dry methods. In the former method it can be washed out into artificial lagoons and it is then called pond ash (Jala and Goyal, 2006). Both methods allow for the dumping of ash on open land, where soil degradation can take place and humans and the environment can be put in danger (Kim 2006; Jegadeesan *et al*., 2008). In South Africa, fly ash is being disposed of by pumping it in slurry form into settling ponds or stockpiled on land (dry method) (Fatoba, 2007).

2.8.2 Morphological and physico-chemical properties

The physical and chemical properties of fly ash depend on the coal's geological origin, combustion conditions, efficiency of particulate removal, and degree of weathering before final disposal (Adriano *et al*., 1980, Kashiwakura *et al*., 2009). Therefore ash produced by burning of anthracite, bituminous and lignite coal has different compositions. In most coal producing countries like Australia and South Africa significant differences are found in the composition of fly ash obtained from different power stations (Bezuidenhout, 1995). This reflects upon the differences found in the parent coal composition from the different seams and different coal mines (Bezuidenhout, 1995).

The morphological appearance of fly ash can be related to the reactive properties of fly ash. Fly ash consists of spherical glass like particles ranging in size from 0.01 to 100 microns (Chang *et al*., 1977; Fatoba, 2007). The spherical, glassy and transparent spheres are formed by the melting of the silicate materials during combustion (Adriano *et al*., 1980; Mattigod *et al*., 1990). Some particles are hollow, empty spheres (cenospheres) and others (plerospheres) are filled with smaller amorphous particles and crystals (Adriano *et al*., 1980).

The colour of fly ash varies from grey to black, hence the lighter the colour, the lower the unburned carbon content of fly ash (Adriano *et al*., 1980). Fly ash in some cases has a smooth, hydrophilic surface and is extremely porous. These surfaces contain higher amounts of CaO which will easily dissolve into solution at a faster rate than the elements locked in the glass matrix (Mattigod *et al*., 1990; Kim, 2003).

Fly ash normally has a low bulk density and high surface area (Kumar *et al*., 2000; Basu *et al*., 2009). The specific gravity of the fly ash ranges from 2.1–2.6g/cm^3. Mean particle density for magnetic and non magnetic particles is 2.7 and 3.4g/cm^3 respectively while bulk density varies from 1.0–1.8 g/cm (Mattigod *et al*., 1990; Basu *et al*., 2009). The specific surface area of fly ash can range from 200-300m^2/kg (Mattigod *et al*., 1990). The pH varies from 4.5 to 12.0 and this depends on the sulphur content of the parent material (Jala and Goyal, 2006).

Two main types of ash exist: class F (low lime) and class C (high lime) based on silica, alumina and iron oxide content of fly ash (Manz, 1999; Jegadeesan *et al*.,

2008). Elemental analysis shows that fly ash is an amorphous ferro-alumino silicate mineral that consists of approximately 95-99% of Si, Al, Fe and Ca, 0.5-3.5% Na, P, K and S, while the rest is trace elements (Warren and Dudas, 1984; Kalra *et al*., 1998; Kumar *et al*., 2000) and many trace elements are located in the smaller particles (Fytianos *et al*., 1998; Iyer, 2002).

Typical minerals found are quartz (SiO_2), mullite ($3Al_2O_3.2SiO_2$), hematite and magnetite (Adriano *et al*., 1980).

2.9 Uses of fly ash

Local legislation in South Africa requires more effective ways of disposing ash (Fatoba, 2007) and to date fly ash is used in agriculture, wasteland reclamation and for civil engineering purposes (Manz, 1999; Jala and Goyal, 2006).

The use of fly ash can have several benefits, such as conservation of natural resources by a decrease in the demand for landfill space. This can lead to an overall decrease in the cost of electricity generation as minimal resources, thus less cost, will be used for waste management. Fly ash can be applied to acidic strip mine spoils to neutralize acidity of acid mine drainage (AMD) (O' Brien, 2000; Dutta *et al*., 2009). It has also been used for the treatment of soils and acid mine drainage, as an additive to cement and concrete products and for synthesis of zeolites (Jala and Goyal, 2006). As fly ash contains all the elements in soil except organic C and nitrogen, it serves as a promising additive for agricultural purposes (Kumar *et al*., 2000).

2.9.1 Use of fly ash in concrete

The pozzolanic behaviour of fly ash allows it to replace up to 15% of Portland cement (Okoh *et al*, 1997). Portland cement is hydraulic cement that contains Ca_3SiO_5, Ca_2SiO_4, $Ca_3Al_2O_6$ and during setting of the concrete, the calcium silicates undergo solidification, which is the hydration and hydrolysis to form a gelatinous hydrated silicate on the surface of sand and rock particles. In due time the removal of water from the hydrates by dry cement particles leads to the hardening of concrete.

$$2Ca_3SiO_5\ (s) + 6H_2O(l) \rightarrow Ca_3Si_2O_7.3H_2O(s) + 3Ca(OH)_2\ (s)$$

In the presence of moisture, the siliceous and/or siliceous-alumina components in fly ash react with calcium hydroxide, a by-product of the above reaction between cement

and water, to form additional cementitious compounds. These compounds provide additional bonding and strength (Okoh, *et al*, 1997, Manz 1999).

Traditionally, with bituminous-type fly ashes, only 15-25% of cement was replaced, but with high-lime fly ashes replacements of 25–40% and up to 75% can be achieved (Manz, 1999).

2.9.2 Use of fly ash in agriculture

The composition of fly ash makes it a promising additive for agricultural purposes (Kumar *et al*., 2000; Pathan *et al*., 2003; Spark and Swift, 2008). A fair amount of work has been done during the last forty years to justify the use of fly ash in agriculture (Basu *et al*., 2009).

- **Improvement of soil properties**

Reported benefits related to soil improvement include the modification of soil texture, bulk density, improvement of water holding capacity and changing pH (Kumar *et al*., 2000; Jala and Goyal, 2006). It also reduces soil crusting and has a positive effect on growth and yield of crops (Kumar *et al*., 2000; Tripathi *et al*., 2009).

The fine particle size of fly ash makes it ideal for texture amendments and can turn sandy and clay soils into loamy soils if applied in vast quantities of 70 t/ha (Basu *et al*., 2009). The silt size range of fly ash plays a role in lowering the bulk density of soils (Adriano *et al*., 1980; Sharma and Kalra, 2006). This in turn improves porosity, workability of the soil, root penetration and moisture retention of soil (Kumar *et al*., 2000; Pathan *et al*., 2003). Chang *et al*. (1977) reported that an 8% (w/w) addition of fly ash increases the water holding capacity and that hydraulic conductivity improved with low application rates but deteriorate at high application rates. Fly ash reduces surface encrustation, which improves soil aeration and improvement of plant germination (Kumar *et al*., 2000), and increases the electrical conductivity (McLay *et al*., 1994b).

Fly ash is enriched with S, Ca, Mo, Sr, B and Se (Fytianos *et al*., 1998). Therefore an inevitable benefit of the addition of essential plant nutrients takes place when fly ash is added. The excessive use of unweathered fly ash has the drawback of potentially

increasing soil salinity and toxic levels of certain trace elements (Adriano *et al*., 1980; Pathan *et al*., 2003) like B, Cd, Mn, Sr and Se. The lime in fly ash readily reacts with acidic components in soil and release nutrients like S, B and Mo in forms and amounts beneficial to crops (Jala and Goyal, 2006; Pandey *et al*., 2009) and an increase in K and P is normally found (Kumar *et al*., 2000).

Overall the physical properties of the soil are being improved and heavy metals are below detectable levels in soil. Results so far show that with the correct application levels, the concern regarding heavy metals and radioactivity levels hold no ground (Kalra *et al*., 1998; Wright *et al*., 1998; Kumar *et al*., 2000; Sharma and Kalra; 2006).

- **Growth and yield of crops**

Various workers have reported on the positive impact of fly ash on plant growth and yield. Yield increases of 45% and 29% have been reported with potato and tomato respectively at the Indian regional research laboratory (Kumar *et al*., 2000).

Crop responses depend on a combination of factors such as method of application, physicochemical properties of the ash and soil, precipitation and plant species., but the overall response is positive (Pandey *et al*., 2009). In the USA, the addition of 8% (w/w) fly ash in acidic soils resulted in higher yields of several agronomic crops mainly due to increased availability of S to plants (Jala and Goyal, 2006).

Fly ash is not an optimal source of P and N, but it nonetheless accelerates the uptake of Ca and Mg by legumes (Adriano *et al*., 1980). High concentrations of elements such as Na, K, Ca, Mg, Zn and Fe in fly ash increase yields of agricultural crops, but the application of unweathered fly ash at high levels results in the accumulation of elements such as B, Se, Mo and Al in crops (Jala and Goyal, 2006; Sharma and Kalra, 2006). Selenium accumulation in plants with fly ash addition merits close monitoring of appropriate quantities and higher B availability limits the use of fly ash at high levels in crop production but it can be overcome by proper weathering of fly ash (Jala and Goyal, 2006; Kashiwakura *et al*., 2009).

Acid mine strips treated with fly ash showed an increase in yield due to increased plant nutrient availability, prevention of toxic effects of Al and Mn by neutralizing the

soil (Adriano *et al*, 1980; Petrik *et al*., 2003). Most of the studies indicate that the chemical constituents of fly ash can improve growth of crops, but care should be taken with the application rate to prevent detrimental accumulation of trace elements.

2.10 Dissolution behaviour of fly ash

Knowledge of the dissolution (leaching) behaviour of any liming material is imperative. It gives insight into the behaviour of the material under a given set of external conditions, and this in turn determines the liming interval. Liming interval is crucial as the bulk of the expense of liming is in transportation. Dissolution behaviour is even more applicable to fly ash as it is extremely varied in physical and chemical properties.

Leaching is related to the solubility of materials and can be influenced by pH, temperature, complexation, oxidation/reduction potential and several critical factors, including specific element solubility and availability or release potential (Kim, 2002; Kim, 2003; Fatoba 2007). According to Fatoba (2007) and Bendz *et al*. (2007), the larger surface area is inclined to hydrolysis. The surface layer of fly ash particles are only microns thick, but contain significant amounts of leachable material (Iyer, 2002).

It has been found that the acid neutralising capacity and carbonation reactions are good indicators of the pH changes observed in the leaching process (Fatoba, 2007) and hydration plays an important role in chemical weathering of ash as it transforms the primary minerals (Adriano *et al*., 1980).

Fly ash consists of three groups of solid components. The first group has low water reactivity but possess surface electric charge. These solids are made up of silica, Al_2O_3, Fe_2O_3 and TiO_2. The second group is the metals or metalloids adsorbed onto the oxide surfaces. They are the heavy metals or oxyanions adsorbed onto the surface of the oxides which are presented by the smallest fly ash particles. The third group is the highly water reactive compounds which are oxides of Ca, Mg, K, Na, Ba and gypsum (Kim, 2003).

Most fly ash leachates are alkaline with a pH ranging between 11 and 13. The dissolution and hydrolysis of oxide components such as CaO and MgO in fly ash

contributes to this high pH value. The dissolution of soluble acids, such as B_2O_3, and salts containing hydrolysable constituents, such as $Fe_2(SO_4)_3$ and $Al_2(SO_4)_3$, may contribute to lower pH values (Reardon *et al*., 1995).

Mineral acids dissolve alkaline fly ash much more than water and have consequently been used to characterize the reactivity of alkaline ashes (Warren and Dudas, 1984). An increase in concentration of the hydronium ion (acid) enhances the dissolution of aluminium. Aluminium dissolution is controlled by amorphous $Al(OH)_3$ for a pH ranging between 6 and 9, and by gibbsite for pH higher than 9. The release of silicon is said to be governed by the solubility of quartz (SiO_2) at pH lower than 10 and by solubility of wairakite ($CaAl_2Si_4O_{122}O$) at higher pH values (Tiruta-Barna *et al*., 2006).

Acidic solutions slowly attack iron oxides and even aluminosilicate minerals (Praharaj *et al*., 2002). After a swift initial pH rise of the effluent due to CaO and MgO hydrolysis, the pH reaches a stable state where the soluble species on the surface of the fly ash particle is dissolved in an aqueous solution (Warren and Dudas, 1984). The pH buffering system is initially set up by the dissolution of soluble components of the fly ash. Different buffering stages occur, depending on the nature of the buffering components (Fatoba, 2007). Warren and Dudas (1985) found that the leachate characteristics after weathering of the ash were due to the release of high levels of Si and Al from the glass phases.

2.11 Effect of gypsum in ameliorating subsoil acidity

Gypsum ($CaSO_4.2H_2O$) is a common mineral that is used in agriculture as a Ca source and a soil conditioner for sodic soils. It improves water infiltration, reclaims sodic soils, decreases runoff and erosion, and can be used to ameliorate acidity in soil profiles (Oates and Caldwell, 1985, Shainberg *et al*., 1989). Gypsum occurs geologically as an evaporite mineral associated with sedimentary deposits and is also produced as a byproduct of industrial processes (Korcak, 1998). Phosphogypsum is produced as a by-product in the fertilizer industry and originates from the production of phosphoric acid from rock phosphate. The composition of phosphogypsum

depends on the source of rock phosphate and the manufacturing process of phosphoric acid (Sumner, 1990; Korcak, 1998). Byproduct gypsum contains some F, P and Al as impurities (Oates and Caldwell, 1985), but the most important property of gypsum for agricultural purposes is its solubility (2.5 g/L in water) as it is more soluble than $CaCO_3$ (0.15 mg/L in water) (Korcak, 1998).

In soils with acidic subsoils, root growth of crops in limed soils is restricted to surface layers as lime does not readily move into the subsoil (Baligar *et al*., 1997). Due to the low mobility of lime's alkaline fraction, subsoil acidity cannot be remedied by the incorporation of lime in the plough layer only (Shainberg *et al*., 1989; Kirchoff *et al*., 1991; Tang *et al*., 2000). When lime is applied, the vertical movement of the Ca^{2+} and Mg^{2+} may be substantial even though negative charges are created by pH increases in variable charge soils. OH^- and HCO_3^- are consumed by acidity in the topsoil and do not reach the subsoil, unless unprofitable levels of lime are applied. This unprofitability and generation of variable charge limits the effect of liming (Alva *et al*., 1990). Thus where Al toxicity rather than Ca^{2+} deficiency limits root growth and when mechanical methods are beyond the financial means of most farmers, gypsum can be used (Farina and Channon, 1988a; Shainberg *et al*., 1989; Farina *et al*., 2000a).

The soil's reaction to gypsum application depends on the charge surfaces which in turn depend on the mineralogy, pH, ionic strength and solution/solid ratio (Alva *et al*., 1990; Wang *et al*., 1999). Gypsum does not have a direct liming effect; it acts indirectly as a soil ameliorant (Evangelou, 1996). The mechanism by which gypsum ameliorates subsoil acidity is by a combination of SO_4^{2-}-induced surface charge development, increased cation retention and diminishing exchangeable Al. The effects are greater in soils with dominant variable-charge characteristics than in those dominant in permanent-charge characteristics (Alva *et al*., 1990). When it is added to an acidic or an aluminium rich soil, aluminium is removed from the soil solution as insoluble aluminium hydroxyl sulfates (Evangelou, 1996).

Numerous propositions have been made to explain how gypsum ameliorates acidity. 'Self liming' (sulphate displacing OH^- from the soil surface into soil solution) is one proposal by Reeve and Sumner in 1972 as quoted by McLay *et al*. (1994b). The self-

liming model explains the decrease in soil solution and exchangeable Al^{3+} with the following equation:

$$Al(OH)_3 + CaSO_4 \rightarrow AlOHSO_4^+ + Ca(OH)_2$$

The pH change of a soil in equilibrium with a gypsum solution is the net result of the balance between reactions of opposing pH consequences:

(i) The salt effect, where the addition of Ca^{2+} encourages H^+ dissociation and Al^{3+} exchange from cation exchange sites; it lowers pH.

(ii) Release of OH^- due to ligand exchange between SO_4^{2-} and OH^-; it increases pH.

The pH change is usually small (0.2–0.3 units) and the result will depend on the extent of the two reactions (Shainberg *et al*., 1989, Wang *et al*., 1999).

After Al^{3+} is displaced from the cation exchange sites by Ca^{2+} (due to the increased Ca^{2+} concentration), it occurs in many forms (Oates and Caldwell, 1985). This soluble Al is made insoluble by the formation of an ($Al\text{-}SO_4$) phase and supersaturation with respect to ($AlOHSO_4$) also occurs (Alva *et al*., 1990). Fluoride can form strong complexes with Al when it is present in soil. Aluminium fluoride complexes can also be found in addition to $Al\text{-}SO_4^+$ complexes, thus decreasing soluble Al^{3+} (Oates and Caldwell, 1985).

A surface application of gypsum in the region of 4 t/ha is effective for highly weathered soils that contain aluminium oxides or iron oxides and dolomitic lime instead of calcitic lime should be used with gypsum to alleviate soil acidity (Du Toit, 1999).

2.12 A review on use of gypsum and/or fly ash in field trials

The use of gypsum is limited to areas where it is available at reasonable cost. Research on gypsum use for acidic soils has mainly been done in Brazil, the United States of America and South Africa with the origins in findings of Sumner and Reeve as quoted by Shainberg *et al*. (1989). The data on the use of gypsum and phosphogypsum in field trials explicitly illustrate beneficial effects of high gypsum rates on yield of maize, beans and other crops (Shainberg *et al*., 1989; Smith *et al*., 1994; Wang *et al*., 1999).

Brazilian findings show that first year responses can be obtained with application rates as low as 1-2tons/ha, but few beneficial effects are seen on the highly weathered acidic soils of South Africa (Farina *et al*, 2000a) due to the higher precipitation rate and different soil physical and/or chemical properties (Shainberg *et al*., 1989). The benefit of gypsum is especially highlighted during moisture stress as yields on control plots are significantly lower than the gypsum treated plots and the benefits increased over time (Farina *et al*., 2000a).The good results of gypsum highlighted during drought periods is a consequence of the removed Al toxicity deeper in the subsoil. When soluble Al is removed from the subsoil the roots can grow deeper to absorb the moisture in subsoil (Farina *et al*., 2000a).

Gypsum additions can have negative and positive plant responses (Alva *et al*., 1990), and this shows that the chemistry of gypsum in the soil system is not fully understood. Negative results have been obtained in a field trial done by Murata *et al*. (2002) in Zimbabwe. These researchers evaluated the effects of four calcium-containing materials on soil pH, nutrient availability and productivity of groundnut (*Arachis hypogaea*) on acid soils at sites in Zimbabwe. The materials were calcitic limestone, dolomitic limestone, gypsum and single super phosphate. Gypsum and single super phosphate applications on their own had no effect on pH, calcium and magnesium levels. Combining gypsum or superphospate with calcitic lime had the same effect as calcitic lime alone. Gypsum did not deliver yields significantly different from untreated plots.

McLay *et al*. (1994a) found that gypsum caused Ca^{2+}, SO_4^{2-} and the ionic strength to increase significantly in both topsoil and subsoil by the end of the first year. Gypsum had a minimal effect on pH or total Al, but the amount of Al present as toxic monomeric Al decreased and the amount present as non-toxic $AlSO_4^+$ ion pairs increased, therefore decreasing the Al toxicity to wheat. Magnesium was displaced from the topsoil by gypsum and leached to the subsoil. The SO_4^{2-} increased in the subsoil solution, which increased the ionic strength, thereby decreasing the activity of Al^{3+} and increasing $AlSO_4^+$.

Findings on plant composition are unanimous in the fact that leaf Ca and S is elevated while Mg content is decreased (Farina *et al*, 1988b; Shainberg et. al, 1989; Alva *et al*.,

1990; McLay *et al*., 1994a,). Leaf K is also suppressed by gypsum application. This is explained by the antagonistic effect that the increased Ca^{2+} and SO_4^{2-} levels have on K^+ and Mg^{2+} adsorption. Root growth is enhanced as gypsum increased Ca^{2+} availability and therefore increased Ca^{2+} plant uptake due to decreased Al availability. Further, the P from phosphogypsum might be beneficial to crop growth (Oates and Caldwell; 1985; Shainberg *et al*., 1989).

Feldhake and Ritchey (1996) investigated the effect of flue gas desulphurisation gypsum (FGD), a coal combustion by-product, on orchard grass root density which is used for pasture. It was found that greater root growth and water uptake was obtained and the response in severe drought was similar to that of a limed soil. The Mn content of the leaves increased and care should be taken in application levels so as not to reach toxic levels in foliage (Feldhake and Ritchey, 1996).

According to Shainberg *et al*. (1989), in South Africa, Farina and Channon (1988b) planted maize on an Ultisol of clay loam texture treated with 5tons/ha of mined gypsum each year in the first two years and 15tons/ha of dolomitic lime on each plot. Severe drought limited grain yield in the first year but deficient S nutritional effect was eliminated overall. Yield increases were obtained for the five seasons following application.

Wright *et al*. (1998) treated acidic soils with 1.25–80g/kg of eight different coal combustion products. Low application rates did not inhibit wheat seedling root growth and fly ash did not limit root growth. Foliar concentrations of Cu, Zn, Ni, Pb, Cd and Cr were similar in treated and untreated plots. Foliar B, Se, As and Mo increased in treated soils, but Se from fly ash reached potentially unsafe levels, due to high application rates.

With gypsum application exchangeable Ca^{2+} increases uniformly down the profile and Mg^{2+} is reduced in the upper part of profile and accumulates in the lower part (Farina *et al*, 1988b; Shainberg et.al, 1989). K^+ behaviour with gypsum application differs according to location. Exchangeable Al and Al saturation is reduced down the profile and little or no effect on pH is seen (Shainberg *et al*., 1989). Sulfate is strongly

retained in the subsoil (Pavan *et al*. 1984; Alva *et al*; 1990) of highly weathered soils and NO_3^- is displaced from the profile.

2.13 Conclusion

Soil acidity is greatly escalated by human activities and the amelioration of such soils with lime is often costly and it takes a few years before returns on investment are seen. An industrial waste product such as fly ash can therefore be used as an alternative. The use of fly ash as a liming alternative has been researched extensively and many benefits are illustrated. Fly ash has the advantage that it has a fine particle size, contain more micronutrients than lime, and it can improve the texture of soils.

Literature on the use of Calmasil as a liming material is limited, but it has successfully been used in the Kwazulu-Natal sugarcane industry for Si addition to increase sugarcane resistance to eldana infestation (Meyer and Keeping, 2005; Kanamugire *et al*., 2006).

Dissolution studies of fly ash emphasise the uniqueness and variability of different fly ashes. Each fly ash therefore requires its own dissolution study to evaluate the possible nutrients and trace metals that might be released as excessive application of fly ash might lead to trace metal toxicity.

Gypsum is regularly used in combination with lime in field trials as it is more soluble and it aids in the downward movement of the lime and nutrients, especially Ca^{2+}. Contradicting results regarding yield and foliar composition of crops have been found, but this is due to the different climatic conditions, crops and soil types.

It is apparent that the chemistry and mineralogy of the soil, liming materials and the specific crop requirements needs to be understood to fully comprehend and explain the effect of gypsum and fly ash on soil and plants. This dissertation will evaluate how these results fit in the current global scenario and gain insight or understanding to the synergistic or antagonistic effects between the selected soil type, crop species and ameliorant used.

Chapter 3

Dissolution behaviour of Duvha fly ash, lime and Calmasil

3.1 Introduction

The dissolution behaviour of a liming material gives insight into the behaviour of the material under a given set of external conditions. This information aids in making more informed and therefore better decisions regarding both the application rate and the frequency of application to soils. It is essential to know the composition and behaviour of fly ash if it is to be used as a liming material.

Work has been done on various South African fly ashes to study the chemical and mineralogical composition and leaching behaviour (Willis, 1987; Bezuidenhout, 1995; Fatoba, 2007). The composition varies depending on the source (Willis, 1987; Bezuidenhout, 1995), and so site specific studies are required to understand the dissolution behaviour. This chapter is a study of the dissolution behaviour of fly ash from Duhva power station compared to the leaching behaviour of calcitic lime and Calmasil that are other locally available liming products.

3.2 Physical, chemical and mineralogical and properties of fly ash

Fly ash is a spherical fine particle size material that ranges from 0.01 – 100 microns in particle size. Some particles are hollow, empty spheres (cenospheres) and others (plerospheres) are filled with smaller amorphous particles and crystals (Adriano *et al*., 1980). In Table 3.1 some of the important physical properties of fly ash are given.

Table 3.1 Physical properties of fly ash (after Mattigod *et al*., 1990)

Physical property	Fly ash
Mean particle diameter (μm)	20-80
Specific surface area (m^2/kg)	20020-3060
Specific gravity	1.59-3.1
Dry bulk density (μg/m)	1.01-1.43
Coefficient of permeability (m/s)	$5*10^{-9} – 1*10^{-6}$
Uniformity coefficient (D_{60}/D_{10})	2 - 9.8

According to the ASTM (American Society for Testing and Materials), two main types of ash exist: class F (low lime) and class C (high lime) based on silica, alumina and iron oxide content of fly ash (Manz, 1999). Many trace elements are located in the smaller particles (Jala and Goyal, 2006).

Expressed as oxides, the elements in fly ash have the following typical mass percentages: SiO_2 (65.3%), Al_2O_3 (25.2%), Fe_2O_3 (3.4%), CaO (3.1%), Na_2O (1.6%) TiO_2 (0.98%), MgO (0.89%) and K_2O (0.89%) (Adriano *et al*., 1980; Kim *et al*., 2003). Trace elements such as Ga, Se Ge, As and Pb are enriched in South African fly ash (Bezuidenhout, 1995). The trace elements are associated with the finer fractions of the fly ash particles (Iyer, 2002). Knowledge of the mineralogy is important as it determines which elements will be the greatest in solution and gives insight into the formation of secondary minerals.

3.3 Materials and methods

- **pH and EC measurements**

A saturated paste extract was prepared using the method of Rhoades (1982). EC (electrical conductivity) of the supernatant liquid was measured using a Cyberscan 510 conductivity meter and pH of the supernatant liquid was measured using a Metrohm 827 pH meter. Cations were determined with AAS (Atomic Adsorption Spectroscopy) and anions with IC (Ion Chromatography).

- **Morphology**

Images of Duvha fly ash were obtained by performing SEM (Scanning electron microscopy) analysis on the sample with a Leo® 1430VP Scanning Electron Microscope. An EDX (Energy Dispersive X-ray Spectroscopy) is coupled to the SEM and it is mostly used to relate qualitative elemental composition to morphological characteristics.

- **Elemental characterization**

The elemental analysis was performed with XRFS (X-ray fluorescence spectrometry) according to the method cited in Mbakwe (2008). This analysis was performed on the calcitic lime and Calmasil as well.

- **Mineralogical characterization**

Mineralogical analysis was performed via XRD (X-ray diffraction). Dry samples were analysed on a Bruker-Nonius SMART Apex I diffractometer.

- **Particle size and surface area analysis**

The particle size was determined by Static Laser Light Scattering, using a Saturn DigiSizer 5200.

- **Batch dissolution experiment 1**

This method is based on work undertaken by Cavè (2002) and is used to determine the initial dissolution behaviour over a relatively short period. Time dependence data was collected and the dependence of the dissolution behaviour under different pH values wasd investigated. 0.01M NaCl stock solution was used to prepare solutions of pH 2, 3, 4, 5, 6 and 7 by addition of 0.01M HCl or 0.01M NaOH. The pH 2 solution was prepared from pure 0.01M HCl. Solutions of pH 3,4, 5, 6 and 7 were prepared by adding NaCl solution into glass beakers with a calibrated glass electrode pH probe immersed in it. Whilst stirring, the solutions were brought to the exact pH by drop wise addition of the 0.01M HCl or 0.01M NaOH solutions.

0.1g of unweathered fly ash was weighed into 50ml polypropylene centrifuge tubes. To this 30ml of the pH-adjusted solutions was added to the centrifuge tubes and the screw-top lids tightened and sealed with masking tape. The tubes were subsequently mounted horizontally on a reciprocating shaker and agitated at 150 cycles per minute for two days.

The samples were removed from the shaker after 48 hours and centrifuged. The pH of the supernatant was measured before siphoning off the top 25ml for analysis. This siphoned solution was filtered and analysed with ICP-MS. Deionised water was added to the remaining ash in the centrifuge tube and centrifuged. The supernatant was decanted. This was repeated three times to satisfactorily rinse the ash. The ash was then decanted into porcelain crucibles and left in an oven for 48 hours at 105^{o}C.

This procedure was repeated for fresh unweathered fly ash samples, but they were agitated on the reciprocating shaker for 2, 4, 6, 8 and 10 days.

The supernatant solutions were filtered through a 0.45µm membrane filter to remove solids. The total elemental concentration of cations (major, minor and trace elements) was determined with ICP-MS. The model used is the Agilent 7500ce ICP-MS with an Octopole Reaction System, using He as collision gas.

The same procedure was followed in determining the solution behaviour of Calmasil and calcitic lime. However, these materials were only evaluated using the leachate solutions of initial pH 2, 4 and 6 and agitated for 2, 6 and 10 days. To have an indication of the long term behaviour of these two materials it was also agitated continuously for 28 days. This step was done to evaluate the long term behaviour as these two materials were not included in the second batch experiment, which is a sequential rinse and long term evaluation.

- **Batch dissolution experiment 2**

The long term dissolution behaviour was then investigated as care should be taken with the use of short term reaction times for the measurements of silicate dissolution rates (Cavè, 2002). In long term experiments solute build up can take place. To prevent this scenario, Cavè (2002) employed a long term "sequential rinse" method to determine the dissolution rate of apophyllite. This method is advantageous in the fact that it prevents solute build up during long term dissolution experiments. The entire reacting solution is removed at regular weekly intervals and fresh solution is added to the already dissolving mineral.
The 0.01M NaCl stock solution was used to prepare solutions of pH 2, 3, 4, 5, 6 and 7 by addition of 0.01M HCl or 0.01M NaOH as for batch experiment 1.

0.1g of unweathered fly ash samples were weighed out in 50ml polypropylene centrifuge tubes. 30ml of the pH-adjusted solutions was added to the centrifuge tubes and the screw-top lids were tightened and sealed with masking tape. The tubes were subsequently mounted horizontally on a reciprocating shaker and agitated at 90 cycles per minute.
The samples were removed from the shaker after 48 hours and centrifuged. The pH of the supernatant was measured before siphoning off the top 25ml for analysis. This siphoned solution was filtered and analysed by ICP-MS. Fresh solutions were then added to the tubes and the pH adjusted to the initial pH values of 2, 3, 4, 5, 6 and 7.

Samples were then returned to the reciprocating shaker and the speed increased to 150 cycles per minute. The tests were continued for a total of four rinses which lasted 672 hours in total.

Deionised water was added to the remaining ash in the centrifuge tube and centrifuged. The supernatant was decanted. This was done three times to satisfactorily rinse the ash. The ash was then decanted into porcelain crucibles and left in oven for 48 hours at 105^{o}C.

The solutions were filtered through a 0.45µm membrane filter to remove solids. The total elemental concentration of cations (major, minor and trace elements) was determined using ICP-MS.

3.3 Results and discussion

3.3.1 Saturated paste extract pH, EC and major ions in fly ash

In Table 3.2 the data for pH, EC and major ions obtained in the saturated paste extract of fly ash are presented. The fly ash is clearly alkaline with high levels of soluble Ca, Mg and SO_4^{2-}. According to Adriano *et al*. (1980) and Mattigod *et al*. (1990) most alkaline fly ashes have a pH range of 8-12 or greater than 12, but this ash sample might possibly have had some period of atmospheric contact if the pH is only 9.9, indicating partial carbonation with atmospheric CO_2.

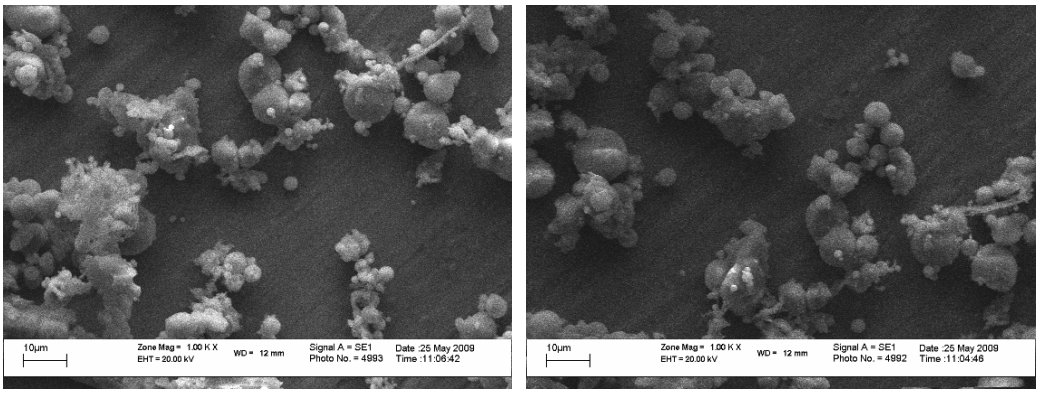
Table 3.2 pH, EC and major ions in saturated paste extract of fly ash after 24hr of equilibrium (concentration in ppb, with * = ppm)

pH	EC(µS)	Al	Si	*Fe	*B	V	Cr	K	*Ca	*Mg	*Na	*Cl	*SO_4
9.93	1159	15	24.9	2.11	2.62	733.4	899.60	23.69	50.59	6.16	1.6	13.5	721

3.3.2 Morphology

Figures 3.1 (a) and (b) indicate the morphology of the fly ash. These images reflect the physical surface appearance of the material. A study of the images showed that the fly ash consists of opaque spherical particles with smooth surfaces. Agglomeration of some particles is observed, but no cenospheres or plerospheres could be distinguished from the images. Fatoba (2007) states that it is the high temperature during the coal

combustion process that leads to the spherical shape and agglomeration of the fly ash particles. Table 3.3 shows the SEM-EDX spot analysis (weight %) of three different spots which indicates upon a fairly uniform distribution of elements in the fly ash.



(a) (b)

Figures 3.1 (a) and (b) SEM images of morphological features of Duvha fly ash (x1000 magnification)

Table 3.3 SEM-EDX spot analysis (weight %) of unweathered Duvha fly ash

Element	Mg	Al	Si	K	Ca	Ti	Fe	O	Total
Spot 1	0.29	17.17	26.49	0.7	2.086	1.222	3.58	48.5	100
Spot 2	0.47	17.5	25.75	0.47	2.164	1.502	3.86	48.3	100
Spot 3	0.22	17.26	25.45	0.61	2.736	1.106	4.8	47.8	100
Average	0.30	17.31	25.90	0.59	2.33	1.28	4.08	48.2	-
Standard deviation	0.13	0.17	0.54	0.12	0.35	0.20	0.64	0.33	-

3.3.3 Elemental composition

The elemental analysis in Table 3.4 indicates that the major elements in the fly ash are SiO_2, Al_2O_3, Fe_2O_3 and CaO. This fly ash is of the Class F type as the sum of SiO_2, Al_2O_3 and Fe_2O_3 is more than 70% (Mattigod *et al*., 1990; Manz 1999). Calmasil predominantly consists of Ca, Si and Mg, while lime mainly contains Ca and Si. Fly ash contains higher amounts of trace elements. The total LOI (loss on ignition) for Calmasil and lime is much greater than fly ash as they contain more unburned carbon.

Table 3.4 XRF elemental composition of liming materials (after Mbakwe*, 2008)

	Ash	Calmasil	Lime
SiO_2 (%)	55.1	15.0	15.5
Al_2O_3 (%)	28.6	1.78	1.44
MgO (%)	0.746	7.29	4.60
CaO (%)	2.74	32.5	37.9
Fe_2O_3 (%)	5.60	2.32	0.779
MnO (%)	0.047	0.48	0.042
TiO_2 (%)	1.66	0.53	0.125
Cr_2O_3 (%)	0.050	1.37	0.008
Na_2O (%)	0.068	n.d.	0.045
K_2O (%)	0.655	n.d.	0.104
P_2O_5 (%)	0.438	n.d.	0.367
NiO (%)	0.012	0.170	b.d.l.
LOI (%)	4.48	38.56	39.3

n.d. = Not determined; b.d.l. = below detection limit

*These results were obtained from Mbakwe (2008) as his experimental work was done on the exact same liming materials used in this study.

3.3.4 Mineralogical composition

Gaining insight into the mineralogy of fly ash will aid in explaining and understanding its elemental dissolution behaviour. The XRD analysis in Figure 3.2 shows that an array of minerals may exist in the fly ash. These possible mineral species were identified using XRD software and confirmation of minor phases would be needed through complementary analyses. The major crystalline mineral phases are quartz (SiO_2), mullite ($3Al_2O_3.2SiO_2$) and magnetite. The minor peaks mainly represent α–alumina, gypsum (Ca_2SO_4), which contributes to Ca, magnetite-maghemite contributing to Fe and barite ($BaSO_4$) which can contribute to soluble Ba.

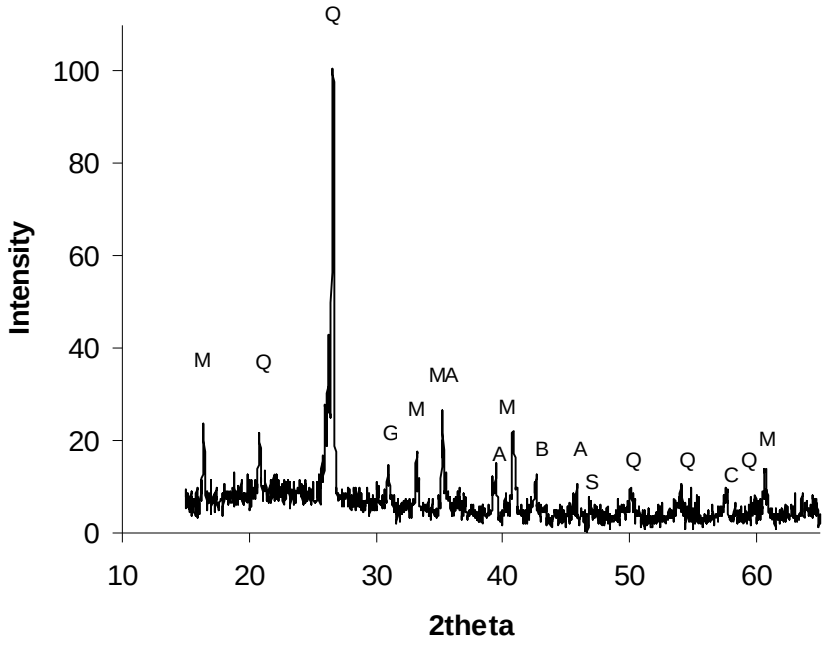


Figure 3.2 X-ray diffractogram of the clay fraction of unweathered Duvha fly ash (Q=quartz (1.82 Å, 2.46 Å, 3.34 Å and 4.26Å); M=mullite (2.21 Å, 2.69 Å); G=gypsum (2.89 Å); B=barite (2.12 Å); C=calcite (1.6 Å); MA=magnetite – maghemite (2.53 Å); A=α–alumina (1.98 Å) and S= strontianite (1.93 Å))

3.3.5 Particle size and surface area

In Table 3.5 the surface area measurements of the fly ash is listed. The distribution and concentration of elements according the partitioning of different particle sizes was not evaluated, "but it is known that smaller particles result in [a] greater surface area". Fly ash has a finer particle size than Calmasil's 166 microns. Fytianos *et al*., (1998) and Mattigod *et al*. (1990) explained that an increased surface area of fly ash results in high surface concentrations of elements that are volatilised during combustion which then condense onto the particles.

Table 3.5 Particle size and surface area results of Duvha fly ash

Mean particle size (μm)	49.53 ± 1.735
Specific surface area (m^2/g)	2.3714

3.3.6 Batch dissolution experiment 1 on fly ash

ICP MS analysis delivered results on an array of 24 cations (Appendix 6), but the discussion of the results will be limited to the major cations and important trace elements released in noteworthy quantities. The major elements in the fly ash matrix are Al, Si, Fe, with noteworthy percentages of Ca, Mg, K and Na (Adriano *et al*., 1980, Warren and Dudas, 1984). The solutions of different pH's represent the possible solutions the fly ash can be exposed to in the environment. Acidic solutions represent the contact with acidic soil solutions or in some cases acid mine drainage, whereas the near-neutral solutions represent ground-water or rain water. The results of this batch experiment firstly indicate the effect of time on the dissolution of elements and secondly the effect of pH on the short term dissolution behaviour of the minerals.

- **Solubility of elements in Duvha fly ash in acidic pH range 2 - 4**

The solubility of Al, Fe and Si is greatest in the most acidic solution as seen in Figure 3.3. Compared to the pH 2 solution, very little Al, Fe and Si are released in the rest of the supernatants. According to Fatoba (2007) Si and Al are mainly contained in the aluminosilicate and silicate phases of fly ash and this accounts for the low solubility. The solubility of silicon thus increased by the disintegration of the amorphous glass phases in the acidic solutions (Fatoba, 2007).

It is observed that Na concentration (Figure 3.4) is significant over the whole pH range and this is due to the fact that it is part of the fresh leaching solution, while Ca and Mg are more soluble in the pH 2 solutions and their concentration is inversely proportional to the pH. The solubility of K increased with increasing pH as dissolution is highly water reactive (Kim, 2003) . Kazonich and Kim (1999) and Kim *et al*. (2003) states that Ca, Na and K have solubility over the entire pH range, but they are significantly soluble in the higher pH range, which was not evaluated in this exercise.

As indicated in Figure 3.4, a considerable amount of P is released in solutions of an initial pH of 2 and 3, as the fly ash contains a relatively high percentage of P (0.438%) as indicated by the XRF results. Concentration of trace elements, such as Pb, B, Be, Mn, Ni, Zn, As, Se, Cr, V, Ti, Mo, and Cd are greatest and only significant in the acidic solutions as illustrated in Appendix 6. The increase in the solubility of all metals in the acidic pH range can be attributed to the intensified attack on the ash

mineral phases that contain these elements (Fytianos *et al*., 1998). High concentrations of Na at pH 2 are once again due to the fact that it is the main component of the leaching solution.

- **Solubility of elements in Duvha fly ash in near neutral to neutral pH range 5 - 7**

The solubility of all elements, except K has decreased in these solutions. In this range the most soluble elements are Na, K, Ca and Mg in that order.

- **Solubility of elements over time**

The release of Al, Si, Fe, Ca, Mg, and Na is proportional to the contact time of the leachate with the ash minerals, especially in the acidic solutions. In the near neutral solution range of pH 5-7, the Al, Si and Fe shows an increase in dissolution concentration over time, but after four days the soluble concentration drops, and increases again after two days. This is possibly due to the fact that the precipitation of dissolved elements occurs (Jegadeesan *et al*., 2008).

In acidic solutions, the release of most trace metals such as Pb, Ba,, V, Cr, Be, Cu, Sr, Mn,, Zn, As, Ni and Se increase over time except for Ti, Mo and Cd. Ti is released in a similar pattern as Al, Si and Fe over time. No trend can be observed with the release of Mo and Cd over time.

In neutral solutions the same pattern persists with Ba, B, V, Cr, Be, Sr, P, As and Se increasing over time , but not for Ti, Mo and Cd. The dissolution rate of Pb, Cd, Mn, Ni, Cu and Mo varies widely. Zn concentration decreases initially but after 6 days an increase in soluble concentration is obtained.

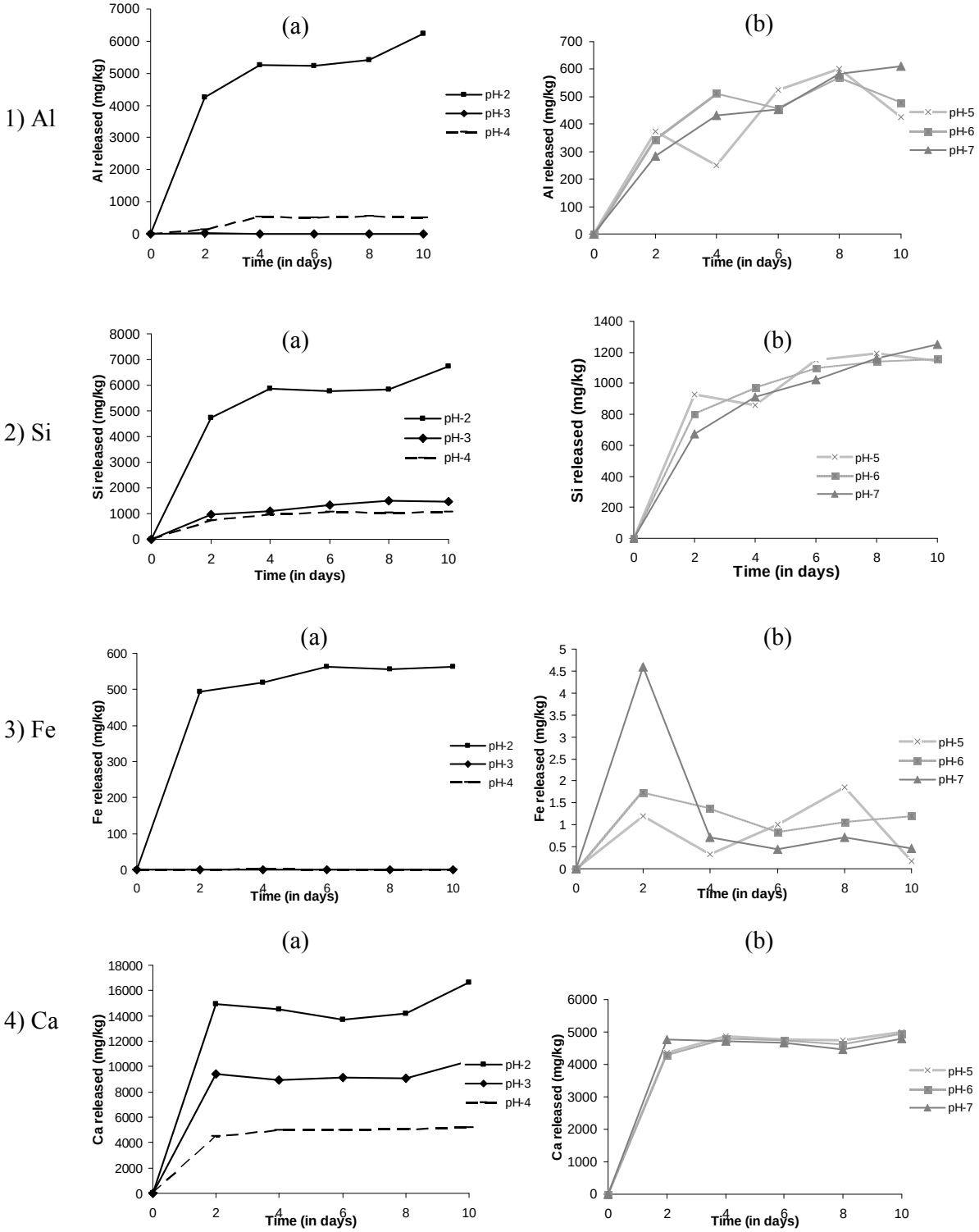


Figure 3.3 Concentration of soluble elements released from Duvha fly ash in contact with (a) an acidic and (b) near-neutral solution over time for 1) Al, 2) Si, 3) Fe and 4) Ca

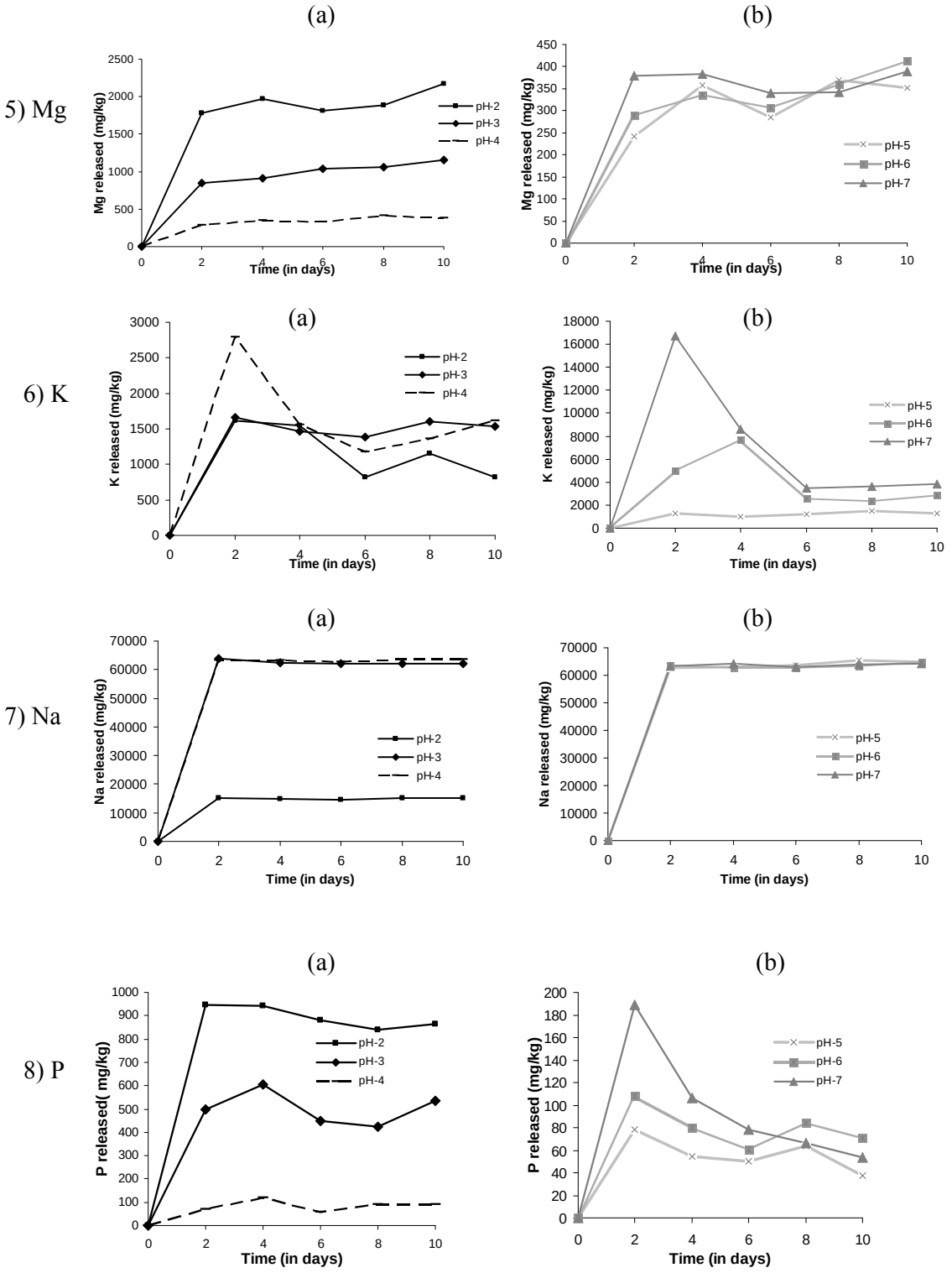


Figure 3.4 Concentration of soluble elements released from Duvha fly ash in contact with (a) an acidic and (b) near-neutral solution over time for 5) Mg, 6) K, 7) Na and 8) P

- **pH change in solution over time**

Figure 3.5 shows the change in the initial pH of the sequential leachates over time. The solution of initial pH 2 shows no significant pH changes as the final pH after 10 days of agitation has increased by no more than 0.37 units. This could be due to release of hydrogen as a result of the hydrolysis reaction of soluble Fe and Al.

The rest of the solutions experienced a sharp increase in pH after two days and thereafter is constant within this region of the increased pH.

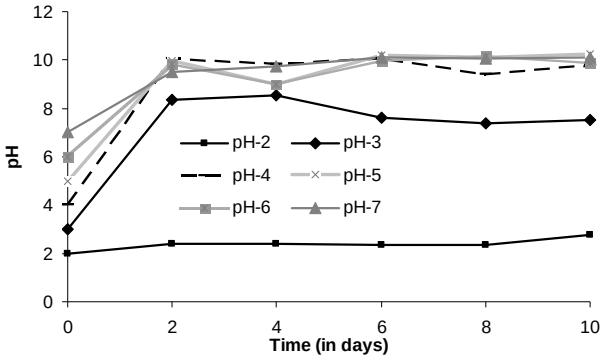


Figure 3.5 Change in initial pH of leachates collected after respective contact time with fly ash

3.3.7 Batch dissolution experiment 1 on Calmasil and calcitic lime

The majority of elements display a bell shaped behaviour (Figure 3.6) indicating initial dissolution, followed by re-precipitation over time. There is some suggestion of bimodal dissolution but in the absence of evidence to indicate that this is reproducible the stepped increase in dissolution is interpreted as having resulted from variation in the experimental conditions.

The dissolution of Calmasil indicates, as expected, that Ca, Mg and Si are released in the greatest quantities and in decreasing order respectively. Ca and Mg solubility is at maximum at pH 2. K is highly soluble and solubility is over the whole pH range with maximum solubility in the neutral range and minimum solubility at pH 4. Aluminium is detected in minor quantities and it is more soluble, but still insignificant in the higher pH ranges. Sr and Ba are released in greater quantities than most trace elements and they are more soluble in the acidic range. Most trace elements concentrations are negligible even in the most acidic solution and only Cr, V and Mo

delivers detectable, but not appreciable levels, although not as high as the trace element levels in Duvha fly ash (Appendix 6).

The extractant of lime has much higher Ca concentrations in the pH 2 extractant and minimum solubility is displayed at higher pH values. Ca dominates the extractants, followed by Mg and K as displayed in Figures 3.6. Significant levels of K are released in higher pH regions. The solubility of Mg in calcitic lime is an order greater in the pH 2 extractant than in the solutions of greater pH. The only trace elements that are released in detectable concentrations in lime are Sr and V (Appendix 6). The K that is released in Calmasil and lime after six days precipitates again.

When comparing Calmasil and calcitic lime to fly ash it is noticeable that fly ash releases more Al, Fe, P, K, trace elements and essential micronutrients such as Mo, B, Zn, Se and Cu. Ca and Mg is released in the order of Calmasil > lime > fly ash. Calmasil releases the greatest quantities of Si followed by fly ash and lime.

- **pH change in solution over time**

Figure 3.7 shows the change in the initial pH of the sequential extractants over time as it reacts with Calmasil and lime respectively. The neutralising effect of Calmasil> lime>ash as the solution of pH 2 is not as well buffered as when fly ash was used. It is seen that Calmasil has the greatest neutralising effect.

3.3.8 Batch dissolution experiment 2 on fly ash

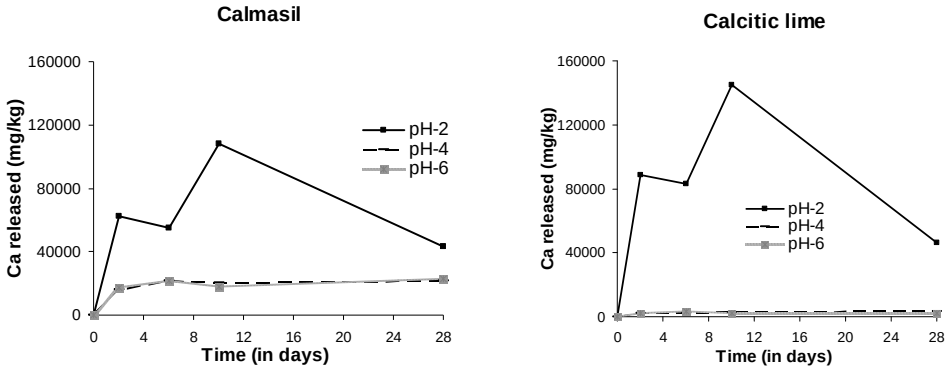
This experiment was designed to determine the long term dissolution behaviour of fly ash and prevent the re-precipitation of solid material that was found in the first batch experiment. As fresh leachates were used consecutively, the leaching behaviour is best described when cumulative volume is considered. The cumulative amount leached per unit sample mass (as displayed in Figure 3.8 and Figure 3.9) was calculated.

The cumulative amount of any element leached in mg/kg, M_L, is then the sum of all the concentrations as shown here;

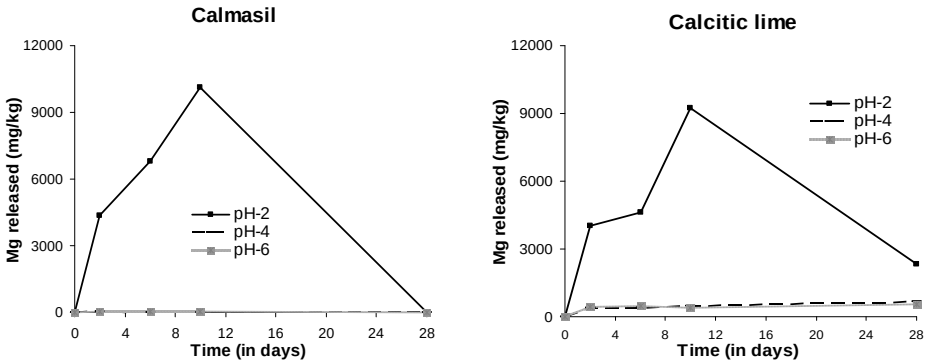
$$M_L = (\text{sum } (C*V)) / S,$$

where V is the volume of individual leachate sample in L; and S is the mass of the sample in kg.

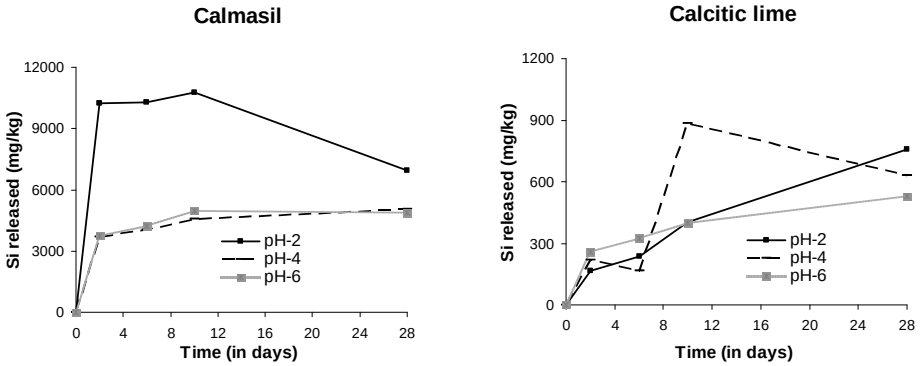
1) Ca



2) Mg



3) Si



4) K

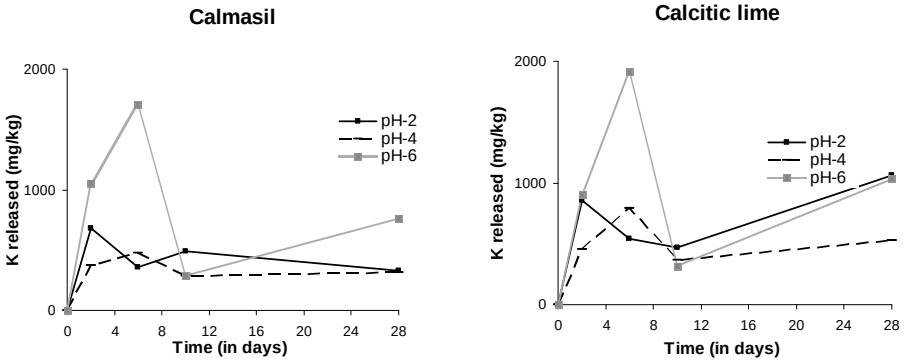


Figure 3.6 Concentration of soluble elements 1) Ca, 2) Mg, 3) Si, and 4) K released in Camasil and calcitic lime as a function of time and pH

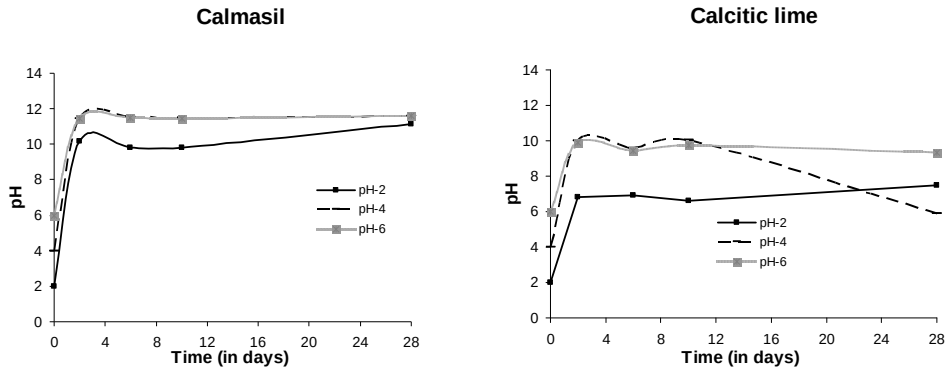


Figure 3.7 Change in initial pH of leachates collected after respective contact time with Calmasil and calcitic lime respectively.

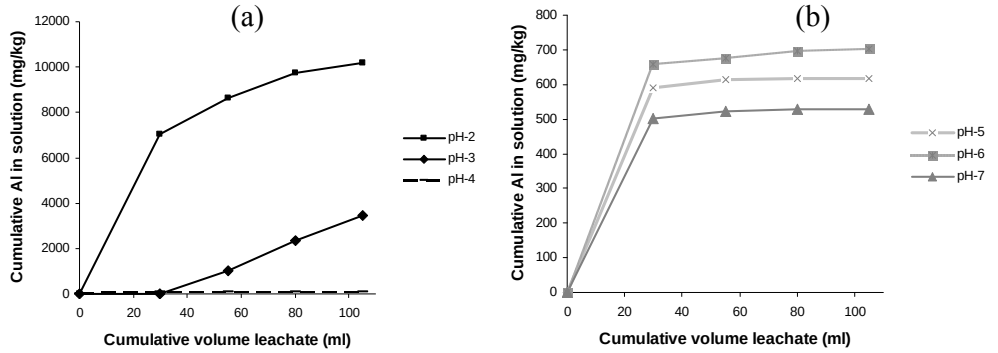
- **Solubility of elements over pH range**

The relative solubility of Al, Si and Fe is small and only considerable in the most acidic solution of pH 2. However Si has greater solubility over the rest of the pH range than Al and Fe. P has great solubility over the entire pH range.

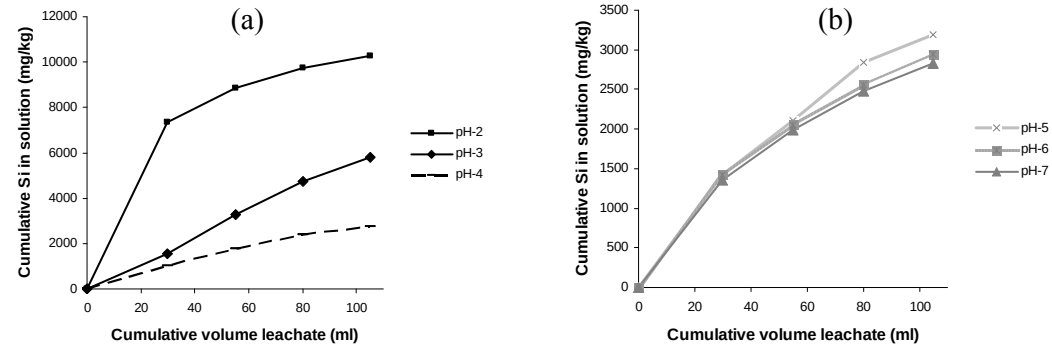
Mg and Na are soluble over the entire pH range and solubility is inversely proportional to pH, although the Mg solubility is relatively small. Ca is released in greater quantities in the acidic range. The relative solubility of Ca, Na, and K is much greater than the rest of the cations, contrary to the Mg concentration that is relatively small and almost constant. This is in accordance with Mattigod *et al*. (1990) who conclude from previous summaries on fly ash leachates that a greater fraction of Ca is dissolved from fly ash, whereas insignificant fractions of Si, Al, Fe and Mg are released.

As shown in Appendix 6, the maximum solubility of the trace elements is evidently in the leachate with an initial pH of 2 and concentrations of all trace elements are inversely proportional to the initial pH of the solutions. Arsenic, B, Mo and V appear to be slightly soluble over the entire pH range. Although Ba and Sr are trace elements and not detected by XRF in the unweathered fly ash, of all the trace elements, they are released in the greatest quantities. Their origin is possibly from the barite and strontianite, respectively.

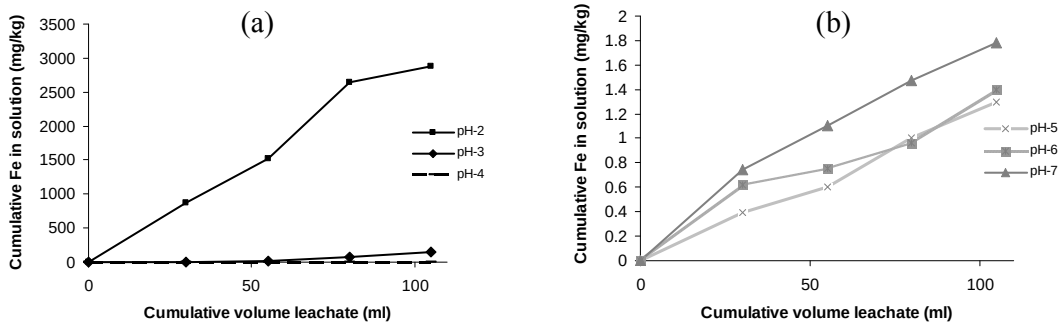
1) Al



2) Si



3) Fe



4) Ca

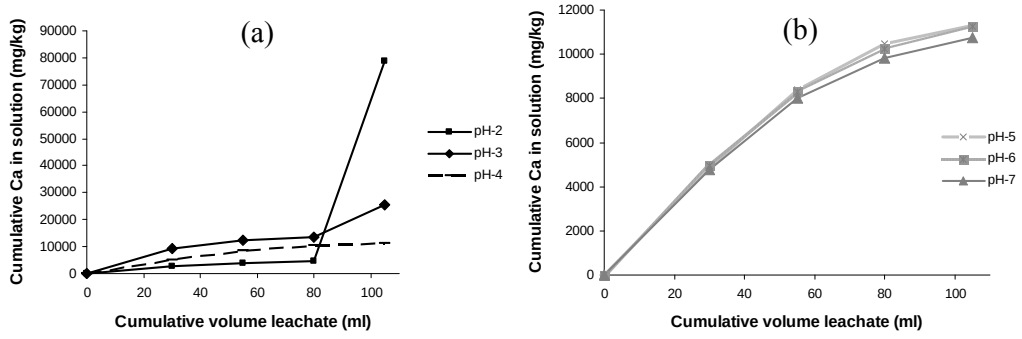
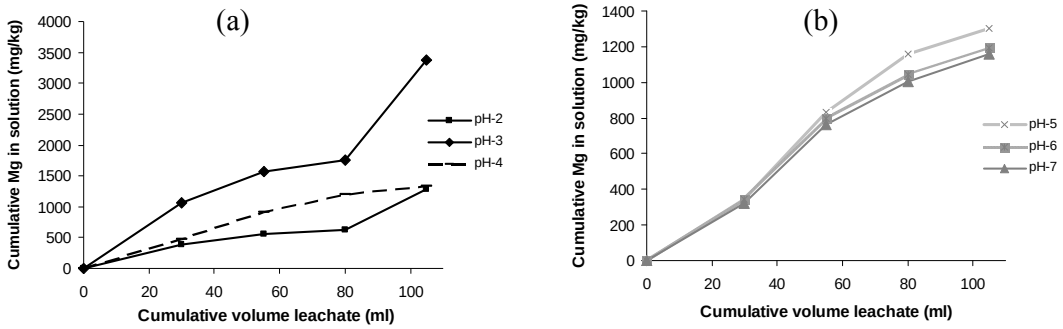
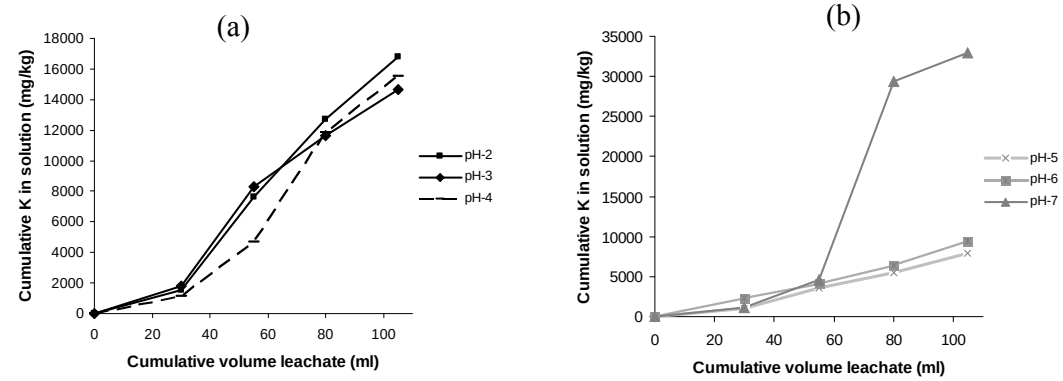


Figure 3.8 Cumulative concentrations of soluble elements released from Duvha fly ash leached over four weeks in four sequential leachates with (a) an acidic and (b) near-neutral solution for 1) Al, 2) Si, 3) Fe and 4) Ca

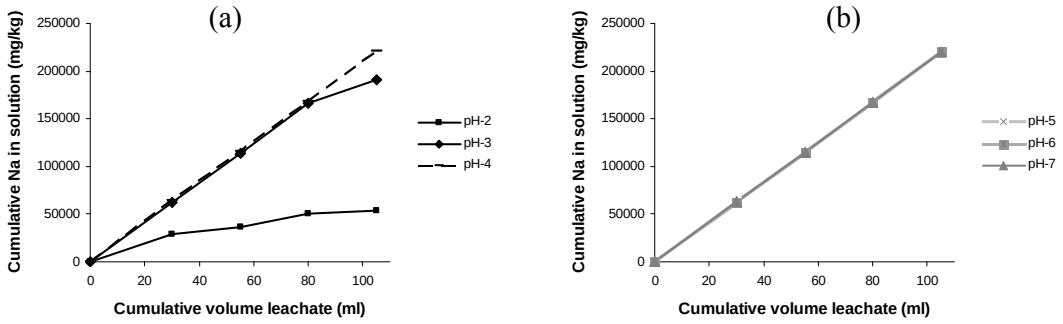
5) Mg



6) K



7) Na



8) P

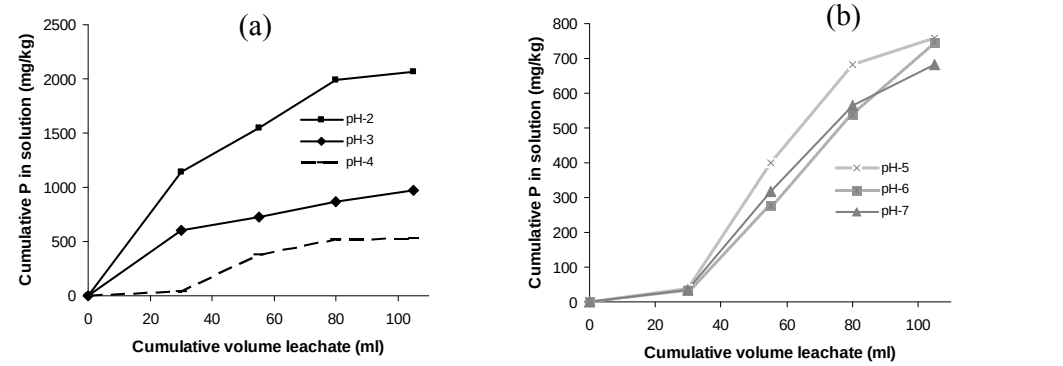


Figure 3.9 Cumulative concentrations of soluble elements released from Duvha fly ash leached over four weeks in four sequential leachates with (a) an acidic and (b) near-neutral solution for 5) Mg, 6) K, 7) Na and 8) P

- **Solubility over time**

Across the whole pH range, the initial leachates show higher solubility of Al, Si and P and the concentration declines in subsequent leachates. Mg and Na are released in greater concentration in the initial leachate, decrease in the subsequent leachates and increase in concentration again in later leachates. On the other hand Fe and K are less soluble initially but subsequent leachates contain higher concentrations thereof, indicating a longer time to dissolve. The pattern of K release suggests a gradual and increasing release whereas it decreases after protracted sequential leaching over four weeks. The maximum solubility of most trace elements occurs in the initial leachates and very little is released in the subsequent leachates.

- **pH change in solutions**

Figure 3.10 illustrates how the pH of the four sequential leachates changes after 7 days of reaction with the fly ash.

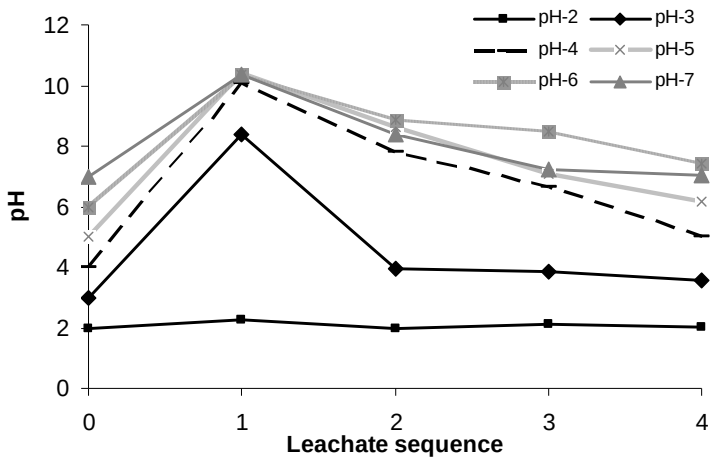


Figure 3.10 pH changes of the four sequential leachates after 7 days of reaction with the fly ash.

Leachate of an initial pH 2 remains unaltered, whereas the first aliquots of fresh leachates of an initial pH 3, 4, 5, 6 and 7 have undergone an increase in pH after reacting with the unweathered fly ash for the first 7 days. This indicates that the compounds released neutralised the first set of leachates substantially. The hydrolysis of CaO and dissolution of the soluble surface salts promotes the release of Ca, Na, K

and thus solution alkalinity (Warren and Dudas, 1984). The third and fourth aliquots of leachates added to the already dissolving fly ash maintained their initial pH or indicate an insignificant pH change. This suggests that the neutralising compounds are released by the fly ash in the first 7 days of reaction. Thereafter insignificant amounts of neutralising compounds are released.

3.4 Conclusions

The dissolution analyses of fly ash indicate that Na, Ca and K are soluble through the entire pH range and metallic cations are more soluble in acidic solutions, while Al, Si and Fe are sparingly soluble. Calcitic lime mainly leaches Ca, K and Mg while Ca, Si and Mg can be easily extracted from Calmasil. Unlike in fly ash, no significant concentrations of trace elements can be found in Calmasil or calcitic lime.

Based on these results it could be expected that, as is the case with Calmasil and lime, fly ash will release Ca, Mg, K and Si and P for plant nutrition. Fly ash has the added advantage that it contains more soluble trace elements; especially Zn. Boron is also released in great quantities. In the acidic environment the trace elements can be released from fly ash and if not present in harmful concentrations these elements can enrich the soil with micronutrients for plant availability. Such findings resonate with literature which states that placing fly ash under acidic conditions (pH < 4) would result in trace metal mobilization due to dissolution (Jegadeesan *et al*., 2008).

The neutralising capacity is in the order of Calmasil > lime > fly ash. Despite this, fly ash has a finer particle size than Calmasil and this should aid dissolution and element mobilization.

The results from such controlled laboratory experiments can be compared with those of the field trial described in the next chapter.

Chapter 4

A comparison of coal ash, lime and Calmasil in alleviating the effects of subsoil acidity

4.1 Introduction

The greatest hindrance of acidic soils is the subsurface acidity (McLay *et al*., 1994a). Subsoil acidity cause low crop yields due to the constraints on soil fertility indicators such as pH, Ca, and Mg. Liming of acidic soils with agricultural limeste is an ancient agricultural practice to overcome problems associated with acidity, but returns on investments are slow and the effectiveness is limited to the depth to which the lime was incorporated. Cheaper alternatives such as industrial waste, more specifically fly ash, are proposed. However, the liming process, irrespective of material used, is complicated by the differences in the efficacy of lime across diverse soil environments (Farina and Channon, 2000b). Recommendations regarding the use and application of any industrial waste require a field trial under the specific soil conditions of its intended use.

This chapter reports on the performance of three liming materials, namely fly ash, Calmasil and calcitic lime in the field .It will be determined whether fly ash is as effective and practical as an alkalinity source as other available and established liming materials. This field trial was conducted to compare the effectiveness of fly ash to calcitic lime and Calmasil, with and without gypsum, in relation to alleviation of subsoil acidity, nutrient movement down the profile, root development and yield.

4.2 Materials and methods

4.2.1 Site description

Numerous coal power stations are situated in Mpumalanga Province, South Africa, and the agricultural soils surrounding these areas have naturally occurring acidic soils as seen in Figure 4.1. The experiment was initiated in July 2007 on Beestepan Farm, close to Middelburg, a town located in the Highveld area of Mpumalanga Province of

South Africa (25° 46' 60S, 29° 28' 0E), with an average annual precipitation of >800mm, most of it precipitating between October and March (Appendix2, Table 8). An area of 7776m^2, forming part of a 100ha field was cleared of wattles which had been growing for 15 years previously. The trial area was divided into 72 plots of 9m×12m (108m^2) each. The soils in the field site are predominantly of the Bainsvlei (orthic A - red apedal B - soft plintic B) and Avalon (orthic A - yellow-brown apedal B - soft plinthic B) soil forms, according to the soil classification system of South Africa (MacVicar *et al*., 1977). Nomenclature under the IUSS Working Group WRB (2006) would classify the soil as a plinthic Acrisol (dystric, rhodic).

Figure 4.2 illustrates the Avalon form profile and the soil is of a sandy loam texture with saprolite approximately 1m below the soil surface. Before the application of any treatments to the soil, top- (0-20cm) and subsoil (20-40cm) samples were taken from each plot and analysed for pH, exchangeable acidity, Ca and Mg concentrations. The values obtained were reasonably comparable across the area and Table 4.1 displays the averages of the 72 plots.

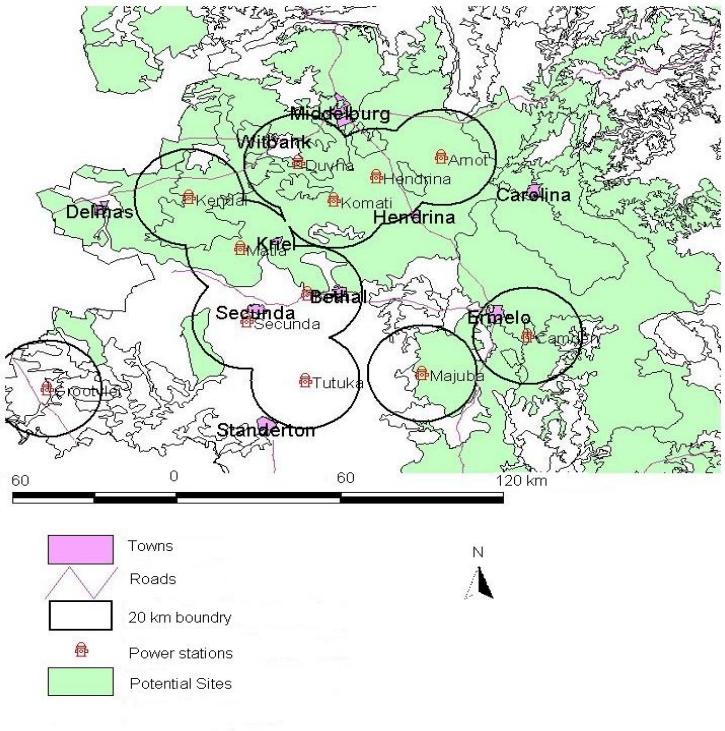


Figure 4.1 Location of power stations in relation to areas of acidic soil (highlighted in green) on the Mpumalanga highveld. The circles represent an area of 20km radius around each power station (after Mbakwe, 2008)

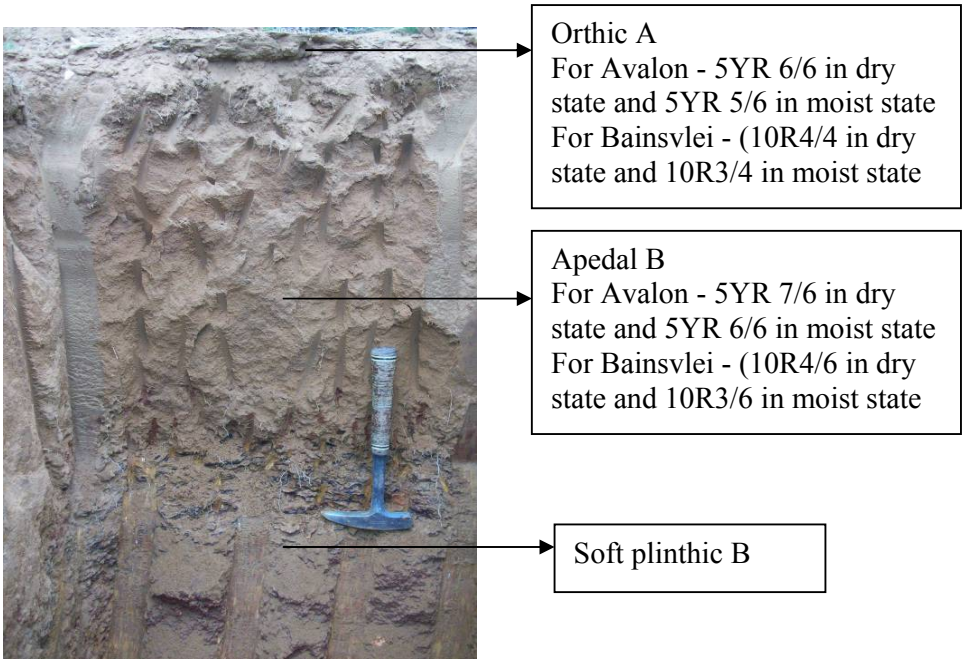


Figure 4.2 Soil profile of the Avalon form at Beestepan field trial in Mpumalanga

Table 4.1 Average and standard deviation of chemical properties of the soil before the application of any treatments (after Mbakwe, 2008)

Property	Topsoil	Subsoil
pH	3.8±0.06	4.1±0.09
Exchangeable acidity ($mmol_c/kg$)	6.83±1.14	7.11±0.99
Ca (mg/kg)	53.6±57.5	47.04±24.0
Mg (mg/kg)	13.4±13.2	16.4±18.5

Table 4.2 Texture of top- and subsoil

Soil	%Sand	%Silt	% Clay	Texture
Topsoil	78	11	11	Sandy loam
Subsoil	78	8	13	Sandy loam

4.2.2 Experimental layout and treatments

A factorial field trial (4*4*2) was used to test the effectiveness of the different liming materials. The site has an average topsoil pH_{KCl} of 4.1 and soil texture is displayed in Table 4.2. The soil was thus further acidified with a basal treatment of 6kg/plot of ammonium sulphate to enhance the effect of the liming materials.

Three alkaline materials are compared in the field trial, namely fly ash, Calmasil and calcitic lime. In order to observe the effectiveness of gypsum down the profile each treatment was applied both with and without gypsum. The chemical properties of all the materials used are displayed in Table 4.3. Gypsum was applied in the form of phosphogypsum. The fly ash was obtained from the Duvha coal power station in Mpumalanga. Calcitic lime was obtained from Immerpan lime and Calmasil is a locally produced alkaline stainless steel slag material and it predominantly consists of calcium, magnesium and silicon.

Table 4.3 Chemical properties of soil amendments used in field trial (after Mbakwe, 2008)

	Ash	Calmasil	Lime	Gypsum
pH	10.0	11.9	8.53	3.45
EC (dS/m)	0.235	2.16	0.317	2.09
CCE (%)	10	99	77	n.d.

n.d. = not determined

The three liming materials, fly ash, Calmasil and lime, were applied at four levels, based on the lime requirement value and their respective CCE values. Treatments were applied by hand and disc ploughed into the soil to a depth of approximately 20cm. The four levels applied were 0, ½-, 1-, and 2 times the lime requirement of the soil and each treatment was applied in triplicate. The lime requirement value was determined using the AOAC (2005) method as quoted by Mbakwe (2008) and the exchangeable Al method (McLean, 1982). The same treatments were duplicated and to these 4t/ha of gypsum was added. The actual application rates of the different materials are shown in Table 4.4.

The experimental design has been randomized to reduce spatial variability of the plots and the layout is shown in Appendix 1. At end November 2007 after the first rains, bean seeds were sown at a plant population density of 45000/ha and harvested in April 2008 (Figure 4.3). As the soil was uniformly deficient in Zn and P, 2mg Zn per kg soil in the form of $ZnSO_4$ was applied and 15mg P per kg soil in the form of Supergrow (20.3% P) was added manually to each plot in September 2008.

For the second season, in November 2008, after the first rains, maize seed of variety Phb 30D07B was planted at a population density of 45000/ha. The border rows for each plot were thinned two weeks later to allow better access to all the plots throughout the season. In June 2009 maize was harvested manually

In both seasons a basal dressing of 4:3:4 (40) at 200kg/ha and urea at 120kg/ha was applied to all plots in order to reduce the likelihood of other growth limiting factors playing a role. Harvesting in each plot took place in a central area of 43.35m^2 in order to minimise any treatment interference that may have arisen from movement of materials from adjacent plots.

Table 4.4 Actual application rates of amendments per plot and equivalent levels per hectare

Material		kg/plot	kg/ha	t/ha
Lime/Calmasil	**L0/C0**	**0**	**0**	**0**
	L1/C1	**10**	**926**	**1**
	L2/C2	**20**	**1852**	**2**
	L3/C3	**40**	**3704**	**4**
Ash	**A0**	**0**	**0**	**0**
	A1	**75**	**6944**	**7**
	A2	**150**	**13889**	**14**
	A3	**300**	**27778**	**28**
Gypsum	**G0**	**0**	**0**	**0**
	G1	**43**	**3981**	**4**

4.3.3 Sample collection and analyses

In July 2007, soil samples were collected at 0-20cm and 30-40cm depth increments before any treatments were applied. In December 2007, control plots and plots with only the addition of gypsum was evaluated (sampled at 10cm depth increments) to compare the effect of gypsum on nutrient movement down the soil profile. In January 2008, during early pod development of the beans, 15 topsoil samples were collected from each plot using a soil auger, and bulked together to form a composite sample. Bean leaf samples were also taken at this stage.

In July 2008 two core samples per plot were taken to a depth of 50cm at 10cm intervals and composited. In January 2009 maize leaf samples were taken at the tassle stage (Figure 4.4). Finally in June 2009, after the maize harvest soil was sampled at 20cm intervals to a depth of 80cm. Top- and subsoil samples had moisture content values of 4-6% and 8-12% respectively at harvesting.

Figure 4.3 Harvesting of beans in April 2008

Figure 4.4: Maize during tassle stage in January 2009

The soil samples were air dried and passed through a 2mm sieve. The following analyses were performed on all samples.

- **Soil pH**

Soil pH was measured in a 1:2.5 soil:1M KCl and 1:2.5 soil:water mixture respectively. These mixtures were shaken on a reciprocating shaker for 15 minutes and allowed to stand for 5 minutes. The pH of the supernatant was measured with a

Metrohm 744 pH meter (White, 1997). If the pH in KCl was found to be less than 4.5, the titratable acidity was measured (White, 1997).

- **Titratable acidity**

A 1:10 soil:1M KCl mixture was shaken for 4 minutes on a reciprocating shaker. The solution was filtered through a Whatman no 2 filter paper and 25ml of this filtrate pipetted into a 250cm^3 conical flask. Six drops of phenolphthalein was added into the conical flask and the solution was titrated to a pink end point with 0.01M NaOH (White, 1997).

- **Extractable cations**

A 1:5 soil:1M NH_4OAc (pH = 7) mixture was shaken on reciprocating shaker for 60 minutes. This solution was then filtered through a Whatman no 2 filter paper and the filtrate was analysed by atomic adsorption spectrometry (AAS) for Ca, Mg, K and Na.

- **Water soluble anions and electrical conductivity (EC)**

A 1:5 soil:water mixture was shaken on a reciprocating shaker for 60 minutes. Thereafter the solution was centrifuged at 5000 rpm for 20 minutes. The electrical conductivity of the supernatant was measured using a Jenway 4510 Conductivity Meter. The solution was filtered through a Whatman no 44 filter paper and the filtrate analysed for Ca, Mg, K and Na by AAS and NO_3, SO_4 and Cl by ion chromatography (IC).

- **Foliar analysis**

Leaf samples were dried at 50-60^{o}C for 24 hours overnight. Thereafter samples were milled and prepared for cation analysis following the method described by Du Preez *et al*. (1981).

- **Root growth**

Root growth was measured by measuring root length in every plot, after a 1m profile was prepared and visual observations were made regarding the root density.

For July 2008 soil data the average value of 0-10cm and 10-20cm was compared to 0-20cm soil data of June 2009 data. Similarly the 20-30cm and 30-40cm data of July 2008 was averaged to compare to the 20-40cm data of June 2009.

Soil and yield data were analysed with analysis of variance (ANOVA) using a factorial design with Statistica software. When there was a significant interaction ($p = 0.05$), it was interpreted with Bonferroni multiple comparisons. If there was no significant interaction the main effects were also interpreted using Bonferroni multiple comparisons.

4.3 Results and discussion

Analytical results of soil and plant data are shown in Appendix 3 and error estimates are represented graphically. The soil data compared are the soil sampled in July 2007, July 2008 and June 2009 respectively. The effect of each treatment on nutrient movement down the soil profile are represented graphically for every individual year and displayed in Appendix 4 and Appendix 5.

The results discussed here will deal with the effect of the three different treatments at four application rates and both with and without gypsum on soil fertility properties 0-40cm down the profile and over time. The application rates are referred to as the percentage of optimum alkalinity added. Percentages of 0%, 50%, 100% and 200% corresponds to 0-, ½-, 1 and 2 times the lime requirements value.

4.3.1 pH

The effect of the application level of liming materials (as % of optimum alkalinity) on pH is illustrated in Fig 4.5. Initially the top- and subsoil of the control plots had an average pH value of 3.8 and 4.1 respectively. After one season the pH of untreated topsoil increased to 4.0. This phenomenon cannot be explained and is probably due to liming material that accidentally landed on the plots but is also understandable with the spatial variation over space that naturally occurs. The application of treatments raised the topsoil pH, with Calmasil at its highest application raising pH to 4.5 and performing better than lime and ash at 4.2 and 4.1 respectively. The liming potential of ash is derived from the hydrolysis of CaO and MgO (Sharma and Kalra, 2006).

The addition of gypsum, a neutral salt, merely increases the pH by an insignificant undetectable 0.03 units. The known benefits of gypsum are its solubility and mobility in the soil as well as phenomenon known as 'the self liming effect' (McLay *et al*., 1994b). However gypsum alone is not expected to have raised pH. The gypsum with the liming materials increased the pH noticeably more, but it still remains acidic. These findings on gypsum are in agreement with results obtained by Farina and Channon (1988b) and Toma *et al*. (1999).

In subsoils at 20-40cm, the increasing treatment trend remains with Calmasil > ash> lime. The effect of treatments in the subsoil are not as pronounced as in the topsoil yet. This could be due to the limited downward movement of the liming materials. As expected, gypsum movement down the profile did not increase pH significantly. Calmasil treatments are responsible for the only statistically significant changes and the interaction of treatment level, liming material type and gypsum is significant. Gypsum application alone had no significant effect.

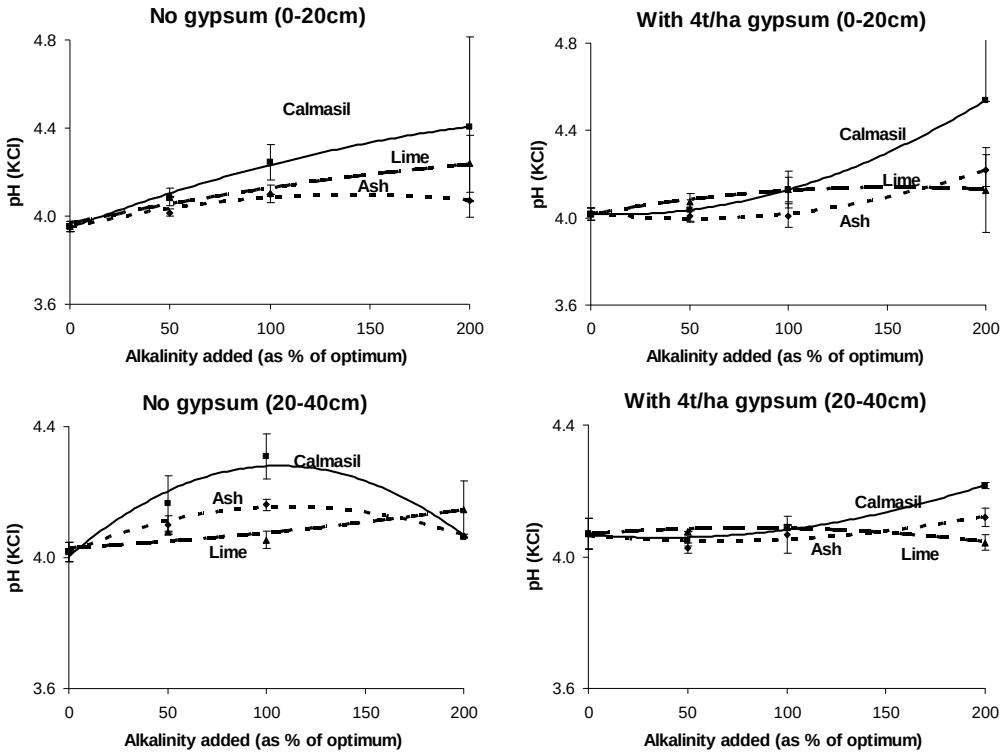


Figure 4.5: Effect of lime, Calmasil and ash on pH (KCl) in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical lines denote standard error bars

The effect of liming materials on pH after two years is shown in Figure 4.6. Over time values of 5.58, 4.48 and 4.18 at highest application of Calmasil, lime and fly ash are obtained respectively. Gyspum applied on unlimed plots still had no effect on pH, although it improves the performance of ash and lime.

In the subsoil the treatment trends are similar as in the topsoil but the pH increase is not as prominent. One should not expect a pH change from gypsum as it is a neutral salt. Nevertheless, reports of gypsum having little or no effect on pH (Oates and Caldwell., 1985, Alva *et al*., 1990) as well as negative effects (Shamshuddin *et al*, 1998) on pH exist. The negative pH response is due to exchangeable Al that is high in the Ultisol as a result of Al replacement by Ca (Shamshuddin *et al*, 1998).

If a negative or no effect on pH occurs through addition of gypsum, then the replacement of Al and H by Ca (also known as the salt effect) is the dominant reaction. If a positive effect on pH occurs, then this is due to the self liming effect as explained by Reeves and Sumner in 1972 as a sulphate sorption and hence OH release (Toma *et al*., 1999). Positive pH effects could also be due to the formation of an aluminum-hydroxy sulphate and thus precipitation of soluble Al (Hue *et al*., 1986).

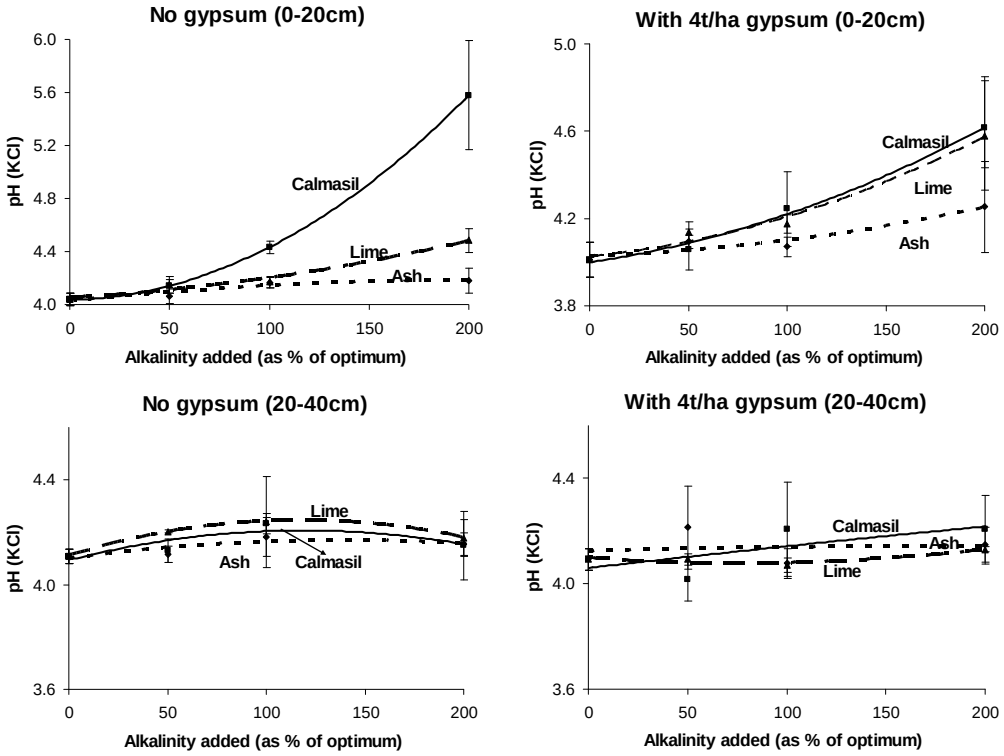


Figure 4.6: Effect of lime, Calmasil and ash on pH (KCl) in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical lines denote standard error bars

In this study it appears that the salt effect was counteracted by the OH release which resulted in no net detectable pH change. The self liming effect of gypsum is not a sustainable practice to neutralise topsoil acidity and other liming materials should be applied. Gypsum is purely an ameliorant for subsoil acidity (Wang *et al*., 1999).

4.3.2 Acidity

Unsurprisingly, control values of 2007 have risen from 6.8mmol$_c$/kg to 12.33mmol$_c$/kg in the topsoil and from 6.8 to 12.43mmol$_c$/kg in the topsoil in 2008.

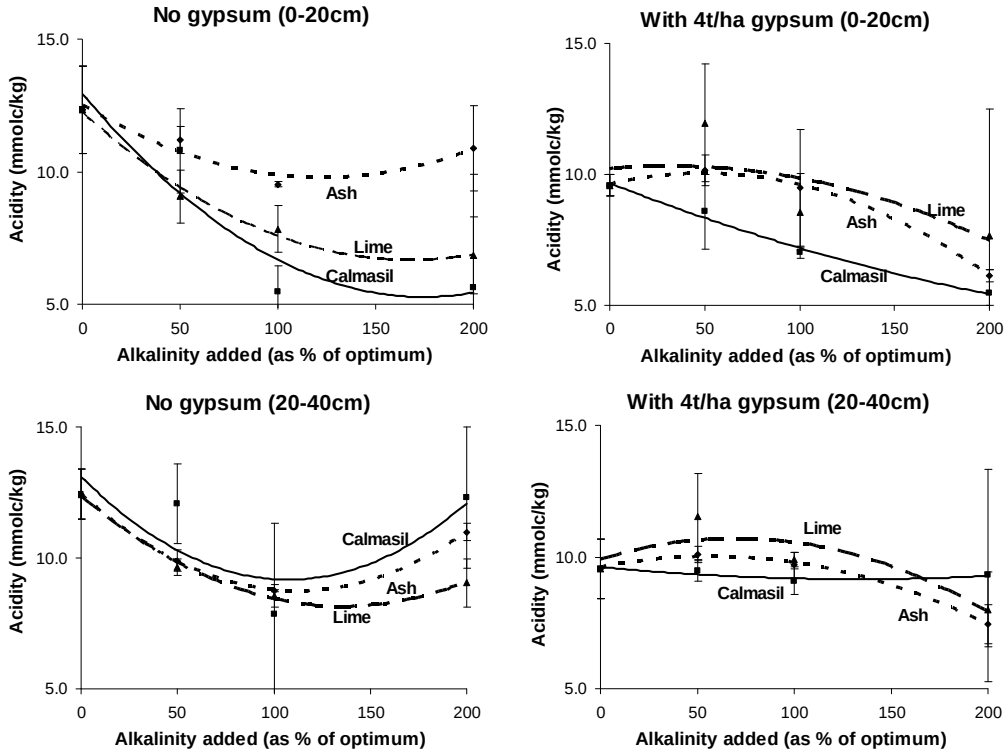


Figure 4.7 Effect of lime, Calmasil and ash on acidity in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical lines denote standard error bars

Calmasil shows the greatest reduction of acidity to 5.64mmol$_c$/kg, followed by lime at 6.83mmol$_c$/kg and ash to a value of 10.83mmol$_c$/kg in the topsoil (Figure 4.7). The acidity of unlimed gypsum plots have been slightly improved to 10.5mmol$_c$/kg in the topsoil. In combination with the application of gypsum in the topsoil the performance of the ash has improved considerably, decreasing the acidity by 6.3mmol$_c$/kg at 200% optimum alkalinity of ash. This effect of ash and gypsum application is statistically significant.

The performance of the treatments is less effective in the subsoil. Application of gypsum alone ameliorates subsoil acidity as minimal as in topsoil. Lime is superior in subsoil with and without gypsum and gypsum improves the performance of ash. Calmasil is less effective in subsoil.

In 2009, after the second season, as illustrated in Figure 4.8, the ameliorants still successfully decrease the acidity. At 200% optimum alkalinity and without gypsum, Calmasil decrease acidity by 87%, lime by 69% and ash by 24%. Over time, gypsum addition alone did not decrease acidity significantly but works in conjunction with lime and ash to be on par with Calmasil's performance. However, statistical analysis indicates that the application of lime is significant in season one and two. The effect of the treatments is less in subsoil as Calmasil, lime and ash alleviates acidity by 20%, 30% and 25% respectively. The effect of lime and Calmasil at highest application is statistically significant while ash is not significant. Gypsum decrease acidity slightly and improve performance of ash and lime

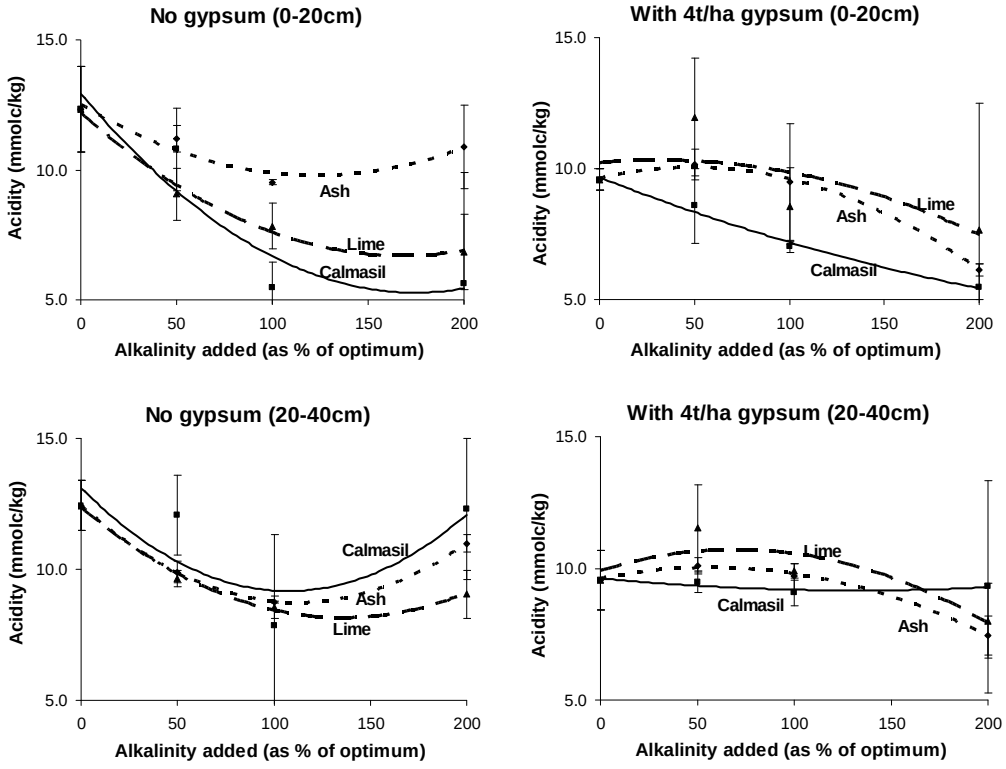


Figure 4.8 Effect of lime, Calmasil and ash on acidity in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical lines denote standard error bars

No change in exchangeable acidity has been observed in a bean pot trial based on the exact same experimental design by Mbakwe (2008), but research done by Toma *et al*. in 1999 and 2005 reports on reduction in exchangeable Al down to 80cm. and the continuous decrease in exchangeable acidity that lasts after 16 years of gypsum application. As the effect of gypsum is time dependant better results might be expected (Farina and Channon, 1998b). Exchangeable Al was reduced to zero by applying fly ash at 40g/kg and it improved root growth of wheat (Wright *et al*; 1998).
The reduction in acidity is associated with the increase in exchangeable Ca, and Mg as liming materials are added to the soils (Toma *et al*, 1999).The possible formation and precipitation of an Al-SO_4 complex was also proposed as a gypsum-induced decrease in exchangeable Al.

4.3.3 Acid saturation

Initial average values of untreated soil in July 2007 were 51.7% and 51.2%. In Figure 4.9, without gypsum, ash application did not significantly reduce acid saturation, but Calmasil and lime reduced it to 24.8% and 34.9% at 200% optimum alkalinity. The addition of gypsum only decreased topsoil acid saturation reduction by 14% and in combination with ash, it largely improved the performance of ash on decreasing acid saturation.
The effect of gypsum application in the subsoil decrease acid saturation by 22.1%, which indicates upon movement down the profile. Ash and Calmasil have not decrease subsoil acid saturation noticeably and perform similarly. At the highest application of Calmasil and ash the acid saturation increase. This cannot be explained but this effect is corrected by gypsum application.
Over two seasons the treatments seems to have decreased acid saturation in topsoil considerably (Figure 4.10). Without gypsum, Calmasil reduced acid saturation by 91% and ash reduced it by 70%. Ash is the poorest performer with having only decreased the acid saturation by 25%. Gypsum on untreated plots seems to decrease acid saturation from 60.52% to 49.35% in topsoil and if applied on limed plots it appears to advance the effect of ash and lime. Statistical analysis indicates that the interaction between treatment level, liming material and gypsum is significant with Calmasil delivering the only significant results at highest level of application.

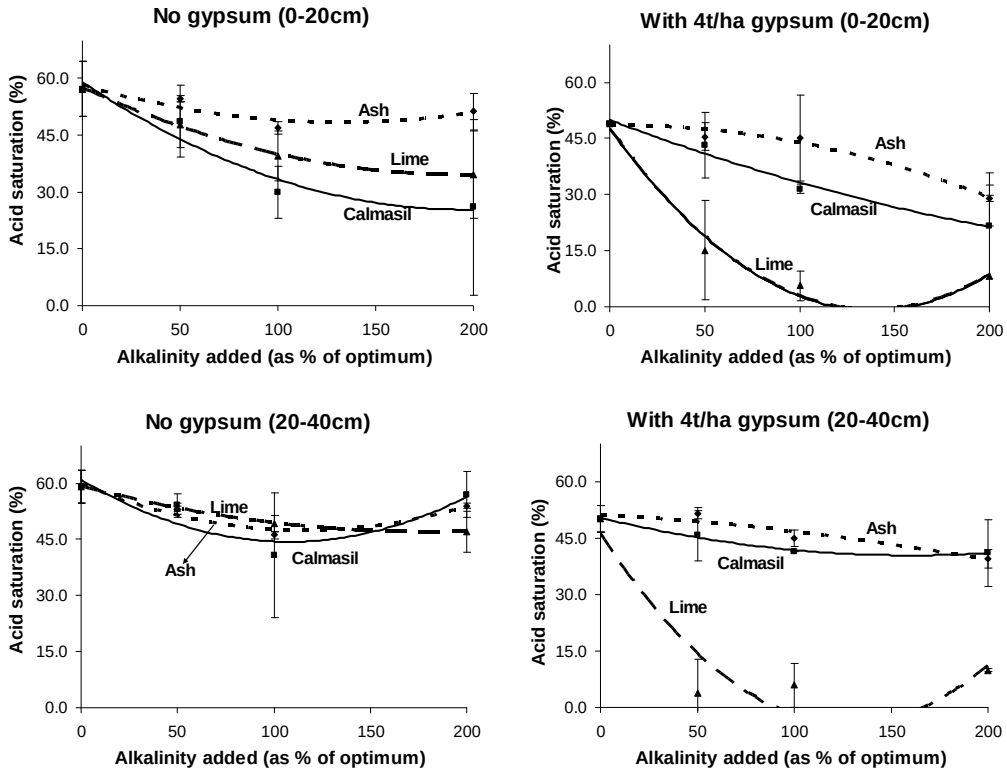


Figure 4.9 Effect of lime, Calmasil and ash on acid saturation in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical lines denote error bars

In the subsoil Calmasil appears to be the only liming material that maintained a positive effect. The beneficial effect of ash and lime has improved slightly. Gypsum on its own decreases the acid saturation down the profile from 64% to 55%, and beneficial effect is observed when gypsum moves down the limed plots with lime. Farina and Channon (1988b) and Mbakwe (2008) reported significant results on the reduction of acid saturation. The reduction in acid saturation is attributed to the Ca and Mg, and the decrease in exchangeable acidity, especially when gypsum is applied.

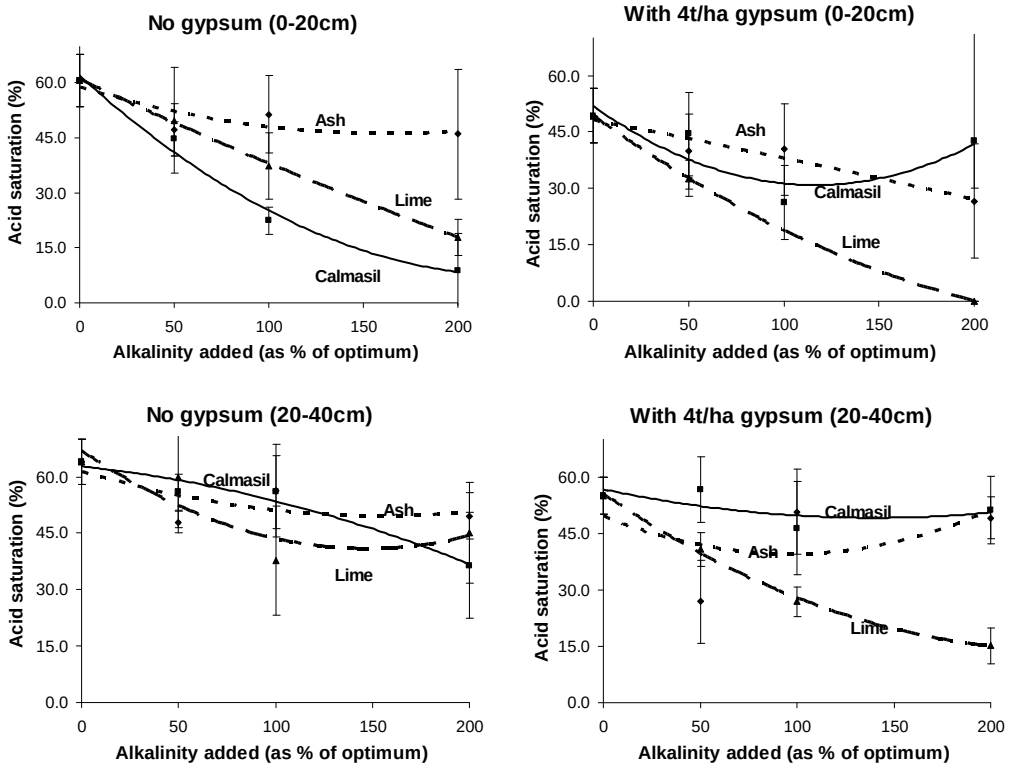


Figure 4.10 Effect of lime, Calmasil and ash on acid saturation in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical lines denote standard error bars

4.3.4 Extractable cations

Calcium

In 2007, Ca content of untreated plots was 53.6mg/kg and 47.0mg/kg in the top- and subsoil respectively. One year later the control pots have increased to 74.74mg/kg and 61.3mg/kg respectively. A positive and linear response to treatment application is observed, with Calmasil, lime and ash increasing Ca content to 249mg/kg, 171.8 mg/kg and 102mg/kg respectively (Figure 4.11) at 200% optimum alkalinity. Gypsum application alone on unlimed plots increased topsoil Ca to 124.6mg/kg. As expected, the addition of gypsum to liming materials causes Ca content to increase further. This is in agreement with work done by researchers such as Farina and Channon (1988a) and McLay *et al*. (1994a).

Less Ca occurs in the subsoil, but the concentration is nonetheless raised by the liming materials, though not as substantial as in topsoil. This might be due to the low solubility of the materials and slow movement down the profile. Gypsum alone

increases the subsoil Ca content from 61.3mg/kg to 91.5mg/kg and increase Ca content of limed soils, indicating upon greater Ca movement with the application of gypsum. No statistical significant changes took place as a result of the treatments.

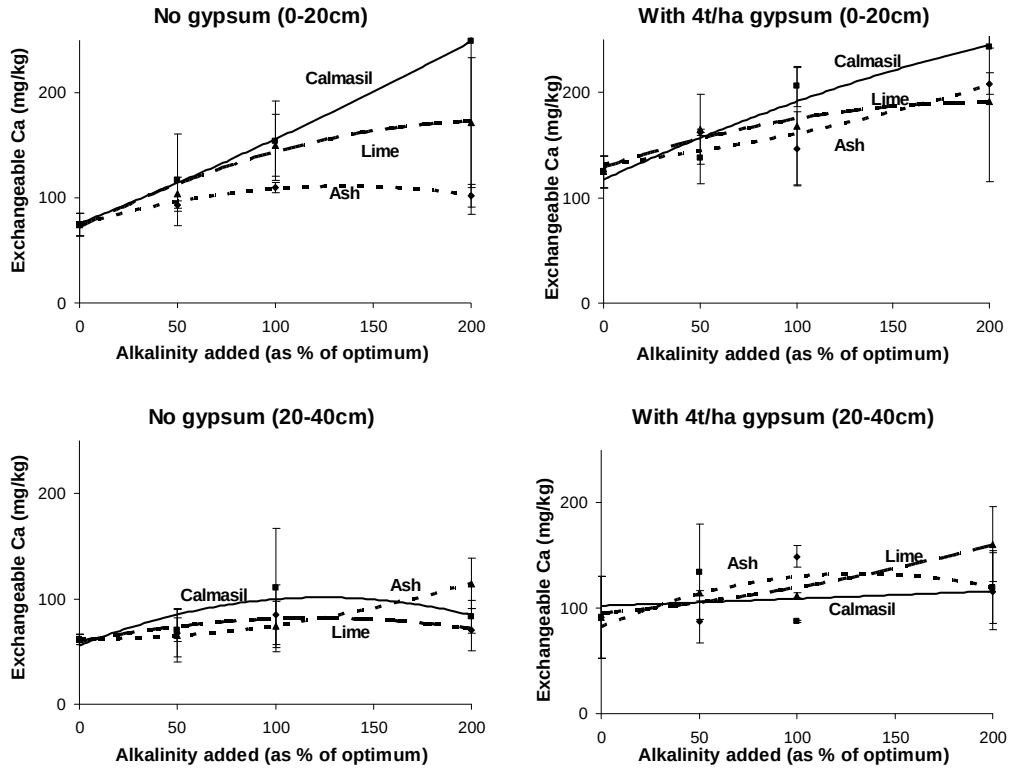


Figure 4.11 Effect of lime, Calmasil and ash on exchangeable Ca in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical lines denote standard error bars

After two seasons, treatments still increased Ca content (Figure 4.12), with Calmasil being the only treatment that is statistically significant. Gypsum only plots still contain 29.9mg/kg more Ca than the control plots. Application of gypsum enhanced the Ca contribution on all limed plots, but is significant on ash plots of highest application level. According to XRF analysis, Calmasil and lime have similar Ca content, but the Calmasil is more soluble than lime as it enhances the exchangeable Ca more.

In the subsoil, Calmasil are superior, followed by lime and ash. Gypsum application indicated gypsum migration downwards to increase unlimed plots to 87.11mg/kg from 38.11mg/kg. Gypsum addition enhances the Ca contribution of lime, ash and Calmasil, but this is negated at 200% optimum alkalinity Calmasil.

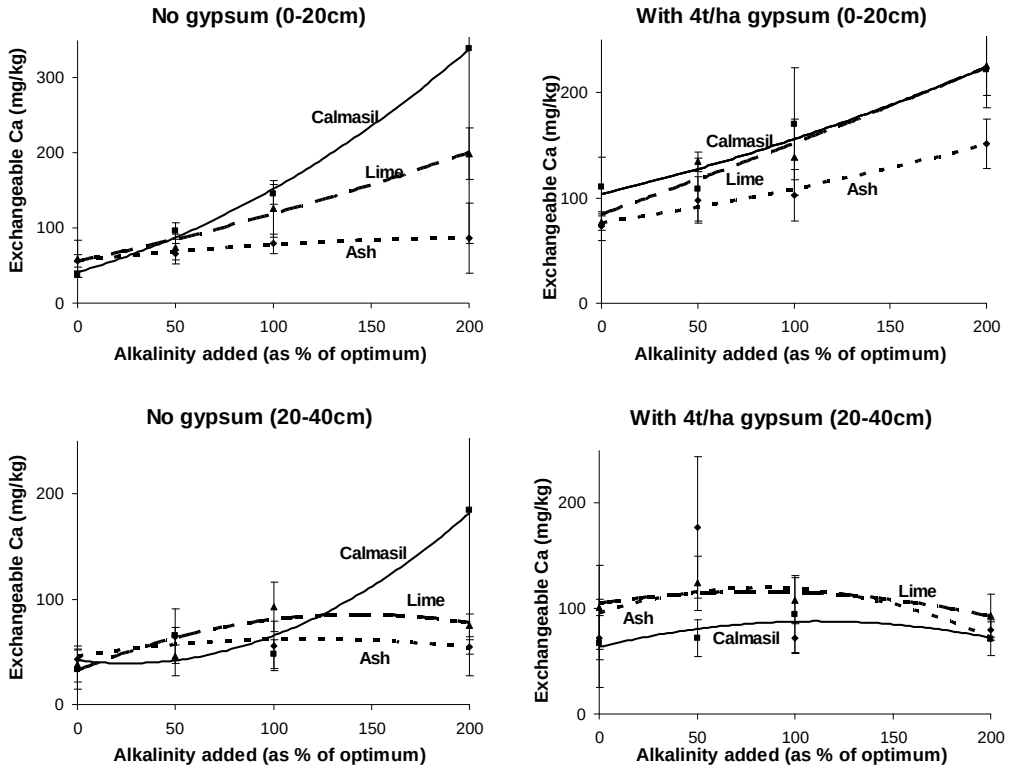


Figure 4.12 Effect of lime, Calmasil and ash on exchangeable Ca in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical lines denote standard error bars

Magnesium

After bean harvesting in 2008, the values of untreated top- and subsoil was 8.9 mg/kg and 9.7mg/kg respectively. The liming materials all maintained increased exchangeable Mg levels. Calmasil, ash and lime increased the value in the topsoil to 36.5mg/kg, 16.1mg/kg and 14.5mg/kg (Figure 4.13). Addition of gypsum to the topsoil has decreased the Mg levels of untreated plots by 1.9 mg/kg and the addition of gypsum on all limed plots has lowered the topsoil Mg content of the plots.

The subsoil control contains similar Mg levels as the topsoil, but the performance trend of treatments displayed in the topsoil remained. Calmasil, ash and lime has increased values to 18.0mg/kg, 13.4mg/kg and 12.9mg/kg. This addition could also be due to the downward movement of topsoil Mg. The addition of gypsum reduced the Mg of limed plots. The additions of gypsum decrease subsoil Mg content of untreated plots from 9.7mg/kg to 6.1mg/kg, indicating upon downward leaching. This effect of gypsum and movement with depth is statistically significant. Ash plots contain more

Mg than lime and lime's MgO content is 4.6% while ash contains 0.75%. This indicates upon the great amounts of ash applied onto the plots.

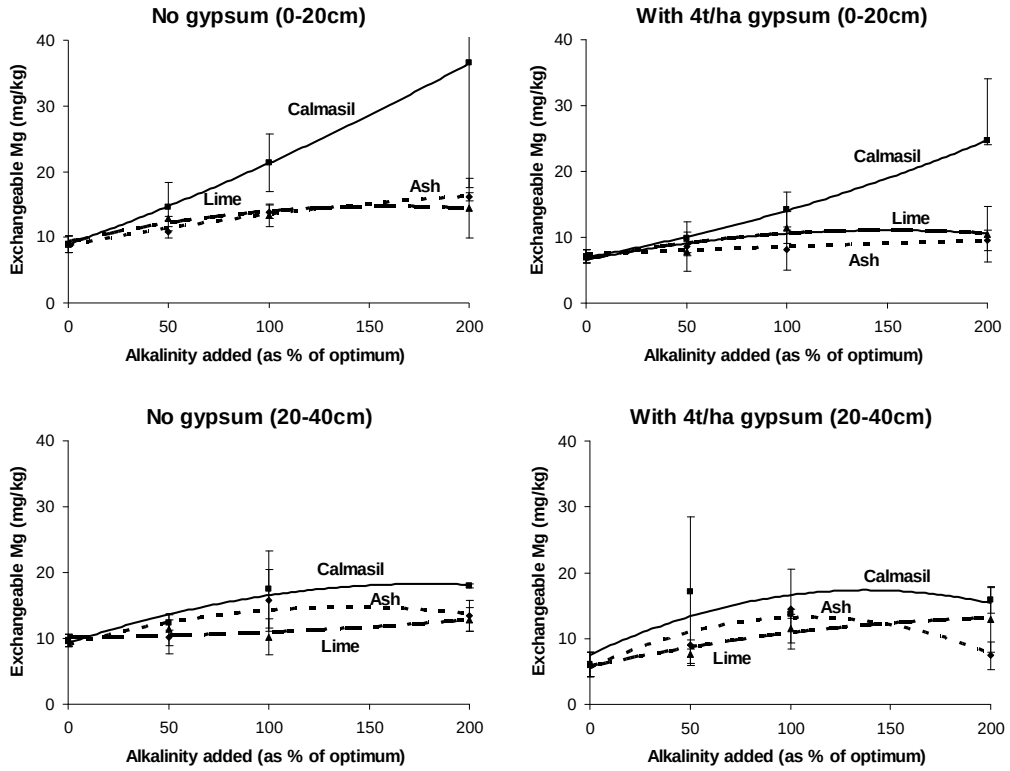


Figure 4.13 Effect of lime, Calmasil and ash on exchangeable Mg in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical lines denote standard error bars

In 2009, treatment trends remain and Calmasil application still maintains the greatest Mg levels (Figure 4.14). Gypsum addition alone has not affected the Mg values during this season, but addition of gypsum to liming materials severely decreased the Mg values to 21.4mg/kg, 13.6mg/kg and 10.17mg/kg for Calmasil, lime and ash.

In subsoil the gypsum lowers the Mg contributions of all limed plots with statistical significance. It is expected that Mg should accumulate in the subsoil after leaching from topsoil, but it has probably moved downwards and passed 40cm after two seasons.

Literature found that gypsum application reduces Mg in upper part of profile and it accumulated in the subsoil (Shainberg *et al*., 1989, McLay *et al*., 1994b). In 1999, Toma and colleagues observed that the application of 35t/ha gypsum allowed

reduction of Mg in 30-50cm layer and it was transferred to lower depths due to replacement of Mg by Ca in gypsum. Even with all the treatments, Mg levels are still low as maize requires 40mg/kg Mg (Du Toit, 1999).

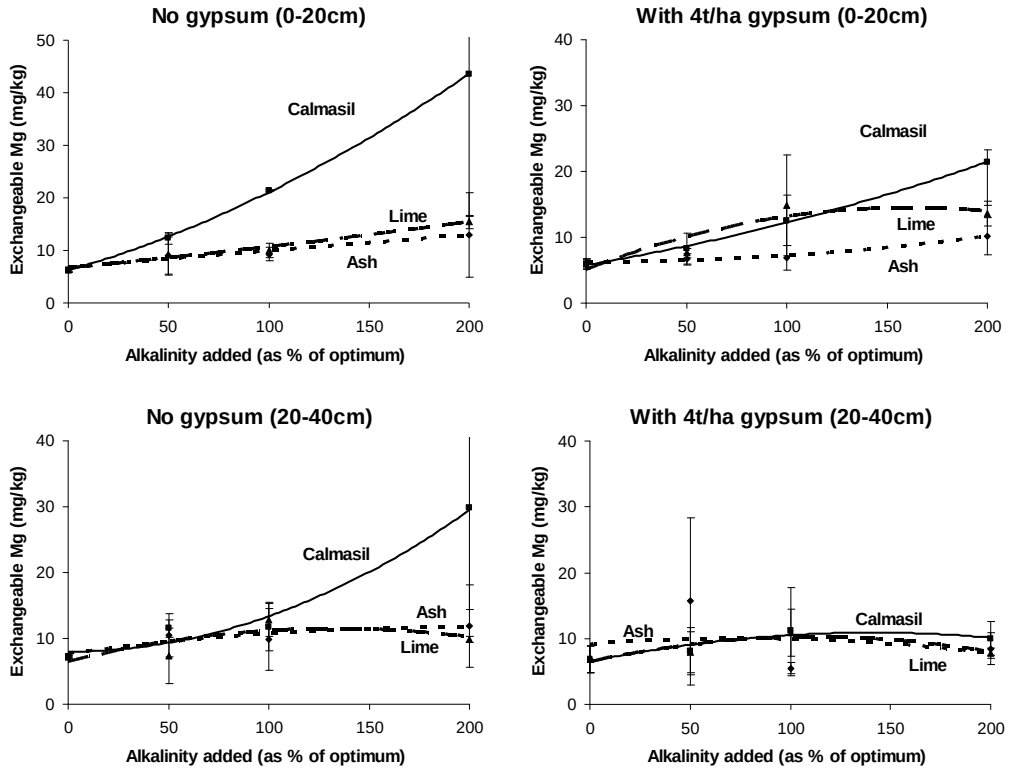


Figure 4.14 Effect of lime, Calmasil and ash on exchangeable Mg in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical lines denote standard error bars

Potassium

Initially in 2008, the K vales of all treatments are similar and significant increases are only observed with higher application rates of liming material as seen in the appendix. Subsoil K values are not significantly altered in the first season.

Two seasons later the K levels obtained was erratic The behaviour of K as a result of gypsum application differs according to location and prior art indicates that in South Africa, little change in K down profile occur (Shainberg *et al*., 1989). Potassium levels were unaltered by addition of calcium-containing materials in a sandy soil (Murata *et al*., 2002).

Sodium

After the first season, the topsoil Na values of limed plots ash plots remained nearly constant at 62.1mg/kg, while liming materials alter Na values insignificantly and erratic in topsoil (Appendix 4 and Appendix 5). Gypsum addition suppresses Na release from liming materials and it decrease the top- and subsoil Na levels of unlimed soils.

4.3.5 Water soluble anions

Low levels of water-soluble ions were measured and an imbalance in ion charge associated with the dataset was found for both seasons

Nitrate

Initially in 2007, the control had NO_3 levels of 120.4mg/kg in topsoil and 174.9mg/kg in subsoil. One season later it declined to 93.5mg/kg and 94.1mg/kg respectively (Figure 4.15). This decline on control plots is expected as nitrate is formed through the process of nitrification, which is a pH dependant process. It is at optimum in pH 8-9 (Shammas, 1986). At lower pH ranges the rate declines and less nitrate is formed due to decreased activity of the autotrophic bacteria, *Nitrosomon*as and *Nictrobacte*r involved in the process.

All liming materials display a steady decrease in NO_3 levels with increasing levels of application. This decrease cannot be explained as an increase of NO_3 concentration is expected with increasing pH. The NO_3 levels are dropped from 93.5mg/kg to 53.4mg/kg and 53.1mg/kg by Calmasil and ash respectively at 200% of optimum alkalinity. Lime is the only material that increases nitrate levels at the highest rate of application.

Use of gypsum alone decreases the topsoil nitrate. This is explained by the presence of SO_4 in the soil that can result in other anions, such as NO_3, being removed from the topsoil (Shamshuddin *et al*., 1998). Nitrate moves downwards and accumulates in the subsoil. If gypsum is used with liming materials, elevated nitrate levels are found. This interaction of gypsum with the liming materials at the highest application level is statistically significant with all liming materials, while gypsum application alone has no statistically significant effect on nitrate levels.

The subsoil contains less nitrates than the topsoil. This is expected as the organic matter decrease down the profile. Movement of Calmasil and lime decrease the NO_3

levels in subsoil as well and only the highest level of their application has increased NO_3 levels. Ash increase the subsoil NO_3 levels but it is decreased to 35.6mg/kg at the highest level of application. Gypsum alone decreases the nitrate levels of subsoil. Gypsum use in combination with the treatments of ash and Calmasil, raise nitrate levels, except at the highest application rate.

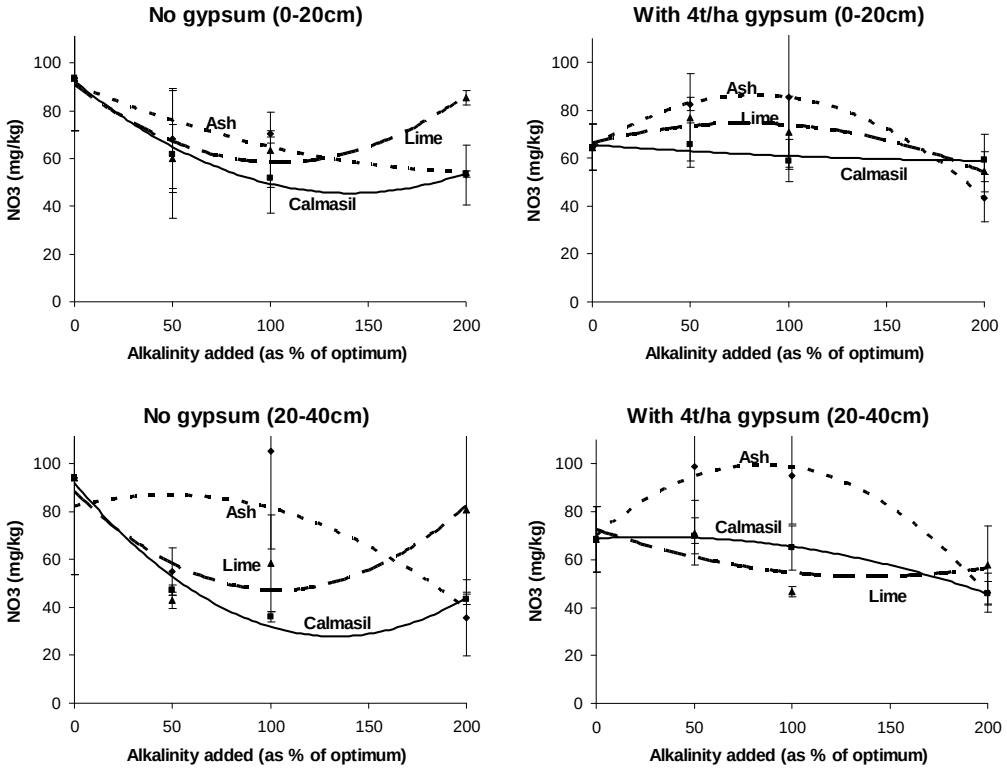


Figure 4.15 Effect of lime, Calmasil and ash on NO_3^- in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical lines denote standard error bars

In the following season the nitrate levels dropped dramatically in top and subsoil to 53.5mg/kg and 49.9mg/kg for the untreated top- and subsoil respectively and this could be due to plant uptake and/or leaching (Figure 4.16). Treatment of soils with any liming material aggravates the situation. Although this scenario persists in the subsoil the effect of liming is not that remarkable. It is evident that using gypsum alone causes lower nitrate levels and cause leaching deep into subsoil. The leaching of nitrate is a worldwide concern as it can contaminate groundwater (Meda *et al*., 2001). Contradictory, McLay *et al* (1994a) found that nitrate tends to be less affected by gypsum and lime applications.

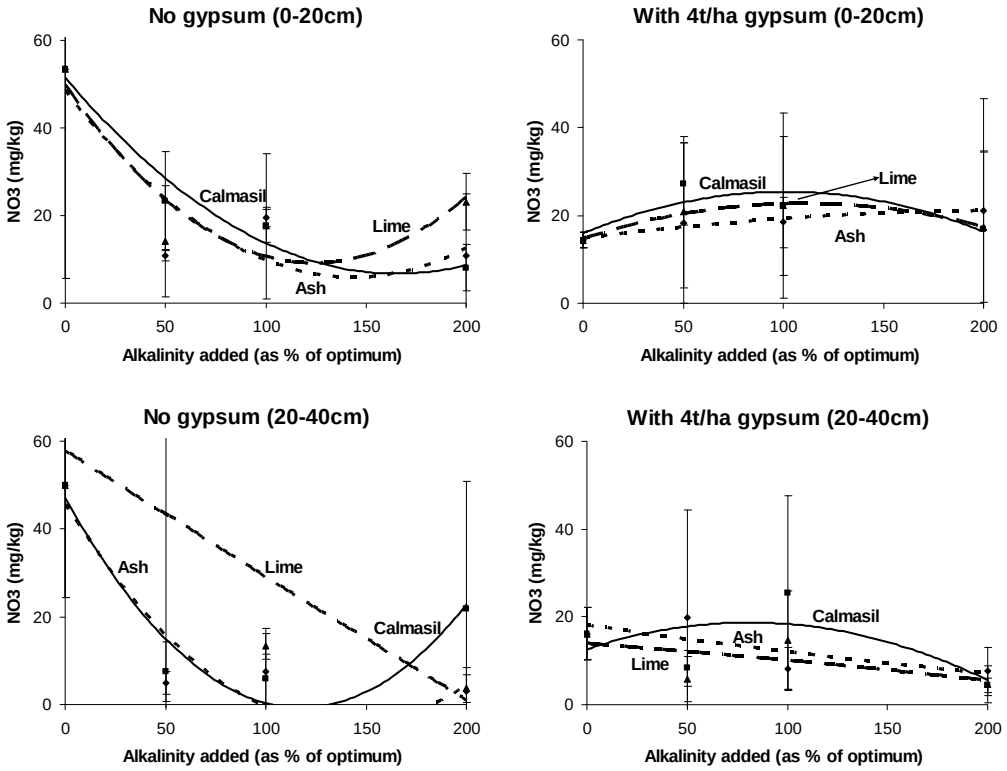


Figure 4.16 Effect of lime, Calmasil and ash on NO_3^- in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical bars denote standard error bars

Sulfate

In 2008 the sulfate values for the untreated top- and subsoil were 156.3mg/kg and 204.2mg/kg (Figure 4.17). This indicates upon sulfate movement, without gypsum, to the subsoil based on the initial virgin soil values of 346mg/kg and 154.7mg/kg in the top- and subsoil in 2007. All three liming materials decrease SO_4 levels initially, but with increasing concentrations of the materials the levels are increased to 150.6mg/kg, 123.7mg/kg and 125.8mg/kg for ash, Calmasil and lime respectively. Liming of topsoil increases the movement of sulphate into the subsoil (Shainberg *et al.*, 1989, McLay *et al.*, 1994b, Shamshuddin *et al.*, 1998), with ash having the greatest effect. Statistically, only Calmasil application causes significant changes. Gypsum application increased all SO_4 levels, and over time it has moved to the subsoil. Gypsum application with liming materials does not alter their decreasing trend. The effect of gypsum application is significant.

The effect of liming material in subsoil display similar behaviour to the topsoil trends and higher levels of SO_4 are obtained in the subsoil due to leaching after one season.

Gypsum in the subsoil increase the SO_4 content of unlimed plots to 298.6mg/kg, while in combination with liming materials the SO_4 levels are raised compared to limed subsoils without gypsum.

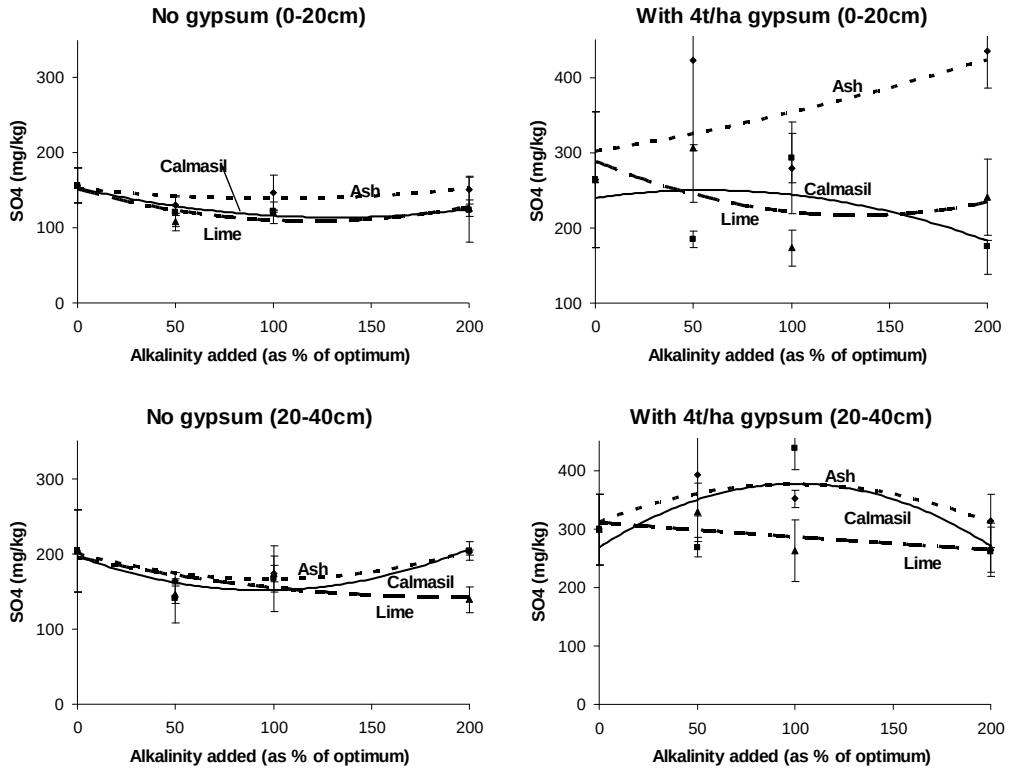


Figure 4.17 Effect of lime, Calmasil and ash on SO_4^{2-} in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical lines denote standard error bars

In the following season (Figure 4.18) topsoil sulfate levels has risen minimally to 168.4mg/kg and 264.9mg/kg for top and subsoil respectively in treated and untreated plots and it could possibly due to the acid rain in the region. The control subsoil sulphate levels have increased by 60mg/kg and this is expected as sulphate is strongly retained in subsoil of highly weathered soils, especially in the gypsum treated plots (Shainberg *et al*, 1989). Gypsum still delivers significant changes, with increasing unlimed plots to 290mg/kg and 378.8mg/kg in top- and subsoil respectively.

Of all three liming materials, ash application seems to increase the sulphate levels most.

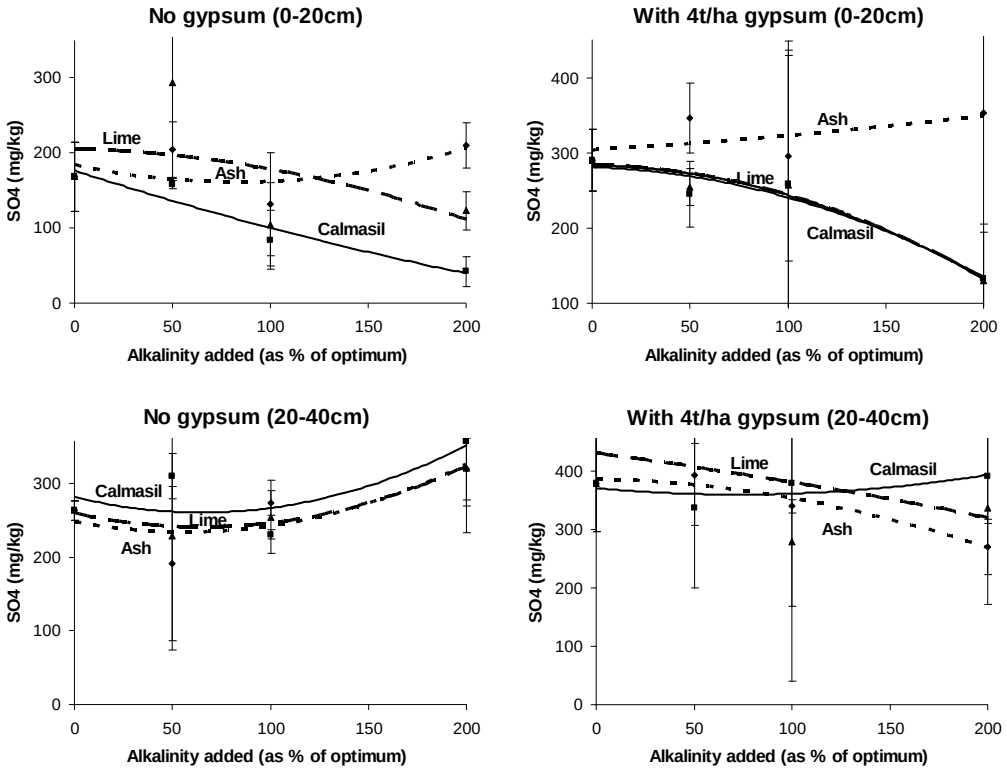


Figure 4.18 Effect of lime, Calmasil and ash on SO_4^{2-} in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical lines denote standard error bars

Chloride

Chloride levels remained effectively unchanged over one season as 20.2mg/kg and 21.6mg/kg are found in untreated top- and subsoil. Application of liming materials does not alter Cl levels (Figure 4.19). In the subsoil, only the highest level of lime material application alter Cl values with lime> Calmasil> ash at 28.5mg/kg, 22.5mg/kg and 19.7mg/kg in that order. Gypsum addition alone has no effect on top- or subsoil of limed and unlimed plots. In 2009 (Figure 4.20), the chloride levels have increased insignificantly on untreated plots and gypsum addition had no effect on unlimed soils. Lime and ash seems to increase chloride levels of top- and subsoil

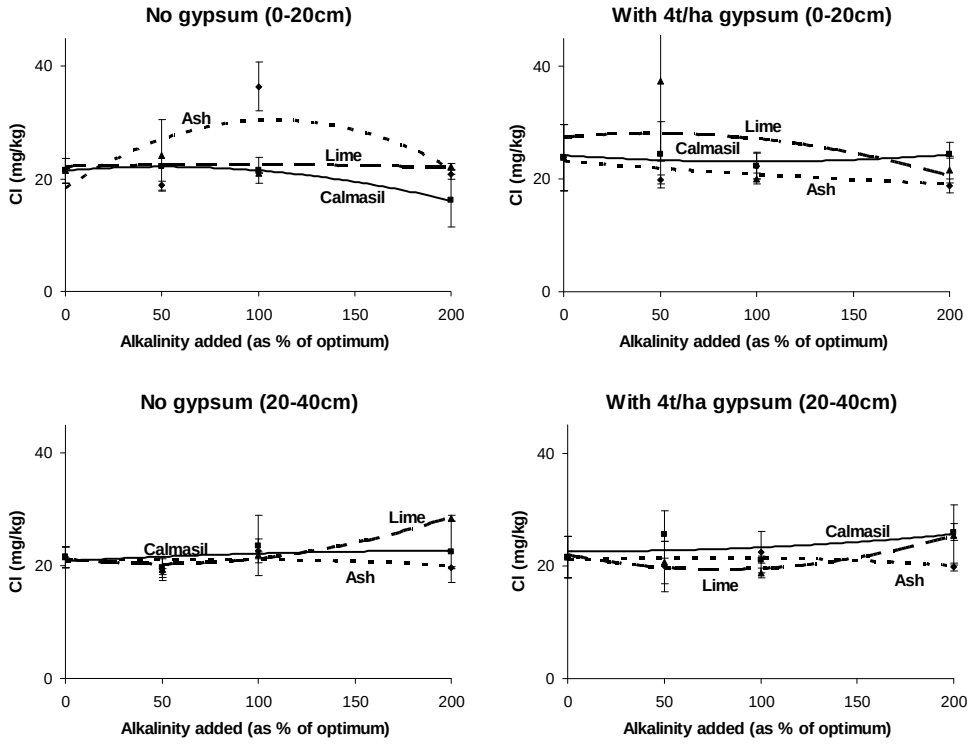


Figure 4.19 Effect of lime, Calmasil and ash on Cl^- in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical lines denote standard error bars

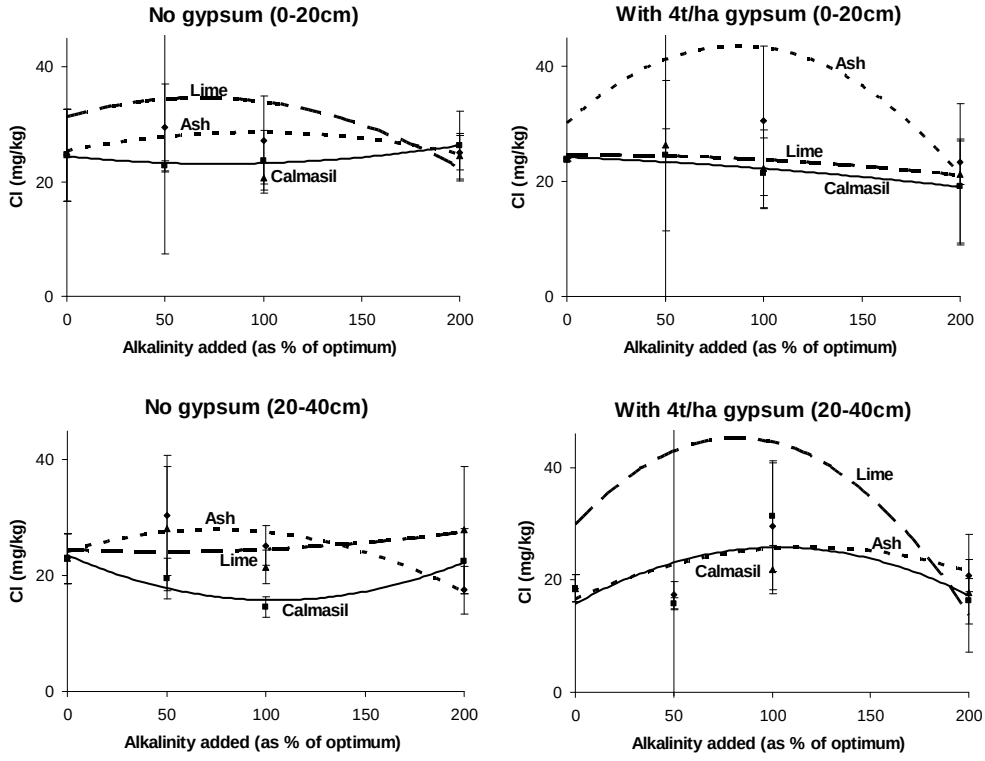


Figure 4.20 Effect of lime, Calmasil and ash on Cl^- in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical lines denote standard error bars

4.3.6 Electrical conductivity

The electrical conductivity (EC) of the soil reflects the soluble salt content of the soil. Calmasil increases the EC value to 0.084 mS/cm and lime to 0.065 mS/cm (Figure 4.21).

Surprisingly the application of gypsum had no effect on the soluble salt content, given the fact that it is a soluble salt. Wright *et al*. (1998) and Toma *et al*. (1999) found EC and soil SO_4 concentration was increased with addition of coal combustion materials and gypsiferous material. Higher EC values in the subsoil were reported after surface application of gypsum, but after continuous leaching into the subsoil, the EC dropped (McLay *et al*., 1994b). This continuous leaching of salts could be an explanation for the decreased EC. However, gypsum and ash applied simultaneously increase the salt content the most according to application rate (Figure 4.21).

The subsoil has a greater salt content than the topsoil, due to leaching, and the concentration has increased with the application of liming materials. Gypsum application with liming materials increases the salt content.

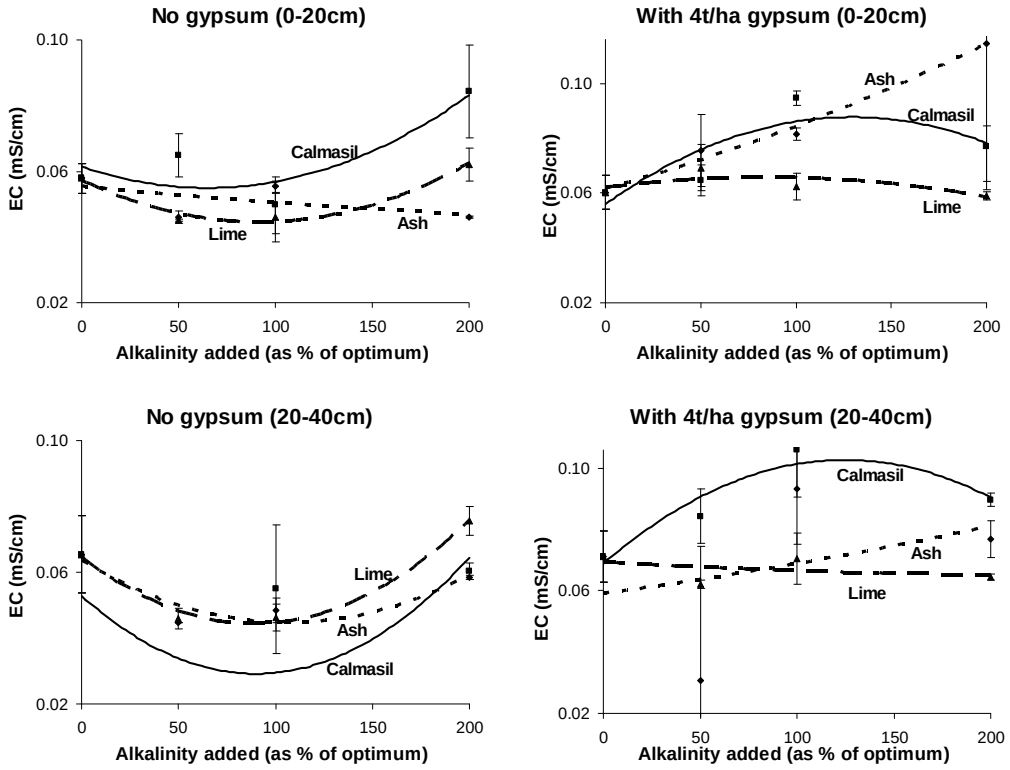


Figure 4.21 Effect of lime, Calmasil and ash on electrical conductivity in top- and subsoil in 2008 (season 1). Points represent means of replicates and vertical bars denote standard error bars

After two seasons (Figure 4.22), lime has contributed more soluble salt to the topsoil than ash and Calmasil. The presence of gypsum with liming materials delivers erratic results. At the highest level of ash application a decrease in salt content is observed. Erratic behaviour is displayed down the profile and with gypsum application the ash now contributes the least salt to the soil.

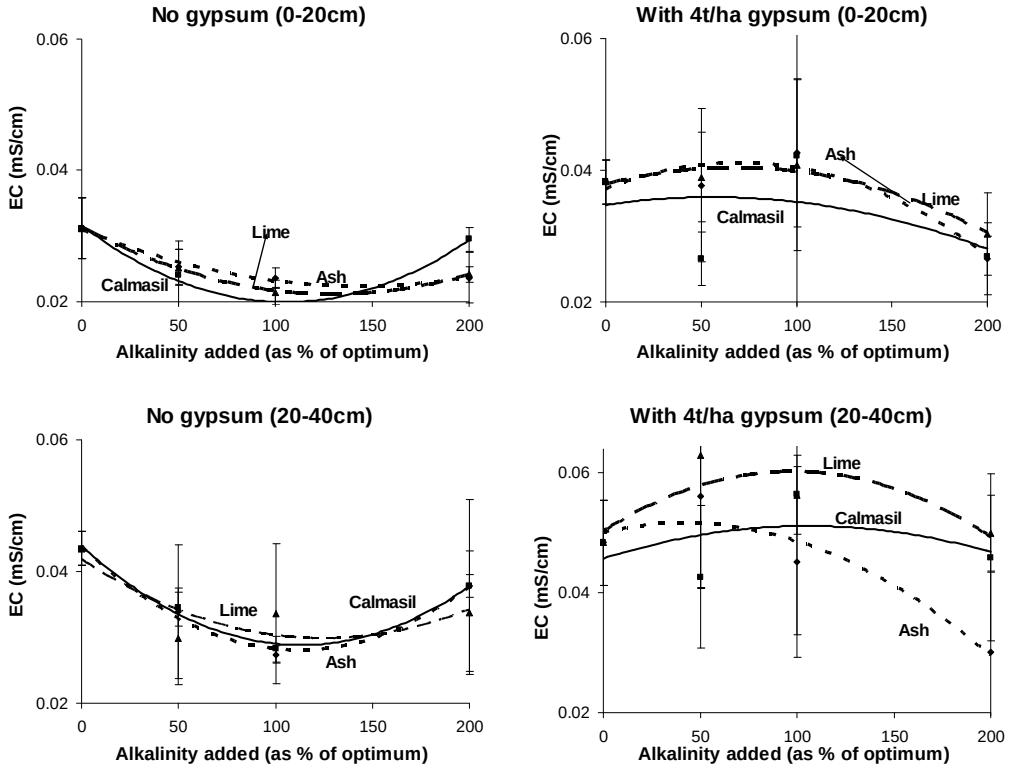


Figure 4.22 Effect of lime, Calmasil and ash on electrical conductivity in top- and subsoil in 2009 (season 2). Points represent means of replicates and vertical bars denote standard error bars

4.3.7 Foliar cation concentrations

The soil supplies plant nutrients for growth and treatments applied to the soil determine which nutrients can be taken up and in which forms as these treatments effect alkalinity. Leaf sample analyses were performed to evaluate if the treatments had an effect on foliar concentrations and hence chemical composition of crops.

Figure 4.23 displays trends in foliar concentration of cations in beans. Soil treated with Calmasil only shows greater Ca foliar concentration than lime and ash plots. Gypsum application alone cause Ca uptake to increase from 1.05% to 1.37%.

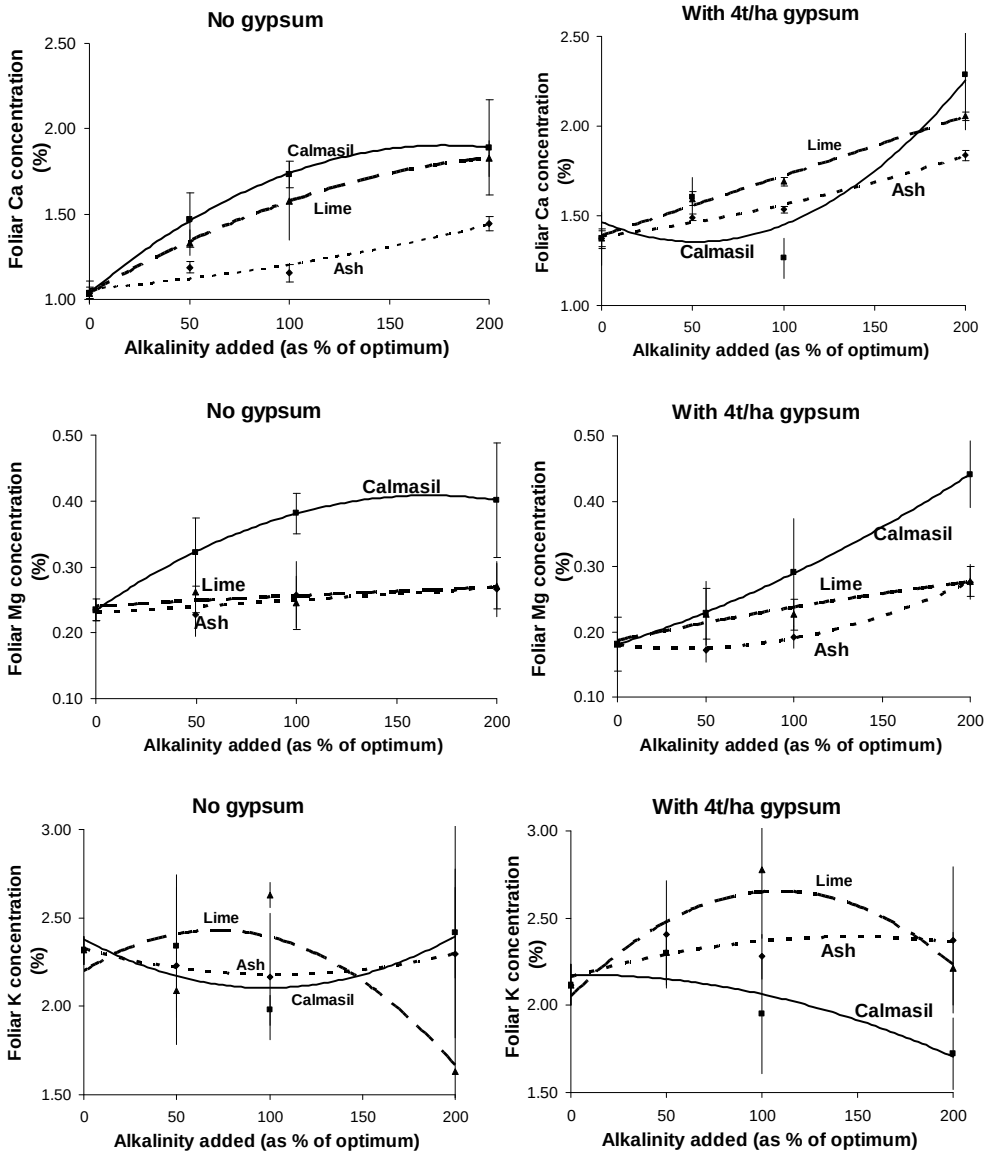


Figure 4.23 Effect of lime, Calmasil and ash on foliar concentration of Ca, Mg and K in beans (season 1). Points represent means of replicates and vertical lines denote standard error bars

With gypsum applied to limed plots the values raise to 2.29%, 2.1% and 1.84% for Calmasil, lime and ash applied at the highest rate respectively. In the presence of gypsum lower Calmasil application levels leads to reduced Ca concentrations.

Calmasil treated soils results in highest concentration of Mg as it contains more Mg than fly ash (0.75%) and lime (4.6%). Lime performs somewhat better than ash. Gypsum alone decreases the Mg content of plants to 1.81%, but gypsum in

combination with the liming materials somewhat increased the Mg concentration in plants.

The bean leaves on the control plots have 2.32% of K. The addition of lime allows greater leaf tissue K concentration, but erratic behaviour is displayed and no trend can be drawn. The leaves of beans grown on soils with only gypsum have a decreased K concentration of 2.12%.

In plots with no gypsum, foliar Ca concentration of maize (Figure 4.24) in ash treated plots is greater than Calmasil and lime at 50% and 100% level of lime requirements. At 200% of lime requirement foliar Ca concentration is dropped in all limed plots with ash plots affected the greatest. Gypsum increase foliar Ca by 0.18% and it increase foliar Ca of all treated plots.

As with beans, all limed plots increase the leaf Mg concentration with increasing levels. Calmasil and ash at highest application decrease Mg concentration. Application of gypsum alone has no effect and decrease the foliar Mg content of plants on Calmasil and ash amended plots somewhat. This could be ascribed to the leaching of Mg with gypsum application (increased Ca) and thus decreased Mg availability to plants.

K concentration decreased with increased levels of liming materials. Gypsum alone decrease the foliar K concentration from 1.63% to 1.56% and the decrease with increasing liming treatment levels persist even with application of gypsum. It might be that the decrease in foliar K concentration is due to the mobility of K. Ranjah *et al*. (2000) observed that high K concentrations suppress Ca and Mg uptake, but in this study it appears that Mg is suppressed by the uptake of Ca in maize. Carran (1991) reported that a Ca induced Mg deficiency arise in clovers when exchangeable Ca:Mg ratio is greater than 20.

The Ca and Mg results are consistent with results obtained by Farina and Channon (1988b).

Zn uptake in ash amended plots is greater due to greater Zn release potential as indicated by dissolution studies. Gypsum application increases the Zn uptake of limed and unlimed plots. The Zn uptake decrease with increasing lime material application as Zn becomes less available for uptake at higher pH regions.

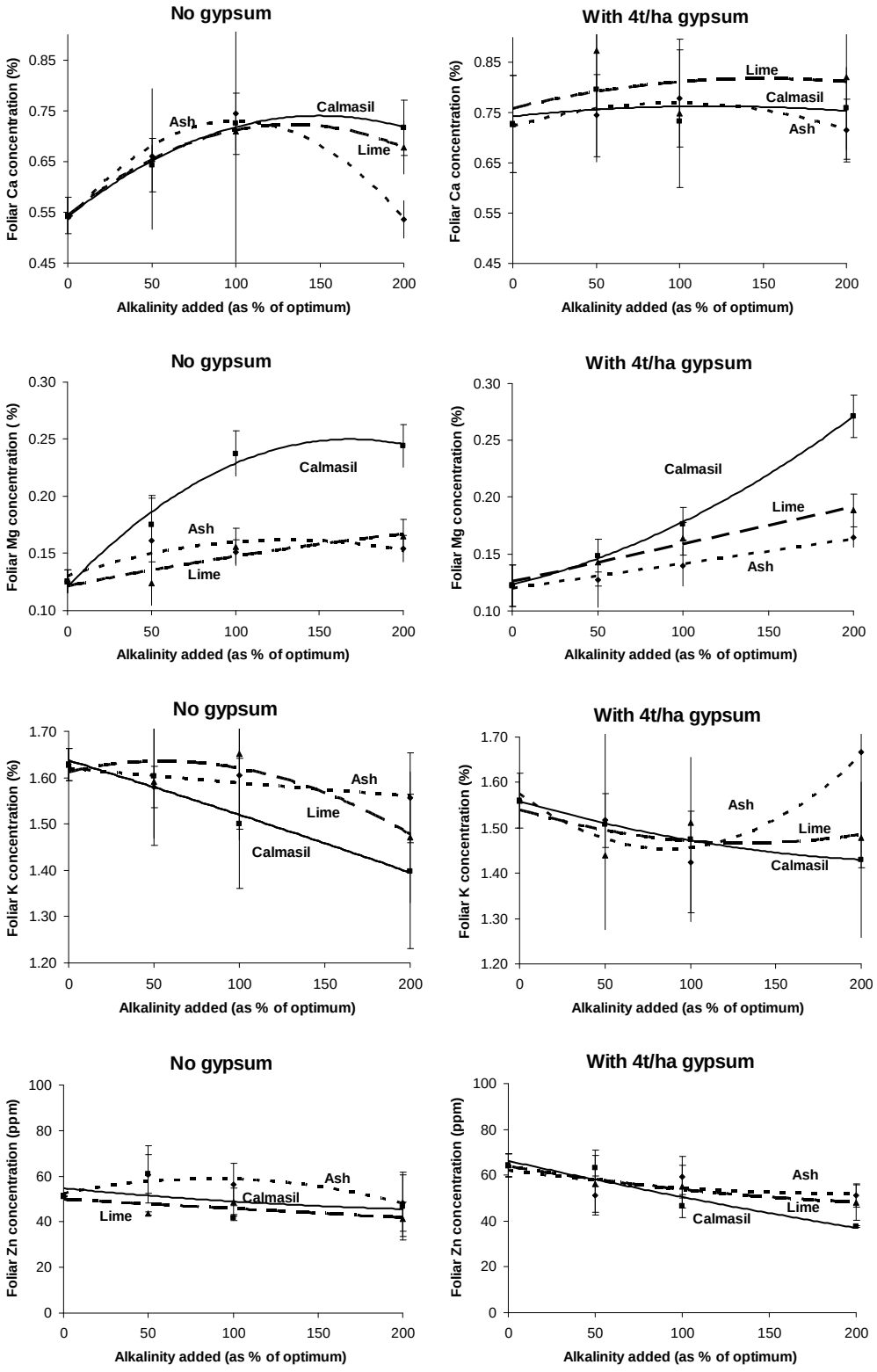


Figure 4.24 Effect of lime, Calmasil on foliar concentration of Ca, Mg, K and Zn in maize (season 2). Points represent means of replicates and vertical lines denote standard error bars

4.3.8 Foliar cation concentration and relation to extractable cations

Plants can only absorb nutrients that are available and relatively easily extractable from the soil. Figure 4.25 and Figure 4.26 display the relationship between soil extractable cations and the foliar cation concentration in beans and maize respectively.

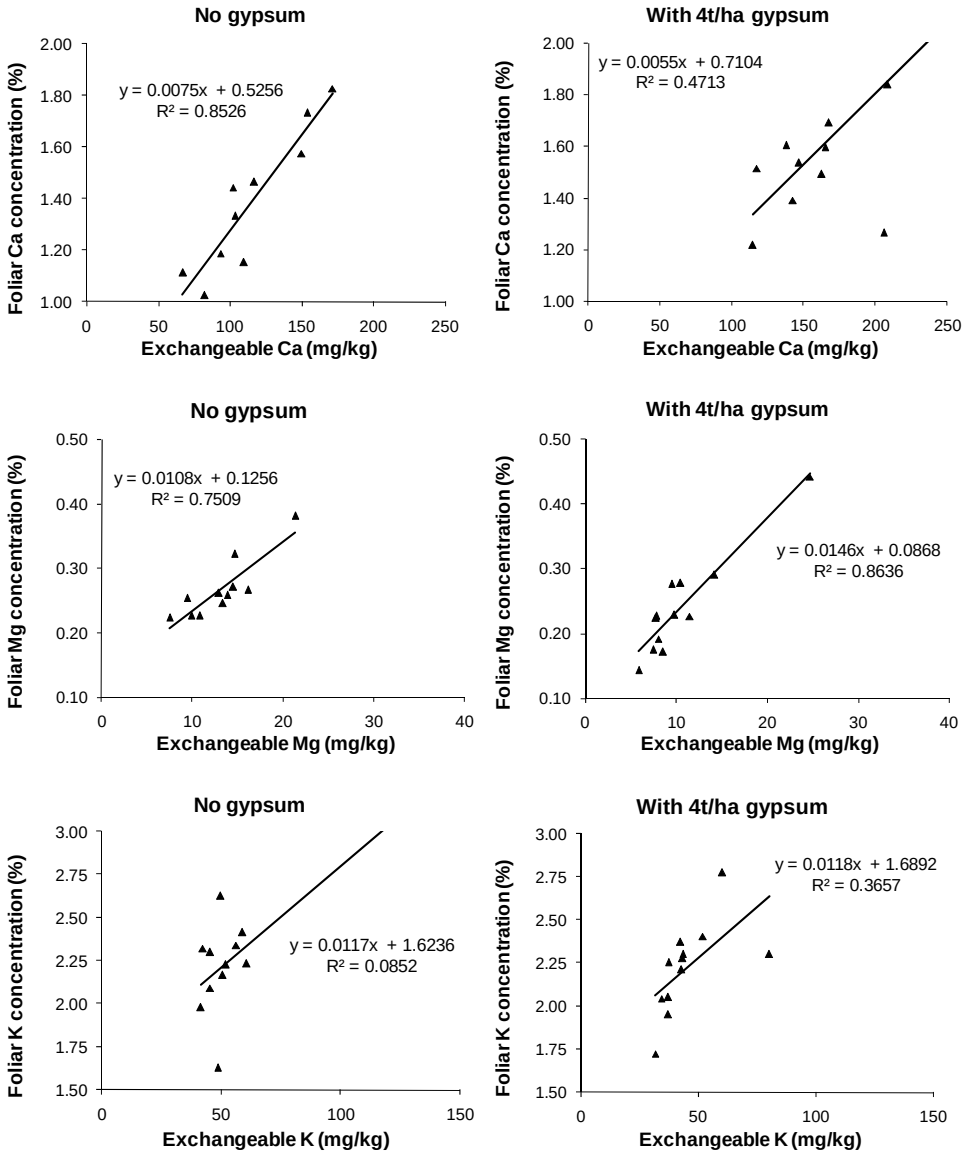


Fig 4.25 Relationship between foliar elemental concentration of beans and extractability of Ca, Mg and K in soil. Points represent means of replicates and vertical lines denote standard error bars

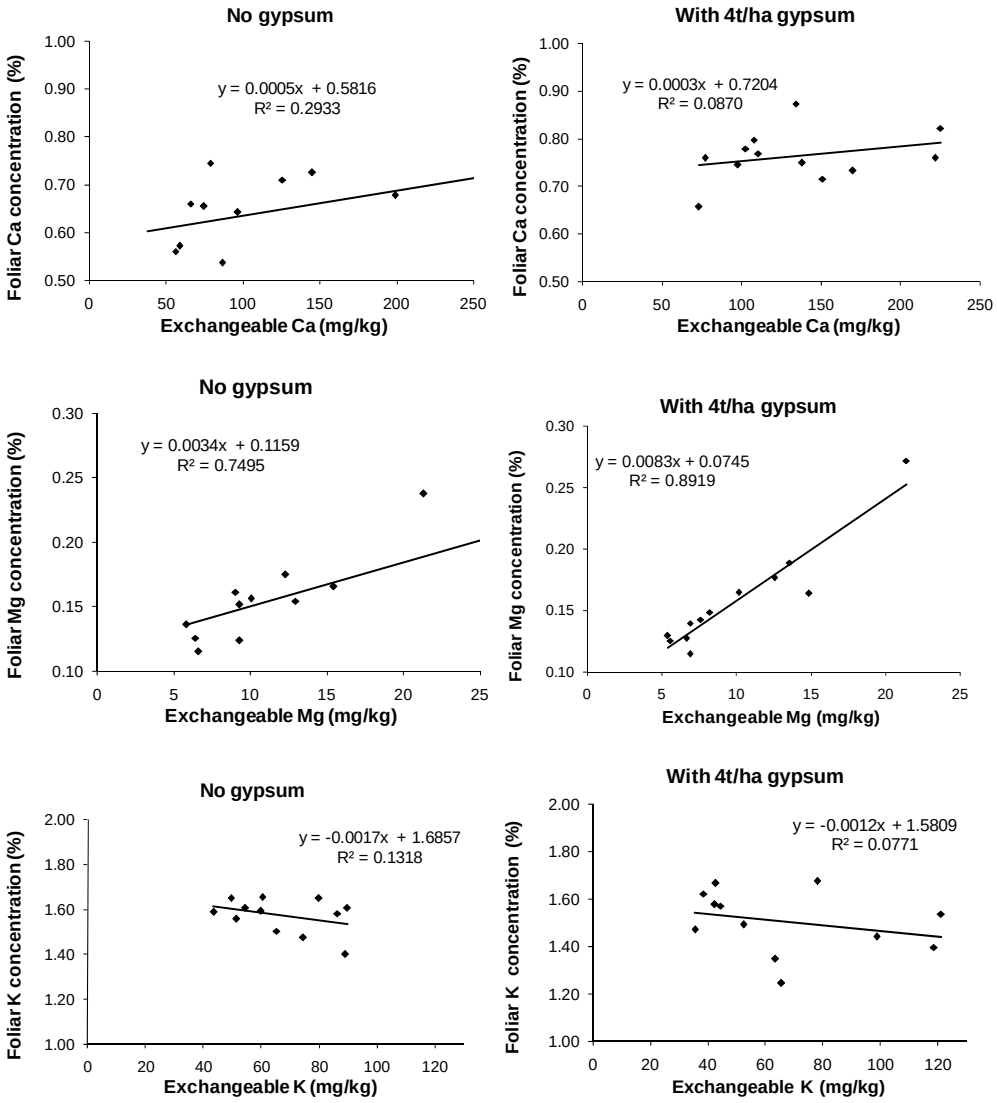


Fig 4.26 Relationship between foliar elemental concentration of maize and extractability of Ca, Mg and K in soil. Points represent means of replicates and vertical lines denote standard error bars

Positive but poor correlations exist between foliar Ca and extractable Ca in both crops. In the limed plots without gypsum, Ca concentrations in beans increased with an increase in soil extractable Ca. Gypsum does not improved the correlation for beans or maize. Strong correlations exist between the foliar Mg content of both crops and the availability of Mg in the topsoil with gypsum application enhances this correlation even more. With beans there is a positive correlation with K and a negative correlation for maize in the following season, but the correlation remains poor. The presence of gypsum has little effect on this scenario.

4.3.9 Foliar cation concentration relation to exchangeable acidity

Exchangeable acidity plays a major role in the availability of elements for plant nutrition. Basic cations such as Ca and Mg may become unavailable due to excess Al in the soil solution.

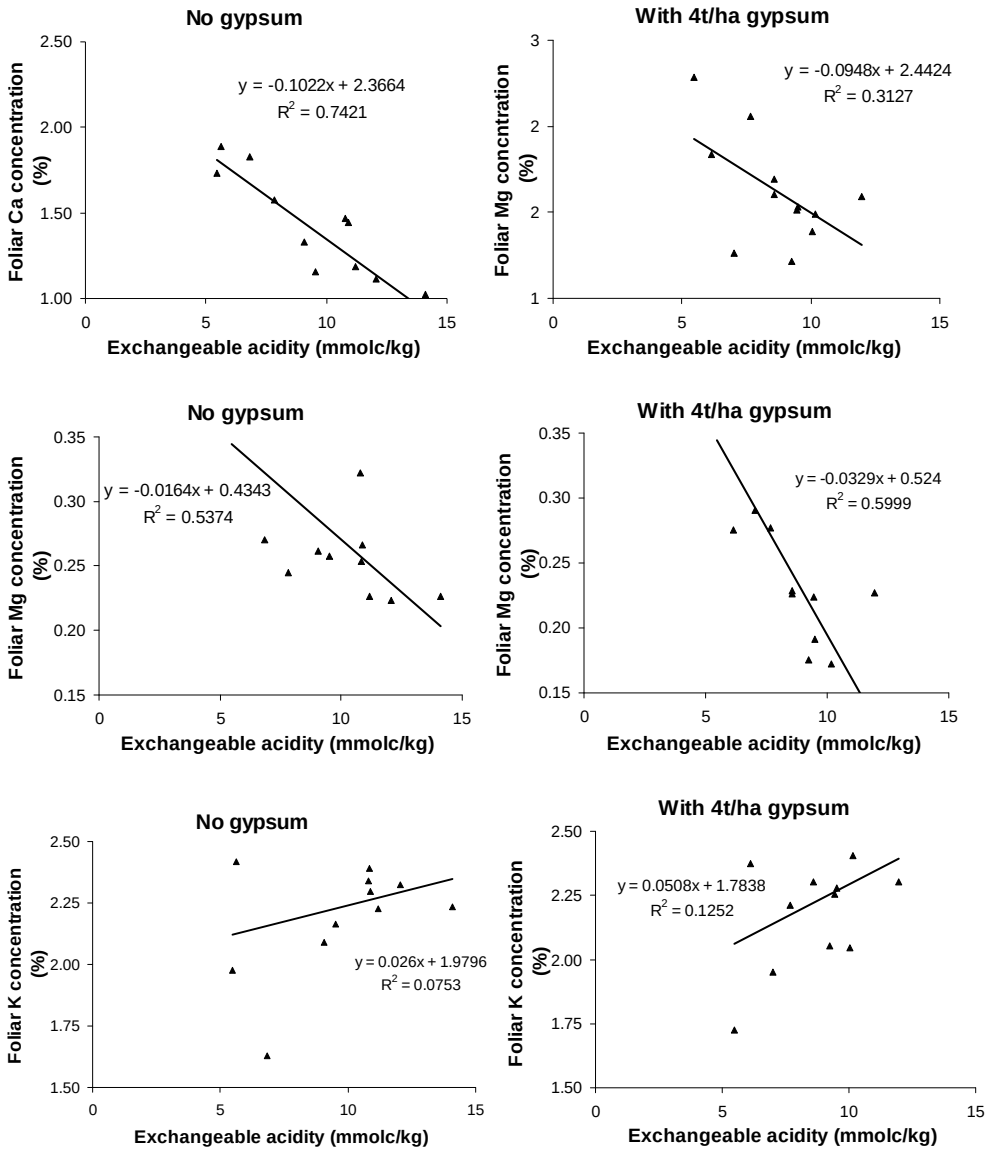


Figure 4.27 Relationship between foliar elemental concentration of beans and exchangeable acidity. Points represent means of replicates and vertical lines denote standard error bars

Strong negative correlations between foliar Ca and Mg and acidity exist as seen in Figure 4.27 and Figure 4.28 which displays that foliar concentration is subdued by increased acidity. Aluminium toxicity in acidic soils decreases the nutrients of maize

(Baligar *et al*., 1997). Gypsum application slightly improves the Ca concentration, but this is due to the added Ca in topsoil.

K concentration seems to increase with exchangeable acidity in both crops. A proposed explanation is manifested in the fact that K uptake is enhanced as Mg and Ca availability is decreased at high acidity. Uptake of K is often suppressed by gypsum application as gypsum increases Ca and S availability which may exert antagonistic effects on Mg and K absorption (Shainberg *et al*., 1989).

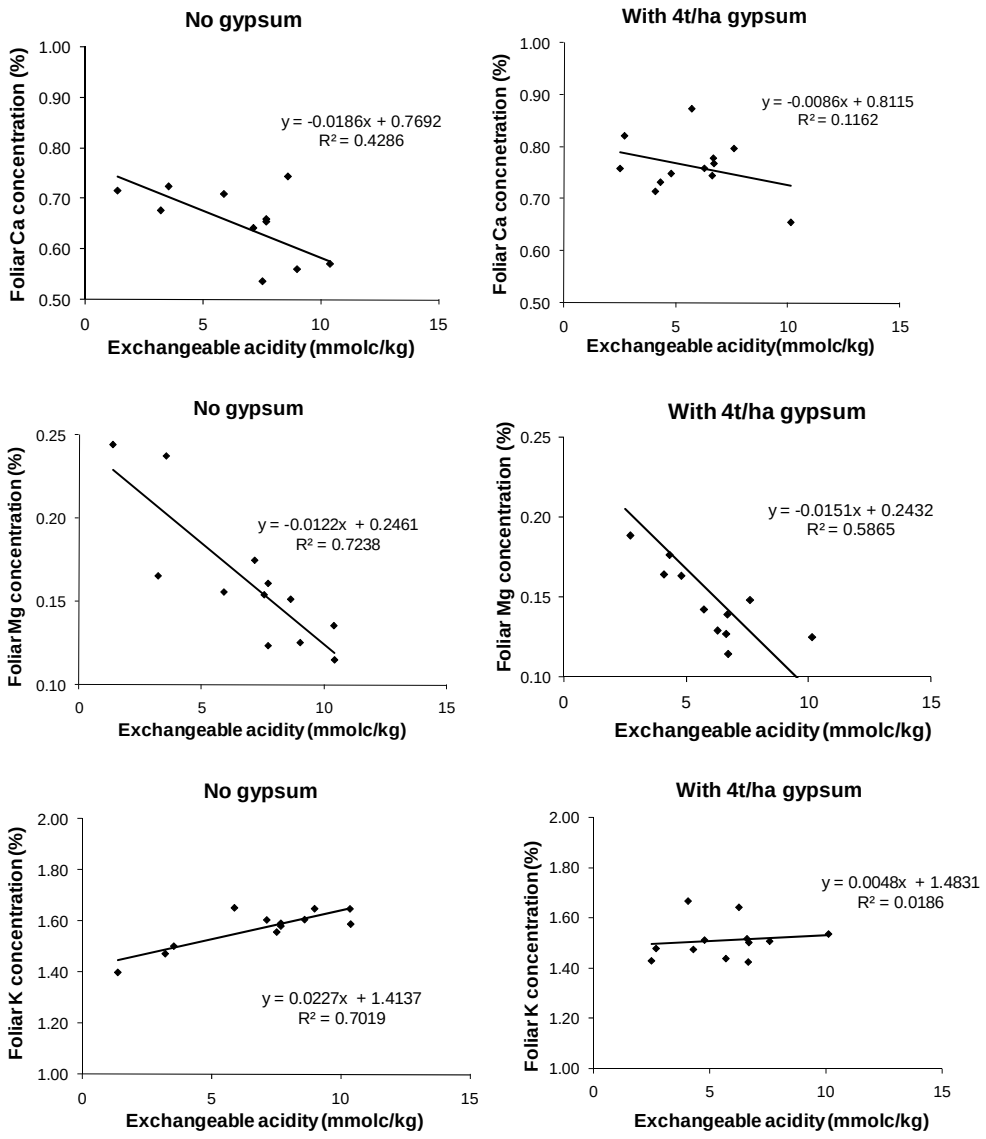


Figure 4.28 Relationship between foliar elemental concentration of maize and exchangeable acidity. Points represent means of replicates and vertical lines denote standard error bars

4.3.10 Root growth

The site had a physical impediment in the form of a Mn lamellae layer that covers 66% of the area at varying depths within the subsoil. On some plots the layer is present at a shallow depth of 30cm and in other plots it occurs as deep as 100m below the surface. This confounded the interpretation of the root growth results as illustrated in (Figure 4.29).

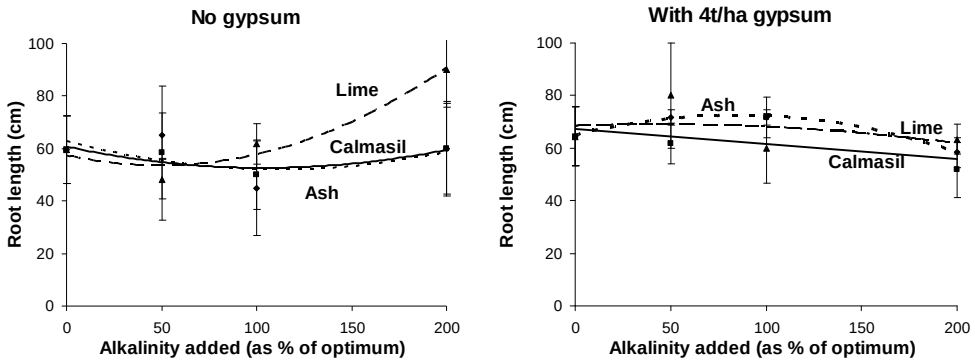


Figure 4.29 Effect of lime, Calmasil and ash on maize root development. Points represent means of replicates and vertical lines denote standard error bars

The lime causes an increase in root growth (Figure 4.29), while ash and Calmasil results in no beneficial effect on roots growth, except at the highest level of liming material addition. The superiority of lime may be due to the absence of the lamella layer in those plots (Appendix B).

Gypsum application alone has a positive impact on root elongation. Gypsum alleviates Al toxicity in subsoil, allowing roots to search for nutrients deeper and wider in the subsoil. Gypsum elevates Ca in soil solution more efficiently than lime and this may contribute to root growth (Shainberg *et al*., 1989). Gypsum treated soil increase Ca uptake, decreased soluble Al concentrations and promotes root growth and yield (Farina and Channon, 1998b)

Gypsum in combination with liming materials slightly enhances root growth, but root growth is negated at highest level of liming material application. The three liming materials compare well with each other. Despite these findings, definite conclusions are difficult to draw due to the Mn layer.

4.3.11 Yield

All liming treatments deliver increased yields (Figure 4.30). Calmasil yields a linear response with higher application rates and deliver the best results compared to lime and fly ash. Calmasil, lime and ash applied at 200% of optimum alkalinity deliver yields of 9063kg/ha, 7671kg/ha and 7553kg/ha respectively. The response of fly ash compares well with lime. Ash at its highest application increase maize from 5569kg/ha to 7553kg/ha. Ash application at 200% optimum alkalinity is in surplus and this could be due to excess of micronutrients. This was also observed by Kalra *et al*. (1998) where maize yield increased up to an addition of 10t/ha lime application and decreased at 50t/ha of fly ash.

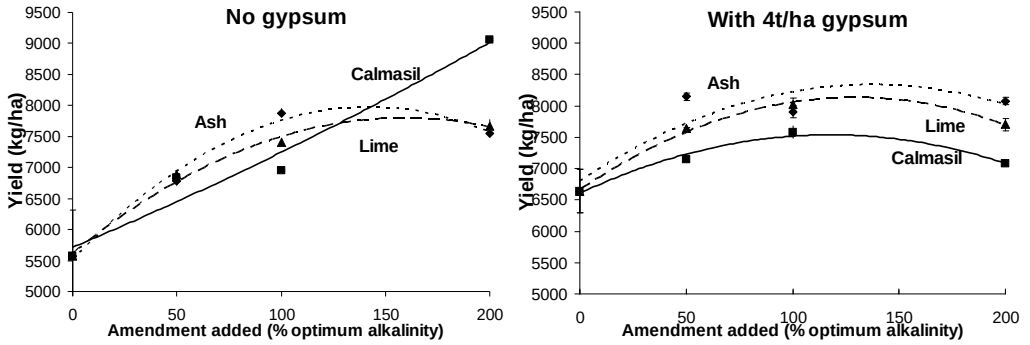


Figure 4.30 Effect of lime, Calmasil, ash and gypsum on maize yield in season 2. Points represent means of replicates and vertical lines denote standard error bars

The addition of liming materials increase yields due to increase in pH, alleviation of acidity and the addition of nutrients (Figure 4.30). In fact, liming treatment concentration, irrespective of the liming material used, has the only statistically significant effect on the yield. The increase in pH in subsoil is not as big a factor as the alleviation of subsoil acidity and the subsequent decrease in acid saturation. Therefore it is a combination of the added nutrients and the reduction in soluble Al in the subsoil that increases yield. Toma *et al*, (1999) stated that the amelioration of subsoil acidity was reflected in the 25-50% increase in corn yield over time.

Fly ash compares well with the other liming materials. Fly ash has the added advantage that it contains more soluble trace elements than the other two liming

materials. Earlier studies suggest that ash can act as a fertilizer for certain soil micronutrients such as B, Mo, Fe, Cu, Mn and Zn (Spark and Swift, 2008).

Gypsum increases maize yield by 1t/ha and this could be due to the added Ca and SO_4. Gypsum is also known to improve the physical properties such as waterholding capacity and texture (Jala and Goyal, 2006), but this was not evaluated. Gypsum and ash has the greatest response at its highest level of application. The application of gypsum alleviates the "surplus effect" of ash applied at 200% lime requirement value and increase yield on these plots to 8077kg/ha.

Gypsum applied with Calmasil and lime has good responses, especially at lower application levels, but the linear response of yield to Calmasil application is negated by gypsum application. It is possibly due to the Mg levels, as Calmasil is a ready source of Mg and gypsum application displaces Mg into the subsoil and thus reduces its availability (Fig 4.13 and Figure 4.14). As displayed in Fig 4.14 the extractable Mg with Calmasil application from 6.3mg/kg to approximately 40mg/kg, whereas the ash and lime increase Mg only to about 15mg/kg and 13mg/kg. In the presence of gypsum, topsoil Mg (even at the highest level of Calmasil addition) decreased to 21.4mg/kg, indicating that the well-known effect of gypsum, in promoting leaching of Mg, has probably resulted in reduced Mg availability (Shainberg *et al*., 1989). Alternatively it could be that the common ion effect is taking place with the addition of gypsum at highest applications of liming materials. The common ion effect occurs when gypsum adds Ca to the soil and suppresses the dissolution of Calmasil and lime and thus the subsequent release of Ca (Mbakwe, 2008).

The yield obtained in this study is in agreement with results on bean yield harvested a year before on this field trial reported in Mbakwe (2008). The effect of gypsum with ash at its highest application rate increased bean yield by 16% and it compares well with the yield obtained with Calmasil.

4.3.12 Metal concentration

It is known that fly ash contains trace metals that are solubilised during acidic conditions (Warren and Dudas, 1984; Mattigod *et al*., 1990; Kim *et al*., 2003; Kim 2005). These metals can be taken up by crops and thus several concerns arise regarding heavy metal accumulation (Jala and Goyal, 2006; Basu *et al*., 2009). To evaluate the levels of total metals accumulated in fly-ash treated plots, bean crops

were harvested during the first season. These beans were compared to beans grown on the untreated plots (Table 4.5). The highest levels of ash application, 100% and 200% of optimum alkalinity, were evaluated.

Table 4.5 Concentration of trace elements in beans from selected experimental treatments (in mg/kg)

Sample	Control (%)	No Gypsum 100% Ash level	No gypsum 200% Ash level
Al	22.17	12.56	17.59
Cr	3.31	2.52	2.67
Mn	24.67	23.94	18.93
Fe	76.35	50.45	62.70
Co	3.10	3.01	3.31
Ni	8.76	8.24	8.06
Cu	7.05	5.35	6.34
Zn	22.85	16.11	19.14
As	0.03	0.02	0.02
Se	0.02	0.01	0.02
Cd	0.02	0.07	0.08
Sn	2.88	2.03	2.45
Sb	0.02	0.05	0.02
Pb	0.92	1.13	0.95

Cd and Pb were the only elements to exceed the levels obtained in the control. Cadmium is below the maximum levels of 0.1mg/kg, while Pb is above the 0.3mg/kg level as set by the Food and Agriculture Organisation (FAO) and WHO (World Health Organisation)(Mohsen and Mohsen, 2008), for all the selected treatments.

To evaluate the accumulation of heavy metals in maize grain, maize grown on plots with the highest treatment levels have been compared to the untreated plots and plots amended with only gypsum (Table 4.6).

Table 4.6 Concentration of trace elements in maize grain from selected experimental treatments (mg/kg)

Sample	Control	G1	G0 A3	G0 C3	G0 L3
Cr	0.42	0.21	0.22	0.30	0.14
Mn	7.65	8.25	6.71	7.52	6.88
Fe	21.38	30.68	21.00	23.91	21.48
Co	0.17	0.12	0.11	0.16	0.14
Ni	1.23	1.53	1.69	1.13	1.15
Cu	4.23	9.90	4.74	5.34	4.13
Zn	20.69	24.46	18.10	22.43	19.54
As	0.01	0.01	0.01	0.01	0.04
Se	0.12	0.11	0.13	0.13	0.10
Sr	0.10	0.47	0.24	0.00	0.10
Mo	0.23	0.68	0.21	0.46	0.25
Cd	0.04	0.03	0.02	0.01	0.02
Pb	0.37	2.30	0.66	0.59	0.86
B	0.82	2.09	1.51	1.26	8.34
Al	7.06	12.84	8.62	6.48	7.49

n.d = not detected

* (G1 = composite sample from G1A0, G1L0 and G1 C0; G0 refers to no gypsum application with the highest level of either ash (A3) lime (L3) or Calmasil (C3))

Accumulation of Pb seems to be only potential limitation to the use of fly ash in crop production as the level is greater than those in unmodified crops. It is however less than that the levels found in the maize treated with commercial gypsum and lime. Lead levels in all crops, including control, are over the threshold level of 0.3mg/kg in foodstuff (Mohsen and Mohsen, 2008), but it does not reach the phytotoxic levels of 30-300 mg/kg for Pb (Henning *et al*., 2001) in maize. As shown by various fly ash research summaries such as Jala & Goyal (2006) and Basu *et al*. (2009), B accumulation increase with ash application, but the maximum level of B in food is not known. This accumulation of B should be greater in the beans as sources of B are legumes, while nuts and grains are poor sources of B (Nielsen, 1997). Compared to agricultural calcitic lime, the crops treated with ash and Calmasil does not display

excessive metal accumulation. The high B levels in lime treated crops cannot be explained.

Wright *et al*. (1998) found that trace element concentration, especially B, Se, As and Mo were found to be higher in ryegrass treated with fly ash than those in untreated soil. The values of the ash treated crops compare well with the untreated crops as the toxic metals are still in an insoluble form in the ash and have not been released for plant uptake.

4.4 Conclusions

Surface application of ash and Calmasil has several benefits. These materials have increased pH, decreased acidity and hence decreased acid saturation, especially Calmasil. The supremacy of Calmasil is due to its higher solubility, high content of Ca, Si and Mg and CCE value of 99%. Fly ash compares well with lime. This could be due to the fact that fly ash is applied at 7.5 times more than the lime level due to its CCE value of 10%, and in doing so it ensures that essential plant nutrients such as Ca, Mg, SO_4, P, K, Zn, Cu, Se, B and Mo are available in sufficient quantities to plants. Benefits in the subsoil due to fly ash application are not evident.

Gypsum does not alter pH, but it decrease acid saturation, especially in the subsoil.

It increases exchangeable Ca and decrease Mg uptake. It improves the soil nutrient status through addition of S. All liming treatments had a remarkable effect on foliar Ca and Mg concentration. Gypsum application as well as liming application decreases the nitrate levels of the soil. SO_4 levels of the topsoil decrease over time and it accumulates in the lower horizons. This effect is enhanced with gypsum application.

Yield data indicates that fly ash compares well with lime and Calmasil. This is despite the fact that ash effects are not as prominent as the effects by Calmasil and lime and is attributed to the release of micronutrients by fly ash in the micronutrient deficient soil. The metal concentrations of crops grown with ash are certainly comparable to unlimed plots. Ash therefore serves as an adequate topsoil liming material as results confirm that the trace metal accumulation risk, which is negligible, is no higher than that of conventional soil ameliorants.

Chapter 5

General discussion and conclusions

Soil acidity has major soil fertility constraints in terms of agricultural production, and liming is required to alleviate these limitations. The incorporation of lime is usually inadequate in ameliorating subsurface acidity, which is often the main cause of low crop yields in acidic regions (Samac and Tesfaye, 2003; Laker 2005). As gypsum is more soluble it assists with the movement of lime into the subsoil (Shainberg *et al*., 1989; Farina *et al*., 2000a). With the inconsistent transport economics, lime is becoming increasingly expensive and thus inaccessible to many farmers. In this study cheaper industrial waste products such as fly ash and Calmasil, in the presence or absence of gypsum, are evaluated.

Dissolution studies indicated that Calmasil is the most soluble of the products, releasing the greatest amount of Ca and Mg and it also contains a large amount of Si. The greatest Ca and Mg content of lime are released in the acidic pH range. Fly ash contains more Al, Si and Fe and it only solubilises in the acidic range of pH 2-3. Fly ash contains significant P and K in addition to minimal Ca and Mg. All trace elements in fly ash are only soluble in pH range of 2 while B, Se, Mo, Sr, Ba, V and As are relatively soluble through the entire pH range.

The findings in this study indicated that Calmasil in comparison to lime and fly ash proves to be the best liming material. This could be related to the high CCE of 99% and solubility in the pH range of 2-7. It has the greatest effect on raising pH, and reducing acidity and acid saturation over time. The contribution to the exchangeable Ca and Mg levels in soil are greatly increased by Calmasil. Lime caused significant increases in pH, Ca and Mg, but its performance is limited in the subsoil.

The fly ash used in this study is of class F type and compares relatively well to calcitic lime. It increases pH, decreases acidity and acid saturation and increased the Ca and Mg content appreciably. These effects remained over the studied period of 24 months. Soil micronutrient data was not tested, but previous literature indicated upon the beneficial effects of fly ash application on elevating available Mo, B and Se levels

in soil for plant uptake (Jala and Goyal, 2006; Zhang *et al*., 2004; Pathan *et al*., 2003).

Calmasil shows the greatest change in subsoil chemical properties. Only the highest level of liming material application resulted in substantial differences in the subsoil, indicating that movement might occurs only at sufficient levels of application

The effect of gypsum on pH increase and acidity alleviation was not as efficient as the individual liming materials used, which is to be expected. However, gypsum application decreased the acid saturation in the topsoil to some extent but the effect is the greatest in the subsoil. This is attributed to the Ca and Mg that gypsum adds to deficient soil and the subsequent downward movement. Gypsum allows Mg to be leached from the topsoil into the subsoil where Mg accumulates. To compensate for the loss of topsoil Mg is it advisable to add supplementary Mg after gypsum application (McLay *et al*, 1994b). SO_4 released from gypsum reduces Al toxicity in subsoil by the so-called 'self-liming' effect as proposed by Sumner (McLay *et al*., 1994b) and it also serves as S source to plants. Results on exchangeable cations indicate that none of all the liming materials, except gypsum moved down to the subsoil most effectively.

Foliar data demonstrated increased foliar concentration of Ca and Mg with decreased soil acidity. Foliar K concentration declined with soil acidity. Gypsum application increased Ca concentration in maize leaves and decreased foliar Ca concentrations in beans. Gypsum application caused a decreased in foliar Mg concentration in both crops.

Fly ash treated soil delivers yields on par with both the lime and Calmasil treated plots, despite its comparatively inferior performance in relation to soil chemical changes. The answer to these phenomena might be in the micronutrients released by ash, as well as the additional P and K, although the release of these nutrients requires further testing.

The root length data illustrates that fly ash competes well with elongating the roots, but the data is overshadowed by the presence of a Mn lamellae layer.

The fly ash was applied at rates of 0-, 7-, 14- and 28t/ha in this study. The highest application of ash might be excessive as decreased yields are obtained. However,

these quantities are comparable to most values used for increased agronomic crop yields where 10-50t/ha (Kalra *et al*., 1998) and 8.1-16.1t/ha (McCarthy *et al*., 1994) of fly ash were used.

The high quantities of ash required to obtain a significant effect could be impractical due to the difficulty in transportation and application of the ash. It should thus be determined which quantities are economically feasible for transportation. This will determine the quantities of fly ash that can be transported over certain distances to make the use of fly ash beneficial. Handling and application of such high quantities could be laborious as it is a fine powder.

High quantities of fly ash also pose the risk of releasing enormous quantities of trace elements in soil, which could enter the groundwater. The use of fly ash with organic and inorganic sources tends to release lower quantities of trace metals in groundwater (Jala and Goyal, 2006). This should be further investigated.

The low macronutrients, e.g. C and N in fly ash can be increased by mixing it with organic waste (Jackson *et al*. 1999), animal manure and sewage sludge (Truter, 2007; Truter and Rethman, 2005). Jackson *et al*. (1999) used fly ash with organic waste (poultry litter or sewage sludge) and applied it at 100-120t/ha to increase the macronutrient content of ash and improve the handling of fly ash (Jackson *et al*., 1999). The drawback of this is that the trace elements might bind with available organic binding sites and thus trace element availability requires examination (Jackson *et al*., 1999).

In this study, crops treated with fly ash contain similar and in some cases even less trace metals than crops treated with commercial gypsum and lime. Fear of metal accumulation is thus not warranted The metal accumulation was only evaluated in the beans and maize kernels as these are the parts that are consumed by humans. Excessive accumulation in leaf tissue might have occurred but this was not evaluated. This leaves opportunity for further investigation into trace metal uptake at different parts of plant, especially with the high as application rates.

The methods used to determine the amount of liming materials applied was based on CCE calculations. Lime recommendations based on CCE does not consider the soil texture or the physical properties and elemental composition of the liming material. Particle size and thus surface area of calcitic limestone does affect the liming

efficiency (Scott et al., 1992). Fly ash has an extremely low CCE of 10%, compared to the calcitic lime CCE of 77%. This means that fly ash should be applied at 7.7 times the rate of lime to obtain the same neutralising capacity. Although the exchangeable Al method (McLean, 1982) supported the amount of liming materials used these methods remained questionable as they are employed for soils in the USA. A more reliable method for South African soils need to be employed, such as the Bornman developed Resin Suspension Method evaluated by Van der Waals and Claassens (2002) or the Eksteen method. The Eksteen method of lime requirement determination is widely used in the Western Cape and is based on the ratio of (Ca + Mg):H, known as the R-value. The quantities of lime required to raise the pH to a specified value can be predetermined quite accurately (Smuts, 2001).

Although fly ash proved to be effective over the two seasons, indicating the slow but continuous release of alkalinity, the question of its longevity remains. Truter and Rethman (2005) showed that the beneficial effects of fly ash persist after four years when re-vegetating fly ash amended soils. It is recommended that weathered fly ash should be used to diminish the possibility of B and Se toxicity (Jala and Goyal, 2006).

The findings from this study have raised many questions that create potential areas for further research. Questions such as the longevity of beneficial ash effects in soil, the synergistic effects of ash and gypsum versus the almost antagonistic effects of gypsum on Calmasil at high applications should be answered.

Amidst these questions it is recognised that the use of the Duvha fly ash in this study serves as a demonstration that the application of fly ash has beneficial effects that can simultaneously solve the environmental problem of fly ash accumulation at waste disposal sites and acidic soil reclamation in the Highveld of Mpumalanga.

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Appendices

Appendix 1: Field trial experimental plot layout

1 **G0 C0**	**2** **G1 C2**	**3** **G1 L0**	**4** **G1 C3**	**5** **G1 L0**	**6** **G1 C0**
7 **G0 L1**	**8** **G1 A0**	**9** **G0 L0**	**10** **G0 C0**	**11** **G1 A3**	**12** **G1 C1**
13 **G0 A2**	**14** **G0 C2**	**15** **G0 C1**	**16** **G1 C1**	**17** **G1 L3**	**18** **G1 A2**
19 **G0 L2**	**20** **G1 L3**	**21** **G0 C2**	**22** **G0 C1**	**23** **G0 L3**	**24** **G1 L1**
25 **G0 C1**	**26** **G0 C0**	**27** **G1 C3**	**28** **G1 A0**	**29** **G0 A2**	**30 G0 L0**
31 **G0 A3**	**32** **G0 L3**	**33** **G1 C3**	**34** **G0 A1**	**35** **G0 L1**	**36** **G1 A0**
37 **G1 L3**	**38** **G1 L0**	**39** **G0 C2**	**40** **G0 L2**	**41** **G1 A3**	**42** **G1 C2**
43 **G1 A2**	**44** **G1 L2**	**45** **G0 L1**	**46** **G1 A1**	**47** **G0 A3**	**48** **G0 A0**
49 **G0 A0**	**50** **G0 A1**	**51** **G1 A3**	**52** **G1 L2**	**53** **G0 A1**	**54** **G1 C0**
55 **G0 C3**	**56** **G0 A0**	**57** **G1 C0**	**58** **G1 A1**	**59** **G0 L2**	**60** **G1 C1**
61 **G0 L3**	**62** **G1 L1**	**63** **G0 A3**	**64** **G0 C3**	**65** **G1 C2**	**66** **G1 L1**
67 **G1 A1**	**68** **G0 L0**	**69** **G0 C3**	**70** **G1 L2**	**71** **G0 A2**	**72** **G1 A2**

Code:

G0 = no gypsum

G1 = 4 t/ha gypsum

A = ash
C = calmasil
L = lime

A0, C0, L0 = control

A1, C1, L1 = 50% alkalinity

A2, C2, L2 = 100% alkalinity

A3, C3, L3 = 200% alkalinity

Appendix 2: Field trial experimental plot layout displaying Mn layer depth in each plot

1 G0 C0	2 G1 C2	3 G1 L0	4 G1 C3	5 G1 L0	6 G1 C0
7 G0 L1	8 G1 A0	9 G0 L0	10 G0 C0	11 G1 A3	12 G1 C1
13 G0 A2	14 G0 C2	15 G0 C1	16 G1 C1	17 G1 L3	18 G1 A2
19 G0 L2	20 G1 L3	21 G0 C2	22 G0 C1	23 G0 L3	24 G1 L1
25 G0 C1	26 G0 C0	27 G1 C3	28 G1 A0	29 G0 A2	30 G0 L0
31 G0 A3	32 G0 L3	33 G1 C3	34 G0 A1	35 G0 L1	36 G1 A0
37 G1 L3	38 G1 L0	39 G0 C2	40 G0 L2	41 G1 A3	42 G1 C2
43 G1 A2	44 G1 L2	45 G0 L1	46 G1 A1	47 G0 A3	48 G0 A0
49 G0 A0	50 G0 A1	51 G1 A3	52 G1 L2	53 G0 A1	54 G1 C0
55 G0 C3	56 G0 A0	57 G1 C0	58 G1 A1	59 G0 L2	60 G1 C1
61 G0 L3	62 G1 L1	63 G0 A3	64 G0 C3	65 G1 C2	66 G1 L1
67 G1 A1	68 G0 L0	69 G0 C3	70 G1 L2	71 G0 A2	72 G1 A2

Code:

Plot – No Mn layer present in plot

Plot- Mn layer at 61-80cm depth

Plot - Mn layer at 41-60cm depth

Plot - Mn layer at 2030-40cm depth

Appendix 3: Analytical soil and plant data over two seasons

Table 1: pH, acidity, exchangeable Ca and Mg and acid saturation for July 2007 - before application of treatments

Treatment	Depth (cm)	pH	Acidity $mmol_c/kg$	Ca mg/kg	Mg	Acid saturation %
G0 A0	0-10	3.83	6.8	76.0	16.0	57.2
G0 A0	10-20	4.13	6.8	43.0	18.0	65.4
G0 A0	0-10	3.70	8.0	96.0	20.0	55.6
G0 A0	10-20	3.99	8.8	121.0	23.0	52.7
G0 A0	0-10	3.76	7.6	95.0	21.0	54.2
G0 A0	10-20	4.20	6.0	103.0	33.0	43.5
G0 A1	0-10	3.78	6.8	99.0	17.0	51.9
G0 A1	10-20	4.15	8.0	58.0	34.0	58.7
G0 A1	0-10	3.91	9.2	92.0	23.0	58.8
G0 A1	10-20	3.82	7.2	55.0	24.0	60.7
G0 A1	0-10	3.76	7.2	105.0	22.0	50.7
G0 A1	10-20	4.19	6.8	66.0	20.0	58.1
G0 A2	0-10	3.80	6.0	106.0	21.0	46.2
G0 A2	10-20	4.03	6.4	40.0	14.0	67.2
G0 A2	0-10	3.77	7.6		17.0	84.8
G0 A2	10-20	4.21	6.8	756.0	246.0	10.6
G0 A2	0-10	3.97	7.6	842.0	330.0	10.0
G0 A2	10-20	4.06	7.2	88.0	38.0	49.2
G0 A3	0-10	3.82	7.2	92.0	17.0	54.7
G0 A3	10-20	4.24	7.2	59.0	26.0	58.9
G0 A3	0-10	3.93	6.4	91.0	17.0	52.0
G0 A3	10-20	4.26	7.2	42.0	22.0	65.1
G0 A3	0-10	3.88	6.4	100.0	52.0	41.1
G0 A3	10-20	4.04	6.8	80.0	51.0	45.7
G0 C0	0-10	3.85	8.0	122.0	20.0	51.0
G0 C0	10-20	4.10	6.0	46.0	18.0	61.6
G0 C0	0-10	3.84	4.8	124.0	29.0	36.0
G0 C0	10-20	4.09	6.8	41.0	17.0	66.6
G0 C0	0-10	3.91	6.0	96.0	17.0	49.3
G0 C0	10-20	4.16	6.8	50.0	18.0	63.3
G0 C1	0-10	3.86	6.8	81.0	16.0	56.1
G0 C1	10-20	4.10	5.2	57.0	17.0	55.3
G0 C1	0-10	3.83	6.0	96.0	19.0	48.7
G0 C1	10-20	4.18	6.8	49.0	20.0	62.7
G0 C1	0-10	3.81	6.0	106.0	0.0	53.1
G0 C1	10-20	4.16	7.6	40.0	15.0	70.4
G0 C2	0-10	3.87	6.0	99.0	20.0	47.8
G0 C2	10-20	4.09	6.8	449.0	145.0	16.6
G0 C2	0-10	3.86	4.8	106.0	20.0	41.0
G0 C2	10-20	4.03	7.6	36.0	33.0	63.1
G0 C2	0-10	3.82	7.2	76.0	18.0	57.9
G0 C2	10-20	4.22	6.8	61.0	26.0	57.0
G0 C3	0-10	3.69	7.6	94.0	21.0	54.4
G0 C3	10-20	3.97	8.4	117.0	24.0	51.9
G0 C3	0-10	3.76	7.6	84.0	42.0	50.1
G0 C3	10-20	3.89	8.8	86.0	56.0	50.1
G0 C3	0-10	3.79	8.4	100.0	40.0	50.6
G0 C3	10-20	3.96	7.2	105.0	73.0	39.4

Table 1 continues…

Treatment	Depth cm	pH	Acidity $mmol_c/kg$	Ca mg/kg	Mg	Acid saturation %
G0 L0	0-10	3.83	6.4	78.0	14.0	56.0
G0 L0	10-20	4.03	5.6	39.0	14.0	64.6
G0 L0	0-10	3.79	6.8	105.0	17.0	50.7
G0 L0	10-20	4.09	6.0	72.0	21.0	53.2
G0 L0	0-10	3.78	6.8	93.0	31.0	48.8
G0 L0	10-20	4.07	8.0	96.0	32.0	52.1
G0 L1	0-10	3.87	6.0	98.0	16.0	49.3
G0 L1	10-20	4.14	5.6	41.0	18.0	61.6
G0 L1	0-10	3.84	7.6	99.0	19.0	54.0
G0 L1	10-20	4.09	7.2	37.0	15.0	70.2
G0 L1	0-10	3.82	6.4	75.0	18.0	55.2
G0 L1	10-20	4.06	6.4	56.0	24.0	57.6
G0 L2	0-10	3.78	7.2	89.0	17.0	55.3
G0 L2	10-20	4.02	6.8	61.0	20.0	59.4
G0 L2	0-10	3.87	6.8	96.0	18.0	52.1
G0 L2	10-20	4.13	5.6	68.0	27.0	50.2
G0 L2	0-10	3.89	6.4	95.0	30.0	47.2
G0 L2	10-20	3.98	8.0	83.0	32.0	54.4
G0 L3	0-10	3.83	8.0	101.0	19.0	54.9
G0 L3	10-20	4.15	8.0	45.0	15.0	69.9
G0 L3	0-10	3.83	5.6	99.0	15.0	47.7
G0 L3	10-20	4.25	6.8	39.0	17.0	67.3
G0 L3	0-10	3.79	7.6	93.0	24.0	53.6
G0 L3	10-20	4.07	6.8	101.0	34.0	46.7
G1 A0	0-10	3.82	5.2	83.0	15.0	49.3
G1 A0	10-20	4.22	6.0	41.0	14.0	65.4
G1 A0	0-10	3.84	6.0	107.0	14.0	48.1
G1 A0	10-20	4.21	5.6	76.0	51.0	41.5
G1 A0	0-10	3.80	6.4	114.0	21.0	46.4
G1 A0	10-20	4.18	7.2	47.0	19.0	65.0
G1 A1	0-10	3.81	6.0	111.0	19.0	45.9
G1 A1	10-20	4.26	4.0	132.0	38.0	29.3
G1 A1	0-10	3.83	7.2	101.0	30.0	49.1
G1 A1	10-20	4.07	8.4	87.0	28.0	56.0
G1 A1	0-10	3.72	8.0	89.0	29.0	54.2
G1 A1	10-20	4.15	7.6	77.0	31.0	54.6
G1 A2	0-10	3.81	7.2	114.0	18.0	50.2
G1 A2	10-20	4.06	7.6	41.0	15.0	70.0
G1 A2	0-10	3.88	7.2	111.0	22.0	49.6
G1 A2	10-20	4.05	6.4	97.0	31.0	46.6
G1 A2	0-10	3.72	8.4	96.0	31.0	53.6
G1 A2	10-20	3.96	8.8	71.0	26.0	61.0
G1 A3	0-10	3.99	2.4	131.0	47.0	18.9
G1 A3	10-20	4.12	6.8	49.0	15.0	65.1
G1 A3	0-10	3.79	6.0	100.0	17.0	48.5
G1 A3	10-20	4.23	6.0	80.0	28.0	49.0
G1 A3	0-10	3.81	6.8	87.0	19.0	53.7
G1 A3	10-20	4.15	7.2	82.0	20.0	55.8

Table 1 continues…

Treatment	Depth cm	pH	Acidity $mmol_c/kg$	Ca mg/kg	Mg	Acid saturation %
G1 C0	0-10	3.88	6.4	64.0	13.0	60.2
G1 C0	10-20	4.05	8.0	39.0	16.0	71.2
G1 C0	0-10	3.74	7.6	85.0	19.0	56.8
G1 C0	10-20	4.10	7.6	392.0	17.0	26.6
G1 C0	0-10	3.76	7.6	85.0	30.0	53.3
G1 C0	10-20	4.12	7.6	89.0	23.0	54.7
G1 C1	0-10	3.76	6.8	114.0	20.0	48.2
G1 C1	10-20	4.09	5.6	84.0	18.0	49.8
G1 C1	0-10	3.83	6.4	87.0	17.0	52.8
G1 C1	10-20	4.18	7.6	40.0	15.0	70.4
G1 C1	0-10	3.78	7.6	82.0	25.0	55.5
G1 C1	10-20	4.18	8.4	67.0	24.0	61.4
G1 C2	0-10	3.76	8.0	79.0	13.0	61.6
G1 C2	10-20	3.99	7.2	40.0	14.0	69.8
G1 C2	0-10	3.80	7.6	74.0	16.0	60.4
G1 C2	10-20	4.24	6.4	80.0	30.0	50.0
G1 C2	0-10	3.80	8.4	99.0	39.0	51.0
G1 C2	10-20	4.18	5.6	84.0	50.0	40.6
G1 C3	0-10	3.86	5.6	84.0	17.0	50.2
G1 C3	10-20	4.02	6.4	49.0	24.0	59.4
G1 C3	0-10	3.94	7.6	90.0	16.0	56.8
G1 C3	10-20	4.31	6.0	59.0	22.0	56.0
G1 C3	0-10	3.92	7.6	81.0	13.0	59.9
G1 C3	10-20	4.20	8.0	61.0	30.0	59.5
G1 L0	0-10	3.91	7.2	80.0	15.0	58.1
G1 L0	10-20	4.06	6.8	52.0	18.0	62.7
G1 L0	0-10	3.88	5.2	136.0	22.0	37.8
G1 L0	10-20	3.99	8.0	54.0	21.0	64.6
G1 L0	0-10	3.78	6.4	101.0	21.0	48.7
G1 L0	10-20	4.15	8.0	51.0	21.0	65.4
G1 L1	0-10	3.89	5.6	131.0	0.0	46.1
G1 L1	10-20	4.05	7.6	82.0	17.0	58.2
G1 L1	0-10	3.82	7.2	97.0	35.0	48.5
G1 L1	10-20	4.20	7.6	59.0	35.0	56.9
G1 L1	0-10	3.86	10.4	95.0	29.0	59.5
G1 L1	10-20	3.97	8.0	77.0	28.0	56.8
G1 L2	0-10	3.86	5.2	64.0	13.0	55.1
G1 L2	10-20	4.15	7.6	701.0	260.0	12.0
G1 L2	0-10	3.93	7.2	112.0	24.0	48.9
G1 L2	10-20	4.12	8.0	68.0	26.0	59.3
G1 L2	0-10	3.92	6.4	104.0	61.0	38.8
G1 L2	10-20	3.97	8.8	93.0	65.0	47.2
G1 L3	0-10	3.83	6.8	107.0	20.0	49.5
G1 L3	10-20	4.07	8.8	41.0	14.0	73.5
G1 L3	0-10	3.86	5.6	121.0	19.0	42.5
G1 L3	10-20	4.08	7.6	48.0	17.0	66.9
G1 L3	0-10	3.77	7.2	90.0	20.0	54.1
G1 L3	10-20	4.18	8.4	63.0	23.0	62.7

Table 2: pH, acidity, acid saturation, EC, exchangeable Ca, Mg, K and Na for June 2008 - one year after treatment application

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	cm		mmolc/kg	%	mS/cm	mg/kg			
G0 A0	0-10	3.95	15.6	60.1	0.055	7.6	95.8	59.3	77.4
G0 A0	10-20	3.99	12.4	62.5	0.056	4.3	68.4	35.6	63.1
G0 A0	20-30	4.03	10.3	55.0	0.067	7.1	90.1	42.8	51.2
G0 A0	30-40	*	*	*	*	*	*	*	*
G0 A0	40-50	*	*	*	*	*	*	*	*
G0 A0	0-10	3.94	12.0	51.7	0.074	12.0	78.6	113.0	77.4
G0 A0	10-20	3.90	14.4	59.2	0.095	13.4	91.4	57.3	63.1
G0 A0	20-30	3.94	12.3	61.3	0.080	11.3	68.0	46.6	51.2
G0 A0	30-40	3.93	15.9	65.9	0.090	12.4	66.0	46.8	61.8
G0 A0	40-50	4.01	14.9	60.9	0.099	21.5	66.1	54.2	70.3
G0 A0	0-10	3.92	13.2	60.3	0.062	10.9	81.8	53.6	54.2
G0 A0	10-20	3.94	17.0	68.8	0.061	11.0	78.3	45.5	40.0
G0 A0	20-30	4.00	12.9	64.2	0.059	9.5	58.2	46.4	53.3
G0 A0	30-40	4.04	13.6	65.6	0.049	10.3	51.5	60.1	48.9
G0 A0	40-50	4.12	12.0	65.0	0.044	8.2	45.7	50.2	50.9
G0 A1	0-10	4.02	10.6	54.7	0.045	10.0	94.3	47.4	46.0
G0 A1	10-20	4.02	14.6	61.2	0.047	10.3	98.1	46.0	53.5
G0 A1	20-30	4.09	10.2	53.5	0.045	13.8	94.3	43.2	44.3
G0 A1	30-40	*	*	*	*	*	*	*	*
G0 A1	40-50	*	*	*	*	*	*	*	*
G0 A1	0-10	3.97	12.2	54.4	0.056	11.1	92.4	71.0	65.4
G0 A1	10-20	4.03	10.1	48.5	0.051	14.3	111.5	63.9	54.0
G0 A1	20-30	4.07	7.7	47.6	0.052	13.0	78.3	40.2	55.7
G0 A1	30-40	4.12	9.0	51.4	0.047	12.2	72.4	40.3	65.9
G0 A1	40-50	4.18	9.6	53.8	0.043	11.3	71.4	33.6	65.8
G0 A1	0-10	4.02	9.7	53.2	0.055	9.4	85.7	46.7	52.7
G0 A1	10-20	4.03	9.9	55.7	0.051	9.5	78.5	36.1	50.6
G0 A1	20-30	4.08	12.6	61.7	0.066	9.4	78.5	40.9	47.8
G0 A1	30-40	4.12	10.2	52.7	0.066	13.0	81.5	47.5	63.1
G0 A1	40-50	4.18	10.4	51.0	0.055	18.2	85.1	61.8	60.0
G0 A2	0-10	4.17	6.8	35.2	0.054	16.2	140.0	65.2	56.1
G0 A2	10-20	4.17	6.6	36.5	0.057	15.9	128.8	50.4	54.6
G0 A2	20-30	4.22	6.3	40.7	0.046	15.3	89.7	43.4	53.6
G0 A2	30-40	4.20	7.1	43.3	0.051	13.3	85.1	39.3	67.6
G0 A2	40-50	4.20	9.6	55.6	0.038	11.0	65.0	31.8	60.7
G0 A2	0-10	4.06	9.8	52.3	0.051	9.1	82.1	39.8	70.2
G0 A2	10-20	4.08	10.0	53.8	0.053	9.6	79.4	38.7	65.5
G0 A2	20-30	4.15	12.1	58.3	0.065	12.0	86.0	43.0	52.1
G0 A2	30-40	*	*	*	*	*	*	*	*
G0 A2	40-50	*	*	*	*	*	*	*	*
G0 A2	0-10	4.06	11.8	50.0	0.059	14.1	118.2	60.8	73.0
G0 A2	10-20	4.04	12.2	54.2	0.083	18.2	110.5	48.0	46.2
G0 A2	20-30	4.15	7.7	37.4	0.085	29.9	139.8	42.3	53.8
G0 A2	30-40	4.10	10.4	50.1	0.090	24.0	109.0	37.6	45.2
G0 A2	40-50	4.10	10.6	51.1	0.095	22.4	97.3	36.9	57.4
G0 A3	0-10	4.06	10.3	50.7	0.046	11.5	101.6	33.5	71.9
G0 A3	10-20	4.02	17.4	69.6	0.046	8.4	70.8	31.8	58.3
G0 A3	20-30	3.99	11.9	54.4	0.058	14.4	97.3	43.1	65.1
G0 A3	30-40	4.07	11.7	55.5	0.059	12.5	92.9	42.5	60.0
G0 A3	40-50	4.19	9.5	50.9	0.042	17.7	87.8	51.6	44.9
G0 A3	0-10	4.05	9.1	45.9	0.049	13.6	115.3	52.4	56.5
G0 A3	10-20	4.08	9.2	50.0	0.056	11.3	94.3	33.4	62.8
G0 A3	20-30	4.09	10.7	56.5	0.052	12.4	88.4	33.6	43.8
G0 A3	30-40	*	*	*	*	*	*	*	*
G0 A3	40-50	*	*	*	*	*	*	*	*
G0 A3	0-10	4.09	9.9	46.9	0.066	24.6	112.9	62.3	43.4
G0 A3	10-20	4.11	9.4	44.4	0.065	27.3	117.2	59.4	50.2
G0 A3	20-30	4.10	9.6	52.7	0.069	18.4	68.2	66.8	45.7
G0 A3	30-40	4.07	10.7	51.4	0.068	22.7	77.7	82.0	51.9
G0 A3	40-50	4.14	15.9	66.2	0.061	16.5	58.7	71.3	46.1

Table 2 continues…

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	cm		mmolc/kg	%	mS/cm	mg/kg			
G0 C0	0-10	3.94	11.2	62.5	0.055	6.3	52.3	34.1	62.5
G0 C0	10-20	3.97	10.9	53.9	0.056	10.0	60.7	34.3	104.8
G0 C0	20-30	4.06	9.2	54.3	0.053	10.4	66.3	38.9	60.0
G0 C0	30-40	*	*	*	*	*	*	*	*
G0 C0	40-50	*	*	*	*	*	*	*	*
G0 C0	0-10	3.92	11.0	55.9	0.052	9.9	72.4	48.9	69.3
G0 C0	10-20	4.02	10.3	51.6	0.042	13.1	89.2	40.7	70.5
G0 C0	20-30	4.05	14.4	64.8	0.043	11.5	73.7	36.4	52.4
G0 C0	30-40	4.02	10.8	58.3	0.046	11.8	71.6	36.7	51.2
G0 C0	40-50	4.02	12.0	59.7	0.044	11.1	65.9	40.3	65.8
G0 C0	0-10	3.98	11.8	62.6	0.058	7.5	59.5	40.5	55.5
G0 C0	10-20	4.04	9.9	6.7	0.054	9.8	2377.5	569.7	52.3
G0 C0	20-30	4.02	10.0	52.0	0.058	14.1	90.5	42.8	55.2
G0 C0	30-40	4.08	17.3	66.6	0.060	13.7	84.6	41.1	52.3
G0 C0	40-50	*	*	*	*	*	*	*	*
G0 C1	0-10	4.07	13.6	53.2	0.060	15.3	137.9	31.2	68.0
G0 C1	10-20	4.02	11.1	57.1	0.070	11.2	73.7	33.4	66.1
G0 C1	20-30	4.09	9.8	55.8		11.2	67.0	36.7	58.7
G0 C1	30-40	*	*	*	*	*	*	*	*
G0 C1	40-50	*	*	*	*	*	*	*	*
G0 C1	0-10	4.09	9.4	41.4	0.057	16.8	143.5	62.3	71.7
G0 C1	10-20	4.08	14.9	62.9	0.042	12.1	84.1	34.6	62.0
G0 C1	20-30	4.12	9.2	52.5	0.050	13.3	75.8	36.1	58.0
G0 C1	30-40	4.28	5.1	32.7	0.045	19.0	107.7	42.3	57.4
G0 C1	40-50	*	*	*	*	*	*	*	*
G0 C1	0-10	4.18	6.0	31.1	0.045	19.6	162.4	51.4	53.2
G0 C1	10-20	4.07	9.7	46.1	0.044	12.9	100.4	124.3	48.4
G0 C1	20-30	4.10	13.9	60.3	0.048	15.3	92.3	36.6	54.0
G0 C1	30-40	4.17	21.2	71.1	0.047	15.6	80.4	40.3	52.3
G0 C1	40-50	4.22	15.3	68.5	0.037	12.0	58.0	38.9	49.1
G0 C2	0-10	4.55	2.8	13.2	0.056	30.4	236.6	42.2	64.0
G0 C2	10-20	4.34	3.4	17.8	0.044	23.7	185.7	33.5	82.3
G0 C2	20-30	4.68	1.6	8.6	0.041	25.4	232.4	36.5	64.8
G0 C2	30-40	4.30	9.8	50.1	0.069	22.2	139.6	37.5	0.0
G0 C2	40-50	*	*	*	*	*	*	*	*
G0 C2	0-10	4.16	6.2	32.3	0.048	21.0	149.6	46.8	57.6
G0 C2	10-20	4.12	8.4	46.6	0.051	13.4	85.1	36.8	75.5
G0 C2	20-30	4.19	8.3	45.6	0.050	16.4	80.5	41.4	78.4
G0 C2	30-40	4.22	10.8	54.9	0.050	17.8	71.8	37.3	65.0
G0 C2	40-50	4.22	7.3	42.9	0.050	23.4	80.0	32.7	68.2
G0 C2	0-10	4.20	5.4	29.6	0.050	21.9	155.7	48.8	45.9
G0 C2	10-20	4.11	6.7	39.7	0.039	17.6	111.0	41.2	48.9
G0 C2	20-30	4.20	6.3	32.8	0.041	22.9	139.0	52.5	63.4
G0 C2	30-40	*	*	*	*	*	*	*	*
G0 C2	40-50	*	*	*	*	*	*	*	*
G0 C3	0-10	4.55	3.9	13.9	0.074	39.4	338.5	56.8	55.1
G0 C3	10-20	4.08	8.2	46.8	0.094	15.7	99.2	39.7	46.4
G0 C3	20-30	4.00	9.8	53.5	0.062	13.9	81.9	33.3	56.5
G0 C3	30-40	4.01	18.4	69.5	0.059	13.9	70.1	36.0	57.3
G0 C3	40-50	4.12	10.4	56.8	0.050	13.6	64.3	39.9	59.3
G0 C3	0-10	5.04	0.1	0.4	0.067	62.2	452.6	77.2	51.5
G0 C3	10-20	4.11	10.5	46.2	0.061	25.6	139.5	44.8	46.2
G0 C3	20-30	4.08	10.9	54.0	0.067	17.6	91.2	51.9	44.4
G0 C3	30-40	4.08	11.0	54.7	0.075	21.5	77.2	61.8	44.1
G0 C3	40-50	4.09	12.8	57.0	0.064	19.2	85.9	60.9	50.7
G0 C3	0-10	4.49	3.9	14.3	0.048	47.9	305.0	72.8	49.3
G0 C3	10-20	4.16	7.2	34.3	0.055	28.1	159.2	62.1	45.8
G0 C3	20-30	4.11	10.4	50.2	0.058	21.8	108.0	54.2	39.1
G0 C3	30-40	4.10	13.2	60.0	0.053	19.3	68.3	54.3	54.6
G0 C3	40-50	4.14	12.2	58.0	0.048	18.4	64.9	54.1	62.0

Table 2 continues…

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	cm		mmolc/kg	%	mS/cm	mg/kg			
G0 L0	0-10	3.90	11.2	60.2	0.062	8.2	57.9	38.2	65.8
G0 L0	10-20	3.89	11.4	68.3	0.064	4.7	41.6	24.7	50.0
G0 L0	20-30	3.97	11.3	72.9	0.070	6.5	59.5	26.7	-0.2
G0 L0	30-40	3.98	11.4	74.1	0.082	6.4	57.5	22.7	0.0
G0 L0	40-50	*	*	*	*	*	*	*	*
G0 L0	0-10	3.89	12.3	59.4	0.064	7.7	82.4	47.4	56.4
G0 L0	10-20	4.04	10.6	48.1	0.067	11.3	128.0	49.7	65.2
G0 L0	20-30	4.03	11.7	59.9	0.059	9.6	76.8	42.7	48.9
G0 L0	30-40	*	*	*	*	*	*	*	*
G0 L0	40-50	*	*	*	*	*	*	*	*
G0 L0	0-10	3.96	13.1	66.2	0.063	7.4	52.2	55.6	47.1
G0 L0	10-20	3.97	13.7	72.0	0.058	5.6	40.5	38.6	42.5
G0 L0	20-30	4.02	12.2	63.5	0.060	7.5	58.7	43.0	54.8
G0 L0	30-40	4.09	10.6	56.5	0.059	12.8	65.8	44.9	62.1
G0 L0	40-50	4.18	8.6	49.8	0.054	16.7	73.3	39.6	58.7
G0 L1	0-10	4.10	7.1	36.2	0.045	15.7	138.9	48.9	70.1
G0 L1	10-20	4.10	7.1	41.5	0.045	15.5	99.7	36.2	63.5
G0 L1	20-30	4.10	8.7	53.8	0.044	11.8	61.4	29.6	61.8
G0 L1	30-40	4.11	8.1	50.3	0.048	13.3	69.7	30.5	60.7
G0 L1	40-50	4.08	9.2	50.6	0.049	15.3	86.0	33.0	58.2
G0 L1	0-10	4.07	9.2	48.8	0.059	9.9	101.9	48.3	58.7
G0 L1	10-20	4.10	10.9	55.3	0.048	10.8	93.5	40.5	51.0
G0 L1	20-30	4.12	9.0	48.8	0.049	11.1	110.9	41.5	45.0
G0 L1	30-40	*	*	*	*	*	*	*	*
G0 L1	40-50	*	*	*	*	*	*	*	*
G0 L1	0-10	4.08	8.7	45.6	0.051	13.5	104.4	57.2	58.4
G0 L1	10-20	4.06	11.3	59.2	0.043	11.7	83.4	41.3	36.7
G0 L1	20-30	4.00	11.8	58.5	0.052	16.1	76.2	41.2	50.4
G0 L1	30-40	4.05	10.8	56.0	0.038	15.7	73.0	44.2	54.5
G0 L1	40-50	*	*	*	*	*	*	*	*
G0 L2	0-10	4.11	6.2	32.5	0.051	15.7	152.5	66.1	53.7
G0 L2	10-20	3.99	9.8	49.7	0.041	11.6	101.7	41.1	63.5
G0 L2	20-30	4.00	9.0	53.3	0.043	11.2	73.4	30.8	57.1
G0 L2	30-40	4.05	9.0	53.8	0.049	9.8	62.4	36.9	65.7
G0 L2	40-50	4.10	8.8	49.1	0.062	14.0	79.4	41.2	67.4
G0 L2	0-10	4.16	6.8	33.7	0.045	14.6	176.6	49.3	45.5
G0 L2	10-20	4.17	6.9	39.2	0.041	13.4	134.1	36.4	45.3
G0 L2	20-30	4.24	7.1	42.7	0.046	13.2	95.9	52.5	53.2
G0 L2	30-40	*	*	*	*	*	*	*	*
G0 L2	40-50	*	*	*	*	*	*	*	*
G0 L2	0-10	4.12	8.6	38.4	0.052	13.5	183.1	61.0	46.2
G0 L2	10-20	4.06	8.7	43.3	0.060	11.3	152.2	44.0	38.6
G0 L2	20-30	3.98	8.7	46.9	0.070	12.0	103.7	48.9	54.6
G0 L2	30-40	4.02	8.7	47.8	0.080	15.0	108.3	52.7	35.0
G0 L2	40-50	4.09	8.8	46.2	0.070	16.0	114.6	51.4	42.7
G0 L3	0-10	4.21	6.3	26.7	0.059	18.0	235.0	54.2	63.0
G0 L3	10-20	4.07	9.0	50.1	0.066	8.7	104.3	24.4	55.3
G0 L3	20-30	4.12	11.9	55.8	0.073	11.3	96.3	41.1	60.8
G0 L3	30-40	4.29	9.1	34.9	0.079	18.2	214.6	62.5	71.0
G0 L3	40-50	*	*	*	*	*	*	*	*
G0 L3	0-10	4.58	2.3	10.8	0.054	19.6	260.6	68.4	55.4
G0 L3	10-20	4.28	4.8	24.9	0.049	14.2	185.6	43.3	66.6
G0 L3	20-30	4.13	8.0	44.0	0.058	12.1	118.3	41.8	51.0
G0 L3	30-40	4.14	6.6	39.8	0.060	13.1	115.5	39.3	49.8
G0 L3	40-50	*	*	*	*	*	*	*	*
G0 L3	0-10	4.20	8.8	41.8	0.067	15.4	150.4	57.5	47.1
G0 L3	10-20	4.09	9.8	52.9	0.049	10.8	93.0	44.1	46.2
G0 L3	20-30	4.01	9.2	52.7	0.057	11.4	77.9	43.1	52.6
G0 L3	30-40	4.20	9.5	54.9	0.045	11.1	63.9	37.1	62.6
G0 L3	40-50	4.24	7.9	45.7	0.060	19.3	88.0	49.9	48.6

Table 2 continues….

Treatment	Depth cm	pH	Acidity mmolc/kg	Acid saturation %	EC mS/cm	Mg mg/kg	Ca	K	Na
G1 A0	0-10	4.00	9.6	49.9	0.057	7.0	109.5	29.8	63.7
G1 A0	10-20	3.98	9.6	56.2	0.064	5.1	76.7	22.1	61.2
G1 A0	20-30	4.01	11.0	57.4	0.074	7.7	81.8	36.4	57.3
G1 A0	30-40	4.05	9.4	51.2	0.076	10.2	92.7	38.7	57.0
G1 A0	40-50	4.12	8.6	45.1	0.024	11.9	113.6	54.6	53.6
G1 A0	0-10	3.99	10.5	52.9	0.053	8.4	100.5	54.2	51.2
G1 A0	10-20	4.04	10.3	49.1	0.065	9.7	121.2	43.1	62.1
G1 A0	20-30	*	*	*	*	*	*	*	*
G1 A0	30-40	*	*	*	*	*	*	*	*
G1 A0	40-50	*	*	*	*	*	*	*	*
G1 A0	0-10	4.02	8.3	42.0	0.062	9.1	156.8	41.2	42.1
G1 A0	10-20	4.01	8.4	44.1	0.071	7.4	137.7	34.8	52.8
G1 A0	20-30	4.02	9.6	53.2	0.068	6.1	108.1	29.4	41.9
G1 A0	30-40	*	*	*	*	*	*	*	*
G1 A0	40-50	*	*	*	*	*	*	*	*
G1 A1	0-10	4.05	7.7	36.8	0.085	9.1	169.7	58.5	56.5
G1 A1	10-20	4.04	10.6	51.1	0.066	7.5	116.4	45.3	59.5
G1 A1	20-30	3.98	10.2	56.2	0.062	5.8	87.2	31.9	53.6
G1 A1	30-40	*	*	*	*	*	*	*	*
G1 A1	40-50	*	*	*	*	*	*	*	*
G1 A1	0-10	3.96	11.8	52.4	0.078	8.1	130.4	42.8	56.0
G1 A1	10-20	3.93	10.2	53.6	0.076	7.0	107.4	35.1	45.0
G1 A1	20-30	3.97	9.0	47.5	0.091	8.9	121.0	43.1	47.4
G1 A1	30-40	4.00	9.7	46.7	0.105	14.4	123.4	50.4	54.7
G1 A1	40-50	4.11	8.4	43.7	0.096	19.3	113.3	49.5	50.9
G1 A1	0-10	4.07	9.8	39.7	0.090	10.3	193.1	81.6	51.7
G1 A1	10-20	3.99	10.9	39.6	0.183	9.4	257.0	48.9	39.2
G1 A1	20-30	4.16	10.4	54.4	0.097	11.1	95.8	44.5	43.8
G1 A1	30-40	4.03	11.0	54.2	0.109	14.4	95.2	51.5	45.4
G1 A1	40-50	4.09	10.5	51.3	0.104	18.2	94.1	50.8	56.0
G1 A2	0-10	3.97	8.4	42.7	0.080	8.1	132.3	50.6	61.4
G1 A2	10-20	3.95	10.4	51.6	0.083	7.0	105.1	44.9	63.2
G1 A2	20-30	4.01	10.0	42.0	0.106	13.2	175.5	43.2	63.2
G1 A2	30-40	4.14	11.8	44.8	0.081	28.2	169.7	34.1	63.9
G1 A2	40-50	*	11.0	52.6	0.064	32.6	87.5	29.1	47.2
G1 A2	0-10	4.12	6.4	28.1	0.083	10.3	225.2	47.3	70.9
G1 A2	10-20	4.04	9.2	41.7	0.099	5.2	179.1	34.6	59.5
G1 A2	20-30	4.06	8.9	43.1	0.096	10.5	147.5	36.8	59.3
G1 A2	30-40	4.09	8.6	38.2	0.111	15.1	165.7	38.6	77.3
G1 A2	40-50	4.13	7.2	34.8	0.097	20.8	159.4	39.7	65.4
G1 A2	0-10	4.05	9.0	40.4	0.084	12.3	157.6	52.3	69.2
G1 A2	10-20	3.93	13.6	66.4	0.075	5.4	80.6	30.8	37.1
G1 A2	20-30	4.01	9.2	54.0	0.085	6.8	103.7	33.6	28.3
G1 A2	30-40	4.09	9.8	47.1	0.099	13.1	133.3	32.5	54.9
G1 A2	40-50	4.11	10.7	48.9	0.111	16.9	118.1	32.7	70.2
G1 A3	0-10	4.42	3.4	15.8	0.079	11.4	265.5	59.0	53.8
G1 A3	10-20	4.24	4.3	19.7	0.150	9.5	255.3	49.6	59.5
G1 A3	20-30	4.12	6.4	36.7	0.073	9.7	127.9	48.0	59.9
G1 A3	30-40	4.09	7.1	38.8	0.081	10.3	130.7	56.2	55.4
G1 A3	40-50	4.27	4.8	26.4	0.088	14.5	167.0	61.1	49.5
G1 A3	0-10	4.21	8.8	37.9	0.052	13.9	180.4	42.4	70.4
G1 A3	10-20	4.17	6.2	34.0	0.060	11.2	149.5	30.3	67.3
G1 A3	20-30	4.19	6.3	34.4	0.068	12.1	155.1	35.9	52.4
G1 A3	30-40	*	*	*	*	*	*	*	*
G1 A3	40-50	*	*	*	*	*	*	*	*
G1 A3	0-10	4.17	6.7	31.4	0.137	6.6	200.9	42.1	69.9
G1 A3	10-20	4.09	7.4	35.0	0.118	4.5	199.0	31.7	60.5
G1 A3	20-30	4.11	8.1	41.8	0.087	5.0	142.0	34.1	67.3
G1 A3	30-40	4.11	8.8	43.4	0.095	7.4	140.8	41.5	64.1
G1 A3	40-50	8.00	7.8	38.6	0.102	6.5	164.5	41.4	57.5

Table 2 continues…

Treatment	Depth cm	pH	Acidity mmolc/kg	Acid saturation %	EC mS/cm	Mg mg/kg	Ca	K	Na
G1 C0	0-10	4.01	8.6	53.0	0.055	5.1	77.5	24.9	61.6
G1 C0	10-20	4.03	9.3	56.6	0.053	4.6	67.1	21.4	65.9
G1 C0	20-30	4.03	9.2	54.5	0.058	4.9	79.4	21.7	63.6
G1 C0	30-40	4.08	9.1	44.2	0.065	6.4	73.7	161.0	72.7
G1 C0	40-50	*	*	*	*	*	*	*	*
G1 C0	0-10	3.99	10.9	49.9	0.073	7.6	142.0	39.9	49.7
G1 C0	10-20	4.01	13.2	62.9	0.060	6.1	86.4	33.4	47.7
G1 C0	20-30	4.08	10.0	48.1	0.059	8.0	136.7	35.8	53.3
G1 C0	30-40	4.09	10.8	51.7	0.082	11.5	116.5	44.6	49.3
G1 C0	40-50	*	*	*	*	*	*	*	*
G1 C0	0-10	3.98	9.0	34.6	0.176	7.0	260.0	48.6	52.0
G1 C0	10-20	3.97	9.2	38.8	0.129	5.0	220.8	38.4	48.6
G1 C0	20-30	4.07	12.2	52.8	0.120	4.5	134.2	41.5	62.6
G1 C0	30-40	3.99	11.8	54.2	0.126	8.5	121.1	48.4	45.7
G1 C0	40-50	4.09	9.8	44.7	0.119	16.6	136.2	60.2	54.4
G1 C1	0-10	4.15	5.5	28.8	0.061	12.2	176.4	45.7	59.0
G1 C1	10-20	4.05	8.6	46.2	0.069	8.0	128.8	24.5	51.5
G1 C1	20-30	4.08	9.0	51.1	0.078	7.5	96.1	24.5	57.7
G1 C1	30-40	4.11	10.5	50.2	0.091	11.0	130.0	31.9	49.9
G1 C1	40-50	*	*	*	*	*	*	*	*
G1 C1	0-10	4.04	8.1	39.6	0.058	13.1	135.4	54.4	71.1
G1 C1	10-20	3.96	10.8	54.3	0.060	8.0	103.2	32.1	55.3
G1 C1	20-30	4.00	10.8	57.2	0.060	8.2	83.8	34.4	54.0
G1 C1	30-40	4.00	9.8	50.0	0.077	12.5	95.3	39.5	69.8
G1 C1	40-50	*	10.1	*	*	*	*	*	*
G1 C1	0-10	4.02	9.2	42.8	0.069	9.5	153.4	59.3	52.2
G1 C1	10-20	3.99	9.4	47.9	0.069	8.0	128.2	45.1	46.6
G1 C1	20-30	4.03	7.8	42.8	0.076	11.9	128.3	43.4	45.1
G1 C1	30-40	4.07	9.0	22.8	0.094	51.9	274.3	173.3	184.6
G1 C1	40-50	4.14	7.4	39.1	0.086	21.5	131.8	41.7	47.2
G1 C2	0-10	4.11	6.5	31.6	0.096	12.0	192.2	27.0	64.5
G1 C2	10-20	4.13	3.2	18.2	0.093	7.9	226.4	23.4	46.4
G1 C2	20-30	4.15	6.7	38.6	0.095	11.7	123.6	27.2	63.9
G1 C2	30-40	4.20	6.3	31.9	0.117	16.5	157.7	26.8	79.8
G1 C2	40-50								
G1 C2	0-10	4.37	4.9	20.2	0.060	23.9	260.6	46.4	69.2
G1 C2	10-20	4.11	7.6	35.6	0.059	15.2	175.6	30.6	65.2
G1 C2	20-30	*	*	*	*	*	*	*	*
G1 C2	30-40	*	*	*	*	*	*	*	*
G1 C2	40-50	*	*	*	*	*	*	*	*
G1 C2	0-10	4.03	*	40.1	0.097	12.4	204.4	52.0	56.9
G1 C2	10-20	4.03	9.8	43.2	0.111	14.0	174.8	44.3	41.8
G1 C2	20-30	4.02	12.2	49.1	0.125	28.2	136.3	53.1	47.8
G1 C2	30-40	3.99	11.2	50.9	0.115	26.2	106.8	56.3	41.8
G1 C2	40-50	4.04	10.8	50.5	0.103	26.4	100.2	59.8	42.2
G1 C3	0-10	4.42	8.4	30.0	0.072	30.8	271.8	38.6	59.2
G1 C3	10-20	4.22	6.9	36.5	0.082	19.5	148.0	22.8	56.1
G1 C3	20-30	4.30	5.1	26.5	0.091	23.1	172.6	24.3	68.8
G1 C3	30-40	4.23	6.6	40.1	0.088	13.9	115.5	24.3	54.1
G1 C3	40-50	4.33	8.6	41.0	0.090	18.0	152.9	28.2	58.2
G1 C3	0-10	4.75	1.2	5.2	0.058	29.7	322.2	35.6	56.6
G1 C3	10-20	4.20	8.2	42.5	0.053	12.9	128.3	23.7	69.7
G1 C3	20-30	4.13	8.3	43.3	0.058	14.4	117.0	29.4	70.6
G1 C3	30-40	4.19	17.7	54.4	0.070	29.5	170.8	30.6	69.2
G1 C3	40-50	4.36	9.2	39.2	0.071	38.9	167.9	26.8	44.9
G1 C3	0-10	5.15	*	*	0.069	33.5	347.9	39.9	42.6
G1 C3	10-20	4.49	3.2	15.8	0.056	21.9	239.5	30.6	52.9
G1 C3	20-30	4.24	5.9	34.6	0.052	14.1	143.5	28.2	46.4
G1 C3	30-40	*	*	*	*	*	*	*	*
G1 C3	40-50	*	*	*	*	*	*	*	*

Table 2 continues….

Treatment	Depth cm	pH	Acidity mmolc/kg	Acid saturation %	EC mS/cm	Mg mg/kg	Ca	K	Na
G1 L0	0-10	4.07	9.2	52.2	0.069	5.6	92.4	28.9	58.5
G1 L0	10-20	4.08	10.9	60.5	0.064	4.8	69.0	25.8	59.9
G1 L0	20-30	4.15	8.5	53.8	0.078	5.1	79.3	26.7	51.5
G1 L0	30-40	4.23	8.5	48.9	0.076	8.7	94.2	29.3	62.8
G1 L0	40-50	4.21	7.0	42.7	0.079	9.2	105.3	30.8	58.8
G1 L0	0-10	4.09	9.2	46.2	0.075	12.9	120.1	42.3	57.1
G1 L0	10-20	4.14	7.4	40.1	0.073	10.3	130.2	46.8	58.3
G1 L0	20-30	4.12	7.4	40.7	0.078	8.0	128.4	39.1	60.7
G1 L0	30-40	4.18	8.4	44.9	0.078	11.2	113.2	35.3	64.3
G1 L0	40-50	4.25	7.5	42.8	0.061	17.3	109.9	19.8	58.9
G1 L0	0-10	3.93	9.7	46.6	0.077	6.6	139.8	46.6	55.6
G1 L0	10-20	3.98	9.0	47.5	0.070	4.7	134.8	32.7	46.4
G1 L0	20-30	4.01	8.6	45.4	0.081	4.0	147.9	32.3	41.5
G1 L0	30-40	4.04	8.5	44.6	0.091	5.2	140.6	39.5	48.7
G1 L0	40-50	4.02	13.6	57.2	0.098	5.9	130.9	39.4	48.5
G1 L1	0-10	4.11	17.4	64.3	0.063	8.5	107.8	34.1	62.0
G1 L1	10-20	4.03	10.2	45.6	0.075	6.1	77.9	221.7	49.1
G1 L1	20-30	4.15	17.2	68.2	0.061	8.3	85.1	32.2	51.0
G1 L1	30-40	4.15	9.7	55.8	0.063	8.8	85.3	31.7	43.5
G1 L1	40-50	*	*	*	*	*	*	*	*
G1 L1	0-10	4.08	8.3	34.6	0.129	8.1	223.2	52.2	56.4
G1 L1	10-20	4.08	9.4	42.5	0.114	5.1	196.6	36.8	36.6
G1 L1	20-30	4.04	10.2	48.8	0.106	4.8	145.4	37.2	49.2
G1 L1	30-40	4.02	10.8	50.9	0.120	6.1	139.4	44.1	41.6
G1 L1	40-50	4.07	11.2	48.5	0.127	11.0	158.5	49.5	40.7
G1 L1	0-10	4.11	14.9	45.1	0.092	13.1	234.1	102.1	63.4
G1 L1	10-20	4.02	11.5	50.2	0.084	6.1	149.3	35.3	57.3
G1 L1	20-30	4.04	10.6	52.5	0.084	6.7	118.4	40.0	49.0
G1 L1	30-40	4.06	10.6	51.7	0.090	11.0	113.8	46.1	47.8
G1 L1	40-50	4.17	10.4	50.6	0.076	12.9	108.7	46.7	57.0
G1 L2	0-10	4.26	7.9	34.5	0.066	11.6	198.7	53.3	63.4
G1 L2	10-20	4.10	8.0	40.1	0.059	7.5	156.0	34.3	61.7
G1 L2	20-30	4.12	10.8	51.7	0.065	6.6	121.7	31.3	61.3
G1 L2	30-40	4.11	8.8	43.5	0.076	9.6	135.5	42.2	64.9
G1 L2	40-50	4.13	8.8	48.9	0.086	10.5	86.6	46.6	63.2
G1 L2	0-10	4.09	8.5	36.3	0.067	12.9	175.6	70.6	76.1
G1 L2	10-20	4.02	10.4	48.7	0.070	11.4	120.4	49.0	63.2
G1 L2	20-30	4.03	7.7	41.6	0.079	12.9	123.1	59.8	46.3
G1 L2	30-40	4.06	9.4	43.7	0.092	18.6	119.6	67.4	65.6
G1 L2	40-50	4.08	9.2	43.1	0.106	20.2	122.8	69.7	59.5
G1 L2	0-10	4.22	6.2	25.7	0.067	15.2	246.3	99.9	42.0
G1 L2	10-20	4.09	10.4	51.4	0.059	10.3	108.2	54.8	48.5
G1 L2	20-30	4.11	10.6	52.7	0.073	10.5	97.0	54.5	54.8
G1 L2	30-40	4.11	12.0	58.2	0.056	11.1	75.9	58.5	55.0
G1 L2	40-50	4.14	11.1	50.8	0.061	18.7	89.1	73.5	65.5
G1 L3	0-10	4.15	5.4	26.5	0.058	12.1	205.4	40.2	60.6
G1 L3	10-20	3.96	15.2	60.8	0.060	7.8	110.9	33.9	62.4
G1 L3	20-30	3.98	9.6	48.8	0.064	9.7	119.4	32.7	55.4
G1 L3	30-40	3.98	10.2	49.5	0.065	13.5	119.3	30.5	58.4
G1 L3	40-50	3.93	12.2	51.5	0.073	21.7	130.5	27.5	55.0
G1 L3	0-10	4.38	2.4	10.5	0.125	15.1	288.6	74.7	57.0
G1 L3	10-20	3.97	9.7	42.1	0.069	7.7	178.5	34.4	65.5
G1 L3	20-30	4.06	6.2	30.7	0.088	11.2	181.5	41.9	67.5
G1 L3	30-40	4.14	5.6	27.0	0.116	11.1	215.7	60.6	43.2
G1 L3	40-50	*	*	*	*	*	*	*	*
G1 L3	0-10	4.26	5.0	21.8	0.065	13.0	241.0	40.7	85.8
G1 L3	10-20	4.04	8.4	45.7	0.071	6.9	123.5	33.8	54.1
G1 L3	20-30	4.04	11.3	56.1	0.068	7.4	106.3	33.5	46.6
G1 L3	30-40	*	5.2	23.6	0.077	24.9	223.4	61.2	48.7
G1 L3	40-50	*	*	*	*	*	*	*	*

Table 3: Water soluble ions (Mg, Ca, K, Na, Cl, NO_3^-, PO_4^{3-}, SO_4^{2-}) for June 2008 – one year after treatment application

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	PO_4	SO_4
Treatment	Depth (cm)	mg/kg							
G0 A0	0-10	2.60	33.1	49.0	34.0	16.9	106.4	0.0	161.0
G0 A0	10-20	2.00	37.1	25.0	36.0	17.9	65.9	0.0	208.4
G0 A0	20-30	3.10	47.1	33.0	33.0	16.9	70.2	0.0	262.9
G0 A0	30-40	*	*	*	*	*	*	*	*
G0 A0	40-50	*	*	*	*	*	*	*	*
G0 A0	0-10	4.40	30.5	58.0	42.0	22.6	142.9	0.0	132.3
G0 A0	10-20	7.00	50.5	46.0	46.0	27.0	190.0	0.0	218.0
G0 A0	20-30	6.50	45.3	34.0	38.0	21.8	233.0	0.0	178.8
G0 A0	30-40	8.00	45.7	34.0	46.0	30.5	268.9	0.0	300.0
G0 A0	40-50	14.00	41.7	37.0	39.0	32.6	348.7	0.0	221.9
G0 A0	0-10	4.40	31.3	30.0	34.0	19.7	81.9	0.0	152.8
G0 A0	10-20	4.90	42.4	30.0	31.0	17.0	54.8	0.0	195.9
G0 A0	20-30	4.00	28.8	35.0	32.0	17.7	47.1	0.0	183.5
G0 A0	30-40	2.60	15.7	40.0	39.0	23.9	52.3	3.4	128.3
G0 A0	40-50	2.00	12.0	31.0	37.0	56.5	86.8	0.0	63.6
G0 A1	0-10	4.10	22.9	34.0	41.0	20.0	45.8	0.0	122.1
G0 A1	10-20	4.40	27.9	25.0	41.0	20.8	48.3	0.0	125.2
G0 A1	20-30	5.60	28.7	22.0	35.0	17.2	41.2	7.6	127.0
G0 A1	30-40	*	*	*	*	*	*	*	*
G0 A1	40-50	*	*	*	*	*	*	*	*
G0 A1	0-10	2.40	21.0	44.0	37.0	19.8	96.1	0.0	146.1
G0 A1	10-20	2.70	21.0	40.0	36.0	18.7	59.0	0.0	141.5
G0 A1	20-30	3.90	22.9	30.0	31.0	14.9	46.9	0.0	168.3
G0 A1	30-40	3.20	16.6	23.0	35.0	17.1	63.8	0.0	118.3
G0 A1	40-50	2.70	16.5	15.0	33.0	16.8	87.1	0.0	81.4
G0 A1	0-10	2.90	27.2	31.0	33.0	18.4	107.1	0.0	93.6
G0 A1	10-20	3.30	30.4	21.0	30.0	15.3	53.6	0.0	151.3
G0 A1	20-30	3.70	32.1	29.0	50.0	23.9	55.6	3.4	202.5
G0 A1	30-40	4.60	29.9	34.0	43.0	21.5	60.0	3.4	204.0
G0 A1	40-50	5.20	22.7	37.0	27.0	14.2	43.6	0.0	179.6
G0 A2	0-10	6.40	25.8	82.0	44.0	81.3	70.2	0.0	101.4
G0 A2	10-20	7.00	27.1	37.0	37.0	56.5	41.5	0.0	112.1
G0 A2	20-30	5.90	26.1	29.0	40.0	25.8	40.4	0.0	137.6
G0 A2	30-40	6.50	28.9	23.0	42.0	22.8	58.6	46.5	118.9
G0 A2	40-50	5.20	23.3	16.0	38.0	21.4	64.6	5.6	80.3
G0 A2	0-10	4.50	26.7	35.0	36.0	20.5	40.0	0.0	135.7
G0 A2	10-20	5.30	31.1	28.0	42.0	23.6	49.7	0.0	140.5
G0 A2	20-30	9.00	45.1	35.0	36.0	22.6	44.3	0.0	218.1
G0 A2	30-40	*	*	*	*	*	*	*	*
G0 A2	40-50	*	*	*	*	*	*	*	*
G0 A2	0-10	5.00	33.4	33.0	33.0	16.5	98.1	0.0	153.5
G0 A2	10-20	9.00	50.9	32.0	39.0	20.1	122.0	0.0	237.7
G0 A2	20-30	10.90	46.2	28.0	49.0	24.0	144.5	0.0	214.8
G0 A2	30-40	11.60	51.6	25.0	40.0	19.7	209.7	0.0	193.0
G0 A2	40-50	12.40	56.4	24.0	39.0	23.0	268.3	0.0	182.7
G0 A3	0-10	5.10	28.4	23.0	43.0	20.7	48.0	0.0	113.8
G0 A3	10-20	4.90	30.1	23.0	38.0	18.6	43.8	13.6	133.0
G0 A3	20-30	9.20	41.4	23.0	38.0	19.9	45.6	3.0	199.1
G0 A3	30-40	8.30	40.9	28.0	32.0	16.4	0.0	0.0	181.6
G0 A3	40-50	7.50	25.8	33.0	33.0	15.8	47.7	0.0	144.0
G0 A3	0-10	2.80	26.3	30.0	40.0	21.6	77.3	0.0	118.8
G0 A3	10-20	3.40	32.4	17.0	45.0	20.6	41.4	0.0	176.8
G0 A3	20-30	4.70	39.2	17.0	31.0	16.2	51.1	0.0	182.7
G0 A3	30-40	*	*	*	*	*	*	*	*
G0 A3	40-50	*	*	*	*	*	*	*	*
G0 A3	0-10	7.50	24.3	35.0	37.0	22.1	60.5	2.7	179.3
G0 A3	10-20	7.10	20.7	34.0	43.0	21.2	47.8	2.6	181.9
G0 A3	20-30	7.50	25.1	45.0	41.0	22.8	44.0	0.0	216.4
G0 A3	30-40	8.10	22.5	56.0	44.0	23.3	48.7	0.0	227.4
G0 A3	40-50	5.40	16.6	53.0	39.0	22.3	57.0	0.0	166.6

Table 3 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	PO_4	SO_4
Treatment	Depth (cm)	mg/kg							
G0 C0	0-10	4.90	27.2	13.0	41.0	21.8	76.7	50.4	119.7
G0 C0	10-20	5.30	26.5	12.0	41.0	22.8	63.7	17.7	155.3
G0 C0	20-30	6.00	24.9	20.0	42.0	21.6	62.6	0.0	158.2
G0 C0	30-40	*	*	*	*	*	*	*	*
G0 C0	40-50	*	*	*	*	*	*	*	*
G0 C0	0-10	5.10	19.1	37.0	41.0	30.6	85.2	3.8	107.1
G0 C0	10-20	5.00	16.7	26.0	40.0	25.5	47.4	0.0	110.5
G0 C0	20-30	6.20	24.9	26.0	33.0	19.0	41.0	0.0	126.9
G0 C0	30-40	6.60	26.9	25.0	35.0	26.4	54.7	0.0	136.3
G0 C0	40-50	5.00	21.6	27.0	36.0	20.2	51.9	0.0	125.2
G0 C0	0-10	5.20	31.6	31.0	43.0	24.6	83.4	0.0	162.0
G0 C0	10-20	5.90	38.0	25.0	35.0	18.4	54.2	0.0	139.5
G0 C0	20-30	8.30	42.1	32.0	38.0	18.2	58.3	5.0	136.6
G0 C0	30-40	8.40	37.3	34.0	44.0	23.2	76.5	2.2	167.1
G0 C0	40-50	*	*	*	*	*	*	*	*
G0 C1	0-10	8.60	48.9	17.0	34.0	19.5	78.3	0.0	151.9
G0 C1	10-20	9.80	49.4	23.0	41.0	26.1	70.2	0.0	218.5
G0 C1	20-30	9.50	47.9	25.0	36.0	19.8	64.1	0.0	227.7
G0 C1	30-40	*	*	*	*	*	*	*	*
G0 C1	40-50	*	*	*	*	*	*	*	*
G0 C1	0-10	5.60	22.9	39.0	49.0	25.8	89.8	0.0	100.9
G0 C1	10-20	5.20	22.3	19.0	31.0	16.9	0.0	50.5	100.0
G0 C1	20-30	5.90	25.3	16.0	46.0	24.0	49.6	0.0	134.6
G0 C1	30-40	5.40	20.2	21.0	41.0	21.6	57.7	0.0	101.9
G0 C1	40-50	*	*	*	*	*	*	*	*
G0 C1	0-10	5.40	23.5	25.0	40.0	21.3	73.3	0.0	67.4
G0 C1	10-20	4.80	19.7	20.0	45.0	23.5	57.7	0.0	86.3
G0 C1	20-30	6.30	26.1	21.0	35.0	19.4	33.0	0.0	134.0
G0 C1	30-40	7.10	26.7	21.0	31.0	15.3	33.6	0.0	133.0
G0 C1	40-50	4.00	13.8	19.0	32.0	17.0	47.0	0.0	72.8
G0 C2	0-10	9.80	41.0	20.0	51.0	29.7	52.4	2.2	151.3
G0 C2	10-20	7.00	29.8	15.0	36.0	21.2	38.9	0.0	116.8
G0 C2	20-30	7.00	35.4	44.0	29.0	47.2	33.6	0.0	128.0
G0 C2	30-40	13.30	59.1	24.0	28.0	18.0	28.8	0.0	253.6
G0 C2	40-50	*	*	*	*	*	*	*	*
G0 C2	0-10	7.20	29.5	25.0	39.0	21.3	76.6	0.0	104.9
G0 C2	10-20	7.30	29.4	20.0	42.0	21.8	48.7	0.0	145.6
G0 C2	20-30	8.70	28.7	25.0	33.0	19.3	34.4	0.0	150.8
G0 C2	30-40	8.80	25.1	21.0	35.0	21.6	46.3	0.0	141.5
G0 C2	40-50	10.70	23.5	17.0	38.0	20.0	49.4	0.0	127.7
G0 C2	0-10	6.40	30.7	34.0	35.0	18.3	57.9	0.0	113.0
G0 C2	10-20	4.80	22.3	22.0	33.0	16.6	36.8	0.0	102.5
G0 C2	20-30	6.20	24.7	27.0	32.0	15.8	35.8	0.0	128.6
G0 C2	30-40	*	*	*	*	*	*	*	*
G0 C2	40-50	*	*	*	*	*	*	*	*
G0 C3	0-10	6.00	47.9	27.0	40.0	20.5	77.1	0.0	196.5
G0 C3	10-20	4.30	28.4	21.0	35.0	17.3	44.8	0.0	168.2
G0 C3	20-30	5.60	36.5	20.0	39.0	38.3	36.0	0.0	231.3
G0 C3	30-40	6.20	35.0	23.0	34.0	16.2	46.6	0.0	241.3
G0 C3	40-50	2.00	20.6	23.0	38.0	20.4	114.0	0.0	89.1
G0 C3	0-10	10.00	46.2	41.0	37.0	0.0	0.0	0.0	0.0
G0 C3	10-20	7.30	33.0	20.0	35.0	19.2	52.7	0.0	162.7
G0 C3	20-30	6.90	30.6	31.0	42.0	21.2	44.1	0.0	197.5
G0 C3	30-40	9.30	32.9	43.0	37.0	22.4	47.4	0.0	241.7
G0 C3	40-50	7.00	23.9	39.0	36.0	20.3	70.6	4.3	165.5
G0 C3	0-10	5.30	26.9	40.0	36.0	18.0	80.2	0.0	82.8
G0 C3	10-20	4.80	23.2	32.0	41.0	21.9	65.6	0.0	132.0
G0 C3	20-30	5.50	23.3	36.0	41.0	19.6	54.5	3.2	156.7
G0 C3	30-40	5.10	16.6	37.0	35.0	17.2	31.9	1.9	154.7
G0 C3	40-50	3.70	11.0	31.0	42.0	22.6	35.3	0.0	122.6

Table 3 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	PO_4	SO_4
Treatment	Depth (cm)	mg/kg							
G0 L0	0-10	5.50	35.6	22.0	40.0	23.6	137.7	0.0	124.1
G0 L0	10-20	4.70	38.4	19.0	28.0	15.1	116.3	0.0	167.5
G0 L0	20-30	7.20	51.8	24.0	35.0	19.5	145.0	0.0	277.5
G0 L0	30-40	7.70	57.0	20.0	33.0	18.0	141.4	17.7	395.2
G0 L0	40-50	*	*	*	*	*	*	*	*
G0 L0	0-10	5.30	41.5	35.0	39.0	20.6	124.8	0.0	149.7
G0 L0	10-20	6.40	51.7	36.0	41.0	17.9	78.8	0.0	211.7
G0 L0	20-30	6.40	38.4	47.0	37.0	20.0	50.3	0.0	203.4
G0 L0	30-40	7.00	36.6	27.0	40.0	19.2	54.6	0.0	230.0
G0 L0	40-50	*	*	*	*	*	*	*	*
G0 L0	0-10	3.40	24.0	40.0	43.0	24.1	107.1	4.7	125.3
G0 L0	10-20	2.80	23.0	23.0	38.0	20.2	66.2	3.5	172.7
G0 L0	20-30	3.60	29.7	27.0	35.0	20.0	52.6	2.5	231.1
G0 L0	30-40	4.90	25.6	27.0	38.0	20.5	58.5	0.0	193.3
G0 L0	40-50	5.60	22.5	22.0	37.0	27.2	96.8	0.0	116.6
G0 L1	0-10	4.50	19.0	22.0	39.0	27.5	49.3	0.0	97.4
G0 L1	10-20	5.50	20.1	20.0	38.0	20.9	40.6	0.0	112.0
G0 L1	20-30	5.80	21.6	21.0	30.0	17.6	22.9	0.0	132.0
G0 L1	30-40	6.80	24.8	19.0	40.0	22.7	35.8	0.0	147.7
G0 L1	40-50	7.70	28.1	19.0	36.0	22.3	45.6	0.0	138.1
G0 L1	0-10	6.10	35.4	34.0	44.0	36.1	99.7	0.0	106.9
G0 L1	10-20	5.30	32.9	25.0	42.0	21.8	58.2	0.0	138.1
G0 L1	20-30	5.30	35.8	27.0	35.0	18.9	71.1	0.0	131.7
G0 L1	30-40	*	*	*	*	*	*	*	*
G0 L1	40-50	*	*	*	*	*	*	*	*
G0 L1	0-10	1.90	22.1	35.0	42.0	22.3	60.9	16.9	95.8
G0 L1	10-20	2.50	23.9	21.0	30.0	16.3	50.6	4.8	99.2
G0 L1	20-30	4.40	25.5	25.0	37.0	17.4	42.3	0.0	148.9
G0 L1	30-40	4.40	26.2	27.0	38.0	18.6	45.0	0.0	159.7
G0 L1	40-50	*	*	*	*	*	*	*	*
G0 L2	0-10	4.50	22.4	31.0	52.0	28.2	72.7	0.0	88.3
G0 L2	10-20	4.20	20.5	26.0	43.0	23.6	50.0	46.7	90.8
G0 L2	20-30	4.80	22.8	20.0	44.0	23.7	36.7	5.7	127.1
G0 L2	30-40	5.70	26.8	27.0	40.0	21.8	59.1	0.0	127.2
G0 L2	40-50	8.90	32.4	29.0	44.0	57.3	63.0	0.0	121.6
G0 L2	0-10	5.30	38.4	31.0	33.0	16.4	66.2	0.0	120.1
G0 L2	10-20	4.50	28.0	18.0	37.0	19.1	38.6	0.0	122.9
G0 L2	20-30	6.20	33.1	21.0	32.0	15.2	33.2	0.0	138.4
G0 L2	30-40	*	*	*	*	*	*	*	*
G0 L2	40-50	*	*	*	*	*	*	*	*
G0 L2	0-10	2.50	32.9	25.0	32.0	18.9	85.0	0.0	122.6
G0 L2	10-20	3.30	44.0	20.0	35.0	20.3	68.4	0.0	178.7
G0 L2	20-30	4.60	46.2	28.0	43.0	25.7	63.1	0.0	231.0
G0 L2	30-40	6.10	54.4	34.0	46.0	23.0	86.6	0.0	234.9
G0 L2	40-50	5.30	31.0	29.0	37.0	22.5	87.1	0.0	178.8
G0 L3	0-10	7.00	47.3	27.0	38.0	20.0	99.8	42.3	90.9
G0 L3	10-20	7.40	59.4	21.0	40.0	21.6	88.8	8.0	162.9
G0 L3	20-30	8.90	49.2	39.0	39.0	44.9	78.8	2.8	152.7
G0 L3	30-40	9.10	54.7	42.0	40.0	49.0	151.6	0.0	112.0
G0 L3	40-50	*	*	*	*	*	*	*	*
G0 L3	0-10	5.30	35.0	42.0	44.0	25.2	81.4	0.0	97.7
G0 L3	10-20	4.90	35.5	22.0	39.0	20.0	56.8	0.0	125.3
G0 L3	20-30	5.40	42.0	23.0	41.0	20.1	39.1	0.0	189.2
G0 L3	30-40	7.70	49.1	23.0	35.0	16.1	46.0	0.0	217.1
G0 L3	40-50	*	*	*	*	*	*	*	*
G0 L3	0-10	3.70	32.0	26.0	44.0	22.6	68.7	0.0	165.7
G0 L3	10-20	3.80	30.2	33.0	36.0	23.7	116.8	15.5	112.6
G0 L3	20-30	2.90	19.2	22.0	34.0	19.3	51.9	0.0	112.5
G0 L3	30-40	3.10	17.7	22.0	33.0	21.6	117.2	3.0	52.5
G0 L3	40-50	5.50	22.7	26.0	43.0	30.3	182.0	12.1	58.5

Table 3 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	PO_4	SO_4
Treatment	Depth (cm)	mg/kg							
G1 A0	0-10	4.20	47.5	16.0	38.0	22.2	56.1	0.0	231.2
G1 A0	10-20	3.70	51.2	14.0	43.0	24.9	54.0	0.0	286.3
G1 A0	20-30	4.30	57.7	19.0	48.0	20.1	69.5	0.0	303.2
G1 A0	30-40	4.70	66.3	22.0	36.0	19.7	69.1	0.0	217.7
G1 A0	40-50	7.30	62.3	31.0	52.0	19.5	41.5	59.6	282.1
G1 A0	0-10	4.10	32.6	40.0	33.0	15.4	56.3	0.0	138.5
G1 A0	10-20	5.20	51.0	30.0	35.0	18.2	48.8	0.0	197.9
G1 A0	20-30	*	*	*	*	*	*	*	*
G1 A0	30-40	*	*	*	*	*	*	*	*
G1 A0	40-50	*	*	*	*	*	*	*	*
G1 A0	0-10	4.90	51.0	23.0	51.0	22.4	59.1	0.0	196.2
G1 A0	10-20	4.50	61.8	18.0	42.0	20.9	47.5	0.0	219.2
G1 A0	20-30	5.00	68.6	19.0	35.0	15.0	39.1	0.0	259.1
G1 A0	30-40	*	*	*	*	*	*	*	*
G1 A0	40-50	*	*	*	*	*	*	*	*
G1 A1	0-10	3.20	75.6	43.0	43.0	20.0	48.3	0.0	363.2
G1 A1	10-20	2.60	53.8	22.0	40.0	19.3	54.0	0.0	252.6
G1 A1	20-30	2.20	50.2	21.0	36.0	17.1	44.2	0.0	283.9
G1 A1	30-40	*	*	*	*	*	*	*	*
G1 A1	40-50	*	*	*	*	*	*	*	*
G1 A1	0-10	3.00	54.8	22.0	50.0	19.8	80.2	0.0	259.1
G1 A1	10-20	3.00	65.5	21.0	44.0	20.0	77.8	0.0	335.5
G1 A1	20-30	4.30	71.3	32.0	38.0	17.3	92.0	0.0	398.7
G1 A1	30-40	7.90	76.1	42.0	43.0	22.4	117.8	0.0	443.2
G1 A1	40-50	9.60	66.4	42.0	38.0	21.7	151.5	0.0	363.1
G1 A1	0-10	3.80	64.9	55.0	40.0	21.5	113.5	50.7	243.9
G1 A1	10-20	6.40	192.3	31.0	38.0	18.7	122.4	0.0	1080.3
G1 A1	20-30	6.40	61.3	31.0	34.0	15.9	91.9	4.0	345.2
G1 A1	30-40	8.30	62.4	41.0	43.0	23.7	125.7	0.0	440.5
G1 A1	40-50	9.30	50.1	38.0	42.0	20.9	127.4	0.0	344.7
G1 A2	0-10	5.50	72.9	32.0	41.0	20.2	75.4	0.0	242.8
G1 A2	10-20	5.40	66.1	34.0	49.0	23.2	61.8	57.5	236.2
G1 A2	20-30	11.90	114.9	33.0	39.0	26.9	114.0	6.4	331.2
G1 A2	30-40	16.10	66.6	12.0	40.0	38.7	128.7	3.2	163.5
G1 A2	40-50	18.10	35.7	12.0	44.0	68.4	171.1	4.2	20.3
G1 A2	0-10	3.20	77.1	27.0	38.0	19.4	84.8	0.0	271.4
G1 A2	10-20	2.10	99.9	23.0	37.0	31.7	47.4	0.0	425.6
G1 A2	20-30	4.80	87.1	25.0	36.0	14.4	36.5	0.0	405.4
G1 A2	30-40	7.40	108.7	26.0	41.0	17.8	69.1	0.0	502.4
G1 A2	40-50	9.80	100.1	25.0	41.0	18.6	61.7	65.4	463.9
G1 A2	0-10	5.10	59.9	31.0	44.0	22.3	160.1	0.0	195.3
G1 A2	10-20	2.70	49.9	21.0	34.0	16.8	83.6	0.0	306.0
G1 A2	20-30	3.80	61.9	25.0	39.0	18.1	92.1	0.0	348.2
G1 A2	30-40	6.50	78.2	23.0	40.0	18.7	130.6	0.0	357.2
G1 A2	40-50	8.50	67.3	37.0	35.0	32.8	161.6	0.0	298.1
G1 A3	0-10	6.20	84.4	34.0	35.0	19.4	41.3	19.8	328.2
G1 A3	10-20	8.40	212.0	35.0	39.0	15.6	37.7	13.0	717.3
G1 A3	20-30	6.50	61.6	39.0	34.0	21.5	41.1	6.8	298.1
G1 A3	30-40	7.00	73.4	43.0	39.0	19.5	56.5	3.0	320.6
G1 A3	40-50	10.00	80.1	49.0	37.0	20.9	55.0	0.0	326.7
G1 A3	0-10	5.50	46.7	27.0	39.0	20.7	60.2	4.4	160.6
G1 A3	10-20	4.80	53.0	16.0	45.0	18.8	36.0	3.6	201.0
G1 A3	20-30	6.20	60.0	22.0	41.0	17.2	39.6	2.1	230.0
G1 A3	30-40	*	*	*	*	*	*	*	*
G1 A3	40-50	*	*	*	*	*	*	*	*
G1 A3	0-10	3.70	157.6	29.0	45.0	19.1	50.0	49.4	711.4
G1 A3	10-20	2.20	128.0	19.0	38.0	19.3	35.1	70.3	494.4
G1 A3	20-30	2.00	70.4	23.0	41.0	22.0	40.7	15.9	313.8
G1 A3	30-40	3.30	81.2	28.0	43.0	19.0	47.2	4.5	371.2
G1 A3	40-50	2.80	93.3	29.0	43.0	18.3	43.5	2.5	412.2

Table 3 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	PO_4	SO_4
Treatment	Depth (cm)	mg/kg							
G1 C0	0-10	3.60	43.0	13.0	38.0	23.1	40.4	10.7	174.7
G1 C0	10-20	2.90	40.9	13.0	38.0	20.9	43.3	9.4	201.4
G1 C0	20-30	3.00	44.3	17.0	38.0	19.6	37.9	10.4	416.7
G1 C0	30-40	4.40	53.1	22.0	35.0	21.2	62.4	0.0	224.2
G1 C0	40-50	*	*	*	*	*	*	*	*
G1 C0	0-10	3.30	50.2	28.0	33.0	15.4	85.8	0.0	261.3
G1 C0	10-20	2.30	41.2	20.0	40.0	20.8	59.6	62.2	183.9
G1 C0	20-30	2.70	46.0	23.0	31.0	14.8	58.8	8.2	213.6
G1 C0	30-40	5.10	59.4	30.0	35.0	16.9	98.3	3.0	276.2
G1 C0	40-50	*	*	*	*	*	*	*	*
G1 C0	0-10	4.90	197.3	36.0	37.0	21.1	101.2	0.0	850.6
G1 C0	10-20	2.60	131.0	20.0	43.0	20.6	76.0	0.0	537.0
G1 C0	20-30	2.50	107.3	32.0	43.0	22.6	92.5	0.0	513.6
G1 C0	30-40	5.80	99.1	41.0	46.0	26.2	155.5	0.0	552.1
G1 C0	40-50	9.60	85.5	45.0	44.0	30.8	185.9	0.0	405.0
G1 C1	0-10	5.50	47.8	23.0	48.0	17.8	47.3	0.0	241.2
G1 C1	10-20	4.90	65.5	15.0	37.0	20.2	56.2	0.0	257.3
G1 C1	20-30	6.70	67.2	19.0	41.0	21.4	76.8	0.0	346.4
G1 C1	30-40	10.60	88.3	23.0	39.0	22.2	85.1	0.0	309.1
G1 C1	40-50	*	*	*	*	*	*	*	*
G1 C1	0-10	6.10	40.8	34.0	40.0	23.2	81.9	53.3	125.4
G1 C1	10-20	5.90	41.9	24.0	42.0	40.3	48.8	8.7	141.3
G1 C1	20-30	5.60	43.3	23.0	50.0	27.8	53.7	3.4	173.0
G1 C1	30-40	10.60	62.8	36.0	38.0	42.0	53.2	0.0	232.9
G1 C1	40-50	*	*	*	*	*	*	*	*
G1 C1	0-10	2.60	38.4	33.0	37.0	19.7	87.4	39.7	165.2
G1 C1	10-20	2.50	36.9	26.0	46.0	25.2	71.6	11.4	178.9
G1 C1	20-30	4.50	48.5	25.0	36.0	18.8	63.4	3.0	250.9
G1 C1	30-40	8.10	55.2	31.0	43.0	21.6	87.3	0.0	298.5
G1 C1	40-50	8.10	51.0	26.0	47.0	21.8	106.0	0.0	246.5
G1 C2	0-10	8.60	98.7	13.0	47.0	22.7	56.9	57.8	344.5
G1 C2	10-20	0.00	121.6	13.0	30.0	15.6	47.3	23.3	373.6
G1 C2	20-30	10.10	90.1	19.0	46.0	20.5	54.5	10.0	336.7
G1 C2	30-40	15.60	129.8	19.0	38.0	19.7	56.8	5.9	484.0
G1 C2	40-50	*	*	*	*	*	*	*	*
G1 C2	0-10	2.90	42.9	28.0	46.0	25.6	75.0	0.0	132.5
G1 C2	10-20	3.50	48.3	17.0	40.0	19.8	50.4	0.0	182.4
G1 C2	20-30	*	*	*	*	*	*	*	*
G1 C2	30-40	*	*	*	*	*	*	*	*
G1 C2	40-50	*	*	*	*	*	*	*	*
G1 C2	0-10	5.10	80.9	27.0	44.0	23.9	64.2	48.7	332.7
G1 C2	10-20	7.80	86.9	30.0	51.0	26.7	60.5	6.8	391.1
G1 C2	20-30	17.40	81.0	43.0	42.0	20.7	62.4	3.5	486.9
G1 C2	30-40	17.30	69.6	50.0	40.0	23.4	86.0	0.0	443.3
G1 C2	40-50	15.60	55.6	48.0	33.0	27.2	162.5	0.0	292.4
G1 C3	0-10	12.10	62.8	25.0	40.0	35.1	61.9	0.0	198.8
G1 C3	10-20	11.70	69.1	19.0	40.0	33.9	53.4	7.6	239.0
G1 C3	20-30	15.50	82.8	21.0	43.0	34.7	60.4	4.9	321.5
G1 C3	30-40	11.00	69.8	24.0	37.0	31.3	37.5	2.8	290.7
G1 C3	40-50	11.00	67.3	24.0	46.0	36.1	45.3	0.0	288.4
G1 C3	0-10	10.20	55.3	25.0	48.0	23.8	58.4	2.5	132.9
G1 C3	10-20	6.70	49.4	12.0	34.0	16.6	43.2	2.7	163.9
G1 C3	20-30	8.90	52.4	17.0	41.0	25.1	41.5	3.7	234.9
G1 C3	30-40	16.20	64.5	15.0	40.0	18.6	47.6	0.0	289.5
G1 C3	40-50	20.00	55.7	11.0	43.0	19.7	42.1	0.0	260.0
G1 C3	0-10	13.70	75.6	24.0	40.0	19.1	80.0	0.0	175.6
G1 C3	10-20	8.70	48.4	17.0	40.0	18.4	58.9	50.5	138.8
G1 C3	20-30	5.90	34.3	14.0	48.0	21.2	46.2	5.0	137.7
G1 C3	30-40	*	*	*	*	*	*	*	*
G1 C3	40-50	*	*	*	*	*	*	*	*

Table 3 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	PO_4	SO_4
Treatment	Depth (cm)	mg/kg							
G1 L0	0-10	3.70	50.6	29.0	46.0	37.9	71.6	4.1	182.1
G1 L0	10-20	3.50	43.6	24.0	38.0	31.5	56.7	6.5	194.0
G1 L0	20-30	3.70	59.1	31.0	38.0	39.7	68.6	2.8	221.1
G1 L0	30-40	6.60	61.4	29.0	38.0	31.4	84.1	0.0	239.5
G1 L0	40-50	7.60	68.7	28.0	33.0	31.3	100.9	0.0	231.2
G1 L0	0-10	7.90	52.6	31.0	44.0	29.2	107.6	0.0	187.2
G1 L0	10-20	9.80	55.9	36.0	40.0	45.0	81.1	0.0	207.4
G1 L0	20-30	6.20	58.8	28.0	45.0	26.0	63.3	0.0	248.6
G1 L0	30-40	8.50	56.2	26.0	42.0	20.2	55.0	0.0	252.2
G1 L0	40-50	10.80	35.3	10.0	41.0	22.2	34.1	0.0	188.4
G1 L0	0-10	3.90	68.0	31.0	44.0	22.0	70.4	0.0	229.0
G1 L0	10-20	2.60	76.1	21.0	39.0	18.3	48.2	0.0	277.9
G1 L0	20-30	2.60	94.5	24.0	35.0	17.9	38.8	0.0	323.1
G1 L0	30-40	3.30	112.4	32.0	35.0	18.7	48.3	0.0	396.9
G1 L0	40-50	4.40	100.2	32.0	40.0	21.3	55.1	65.3	337.6
G1 L1	0-10	6.10	43.4	86.0	49.0	103.5	91.7	0.0	118.3
G1 L1	10-20	6.60	62.5	31.0	39.0	45.7	77.3	0.0	205.3
G1 L1	20-30	5.20	44.2	20.0	41.0	23.3	75.5	53.2	140.1
G1 L1	30-40	5.60	42.1	20.0	49.0	23.1	97.3	10.8	123.3
G1 L1	40-50	*	*	*	*	*	*	*	*
G1 L1	0-10	3.90	115.7	28.0	41.0	18.6	84.9	0.0	502.4
G1 L1	10-20	2.50	90.4	18.0	44.0	19.0	65.3	0.0	405.8
G1 L1	20-30	2.60	85.2	22.0	32.0	15.3	67.3	0.0	415.3
G1 L1	30-40	3.60	91.8	32.0	44.0	24.6	81.4	0.0	581.7
G1 L1	40-50	6.40	89.6	34.0	45.0	22.5	104.7	0.0	593.6
G1 L1	0-10	4.50	70.5	60.0	44.0	20.2	93.5	0.0	308.8
G1 L1	10-20	2.60	68.6	21.0	37.0	17.5	49.9	0.0	300.6
G1 L1	20-30	3.30	66.6	28.0	32.0	15.3	41.9	0.0	324.0
G1 L1	30-40	5.70	68.8	33.0	32.0	22.0	63.1	0.0	387.1
G1 L1	40-50	5.20	46.9	30.0	38.0	18.7	94.6	0.0	229.5
G1 L2	0-10	2.20	44.4	34.0	36.0	18.9	93.6	5.4	132.0
G1 L2	10-20	2.00	47.9	17.0	40.0	18.6	55.3	3.0	173.5
G1 L2	20-30	2.30	54.0	17.0	40.0	19.1	42.8	0.0	229.4
G1 L2	30-40	3.20	62.5	25.0	41.0	19.0	48.7	2.7	279.0
G1 L2	40-50	3.90	72.9	25.0	36.0	16.2	42.6	0.0	334.8
G1 L2	0-10	2.50	36.4	40.0	42.0	19.2	68.1	0.0	160.0
G1 L2	10-20	3.80	47.5	30.0	38.0	17.6	45.8	0.0	240.0
G1 L2	20-30	5.20	49.3	42.0	37.0	17.5	46.4	0.0	290.1
G1 L2	30-40	7.90	56.9	51.0	39.0	16.7	51.0	0.0	366.4
G1 L2	40-50	10.30	72.0	56.0	31.0	15.3	70.6	0.0	430.2
G1 L2	0-10	2.70	33.9	75.0	46.0	24.1	83.1	0.0	177.3
G1 L2	10-20	2.70	27.3	35.0	44.0	22.0	80.5	0.0	156.2
G1 L2	20-30	7.00	32.5	58.0	35.0	21.6	55.8	0.0	155.2
G1 L2	30-40	2.80	23.9	36.0	38.0	18.5	36.2	0.0	253.2
G1 L2	40-50	4.10	28.4	42.0	33.0	15.9	31.1	0.0	208.0
G1 L3	0-10	5.10	43.7	21.0	50.0	26.2	60.6	0.0	136.4
G1 L3	10-20	3.90	46.7	20.0	41.0	24.3	44.9	0.0	171.9
G1 L3	20-30	5.60	50.5	19.0	40.0	21.0	38.8	0.0	201.3
G1 L3	30-40	9.10	59.4	18.0	38.0	20.8	48.0	0.0	229.5
G1 L3	40-50	14.40	60.1	12.0	37.0	18.1	55.4	0.0	237.0
G1 L3	0-10	11.20	147.7	55.0	43.0	25.9	81.6	0.0	462.7
G1 L3	10-20	4.30	67.7	19.0	33.0	16.7	58.3	0.0	196.0
G1 L3	20-30	5.30	78.2	25.0	50.0	24.4	59.3	0.0	270.2
G1 L3	30-40	10.50	127.9	50.0	35.0	40.6	68.0	0.0	414.2
G1 L3	40-50	*	*	*	*	*	*	*	*
G1 L3	0-10	6.20	71.6	23.0	44.0	18.0	38.9	0.0	232.3
G1 L3	10-20	4.40	73.4	23.0	38.0	18.9	42.3	0.0	249.2
G1 L3	20-30	5.50	64.6	25.0	39.0	19.7	40.6	0.0	241.7
G1 L3	30-40	11.50	71.0	37.0	45.0	26.2	92.1	0.0	247.3
G1 L3	40-50	*	*	*	*	*	*	*	*

Table 4: pH, acidity, acid saturation, EC, exchangeable Ca, Mg, K and Na for June 2009 – two years after treatment application

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	**cm**		**mmolc/kg**	**%**	**mS/cm**	**mg/kg**			
G0 A0	0-20	3.94	8.8	53.9	0.023	5.9	49.0	91.2	52.4
G0 A0	20-40	4.15	8.9	56.2	0.024	6.7	45.0	74	51.8
G0 A0	40-60	4.26	9.0	44.1	0.040	22.6	86.0	129.5	42.2
G0 A0	60-80	4.28	15.2	62.1	0.050	20.8	41.0	136.4	46.4
G0 A0	0-20	4.03	9.0	54.0	0.026	5.7	55.0	94.7	47
G0 A0	20-40	4.01	9.4	54.2	0.065	8.8	51.0	113.3	40.6
G0 A0	40-60	4.28	9.4	42.4	0.065	18.3	53.0	268.1	39
G0 A0	60-80	4.43	6.5	38.7	0.066	29.5	29.0	150.5	57.9
G0 A0	0-20	3.99	9.2	51.3	0.030	7.7	65.0	53.2	79.1
G0 A0	20-40	4.14	10.1	62.0	0.036	6	32.0	53.7	62.3
G0 A0	40-60	4.27	8.9	55.1	0.037	8.9	46.0	61.2	60.8
G0 A0	60-80	4.22	13.2	59.9	0.026	23.5	42.0	56.3	76.2
G0 A1	0-20	4	8.8	52.1	0.022	7	52.0	98.9	54
G0 A1	20-40	4.13	8.3	51.2	0.027	8.9	65.0	74.5	47
G0 A1	40-60	4.17	8.7	50.2	0.020	17.8	74.0	44.2	52.4
G0 A1	60-80	4.18	12.8	59.8	0.021	25.5	53.0	50.6	58.1
G0 A1	0-20	4.1	7.0	39.1	0.027	13.2	80.0	119	61.7
G0 A1	20-40	4.14	7.9	45.9	0.046	14.3	73.0	100.6	42.9
G0 A1	40-60	4.22	8.5	53.2	0.030	10.8	44.0	82.5	52.1
G0 A1	60-80	4.39	6.7	42.0	0.034	14.7	55.0	108.8	56.4
G0 A1	0-20	4.09	7.4	50.8	0.026	7	66.0	40.8	51.6
G0 A1	20-40	4.08	9.0	46.6	0.030	8.4	56.0	40.5	132.1
G0 A1	40-60	4.25	7.2	47.9	0.026	15.2	53.0	47.1	62.2
G0 A1	60-80	4.31	11.9	53.8	0.031	34.4	31.0	111.3	68.1
G0 A2	0-20	4.12	7.4	45.4	0.024	10.6	81.0	72.6	48.4
G0 A2	20-40	4.1	9.0	65.2	0.026	5.4	30.0	50.3	36
G0 A2	40-60	4.29	6.3	46.3	0.023	16	58.0	48.7	42.8
G0 A2	60-80	4.4	8.4	46.5	0.022	34.3	56.0	61.4	54.5
G0 A2	0-20	4.17	9.5	63.5	0.022	7.9	65.0	52.1	4.5
G0 A2	20-40	4.24	8.6	61.6	0.029	9.5	60.0	32.9	16.6
G0 A2	40-60	4.44	7.2	42.0	0.019	25.8	74.0	45	69.3
G0 A2	60-80	4.24	18.9	69.1	0.015	41.6	20.0	42.6	66.6
G0 A2	0-20	4.2	9.0	45.5	0.025	9.4	91.0	144	40.8
G0 A2	20-40	4.21	9.0	42.4	0.027	14.7	76.0	156	75.3
G0 A2	40-60	4.28	8.3	40.3	0.019	15.5	69.0	189.6	61.5
G0 A2	60-80	4.46	5.2	29.3	0.017	27.8	71.0	138.8	72.1
G0 A3	0-20	4.14	8.5	51.7	0.023	8.8	74.0	34.3	60
G0 A3	20-40	4.15	8.0	53.9	0.037	9.4	53.0	38.9	56
G0 A3	40-60	4.2	8.2	52.4	0.035	11	57.0	45	58.4
G0 A3	60-80	4.95	2.2	14.7	0.028	47.9	83.0	65.2	61.8
G0 A3	0-20	4.11	9.3	60.3	0.028	7.8	48.0	53.1	38.8
G0 A3	20-40	4.11	7.3	52.3	0.036	7.3	49.0	54.8	51.2
G0 A3	40-60	4.44	7.2	46.4	0.026	22.5	50.0	59.9	55.2
G0 A3	60-80	4.27	19.3	73.0	0.028	17.7	17.0	67.8	71.3
G0 A3	0-20	4.29	4.9	26.3	0.020	22.3	138.0	66.6	74.1
G0 A3	20-40	4.2	7.1	42.7	0.040	18.9	62.0	73.5	67.8
G0 A3	40-60	4.35	7.4	29.5	0.049	25.1	134.0	62.7	167.9
G0 A3	60-80	4.44	5.8	38.6	0.039	38.6	55.0	38.7	50.8

Table 4 continues….

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	**cm**		**mmolc/kg**	**%**	**mS/cm**	**mg/kg**			
G0 C0	0-20	3.98	9.8	64.5	0.031	4	33.0	66.3	39.5
G0 C0	20-40	3.98	10.9	75.9	0.055	3	18.0	72	10.9
G0 C0	40-60	4.39	6.6	40.0	0.063	29	92.0	94.9	11.6
G0 C0	60-80	4.29	7.4	48.7	0.061	39	54.0	46.2	14
G0 C0	0-20	4.24	10.0	72.0	0.032	6.1	40.0	35.5	10.7
G0 C0	20-40	4.2	7.9	59.5	0.034	13.4	54.0	42.3	10.5
G0 C0	40-60	4.41	4.6	27.0	0.037	36.8	152.0	47.2	12.3
G0 C0	60-80	4.3	13.0	66.9	0.065	27.4	58.0	27	12.6
G0 C0	0-20	4.01	11.4	65.5	0.033	7.4	41.0	46.6	48.7
G0 C0	20-40	4.08	11.5	71.9	0.036	5.7	28.0	37.5	38.1
G0 C0	40-60	4.16	11.8	47.9	0.052	32.7	118.0	80.2	50.2
G0 C0	60-80	4.19	16.1	58.9	0.067	37.4	66.0	54.2	78.6
G0 C1	0-20	4.19	6.7	40.4	0.022	12.4	96.0	56.8	60.5
G0 C1	20-40	4.12	10.3	53.7	0.037	12.2	94.0	60.4	37.6
G0 C1	40-60	4.26	8.7	53.9	0.031	12.3	60.0	52.3	47.1
G0 C1	60-80	4.33	13.8	55.1	0.054	39.7	91.0	60.8	42.2
G0 C1	0-20	4.09	7.0	44.1	0.030	13.3	108.0	69.5	12.6
G0 C1	20-40	4.09	8.6	61.5	0.035	9.9	44.0	66.9	14.8
G0 C1	40-60	4.38	7.2	40.9	0.029	42.8	79.0	87.2	14.8
G0 C1	60-80	4.28	15.8	68.8	0.027	29.1	24.0	106.6	19.2
G0 C1	0-20	4.14	7.8	49.6	0.021	11.2	86.0	37	40.3
G0 C1	20-40	4.18	7.6	52.7	0.031	12.4	58.0	40.1	42.2
G0 C1	40-60	4.29	9.5	58.5	0.046	15.7	50.0	48.9	38.6
G0 C1	60-80	4.4	11.0	48.6	0.054	50.4	55.0	101	48.2
G0 C2	0-20	4.45	3.2	19.9	0.021	21.4	149.0	53.1	57
G0 C2	20-40	4.27	6.3	45.2	0.028	15.8	58.0	50.7	49.4
G0 C2	40-60	4.33	9.8	50.8	0.017	41.1	43.0	69.2	48.5
G0 C2	60-80	4.19	16.5	62.7	0.015	48.1	24.0	61.4	69.6
G0 C2	0-20	4.47	3.1	20.8	0.016	21.1	156.0	69	13.4
G0 C2	20-40	4.19	8.6	64.1	0.030	8.7	32.0	67.9	17.4
G0 C2	40-60	4.45	7.0	54.2	0.024	19.3	35.0	77.2	14.3
G0 C2	60-80	4.45	9.0	49.5	0.034	47.5	30.0	113	18.8
G0 C2	0-20	4.38	4.3	26.6	0.021	21.5	131.0	73.4	39
G0 C2	20-40	4.24	9.2	58.6	0.027	10.7	53.0	34.6	47.1
G0 C2	40-60	4.32	10.2	52.0	0.023	23.8	84.0	38.7	50.6
G0 C2	60-80	4.28	18.9	65.5	0.027	32.7	51.0	93.1	52.7
G0 C3	0-20	5.31	2.2	20.5	0.028	15.8	76.0	52.2	51.1
G0 C3	20-40	4.06	8.9	26.5	0.052	43.7	364.0	46	40.8
G0 C3	40-60	4.27	8.0	48.0	0.032	18.6	66.0	44.9	62.2
G0 C3	60-80	4.31	8.6	52.1	0.055	26.9	34.0	62.4	55.3
G0 C3	0-20	5.38	1.1	4.1	0.030	44.9	346.0	114.4	46.8
G0 C3	20-40	4.09	9.4	52.7	0.035	13.3	68.0	54.1	57.6
G0 C3	40-60	4.11	7.7	43.4	0.054	24.2	71.0	86.3	51.3
G0 C3	60-80	4.28	7.6	47.6	0.036	16.2	52.0	87.7	51
G0 C3	0-20	6.05	0.8	1.9	0.031	70	595.0	100	78.7
G0 C3	20-40	4.3	5.5	30.3	0.026	32.3	122.0	72.6	46.9
G0 C3	40-60	4.39	5.2	26.9	0.060	31.8	139.0	95.3	50
G0 C3	60-80	4.4	5.7	32.1	0.032	30.3	77.0	85	81.7

Table 4 continues…

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	cm		mmolc/kg	%	mS/cm	mg/kg			
G0 L0	0-20	3.94	12.4	79.5	0.035	4	33.0	29.4	10.8
G0 L0	20-40	4.13	11.1	80.3	0.054	3.3	20.0	36.9	11.8
G0 L0	40-60	4.31	6.1	53.0	0.046	10	57.0	45.1	12.8
G0 L0	60-80	4.28	12.6	53.5	0.084	45.1	108.0	44.9	15.1
G0 L0	0-20	4.14	9.8	56.0	0.030	5.9	81.0	34.2	52.9
G0 L0	20-40	4.15	11.8	64.8	0.042	5.9	41.0	68.9	48.1
G0 L0	40-60	4.24	9.4	47.6	0.037	22.5	101.0	54.9	45.6
G0 L0	60-80	4.24	12.4	55.0	0.046	31.5	87.0	43.8	46.7
G0 L0	0-20	4.06	9.0	48.9	0.041	10	63.0	66.9	85.6
G0 L0	20-40	4.14	8.7	51.0	0.043	11.9	54.0	62.7	71.1
G0 L0	40-60	4.31	8.1	43.8	0.046	20.9	75.0	67.3	74
G0 L0	60-80	4.44	6.2	37.2	0.051	35.6	67.0	55.8	64
G0 L1	0-20	4.08	8.4	57.5	0.025	7.5	65.0	52.1	23.9
G0 L1	20-40	4.21	7.8	69.1	0.037	5	34.0	35.5	10.3
G0 L1	40-60	4.55	5.5	42.2	0.033	28.6	63.0	55.2	14
G0 L1	60-80	4.27	16.1	72.9	0.039	33.3	21.0	51.2	19.4
G0 L1	0-20	4.17	9.6	58.8	0.023	6.5	65.0	32.8	47.7
G0 L1	20-40	4.2	9.4	66.3	0.023	4.7	36.0	27.5	42.8
G0 L1	40-60	4.28	12.9	53.7	0.044	37.1	81.0	47.3	63.2
G0 L1	60-80	4.31	15.6	63.5	0.042	39.4	30.0	54.9	64.5
G0 L1	0-20	4.2	5.1	33.1	0.028	13.9	94.0	94.7	47.3
G0 L1	20-40	4.2	6.5	44.6	0.030	12.2	68.0	69.6	43.4
G0 L1	40-60	4.32	6.6	42.2	0.023	20.2	72.0	50	58.5
G0 L1	60-80	4.35	12.6	59.2	0.030	33	34.0	95.1	42
G0 L2	0-20	4.14	6.7	47.5	0.021	8.5	94.0	54.6	14.1
G0 L2	20-40	4.15	6.2	43.8	0.039	15.3	94.0	52.8	15.8
G0 L2	40-60	4.37	7.5	56.4	0.032	14.2	47.0	63.2	15.3
G0 L2	60-80	4.61	5.1	37.8	0.040	41.3	30.0	104	17
G0 L2	0-20	4.22	5.6	29.9	0.024	11.2	168.0	63	48.4
G0 L2	20-40	4.44	4.5	21.1	0.021	12.8	116.0	329.2	36.7
G0 L2	40-60	4.2	13.4	50.4	0.047	48.1	107.0	69.6	47
G0 L2	60-80	4.02	21.4	67.8	0.029	55.9	35.0	55.7	54.1
G0 L2	0-20	4.15	5.4	34.7	0.020	10.5	115.0	63.4	45.5
G0 L2	20-40	4.13	8.0	48.1	0.040	10.3	69.0	65.4	61.1
G0 L2	40-60	4.28	6.4	49.3	0.031	13.4	49.0	53.5	39
G0 L2	60-80	4.39	7.5	45.3	0.052	31.7	43.0	75.3	53.9
G0 L3	0-20	4.51	4.0	21.5	0.025	14.4	206.0	95.9	15.6
G0 L3	20-40	4.25	9.2	55.3	0.037	9.8	71.0	90.4	17.3
G0 L3	40-60	4.59	4.1	24.6	0.025	39.2	127.0	81.1	18.3
G0 L3	60-80	4.6	4.9	29.2	0.019	39.1	118.0	81.8	15
G0 L3	0-20	4.56	2.2	12.2	0.023	16.9	229.0	42.9	49
G0 L3	20-40	4.11	7.2	50.1	0.023	9.5	67.0	40.9	45.4
G0 L3	40-60	4.25	8.8	40.1	0.031	29.8	134.0	56.4	57.9
G0 L3	60-80	4.2	12.8	55.1	0.029	26.8	86.0	40.6	64.6
G0 L3	0-20	4.38	3.4	20.1	0.024	15	162.0	84.3	50.3
G0 L3	20-40	4.18	4.4	30.0	0.041	10.4	87.0	67	76.2
G0 L3	40-60	4.31	6.1	40.0	0.032	12.2	69.0	75.4	62.7
G0 L3	60-80	4.64	7.4	43.3	0.035	30.5	50.0	69	65.2

Table 4 continues…

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	**cm**		**mmolc/kg**	**%**	**mS/cm**	**mg/kg**			
G1 A0	0-20	3.97	7.4	56.0	0.031	5.7	73.0	44.8	13
G1 A0	20-40	4.09	8.2	67.0	0.044	3.9	48.0	33.2	10.5
G1 A0	40-60	4.38	5.7	42.0	0.058	11.1	107.0	43.9	10.1
G1 A0	60-80	4.33	5.9	42.6	0.045	37.8	56.0	57.4	12.5
G1 A0	0-20	3.97	10.7	53.8	0.041	6.5	87.0	69.4	58
G1 A0	20-40	4.08	11.6	57.2	0.035	15.6	84.0	37.6	51.6
G1 A0	40-60	4.14	18.5	64.5	0.026	50.5	39.0	45.9	65.4
G1 A0	60-80	4.08	14.0	57.9	0.018	50.2	22.0	93.6	58.1
G1 A0	0-20	3.82	12.2	62.7	0.053	4.5	60.0	75.9	44.8
G1 A0	20-40	3.97	9.8	52.7	0.046	6.7	85.0	68.4	50.8
G1 A0	40-60	4.17	9.4	40.9	0.044	22.4	163.0	53.1	49
G1 A0	60-80	4.27	10.4	44.1	0.093	46.3	111.0	48.7	56.8
G1 A1	0-20	4.06	6.5	32.1	0.028	6.4	85.0	252.8	58.8
G1 A1	20-40	4.35	3.3	14.4	0.039	30.3	255.0	68	57.4
G1 A1	40-60	4.17	17.7	62.2	0.028	28.9	27.0	181.4	54.1
G1 A1	60-80	4.11	23.0	76.8	0.018	27.2	14.0	75.2	47
G1 A1	0-20	4.11	6.1	36.3	0.051	7.6	123.0	58.2	56.3
G1 A1	20-40	4.04	5.7	34.9	0.067	7.3	139.0	50	40.1
G1 A1	40-60	4.23	3.6	22.0	0.079	25.3	147.0	36.5	58.2
G1 A1	60-80	4.42	5.8	48.0	0.039	23.6	23.0	42	47.3
G1 A1	0-20	4.11	7.2	51.1	0.034	6	86.0	52.3	18.2
G1 A1	20-40	4.25	5.2	31.2	0.062	9.5	138.0	64.2	48.8
G1 A1	40-60	4.47	4.0	32.2	0.038	19.7	74.0	56.7	35.4
G1 A1	60-80	4.33	13.6	58.3	0.012	30.3	25.0	73.4	93.4
G1 A2	0-20	4.02	7.8	54.4	0.031	5	79.0	62.6	13.3
G1 A2	20-40	4.05	9.5	63.7	0.040	4.4	57.0	62.6	13.9
G1 A2	40-60	4.29	6.1	39.4	0.042	19.1	107.0	66.2	16.3
G1 A2	60-80	4.3	8.4	48.8	0.069	20	68.0	57.3	51.8
G1 A2	0-20	4.1	5.7	34.5	0.044	6.9	128.0	73.2	44
G1 A2	20-40	4.14	6.9	44.7	0.033	6.4	84.0	39.7	64.6
G1 A2	40-60	4.12	6.7	45.0	0.041	13.4	80.0	35.9	49.2
G1 A2	60-80	4.25	7.0	43.4	0.024	32.4	31.0	85.2	62.3
G1 A2	0-20	4.09	6.6	32.2	0.053	8.8	101.0	220	55.1
G1 A2	20-40	4.04	9.8	43.7	0.063	5.5	75.0	255.6	43
G1 A2	40-60	4.26	7.2	32.6	0.064	14.2	94.0	289.2	35.9
G1 A2	60-80	4.44	6.4	28.2	0.050	26.2	30.0	368.8	74.7
G1 A3	0-20	4.02	6.6	43.7	0.028	7	125.0	47.2	11.7
G1 A3	20-40	4.09	8.1	53.4	0.044	11.2	86.0	51.9	11.4
G1 A3	40-60	4.21	7.2	39.9	0.026	41.5	104.0	61.7	13.8
G1 A3	60-80	4.48	18.9	80.8	0.019	18.8	20.0	37.4	22.4
G1 A3	0-20	4.42	2.2	14.9	0.021	11.3	171.0	37.2	54.9
G1 A3	20-40	4.22	5.9	42.7	0.017	7.2	85.0	26.1	55.9
G1 A3	40-60	4.38	9.0	46.5	0.017	31.1	89.0	40.6	52.2
G1 A3	60-80	4.28	14.4	65.5	0.015	25.7	22.0	51.1	70.1
G1 A3	0-20	4.32	3.4	21.2	0.031	12.2	158.0	42.7	60.8
G1 A3	20-40	4.14	7.9	51.3	0.030	7	69.0	35.2	58.8
G1 A3	40-60	4.27	6.5	36.5	0.051	16.8	83.0	109	68.4
G1 A3	60-80	4.32	12.4	48.8	0.018	35.8	46.0	196	62.6

Table 4 continues…

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	**cm**		**mmolc/kg**	**%**	**mS/cm**	**mg/kg**			
G1 C0	0-20	4	7.6	56.1	0.035	6	81.0	31.8	12.7
G1 C0	20-40	3.95	10.5	82.0	0.042	3	19.0	24.2	11
G1 C0	40-60	4.35	5.1	33.9	0.039	17.2	144.0	28.6	12.2
G1 C0	60-80	4.18	17.0	77.9	0.049	27.6	24.0	24.2	15.6
G1 C0	0-20	4.08	5.9	36.3	0.025	8.8	115.0	50.6	60
G1 C0	20-40	4.18	6.1	39.3	0.041	11.7	87.0	49.2	64.2
G1 C0	40-60	4.32	6.3	41.4	0.028	23.5	58.0	49.9	63.7
G1 C0	60-80	4.22	17.8	65.9	0.021	15	25.0	70.8	113.3
G1 C0	0-20	4.12	6.6	37.5	0.045	5.9	136.0	51.2	56.1
G1 C0	20-40	4.17	8.2	48.5	0.059	6.8	95.0	46.5	50.5
G1 C0	40-60	4.22	6.6	41.3	0.061	10.4	93.0	58.3	55.7
G1 C0	60-80	4.48	4.7	33.1	0.016	29.7	47.0	83.6	59.6
G1 C1	0-20	3.98	9.0	55.9	0.022	6.6	83.0	69.7	13.9
G1 C1	20-40	3.92	9.6	60.6	0.056	6.5	74.0	53.8	13.5
G1 C1	40-60	4.32	4.2	24.4	0.065	42.5	146.0	67.3	13.9
G1 C1	60-80	4.26	10.4	47.2	0.080	57.5	83.0	73.6	19
G1 C1	0-20	4.16	5.7	33.9	0.027	10.9	141.0	49.7	42.7
G1 C1	20-40	4.07	10.3	62.8	0.033	5.7	54.0	44	41.7
G1 C1	40-60	4.3	4.8	31.7	0.033	21.1	118.0	42.2	38.4
G1 C1	60-80	4.2	10.2	45.8	0.030	53.9	63.0	72.6	58.7
G1 C1	0-20	4.03	8.1	43.7	0.030	7.2	100.0	77.4	66.1
G1 C1	20-40	4.06	8.5	46.7	0.040	12.2	88.0	80.8	50.2
G1 C1	40-60	4.16	7.4	47.3	0.050	6.8	68.0	65.2	59.7
G1 C1	60-80	4.42	4.8	33.7	0.033	37.3	51.0	65.9	46.6
G1 C2	0-20	4.41	2.8	19.2	0.034	17	180.0	32.7	11.5
G1 C2	20-40	4.41	7.4	60.5	0.050	7	64.0	23.9	10.5
G1 C2	40-60	4.22	5.1	45.2	0.060	10	83.0	27.5	11
G1 C2	60-80	4.46	4.9	46.5	0.044	19	62.0	17.9	10.9
G1 C2	0-20	4.07	5.9	37.4	0.023	10.3	113.0	40.6	53.8
G1 C2	20-40	4.07	6.4	41.4	0.037	7.9	84.0	75.7	53.2
G1 C2	40-60	4.24	4.2	18.6	0.059	37.9	205.0	113.2	52.6
G1 C2	60-80	4.16	15.0	65.2	0.049	24.7	48.0	44.7	56.1
G1 C2	0-20	4.25	4.2	22.0	0.070	10.4	218.0	54.6	43
G1 C2	20-40	4.14	6.6	37.3	0.082	18.8	135.0	60.1	30
G1 C2	40-60	4.32	5.4	30.8	0.061	29.2	119.0	66.4	45.4
G1 C2	60-80	4.44	7.0	45.5	0.045	17.3	62.0	47.9	60.5
G1 C3	0-20	4.41	2.8	19.0	0.031	20	180.0	29.6	12.5
G1 C3	20-40	4.07	7.0	54.0	0.061	10	81.0	25.9	10.6
G1 C3	40-60	4.27	6.5	43.1	0.060	32	89.0	39.1	10
G1 C3	60-80	4.53	4.4	34.9	0.064	45.4	31.0	66.3	25.2
G1 C3	0-20	4.56	2.8	15.2	0.026	20.6	218.0	39.6	50
G1 C3	20-40	4.22	9.1	58.4	0.045	7.5	53.0	34.8	52.8
G1 C3	40-60	4.9	9.6	39.7	0.042	49	155.0	29.6	47.7
G1 C3	60-80	4.34	21.9	64.2	0.036	72.8	28.0	92.4	55
G1 C3	0-20	4.87	271.2	93.5	0.025	23.6	268.0	46.6	51
G1 C3	20-40	4.33	5.7	41.0	0.033	12.6	80.0	40.3	48
G1 C3	40-60	4.59	4.6	29.8	0.025	49.3	64.0	48.9	52.1
G1 C3	60-80	4.28	23.4	67.5	0.016	74.8	25.0	48.3	59.4

Table 4 continues

	Depth	pH	Acidity	Acid saturation	EC	Mg	Ca	K	Na
Treatment	cm		mmolc/kg	%	mS/cm	mg/kg			
G1 L0	0-20	4.11	7.7	59.1	0.040	4	71.0	35.2	12.2
G1 L0	20-40	4.14	8.0	55.2	0.074	4	99.0	30.2	10.2
G1 L0	40-60	4.62	2.6	16.7	0.112	11	218.0	25.8	10.5
G1 L0	60-80	4.28	13.9	62.3	0.036	49	53.0	31.7	20
G1 L0	0-20	4.06	2.5	29.2	0.047	6.3	86.0	31.7	11.1
G1 L0	20-40	4.21	4.9	36.3	0.065	5.4	142.0	23.7	10.9
G1 L0	40-60	4.32	4.8	32.8	0.097	11.3	157.0	20.6	10.2
G1 L0	60-80	4.54	3.8	32.4	0.040	24.2	95.0	23.6	13.2
G1 L0	0-20	3.97	8.6	53.3	0.027	5.9	75.0	39.9	53
G1 L0	20-40	4.04	8.8	57.4	0.030	4.7	62.0	36.7	47.8
G1 L0	40-60	4.34	4.7	29.9	0.041	20.5	105.0	58.9	60
G1 L0	60-80	4.15	14.4	61.1	0.043	40.4	31.0	70.5	56
G1 L1	0-20	4.19	5.8	35.2	0.031	7.1	133.0	107.9	13.5
G1 L1	20-40	4.11	7.9	46.0	0.056	5.1	96.0	133.6	14.1
G1 L1	40-60	4.39	3.4	14.1	0.057	40.3	236.0	177.8	17.7
G1 L1	60-80	4.23	14.8	62.4	0.046	35.3	44.0	110.9	21.6
G1 L1	0-20	4.12	5.0	27.1	0.042	7.4	144.0	124.1	58.2
G1 L1	20-40	4.1	7.8	37.9	0.088	7.5	146.0	109.7	46.9
G1 L1	40-60	4.27	5.7	24.7	0.075	28.6	146.0	178.5	69.7
G1 L1	60-80	4.51	4.4	21.5	0.027	51.3	59.0	227.5	68.5
G1 L1	0-20	4.1	6.4	35.5	0.044	8.4	126.0	64.3	67.4
G1 L1	20-40	4.07	6.7	38.6	0.045	11.2	131.0	60.5	36.7
G1 L1	40-60	4.23	5.7	41.3	0.046	20.6	76.0	52.5	29.4
G1 L1	60-80	4.46	7.3	37.1	0.050	59.4	63.0	74.1	53.5
G1 L2	0-20	4.21	3.3	22.6	0.026	9.2	141.0	65	40.4
G1 L2	20-40	4.08	4.3	29.9	0.064	7.3	132.0	34.1	46.7
G1 L2	40-60	4.13	6.6	43.2	0.053	14.6	83.0	54.5	45.6
G1 L2	60-80	4.33	8.0	37.8	0.045	51.7	70.0	122.7	52.7
G1 L2	0-20	4.19	4.9	30.3	0.049	23.6	101.0	67	59.3
G1 L2	20-40	4.04	6.7	40.7	0.052	11.1	101.0	43.9	60.8
G1 L2	40-60	4.13	4.3	27.9	0.029	8.2	134.0	54.5	52.1
G1 L2	60-80	4.08	8.8	43.5	0.038	50.1	50.0	90.8	57.1
G1 L2	0-20	4.13	6.2	27.9	0.048	11.8	173.0	102.3	85.7
G1 L2	20-40	4.09	7.0	37.8	0.053	14.4	91.0	104.3	71.7
G1 L2	40-60	4.15	8.2	37.9	0.028	21.6	72.0	196.1	68.3
G1 L2	60-80	4.24	6.1	29.2	0.040	31.1	81.0	173.8	83.2
G1 L3	0-20	4.45	2.9	15.1	0.037	12.8	236.0	51.5	47.1
G1 L3	20-40	4.13	12.6	56.4	0.054	8	113.0	45.5	52.7
G1 L3	40-60	4.23	6.2	32.4	0.059	18.9	158.0	104.4	15.5
G1 L3	60-80	4.32	15.6	59.0	0.061	35	77.0	60	58.6
G1 L3	0-20	4.87	1.8	10.5	0.026	15.7	247.0	54.7	15.8
G1 L3	20-40	4.12	6.2	49.5	0.043	6.9	72.0	55.3	17.6
G1 L3	40-60	4.51	4.5	33.7	0.024	26.7	86.0	65.2	15.9
G1 L3	60-80	4.16	15.6	71.9	0.017	30.5	16.0	64.9	25
G1 L3	0-20	4.42	3.4	19.9	0.028	12.3	193.0	51.1	42.4
G1 L3	20-40	4.14	7.2	44.7	0.053	8.5	95.0	48.6	49.6
G1 L3	40-60	4.38	7.4	39.1	0.030	39.9	72.0	87	55
G1 L3	60-80	4.32	13.3	60.6	0.042	40.6	21.0	85.7	46.5

Table 5: Water soluble ions (Mg, Ca, K, Na, Cl, NO_3^- and SO_4^{2-}) for June 2009 – two years after treatment application

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	SO_4
Treatment	Depth (cm)	mg/kg						
G0 A0	0-20	2.0	11.9	14.6	8.9	16.9	106.4	161.0
G0 A0	20-40	2.0	11.2	14.7	5.1	17.9	65.9	208.4
G0 A0	40-60	8.6	25.3	19.7	7.1	16.9	70.2	262.9
G0 A0	60-80	14.5	21.3	39.0	9.2	16.2	13.6	126.1
G0 A0	0-20	1.5	11.0	12.5	5.4	64.2	195.8	40.6
G0 A0	20-40	6.8	34.0	36.7	6.7	36.4	85.3	374.8
G0 A0	40-60	14.2	30.4	24.0	11.2	34.9	236.4	163.9
G0 A0	60-80	20.2	13.1	48.4	5.9	24.5	262.3	38.6
G0 A0	0-20	2.9	13.2	18.4	4.9	20.3	17.8	170.9
G0 A0	20-40	3.3	11.9	22.5	3.8	28.6	82.4	166.7
G0 A0	40-60	4.7	15.9	26.9	3.1	29.2	91.8	126.4
G0 A0	60-80	4.3	7.0	10.5	12.0	29.7	81.8	11.5
G0 A1	0-20	2.4	9.5	22.8	5.4	35.7	10.8	233.3
G0 A1	20-40	3.1	16.5	19.4	5.2	38.0	2.0	301.5
G0 A1	40-60	3.4	10.5	6.9	3.9	46.7	9.6	235.0
G0 A1	60-80	4.4	8.1	9.1	6.6	85.1	73.5	130.5
G0 A1	0-20	3.3	14.6	26.0	7.6	31.8	9.8	161.3
G0 A1	20-40	5.1	19.7	13.6	11.9	34.8	6.8	93.0
G0 A1	40-60	4.4	14.7	9.6	8.1	30.9	74.1	160.8
G0 A1	60-80	6.0	17.4	15.8	26.6	17.1	63.8	118.3
G0 A1	0-20	2.6	14.0	11.3	3.6	21.0	12.2	217.1
G0 A1	20-40	2.6	11.1	13.2	4.1	18.6	6.0	179.2
G0 A1	40-60	5.2	12.1	18.0	4.2	26.4	47.5	164.4
G0 A1	60-80	4.5	4.9	38.0	7.2	19.0	110.6	27.6
G0 A2	0-20	1.9	10.6	24.6	7.6	25.9	21.9	174.3
G0 A2	20-40	1.9	9.8	16.4	8.1	24.0	4.2	264.0
G0 A2	40-60	3.4	11.8	10.0	4.7	12.9	6.3	251.1
G0 A2	60-80	3.9	9.5	24.5	11.1	24.6	68.5	5.6
G0 A2	0-20	1.9	10.2	12.0	3.3	20.3	19.3	52.8
G0 A2	20-40	3.8	19.3	11.8	6.6	22.5	0.0	265.2
G0 A2	40-60	3.3	7.3	6.6	8.1	24.1	13.6	163.9
G0 A2	60-80	1.6	3.1	4.8	13.3	18.8	44.3	46.4
G0 A2	0-20	3.7	23.6	26.5	10.0	35.5	17.5	168.6
G0 A2	20-40	6.0	21.4	19.8	11.8	29.0	18.5	293.5
G0 A2	40-60	6.1	19.3	14.8	11.2	30.5	64.5	233.5
G0 A2	60-80	9.0	15.4	9.5	12.8	42.0	94.6	158.3
G0 A3	0-20	2.2	13.3	7.9	6.5	26.3	0.0	245.0
G0 A3	20-40	4.3	20.2	17.5	6.1	22.2	0.0	367.5
G0 A3	40-60	4.5	18.9	19.9	6.2	23.2	7.9	343.8
G0 A3	60-80	8.5	10.6	17.9	6.6	25.7	78.9	208.9
G0 A3	0-20	2.7	15.8	9.2	6.2	21.6	5.4	198.4
G0 A3	20-40	2.9	20.5	11.2	6.3	16.1	0.0	304.1
G0 A3	40-60	4.6	11.2	5.1	13.5	30.7	62.8	98.8
G0 A3	60-80	0.8	3.4	3.2	41.1	46.0	79.3	34.4
G0 A3	0-20	3.9	13.9	11.7	4.5	27.1	26.9	188.1
G0 A3	20-40	8.6	19.5	32.8	3.5	14.2	9.2	288.8
G0 A3	40-60	10.0	34.7	18.2	9.9	37.6	25.0	316.9
G0 A3	60-80	22.4	22.4	4.9	4.8	32.8	210.3	71.3

Table 5 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO3	SO4
Treatment	Depth (cm)	mg/kg						
G0 C0	0-20	1.3	8.8	19.4	14.0	18.6	24.9	203.7
G0 C0	20-40	2.3	18.1	33.4	5.3	24.0	68.5	184.1
G0 C0	40-60	10.0	26.8	50.7	7.0	28.1	270.8	63.6
G0 C0	60-80	10.4	18.4	25.5	10.2	30.3	233.9	32.0
G0 C0	0-20	2.5	13.8	12.9	5.8	18.0	16.0	60.0
G0 C0	20-40	4.8	18.1	19.8	8.6	22.0	6.4	254.0
G0 C0	40-60	8.2	24.4	14.6	6.9	23.0	135.0	137.0
G0 C0	60-80	17.4	32.8	9.3	7.6	22.0	307.0	32.0
G0 C0	0-20	2.7	14.8	17.3	8.3	19.6	0.0	230.7
G0 C0	20-40	3.7	17.6	21.7	6.6	20.1	8.4	361.0
G0 C0	40-60	10.4	26.8	39.3	6.9	39.8	180.5	196.1
G0 C0	60-80	19.1	22.6	27.3	6.3	23.8	282.3	53.8
G0 C1	0-20	2.6	12.8	14.5	7.6	22.6	29.6	151.7
G0 C1	20-40	2.8	16.7	14.2	6.3	15.9	12.9	303.0
G0 C1	40-60	4.1	16.3	13.5	6.9	16.5	47.0	227.4
G0 C1	60-80	15.4	26.5	14.4	7.1	22.8	245.8	23.1
G0 C1	0-20	3.7	21.7	15.8	6.7	21.8	30.1	163.3
G0 C1	20-40	4.8	20.2	13.8	6.5	19.5	0.0	343.6
G0 C1	40-60	6.8	11.4	21.3	6.7	26.6	63.6	194.5
G0 C1	60-80	4.1	4.4	27.2	7.5	24.4	79.1	39.8
G0 C1	0-20	3.1	15.9	12.2	6.4	23.7	10.2	157.6
G0 C1	20-40	4.4	16.4	20.0	6.2	23.0	9.7	284.7
G0 C1	40-60	9.0	22.2	24.5	6.0	33.3	142.7	178.1
G0 C1	60-80	17.9	12.2	52.1	5.8	22.8	255.7	31.9
G0 C2	0-20	3.0	13.9	11.8	7.3	18.9	20.0	119.8
G0 C2	20-40	4.4	16.4	15.5	5.4	12.9	11.2	237.4
G0 C2	40-60	2.8	4.4	13.3	8.3	17.7	45.9	66.1
G0 C2	60-80	2.4	2.9	7.7	9.5	17.1	47.4	21.3
G0 C2	0-20	2.3	10.5	12.1	7.1	22.9	0.0	42.9
G0 C2	20-40	3.5	12.5	19.9	5.8	14.3	6.5	224.5
G0 C2	40-60	4.1	7.2	21.2	6.6	24.2	30.8	179.0
G0 C2	60-80	9.3	6.6	37.6	8.8	21.1	134.6	30.9
G0 C2	0-20	2.4	9.2	25.3	6.7	29.2	32.9	90.1
G0 C2	20-40	4.0	15.2	11.9	5.3	16.5	0.0	231.2
G0 C2	40-60	5.0	14.0	9.8	7.1	26.5	19.8	141.0
G0 C2	60-80	10.9	12.5	19.0	7.7	25.5	144.3	71.5
G0 C3	0-20	6.5	21.1	7.0	3.6	24.9	1.9	62.1
G0 C3	20-40	9.4	26.9	21.6	3.5	16.0	4.0	431.3
G0 C3	40-60	7.6	16.7	16.2	4.2	31.8	84.0	164.5
G0 C3	60-80	18.4	11.6	25.7	4.9	22.8	233.9	4.9
G0 C3	0-20	5.4	20.5	32.5	3.4	32.9	11.6	22.3
G0 C3	20-40	6.2	22.9	52.2	5.5	25.6	55.3	213.5
G0 C3	40-60	12.6	26.1	54.9	3.4	24.5	8.4	437.5
G0 C3	60-80	5.1	13.5	35.8	3.2	20.6	126.4	60.9
G0 C3	0-20	7.9	29.0	13.1	10.8	21.0	10.7	42.6
G0 C3	20-40	17.4	42.5	12.6	11.1	26.0	6.3	430.0
G0 C3	40-60	13.8	41.1	16.2	9.7	22.0	5.3	406.4
G0 C3	60-80	4.3	9.2	3.7	11.7	22.1	14.7	185.3

Table 5 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	SO_4
Treatment	Depth (cm)	mg/kg						
G0 L0	0-20	1.7	16.8	11.0	6.6	15.0	25.0	270.0
G0 L0	20-40	2.3	21.8	19.8	5.6	15.0	73.0	370.0
G0 L0	40-60	4.6	29.3	23.5	7.0	20.0	147.0	218.0
G0 L0	60-80	24.4	47.7	15.1	10.0	24.0	425.0	64.0
G0 L0	0-20	2.1	16.3	9.4	4.0	20.3	45.4	177.4
G0 L0	20-40	3.2	20.5	18.9	7.0	26.8	16.0	360.4
G0 L0	40-60	6.2	20.2	18.5	5.8	28.3	90.4	232.1
G0 L0	60-80	11.4	21.3	16.9	7.5	28.9	178.5	92.9
G0 L0	0-20	3.2	15.2	17.6	10.6	28.8	50.2	201.6
G0 L0	20-40	5.2	17.0	23.3	7.9	15.9	43.5	97.4
G0 L0	40-60	13.6	35.4	19.7	8.2	26.4	210.8	107.0
G0 L0	60-80	18.6	24.6	17.2	8.4	29.0	203.6	63.6
G0 L1	0-20	1.7	11.2	24.0	7.2	32.0	18.0	187.0
G0 L1	20-40	2.4	18.6	24.2	7.4	21.0	10.0	353.0
G0 L1	40-60	6.4	12.6	22.4	7.9	26.0	118.0	54.0
G0 L1	60-80	7.8	5.8	17.4	18.5	19.0	149.0	32.0
G0 L1	0-20	2.4	14.2	49.1	4.2	103.0	0.0	262.2
G0 L1	20-40	2.2	12.0	11.7	3.7	40.4	0.0	281.0
G0 L1	40-60	15.3	22.8	39.4	4.5	53.2	202.2	107.0
G0 L1	60-80	14.3	7.2	18.0	8.5	16.6	186.1	11.7
G0 L1	0-20	2.2	9.9	32.2	6.3	20.9	24.5	434.0
G0 L1	20-40	3.9	19.8	14.2	6.1	23.0	183.3	54.9
G0 L1	40-60	3.5	10.8	12.5	5.8	40.8	3.1	314.9
G0 L1	60-80	7.3	10.5	29.5	6.5	3.0	0.0	8.0
G0 L2	0-20	1.9	13.9	12.3	8.8	23.2	14.3	128.8
G0 L2	20-40	6.2	28.0	13.6	6.9	24.3	11.2	285.1
G0 L2	40-60	5.1	13.9	19.5	5.4	26.7	65.5	152.9
G0 L2	60-80	10.3	7.7	41.8	11.4	25.4	164.1	47.7
G0 L2	0-20	2.2	18.7	12.3	5.9	17.8	16.9	143.7
G0 L2	20-40	2.3	14.1	9.6	6.9	18.5	12.1	198.2
G0 L2	40-60	14.3	21.7	14.8	11.3	28.5	210.9	51.9
G0 L2	60-80	7.9	5.9	4.9	9.9	16.1	84.1	35.5
G0 L2	0-20	2.5	20.5	14.7	4.0	21.0	21.7	40.7
G0 L2	20-40	4.8	24.3	22.6	4.5	21.7	16.6	282.1
G0 L2	40-60	5.5	14.4	19.7	2.8	15.6	82.7	170.0
G0 L2	60-80	18.6	17.8	30.3	4.0	29.4	238.8	17.5
G0 L3	0-20	2.8	25.4	8.8	6.1	23.5	20.5	106.7
G0 L3	20-40	4.5	29.9	12.6	7.1	24.6	0.0	352.7
G0 L3	40-60	5.6	13.5	8.1	8.1	28.7	5.2	241.0
G0 L3	60-80	4.4	10.4	5.3	8.5	28.9	10.4	161.0
G0 L3	0-20	2.9	19.7	9.2	7.2	28.9	30.5	109.9
G0 L3	20-40	2.0	10.5	12.1	7.4	40.2	4.9	262.1
G0 L3	40-60	5.3	15.9	17.1	3.8	22.0	83.1	161.0
G0 L3	60-80	5.8	13.2	10.7	4.5	18.8	105.7	36.9
G0 L3	0-20	3.3	20.4	10.6	4.2	21.1	18.4	152.4
G0 L3	20-40	5.2	34.0	10.4	4.1	19.0	6.0	350.4
G0 L3	40-60	5.7	23.8	6.5	3.9	17.0	19.7	291.9
G0 L3	60-80	11.0	12.6	17.2	5.9	27.5	132.7	49.5

Table 5 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	SO_4
Treatment	Depth (cm)	mg/kg						
G1 A0	0-20	1.5	16.2	18.9	6.9	20.0	12.0	275.0
G1 A0	20-40	2.0	29.2	16.5	6.6	14.0	13.0	399.0
G1 A0	40-60	5.1	50.9	23.9	7.2	14.0	9.0	482.0
G1 A0	60-80	10.6	16.0	28.1	9.7	20.0	182.0	17.0
G1 A0	0-20	2.2	31.0	24.2	7.8	31.7	0.0	324.9
G1 A0	20-40	5.0	19.6	11.9	7.7	19.3	20.4	318.4
G1 A0	40-60	6.3	5.2	9.3	11.6	19.8	88.7	73.5
G1 A0	60-80	3.7	4.4	4.8	10.7	27.0	50.5	50.1
G1 A0	0-20	2.9	27.5	10.1	3.8	19.3	31.5	364.0
G1 A0	20-40	2.7	29.9	26.3	6.1	29.6	31.5	211.0
G1 A0	40-60	9.3	47.6	22.8	7.1	23.1	220.6	230.2
G1 A0	60-80	29.7	51.3	19.9	6.4	30.9	483.7	64.8
G1 A1	0-20	1.7	18.5	13.4	6.8	25.0	0.0	382.2
G1 A1	20-40	5.2	34.7	7.6	6.6	19.1	3.4	294.2
G1 A1	40-60	4.1	5.6	24.8	8.3	23.5	82.7	53.5
G1 A1	60-80	2.0	3.7	10.6	8.8	23.6	26.2	37.6
G1 A1	0-20	3.5	42.0	25.7	4.1	23.4	36.6	362.0
G1 A1	20-40	4.1	68.0	11.8	3.9	14.6	8.4	426.1
G1 A1	40-60	18.6	72.4	8.5	3.9	15.2	15.1	531.7
G1 A1	60-80	12.5	10.6	21.0	5.8	38.9	118.9	76.5
G1 A1	0-20	2.6	27.5	109.4	7.8	125.9	18.5	293.9
G1 A1	20-40	5.2	64.8	18.2	6.6	18.2	47.9	455.9
G1 A1	40-60	8.0	22.7	18.7	7.5	22.8	45.7	261.5
G1 A1	60-80	0.6	2.7	4.5	17.9	17.4	42.1	7.2
G1 A2	0-20	1.7	18.9	17.4	9.4	26.3	13.1	267.5
G1 A2	20-40	1.9	23.4	156.7	7.8	18.1	8.1	347.1
G1 A2	40-60	6.5	29.8	20.0	6.5	16.6	90.5	265.0
G1 A2	60-80	15.0	40.1	21.7	6.4	18.2	319.5	29.2
G1 A2	0-20	2.6	31.6	26.6	10.2	20.2	24.5	447.8
G1 A2	20-40	2.3	23.4	10.9	8.6	40.6	3.5	326.5
G1 A2	40-60	5.7	28.6	11.3	6.9	30.1	0.0	318.6
G1 A2	60-80	5.6	5.1	15.1	6.5	19.7	29.5	210.3
G1 A2	0-20	1.8	10.8	29.7	12.2	45.2	17.6	173.2
G1 A2	20-40	2.8	30.5	23.1	11.1	29.9	13.1	344.9
G1 A2	40-60	6.2	29.0	16.9	10.1	28.1	51.7	295.2
G1 A2	60-80	2.9	4.6	12.5	23.4	27.2	92.3	63.7
G1 A3	0-20	1.8	20.9	10.6	6.8	25.0	14.0	217.0
G1 A3	20-40	4.1	27.9	22.4	6.6	17.5	4.9	265.8
G1 A3	40-60	1.5	3.7	5.6	15.5	28.3	23.2	204.0
G1 A3	60-80	4.2	9.0	15.8	11.3	16.5	56.0	41.4
G1 A3	0-20	1.9	16.9	7.1	6.3	26.0	0.0	132.2
G1 A3	20-40	2.3	26.3	6.1	5.5	21.6	14.0	224.9
G1 A3	40-60	3.6	8.3	5.4	7.5	20.1	32.5	88.2
G1 A3	60-80	1.4	3.3	6.1	14.2	18.1	28.0	20.4
G1 A3	0-20	3.5	25.0	10.2	4.5	18.9	49.4	711.4
G1 A3	20-40	3.5	26.3	11.8	5.1	23.1	4.0	318.0
G1 A3	40-60	9.2	32.8	17.4	4.3	19.6	2.4	408.4
G1 A3	60-80	4.9	6.7	20.3	10.6	21.6	96.4	33.5

Table 5 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	SO_4
Treatment	Depth (cm)	mg/kg						
G1 C0	0-20	2.1	24.1	11.6	9.9	20.0	19.0	292.0
G1 C0	20-40	1.8	14.7	12.6	5.9	15.0	20.0	290.0
G1 C0	40-60	4.7	32.7	7.5	8.1	17.0	46.0	281.0
G1 C0	60-80	14.5	12.7	7.5	10.4	22.0	203.0	45.0
G1 C0	0-20	2.9	16.7	15.0	4.8	26.1	4.1	99.2
G1 C0	20-40	5.0	23.0	22.0	3.6	15.8	6.8	312.8
G1 C0	40-60	6.8	10.3	16.5	3.7	17.6	87.3	119.6
G1 C0	60-80	1.2	3.0	14.1	14.9	17.8	63.1	22.5
G1 C0	0-20	2.7	38.4	13.5	4.2	26.0	14.8	338.7
G1 C0	20-40	4.2	51.1	17.2	4.0	17.2	3.2	466.3
G1 C0	40-60	8.3	51.1	20.6	4.1	17.1	10.3	491.2
G1 C0	60-80	1.6	5.6	14.5	4.7	18.2	15.0	31.4
G1 C1	0-20	1.4	13.4	15.7	7.6	20.6	16.3	204.1
G1 C1	20-40	4.3	51.8	18.3	6.4	14.6	12.4	470.2
G1 C1	40-60	16.3	45.3	16.5	7.8	21.7	231.8	223.5
G1 C1	60-80	27.7	36.0	10.4	12.8	24.4	389.2	38.3
G1 C1	0-20	2.8	21.8	9.5	6.3	13.9	31.6	291.5
G1 C1	20-40	2.4	20.9	9.3	7.1	15.8	8.5	194.6
G1 C1	40-60	5.8	25.1	5.3	6.6	15.3	6.8	279.2
G1 C1	60-80	7.6	7.8	14.9	8.9	14.8	112.9	63.6
G1 C1	0-20	2.4	19.9	28.7	3.7	39.1	33.6	238.5
G1 C1	20-40	2.7	26.7	21.2	3.2	16.8	4.1	345.5
G1 C1	40-60	6.5	37.3	27.8	3.6	19.4	102.8	327.3
G1 C1	60-80	17.1	16.3	12.5	3.9	27.8	184.1	11.5
G1 C2	0-20	3.8	26.2	10.6	6.1	28.6	42.0	157.5
G1 C2	20-40	3.8	35.6	12.1	6.5	28.0	40.0	191.0
G1 C2	40-60	5.9	50.5	15.8	19.9	15.0	15.0	198.0
G1 C2	60-80	8.6	25.6	5.2	5.9	27.0	150.0	86.0
G1 C2	0-20	2.0	15.9	10.8	5.5	17.7	0.0	140.0
G1 C2	20-40	3.4	32.8	8.3	6.3	23.5	0.0	338.3
G1 C2	40-60	14.8	22.5	8.3	6.2	19.3	24.6	451.1
G1 C2	60-80	13.0	16.3	18.8	8.3	21.9	182.4	67.0
G1 C2	0-20	5.4	74.0	13.8	3.8	18.0	24.8	478.5
G1 C2	20-40	13.8	72.7	44.3	6.8	42.3	36.6	605.4
G1 C2	40-60	15.4	44.4	74.3	6.2	79.3	70.5	427.6
G1 C2	60-80	9.8	27.0	8.4	5.1	20.0	161.1	37.1
G1 C3	0-20	3.6	24.4	7.5	5.2	16.0	15.0	215.0
G1 C3	20-40	5.6	49.9	12.9	6.4	16.0	6.0	477.0
G1 C3	40-60	14.8	38.3	18.1	7.7	19.0	11.0	438.0
G1 C3	60-80	19.9	13.0	37.6	9.5	35.0	272.0	70.0
G1 C3	0-20	4.4	20.4	7.9	7.6	28.5	0.0	102.1
G1 C3	20-40	4.3	30.2	12.7	6.4	20.4	2.7	374.3
G1 C3	40-60	14.7	28.7	5.8	6.6	21.9	0.0	370.5
G1 C3	60-80	8.9	3.8	26.9	10730.0	21.0	139.5	55.3
G1 C3	0-20	4.6	24.0	5.8	3.0	13.1	35.5	79.7
G1 C3	20-40	7.3	7.5	8.1	5.6	12.4	4.5	318.1
G1 C3	40-60	5.3	23.8	7.4	3.4	14.3	90.7	38.5
G1 C3	60-80	2.9	3.7	3.8	9.5	16.3	44.4	9.3

Table 5 continues…

Water soluble ions		Mg	Ca	K	Na	Cl	NO_3	SO_4
Treatment	Depth (cm)	mg/kg						
G1 L0	0-20	1.7	25.5	16.9	7.9	28.0	20.0	345.0
G1 L0	20-40	2.1	69.1	17.1	10.0	23.0	41.0	533.0
G1 L0	40-60	7.4	133.5	11.4	8.6	31.0	54.0	761.0
G1 L0	60-80	4.5	9.6	5.5	17.4	23.0	99.0	20.0
G1 L0	0-20	2.8	32.8	13.3	6.6	24.0	28.0	350.0
G1 L0	20-40	3.4	67.3	9.4	7.4	17.0	10.0	511.0
G1 L0	40-60	8.4	101.6	6.8	7.6	19.0	8.0	703.0
G1 L0	60-80	5.3	16.7	6.3	14.8	43.0	61.0	244.0
G1 L0	0-20	1.7	18.3	13.8	5.7	19.3	0.0	221.2
G1 L0	20-40	2.1	28.3	18.0	5.6	15.7	0.0	367.8
G1 L0	40-60	6.9	24.2	27.4	7.3	22.9	22.9	322.1
G1 L0	60-80	8.8	6.0	20.2	27.6	29.1	158.6	33.1
G1 L1	0-20	2.2	28.6	9.1	7.0	28.7	1.3	262.0
G1 L1	20-40	2.9	57.7	11.5	5.4	17.7	0.0	468.0
G1 L1	40-60	12.6	46.6	6.4	9.1	27.0	10.2	461.0
G1 L1	60-80	12.4	13.4	5.8	16.4	32.3	154.6	53.7
G1 L1	0-20	3.2	35.3	19.6	4.5	27.2	34.3	275.2
G1 L1	20-40	5.8	91.6	21.1	4.2	18.4	8.8	645.6
G1 L1	40-60	15.9	57.4	15.8	4.0	17.7	30.9	521.9
G1 L1	60-80	18.9	14.1	9.1	8.0	23.5	185.6	32.7
G1 L1	0-20	2.4	26.2	12.7	6.9	23.1	26.7	227.4
G1 L1	20-40	7.9	76.6	160.5	8.3	182.9	8.9	505.5
G1 L1	40-60	10.9	29.1	11.5	6.7	20.2	78.0	285.7
G1 L1	60-80	19.4	14.4	11.8	18.8	33.7	216.4	43.7
G1 L2	0-20	2.2	20.9	19.1	6.9	20.4	33.3	80.8
G1 L2	20-40	4.0	70.1	13.2	6.3	19.0	27.6	4.2
G1 L2	40-60	7.3	35.9	22.6	7.1	18.4	0.0	125.6
G1 L2	60-80	10.6	12.7	42.1	5.9	22.4	0.0	339.1
G1 L2	0-20	8.6	26.5	29.9	4.0	16.7	4.1	425.9
G1 L2	20-40	5.7	37.4	19.5	4.5	19.6	8.0	443.5
G1 L2	40-60	2.2	15.2	17.7	4.2	20.4	40.0	148.7
G1 L2	60-80	10.3	7.2	34.8	4.4	23.8	146.4	57.4
G1 L2	0-20	2.7	25.1	17.5	10.5	29.8	29.2	263.8
G1 L2	20-40	6.3	27.0	30.0	11.1	26.7	8.3	388.7
G1 L2	40-60	11.6	24.8	76.1	11.3	28.1	8.6	498.7
G1 L2	60-80	8.1	15.3	64.0	10.8	25.6	10.9	269.4
G1 L3	0-20	2.4	25.4	8.0	6.3	17.2	36.9	169.1
G1 L3	20-40	3.8	50.3	10.8	7.0	12.9	8.1	438.3
G1 L3	40-60	7.9	52.9	10.6	5.8	12.3	18.6	412.7
G1 L3	60-80	15.5	28.3	16.2	12.8	22.4	268.0	67.2
G1 L3	0-20	2.8	23.7	7.4	7.0	11.4	5.1	57.1
G1 L3	20-40	3.4	33.7	13.0	8.2	10.3	6.0	146.4
G1 L3	40-60	4.1	12.8	10.5	7.2	10.9	37.9	65.5
G1 L3	60-80	1.3	2.5	6.6	17.0	16.4	59.0	18.5
G1 L3	0-20	2.3	17.7	18.2	8.3	35.1	10.1	165.0
G1 L3	20-40	4.5	42.9	14.3	8.8	29.7	0.0	422.5
G1 L3	40-60	8.2	10.3	39.9	6.8	48.2	48.0	225.8
G1 L3	60-80	12.3	4.5	41.0	6.1	16.2	167.4	53.0

Table 6: Foliar Ca, Mg, and K concentration and yield data for beans (2008) and foliar Ca, Mg, K and Zn concentration and yield data for maize (2009)

	Beans				Maize				
	Ca	Mg	K	Yield	Ca	Mg	K	Zn	Yield
Treatment	%			kg/ha	%			mg/kg	kg/ha
G0 A0	12.5	2.6	20.1	1152.9	4.2	0.9	16.0	56.5	4548.5
G0 A0	8.3	2.1	20.5	460.7	7.6	1.7	16.7	32.0	7253.9
G0 A0	10.0	2.0	26.5	1016.3	5.0	1.1	16.9	50.0	7000.2
G0 A1	12.1	2.5	24.8	1257.0	6.8	2.0	15.7	60.0	7338.4
G0 A1	13.4	2.4	24.9	1264.0	6.4	1.7	15.5	48.5	6966.4
G0 A1	10.2	1.9	17.1	1152.9	6.6	1.2	16.3	73.5	6036.4
G0 A2	11.8	2.7	24.8	1310.3	5.8	1.6	16.8	58.0	8217.7
G0 A2	14.2	3.0	17.8	1490.9	10.8	1.5	16.7	46.5	7034.0
G0 A2	8.6	2.0	22.4	1444.6	5.7	1.4	14.7	64.5	8386.7
G0 A3	12.1	2.2	20.5	1275.6	5.1	1.6	16.1	40.5	7439.9
G0 A3	16.4	2.7	20.0	1812.6	5.2	1.4	14.5	62.5	7051.0
G0 A3	14.8	3.1	28.5	2083.5	5.8	1.7	16.2	42.0	8166.9
G0 C0	8.2	2.7	24.1	740.8	4.3	1.1	16.8	51.0	5157.2
G0 C0	12.7	3.0	26.7	1194.5	5.1	1.7	17.5	64.5	6611.3
G0 C0	8.3	1.9	21.0	988.5	5.6	1.3	15.2	49.0	5191.0
G0 C1	14.8	3.0	19.6	1426.0	7.0	1.9	14.4	68.0	6577.5
G0 C1	16.2	3.8	27.7	1389.0	6.2	1.8	17.4	63.5	7034.0
G0 C1	13.0	2.8	22.9	1326.5	6.1	1.5	16.3	51.5	6898.8
G0 C2	17.4	3.5	20.0	1585.8	7.9	2.6	16.6	41.0	6949.5
G0 C2	18.1	3.8	18.9	1646.0	7.0	2.2	14.6	43.5	7101.7
G0 C2	16.5	4.1	20.5	1303.3	6.8	2.3	13.9	41.0	6814.2
G0 C3	21.5	5.0	24.3	1187.6	7.3	2.5	12.9	38.0	9215.3
G0 C3	15.9	3.4	26.7	2092.8	7.6	2.6	15.9	38.5	8860.2
G0 C3	19.3	3.7	21.5	2083.5	6.6	2.2	13.2	64.0	9113.8
G0 L0	13.2	2.5	18.7	983.9	4.6	1.0	17.3	53.0	3347.9
G0 L0	10.3	2.4	23.6	1129.7	6.6	0.9	14.9	63.0	4599.2
G0 L0	9.9	1.8	27.3	953.8	5.9	1.6	15.5	54.5	6408.4
G0 L1	14.2	2.6	21.7	879.7	5.1	1.0	16.9	44.5	7507.5
G0 L1	13.0	2.3	19.5	1449.2	6.7	1.3	14.6	43.0	6239.3
G0 L1	12.8	2.9	21.6	1342.7	7.8	1.4	16.3	43.5	6915.7
G0 L2	13.1	2.6	25.5	1210.7	6.7	1.6	18.6	54.0	6966.4
G0 L2	17.0	2.7	26.8	1588.1	7.1	1.7	15.1	50.0	7135.5
G0 L2	17.1	2.0	26.6	1419.1	7.5	1.4	15.9	42.0	8133.1
G0 L3	17.7	3.0	23.9	1692.3	7.2	1.8	16.4	44.5	8065.5
G0 L3	19.5	2.8	0.0	1548.7	6.2	1.7	13.9	32.5	6577.5
G0 L3	17.7	2.3	25.0	1694.6	6.9	1.5	13.9	46.5	8369.8
G1 A0	15.5	2.7	19.0	1185.3	7.1	1.1	16.9	65.5	7608.9
G1 A0	15.7	2.4	24.9	1625.1	6.8	1.4	15.8	49.0	7220.0
G1 A0	14.2	1.6	23.7	1465.4	5.8	1.3	13.5	59.0	6171.7
G1 A1	16.7	1.9	25.4	1720.0	6.8	1.1	15.7	50.5	7592.0
G1 A1	12.5	1.5	20.5	1546.4	8.4	1.5	14.5	43.0	8133.1
G1 A1	15.5	1.7	26.3	1164.4	7.1	1.1	15.4	60.0	8724.9
G1 A2	15.8	2.0	24.3	1655.2	8.4	1.4	15.5	59.5	6865.0
G1 A2	13.6	1.7	21.9	1213.1	8.3	1.2	13.3	68.0	8758.7
G1 A2	16.7	2.1	22.2	1486.2	6.7	1.5	14.0	50.0	8099.3
G1 A3	16.2	2.7	27.7	2083.5	7.1	1.7	19.6	53.0	8708.0
G1 A3	22.0	3.1	19.4	2083.5	6.5	1.6	14.7	55.0	7862.6
G1 A3	16.9	2.5	24.2	1870.5	7.8	1.6	15.8	45.5	7659.7

Table 6 continues…

	Beans				Maize				
	Ca	Mg	K	Yield	Ca	Mg	K	Zn	Yield
Treatment	%			kg/ha	%			mg/kg	kg/ha
G1 C0	14.2	1.8	20.5	1301.0	7.6	0.9	14.9	61.5	4903.5
G1 C0	13.1	1.5	21.0	1201.5	7.8	1.1	14.5	72.5	5867.3
G1 C0	14.4	1.0	19.8	1326.5	7.7	1.4	15.7	65.0	8150.0
G1 C1	17.3	2.5	23.0	1815.0	6.3	1.4	15.9	67.5	6898.8
G1 C1	15.4	2.6	24.6	1690.0	9.1	1.7	16.8	68.0	6780.4
G1 C1	15.3	1.7	21.4	1886.7	8.5	1.4	12.5	54.0	7761.1
G1 C2	12.4	3.3	15.7	1708.5	7.9	1.9	14.5	41.5	7169.3
G1 C2	11.7	3.5	20.6	1421.4	6.9	1.7	13.1	51.5	6865.0
G1 C2	13.9	2.0	22.2	1960.8	7.2	1.7	16.7	47.0	8708.0
G1 C3	19.8	4.2	17.4	2065.0	8.2	2.9	13.8	38.0	7152.4
G1 C3	25.9	5.0	19.2	1923.8	7.9	2.7	12.9	37.5	6949.5
G1 C3	22.8	4.0	15.1	1951.5	6.7	2.5	16.2	37.5	7118.6
G1 L0	11.7	1.9	21.0	1298.7	6.4	1.0	17.1	56.5	4802.1
G1 L0	12.5	2.1	21.7	1224.6	6.5	1.9	17.5	46.0	7608.9
G1 L0	12.2	1.2	19.0	1132.0	9.9	1.0	14.7	69.0	7422.9
G1 L1	18.5	2.7	24.9	1868.2	8.0	1.7	14.4	70.0	7490.6
G1 L1	16.4	1.9	23.1	1514.0	10.1	1.4	14.4	46.0	7761.1
G1 L1	13.0	2.3	21.1	1259.4	8.1	1.3	14.4	52.5	7659.7
G1 L2	19.7	2.4	24.5	1919.1	9.2	1.8	12.5	65.5	7811.8
G1 L2	14.1	2.0	26.8	1426.0	6.8	1.6	16.2	48.0	7135.5
G1 L2	16.9	2.4	32.1	1389.0	6.5	1.5	16.8	51.5	9113.8
G1 L3	21.2	3.0	24.5	1393.6	9.6	2.0	14.6	51.5	7727.3
G1 L3	22.5	2.7	21.0	1685.3	8.6	1.8	14.9	53.5	6746.6
G1 L3	18.0	2.6	20.8	1650.6	6.4	1.9	14.9	39.0	8640.4

Table 7: Maize root length and root density description and depth of Mn lamellae layer in each plot

Treatment	Root depth (cm)	Root density	Depth of Mn layer present (cm)
G0 A0	60	Roots fine and sparse, well into C	None
G0 A0	80	Roots right down to plinthic layer	60
G0 A0	70	Roots down to D, but very fine roots in D	60
G0 A1	70	Well developed roots into D	60
G0 A1	70	Roots right down to C. Some into D	60
G0 A1	55	Roots right down to plinthic C	60
G0 A2	40	Common fine roots	60
G0 A2	30	Fine sparse roots	None
G0 A2	65	Poor root development	60
G0 A3	65	Well developed roots into D	70
G0 A3	40	Until end of B	40
G0 A3	75	Dense roots into D	No
G0 C0	30	Down to middle B	80. Fe and Mn concretions at 90cm
G0 C0	40	To middle B	None
G0 C0	60	Medium roots to C	None
G0 C1	65	Excellent roots up to C. Very few in D	60
G0 C1	80	Fine roots into D	None
G0 C1	30	Shallow roots down to B	None
G0 C2	35	Fine roots	40
G0 C2	60	Medium density	60
G0 C2	55	Shallow roots deep into C.	None
G0 C3	40	Poor root development	None
G0 C3	70	Fine and sparse into D	None
G0 C3	70	Fine and sparse	60
G0 L0	50	Poor roots	50. Carbananeous sandste present
G0 L0	70	Poor roots but well into D	None
G0 L0	75	Poor root development but well into D	80
G0 L1	40	Dense roots	None
G0 L1	50	Well developed roots into C	None
G0 L1	55	Fine roots well into C	40
G0 L2	70	No physical limitation, Roots well into D	None
G0 L2	55	Shallow roots deep into C.	None
G0 L2	60	Roots down to C	None
G0 L3	100	Fine sparse roots to E	None
G0 L3	50	Well developed roots into C	50
G0 L3	80	Dense roots into D	80
G1 A0	70	Horisontally into D. Physical impediment	70
G1 A0	40	Well developed roots	None
G1 A0	60	Well developed roots into C	None
G1 A1	75	Roots well into C and D	60
G1 A1	70	Roots down to D, but very fine roots in D	80
G1 A1	70	Roots dense	None
G1 A2	75	Densely rooted up to D	None
G1 A2	70	Deep soil and redder. Fine roots throughout D.	None
G1 A2	70	Excellent roots up well into D	70
G1 A3	55	Dense roots deep into C	None
G1 A3	55	Shallow roots deep into C.	50
G1 A3	65	Roots right down to C. Some into D	60

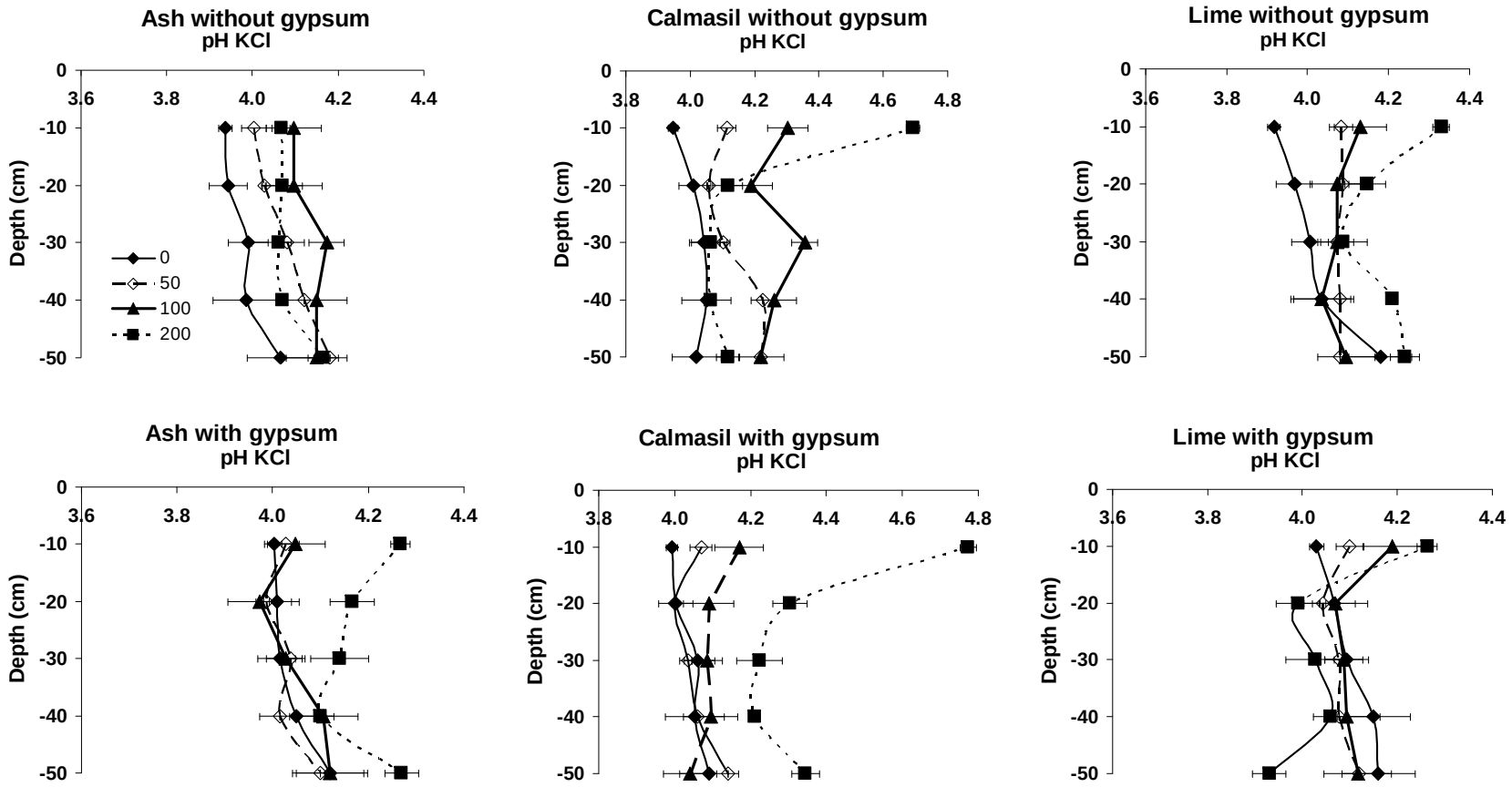
Table 7 continues…

Treatment	Root depth (cm)	Root density	Depth of Mn layer present (cm)
G1 C0	60	Only up to end of C	60
G1 C0	60	Roots well into C	60
G1 C0	70	Roots down to C	60
G1 C1	60	Excellent roots, with fine roots into hard layer	65
G1 C1	55	Excellent roots with fine roots well into C	30
G1 C1	70	Excellent roots with fine roots well into D	70
G1 C2	80	Magical dense roots into end of D	100
G1 C2	65	Magical dense roots into upper D	None
G1 C2	70	Magical dense roots into upper D	None
G1 C3	55	Fine roots to C	60
G1 C3	60	Fine roots to C	40
G1 C3	40	Shallow roots to B	30
G1 L0	60	Dense roots through into C	40
G1 L0	85	Topsoil full of maize roots	90
G1 L0	75	Abundant roots in D	40
G1 L1	100	Fine sparse roots to E	None
G1 L1	80	Dense roots into D	70
G1 L1	60	Abundant roots in C	40
G1 L2	55	Fine roots well into C	40
G1 L2	50	Fine roots right down to C. Some into D	70
G1 L2	75	Excellent roots well into D	80
G1 L3	60	Fine roots	None
G1 L3	70	Excellent roots well into D	40
G1 L3	60	Fine and sparsely common roots into B	None

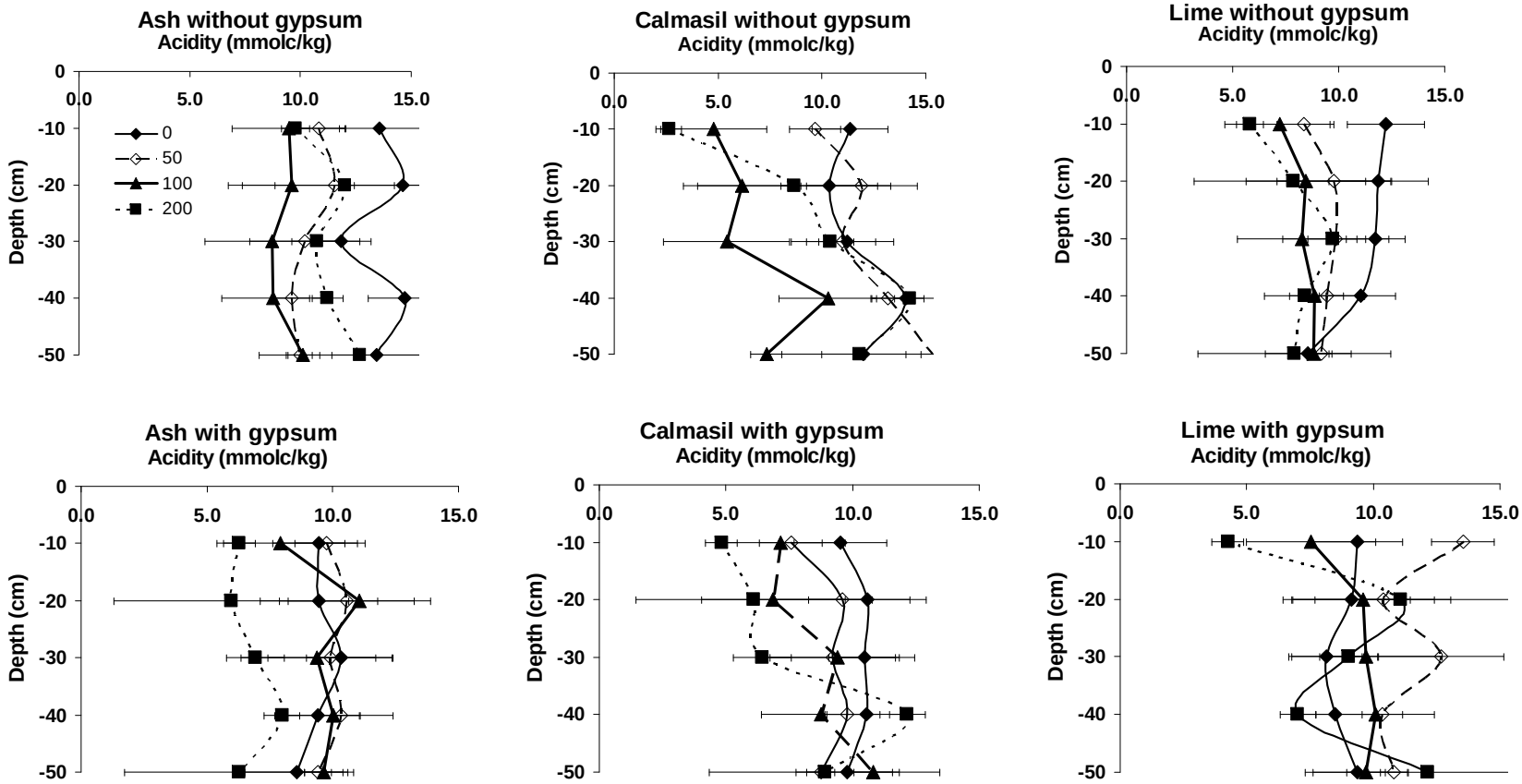
Table 8: Rainfall data for experimental site at Beestepan in Mpumalanga, South Africa in September 2007 – August 2009

Month	2007/2008 Rainfall (mm)	2008/2009 Rainfall (mm)
September	25	0
October	101	63
November	276	165
December	122	126
January	299	229
February	182	85
March	11	66
April	8	0
May	26	32
June	0	37
July	0	0
August	0	0
Annual average	1050	803

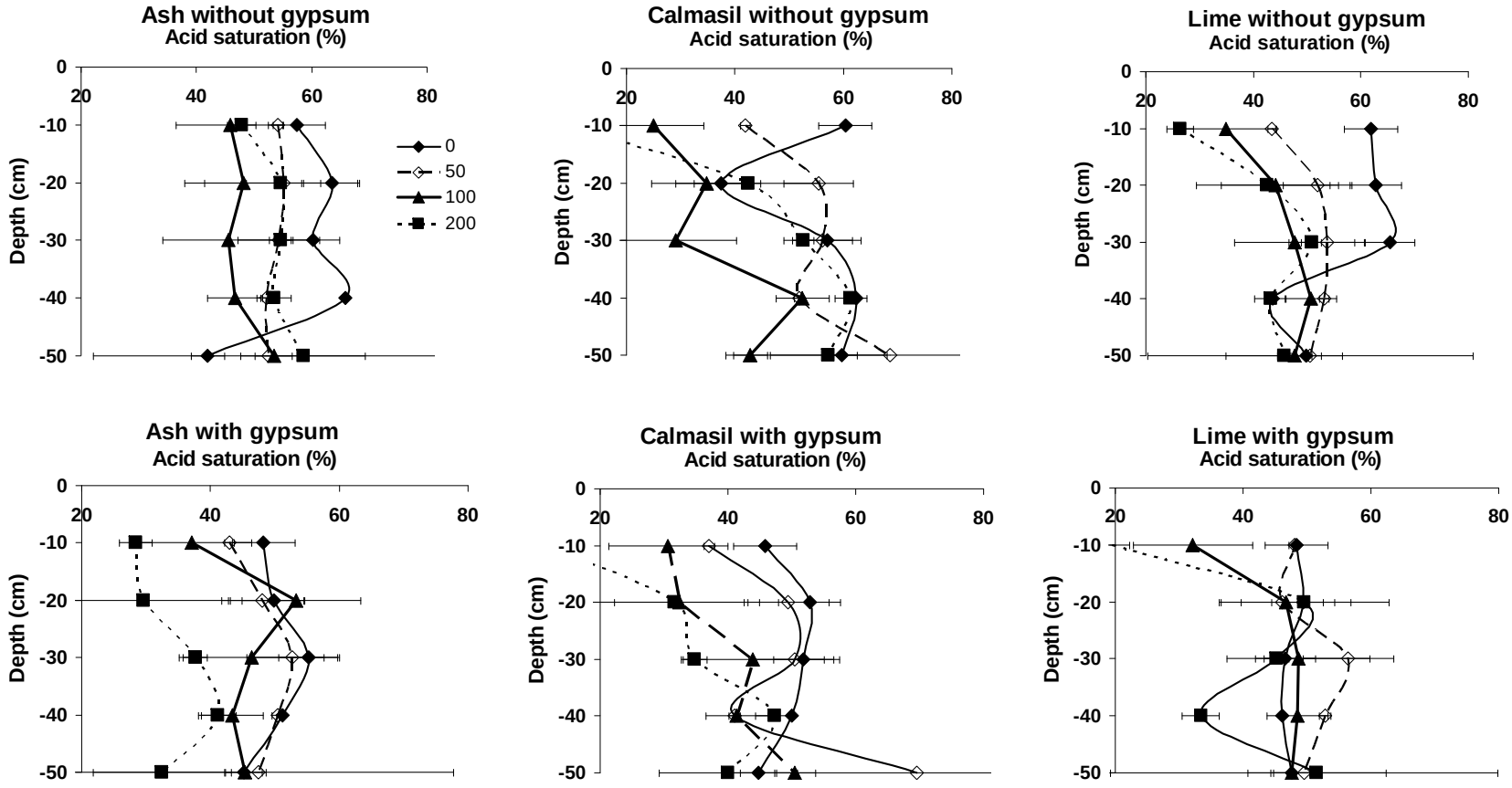
Appendix 4: Graphical representation of chemical analyses data of June 2008 soil samples
pH_{KCl}, acidity, acid saturation, extractable Ca, Mg, Na and K, water soluble Ca, Mg, Na, K, SO_4, NO_3, PO_4, Cl and EC with analytical error estimates, down the soil profile



Appendix 4 continues…



Appendix 4 continues…



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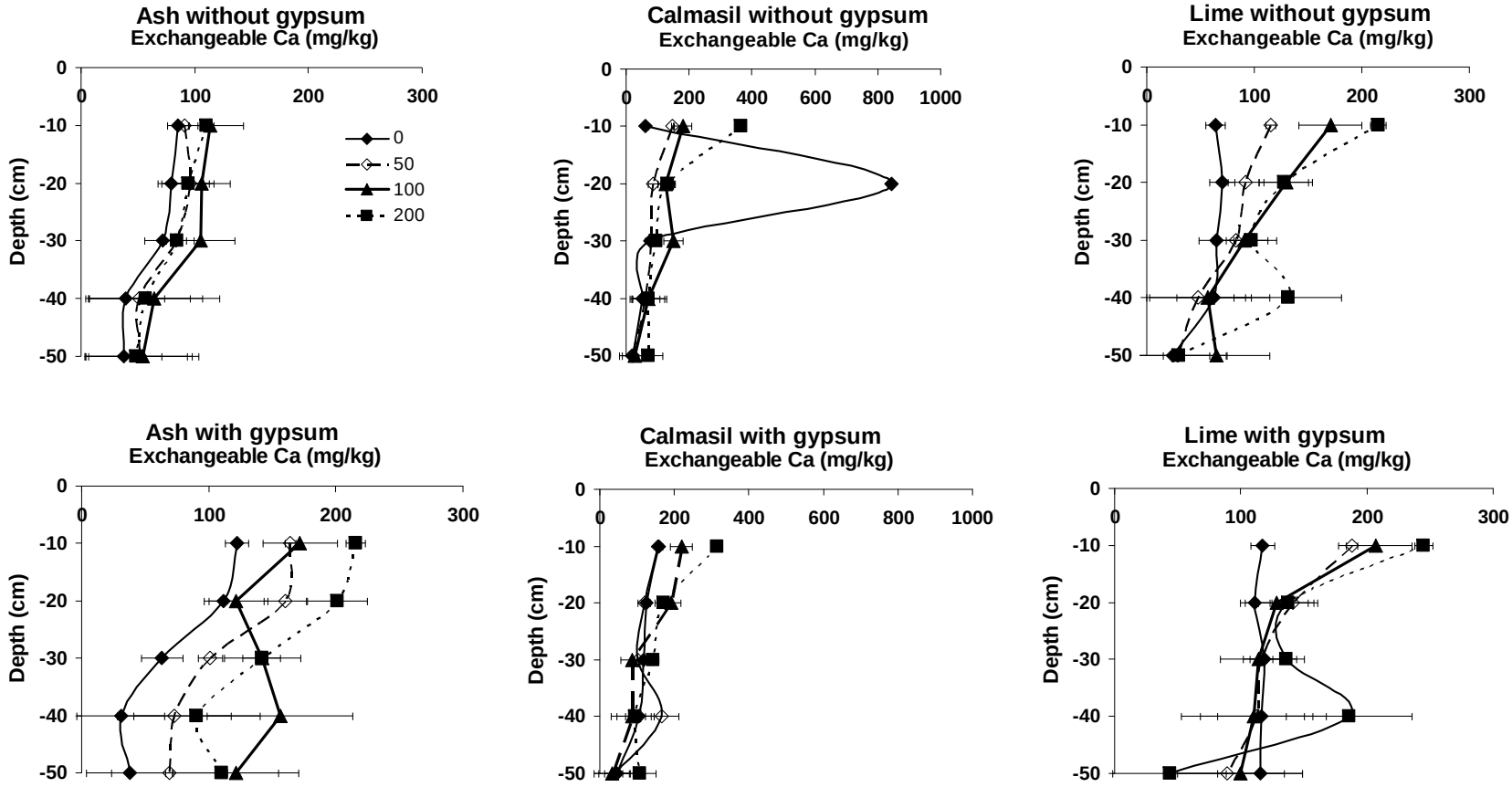

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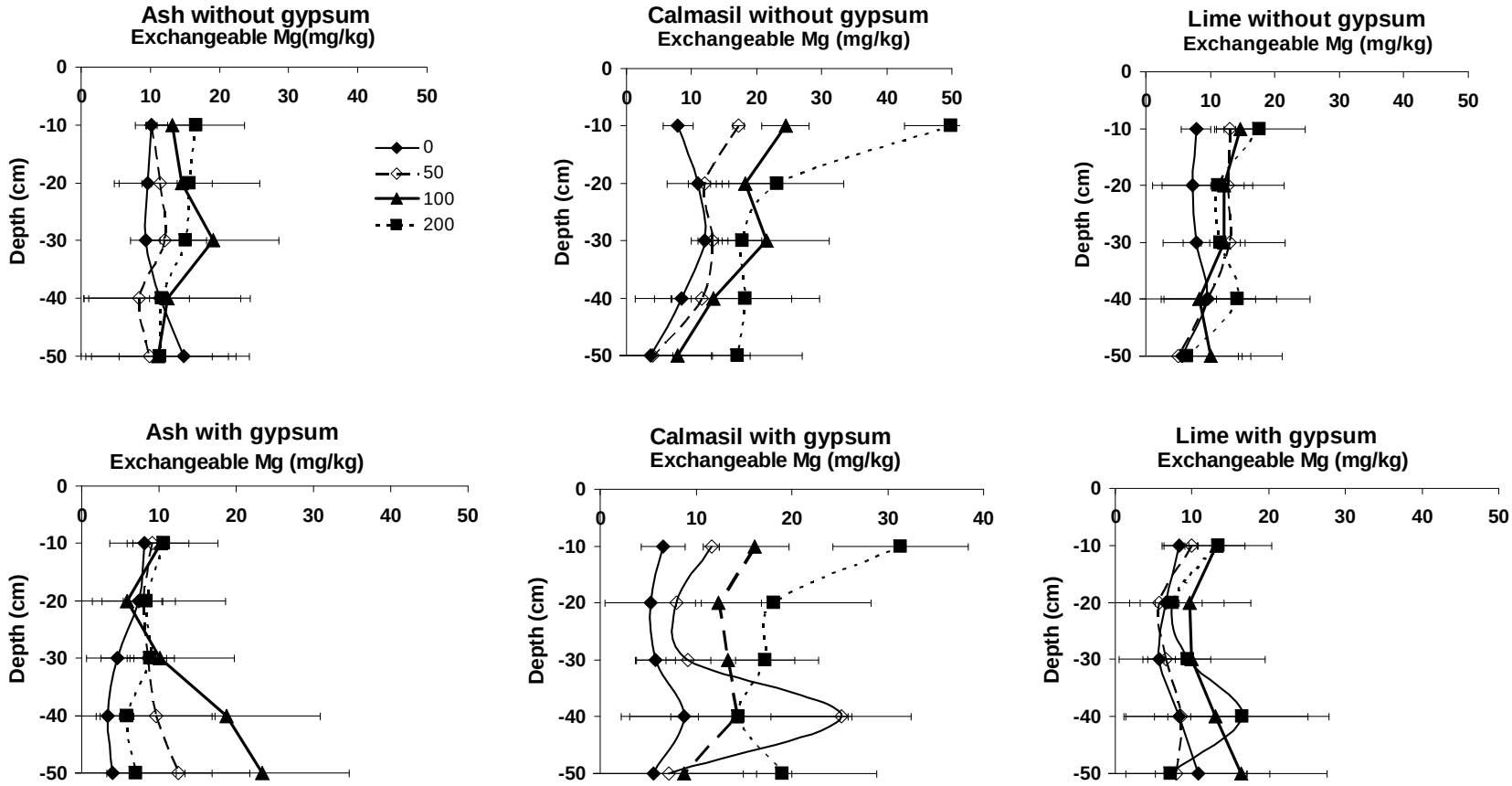

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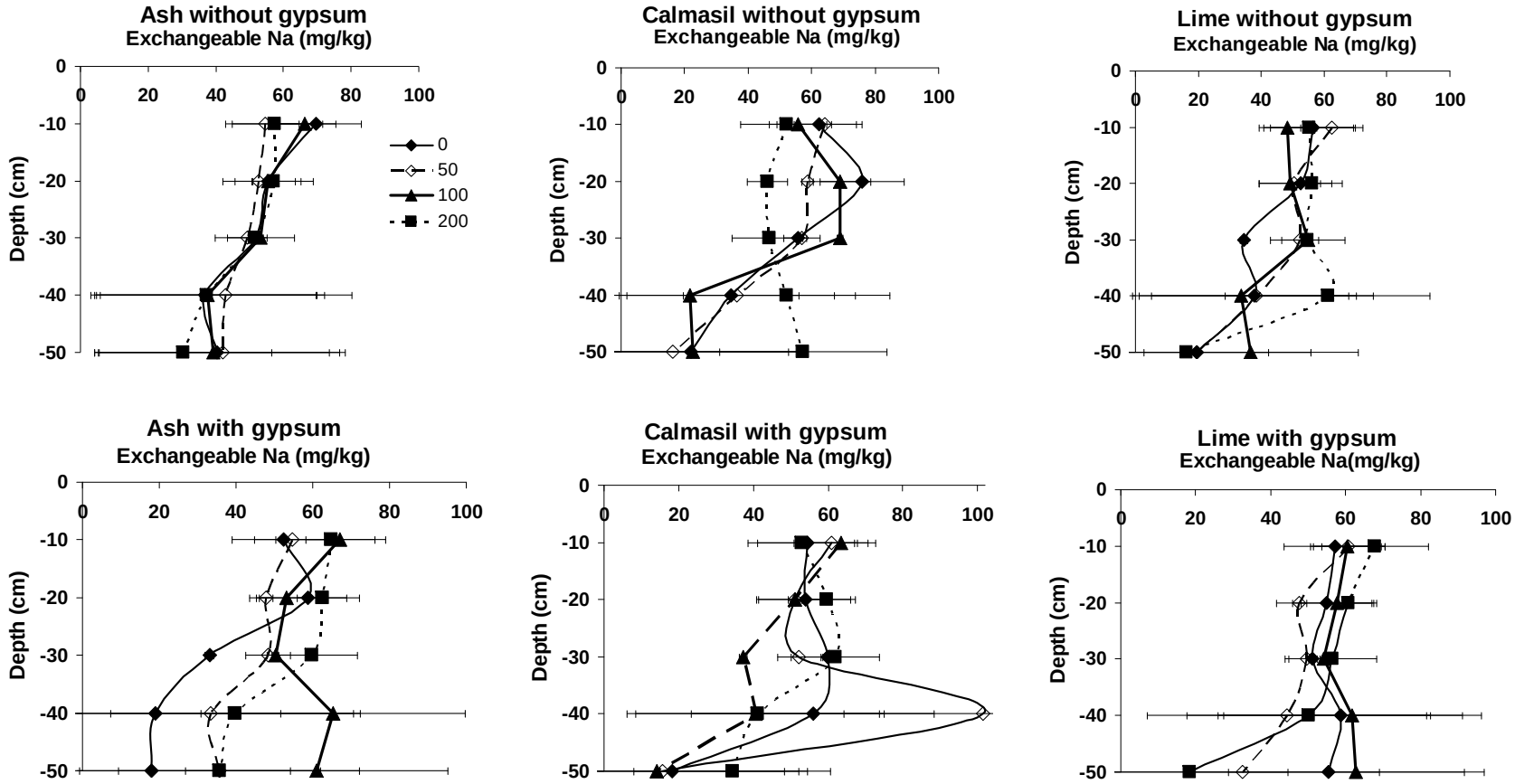

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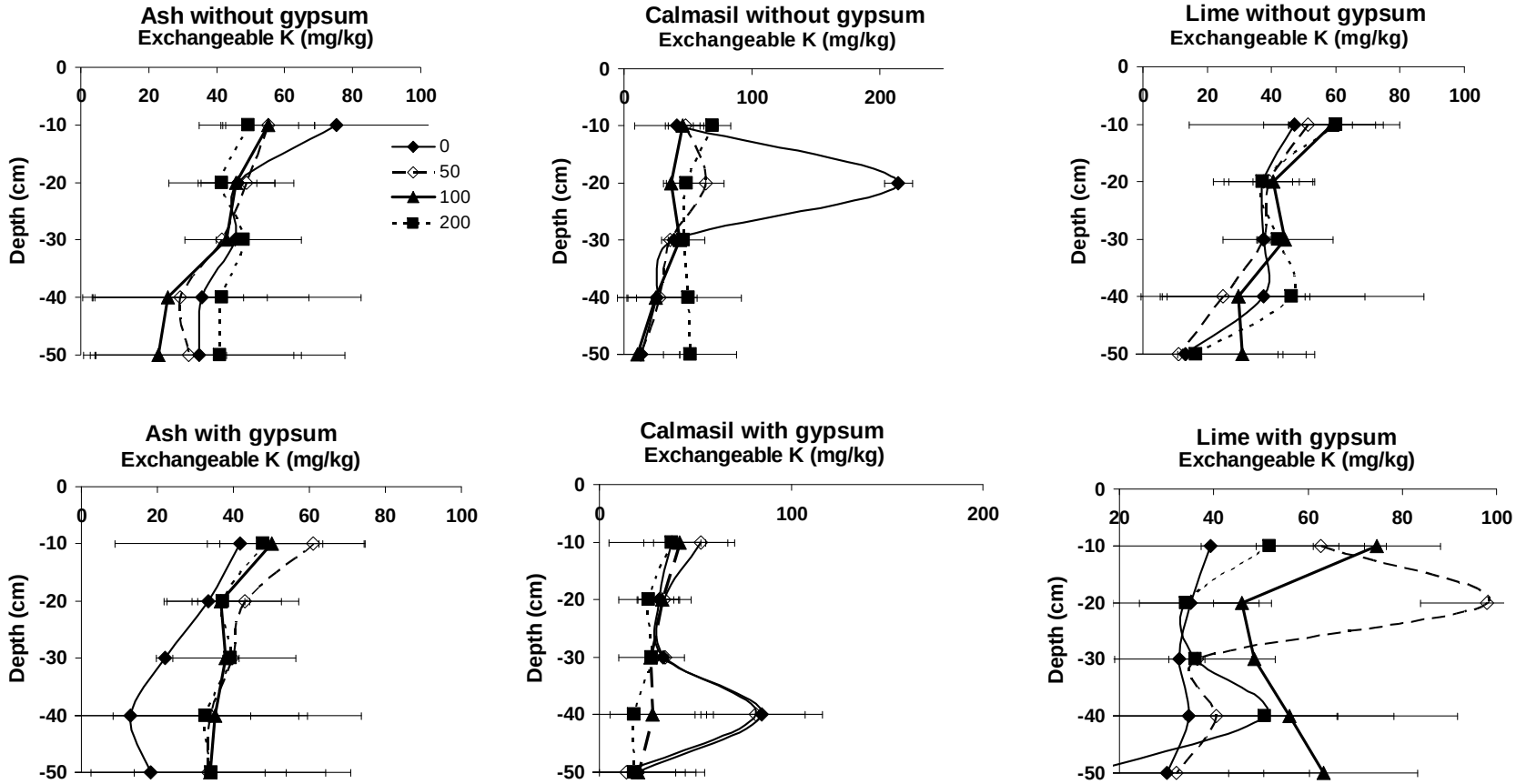

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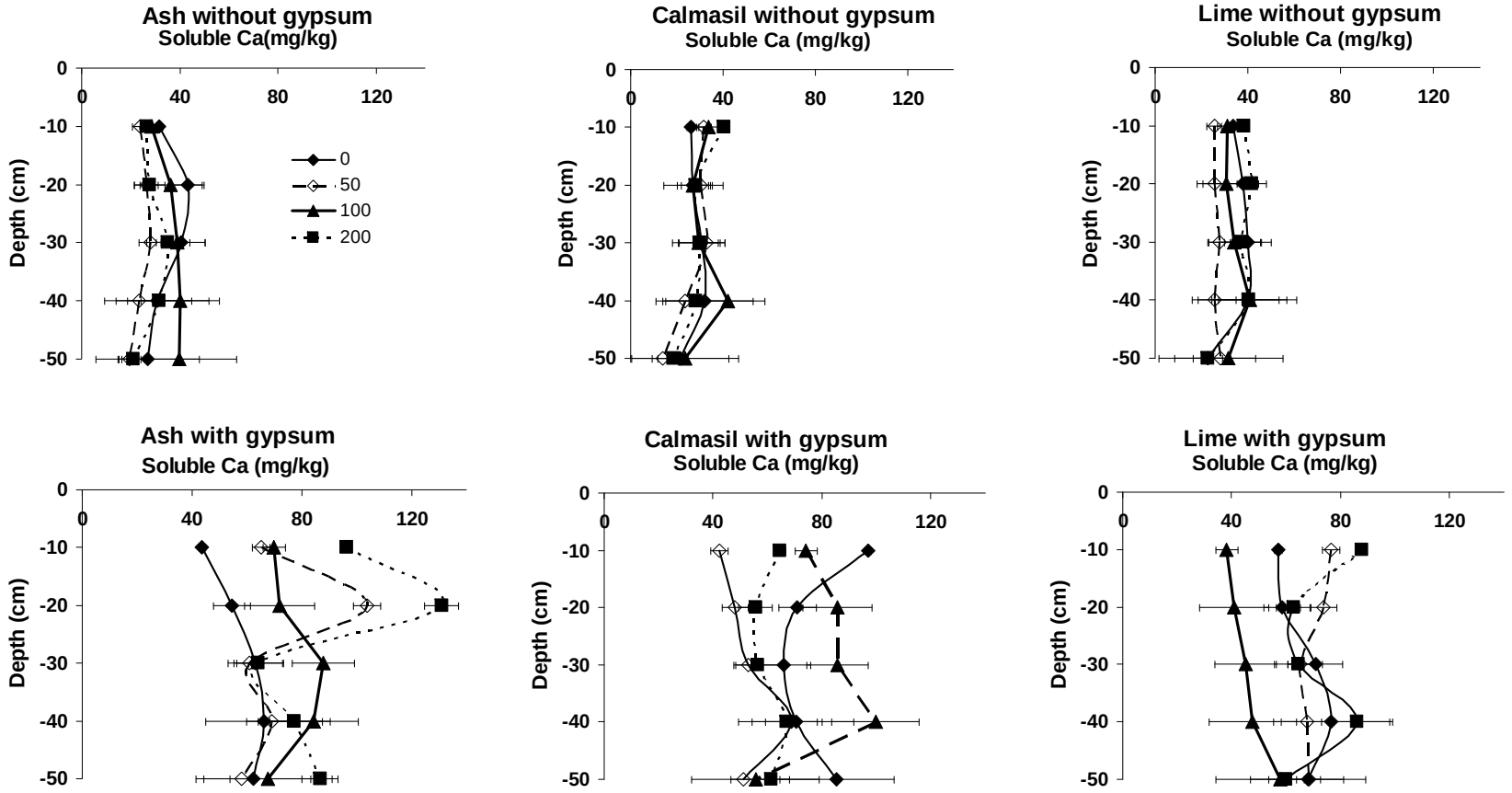

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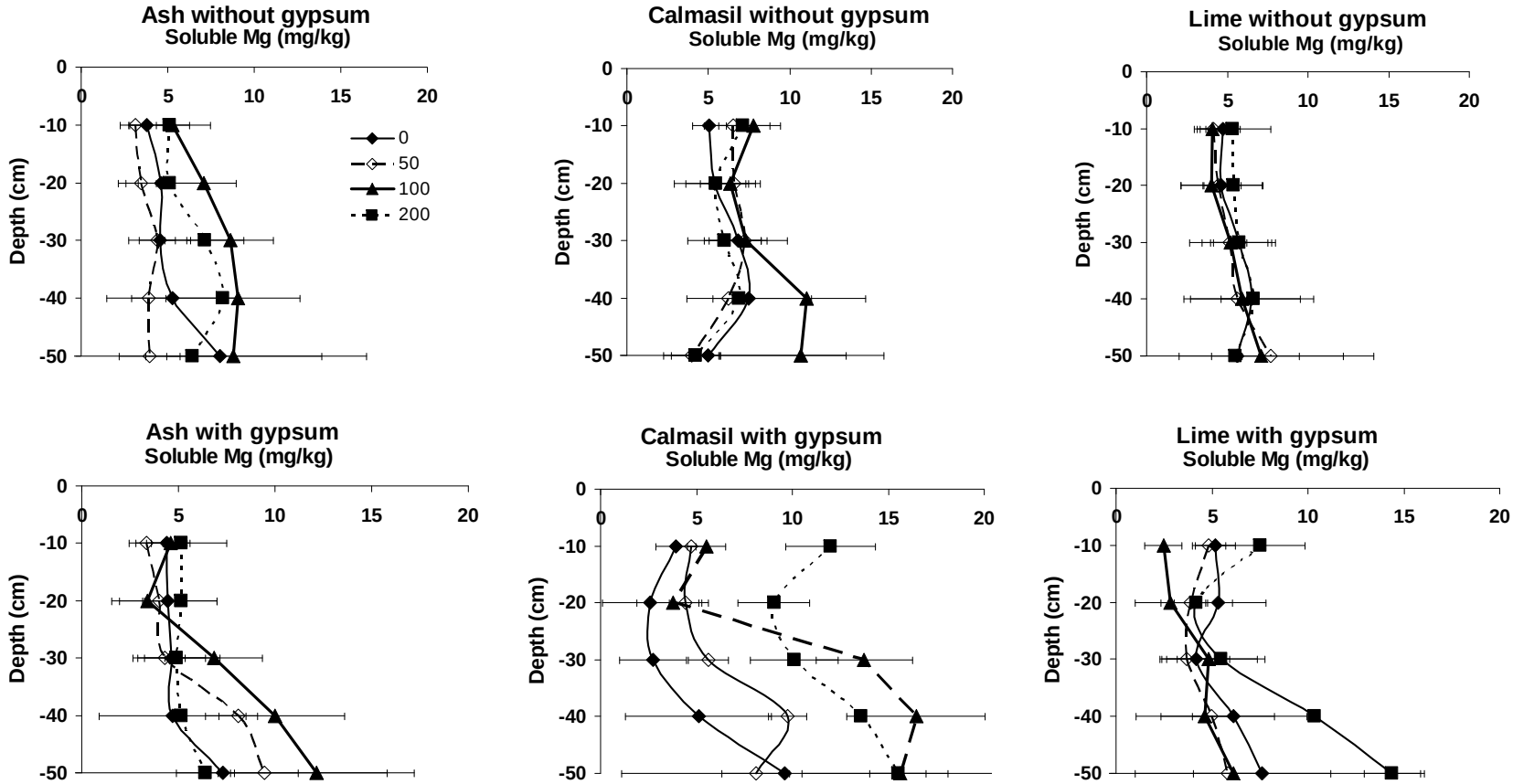

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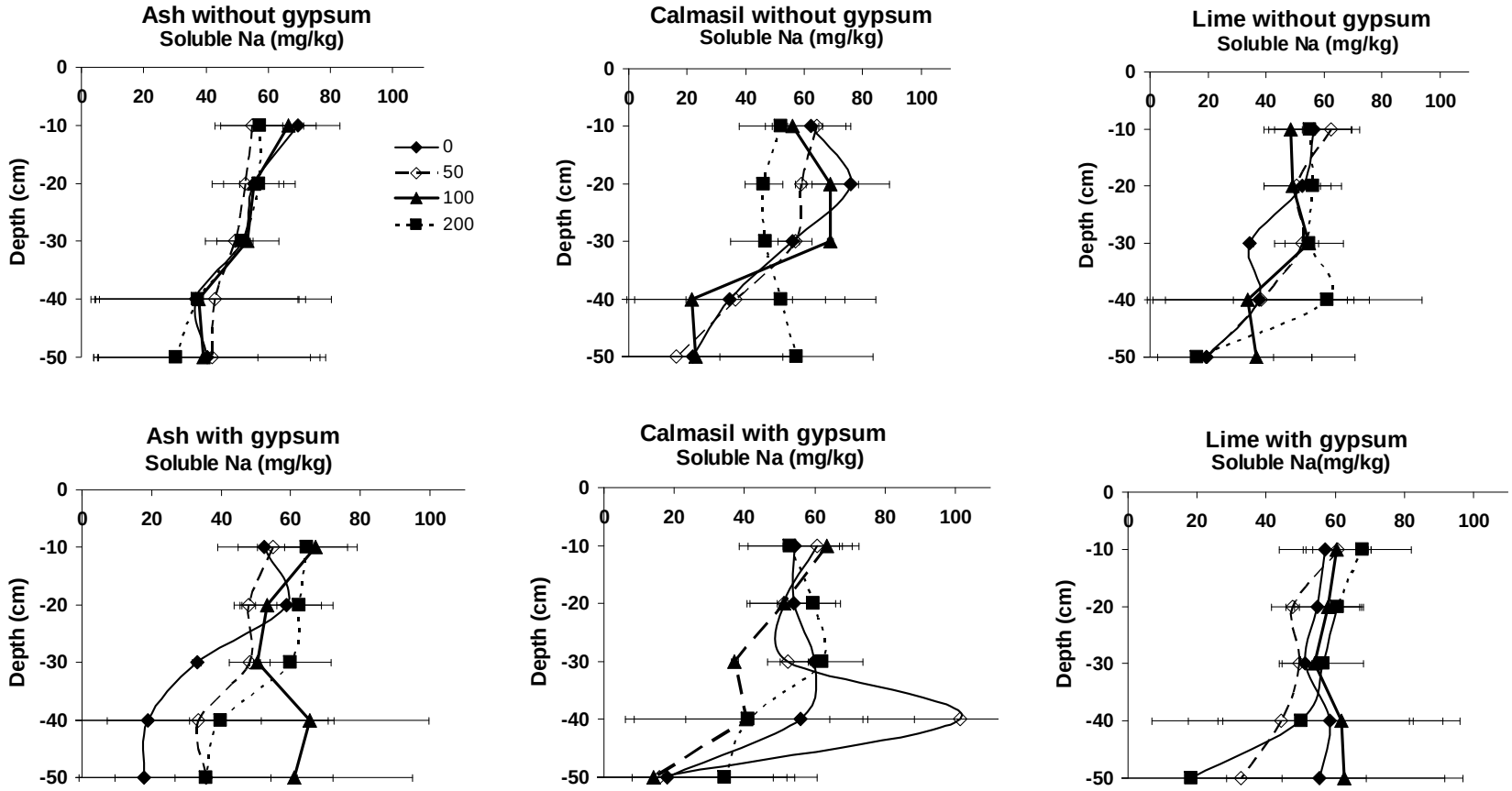

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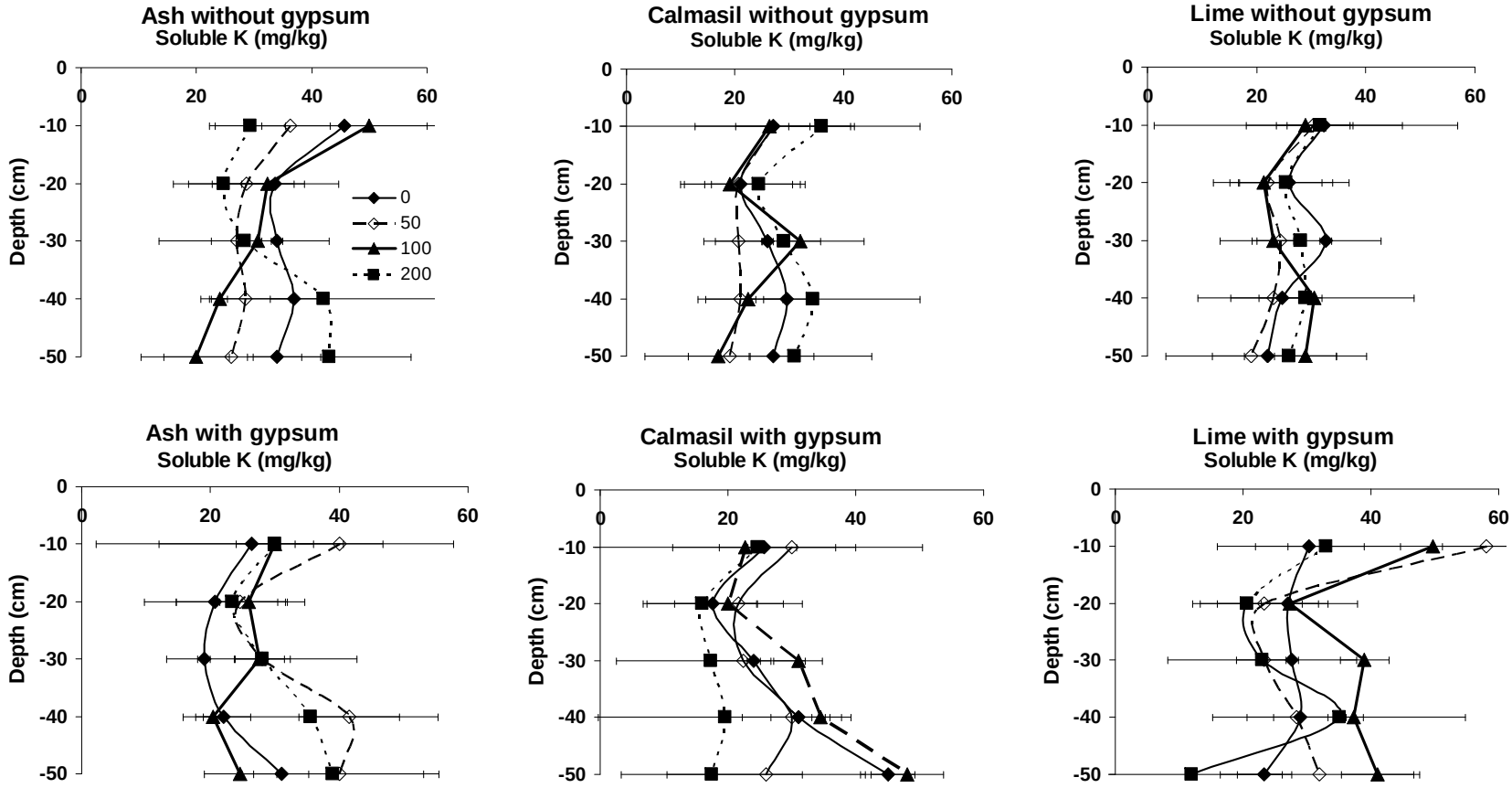

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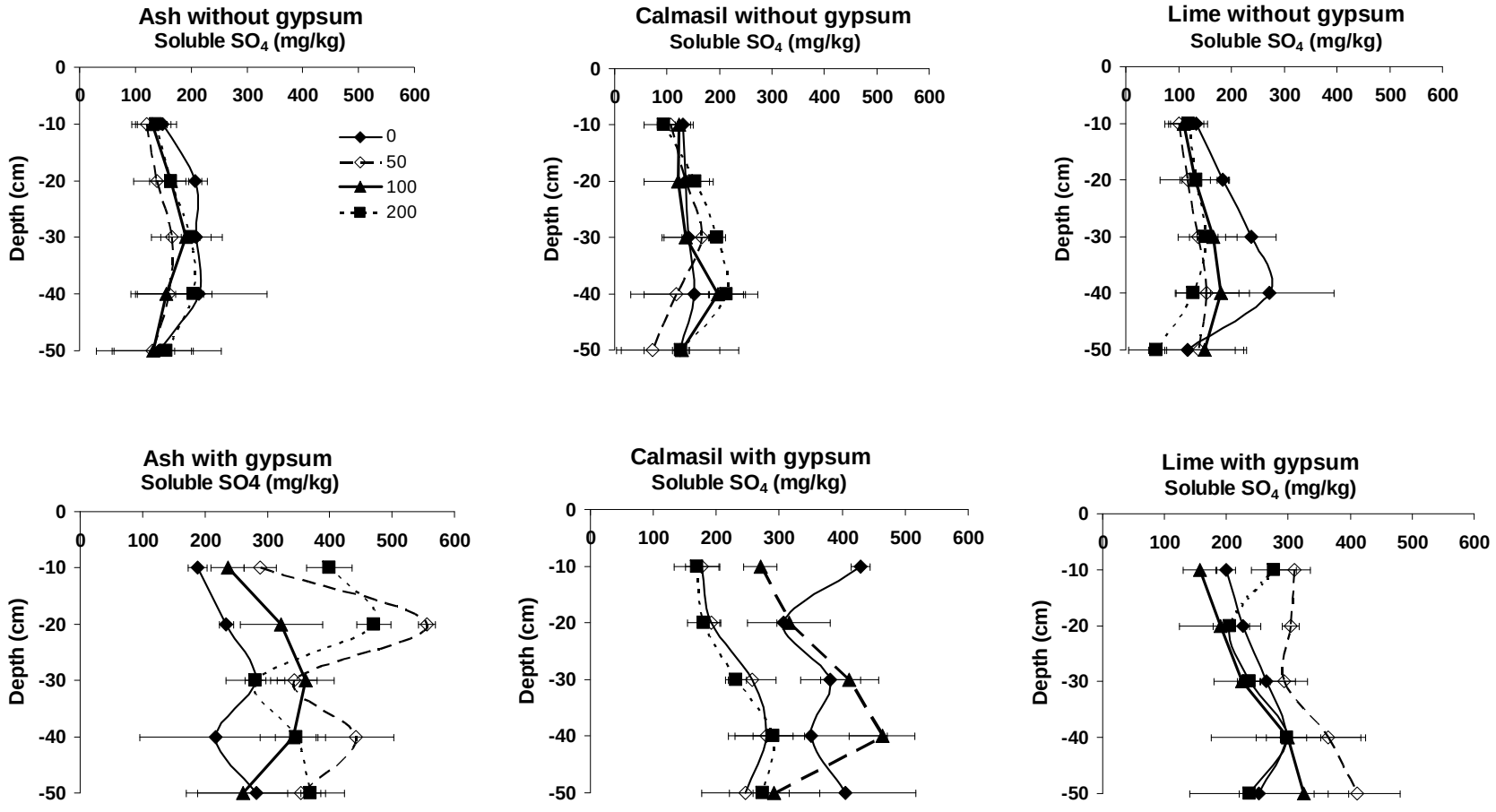

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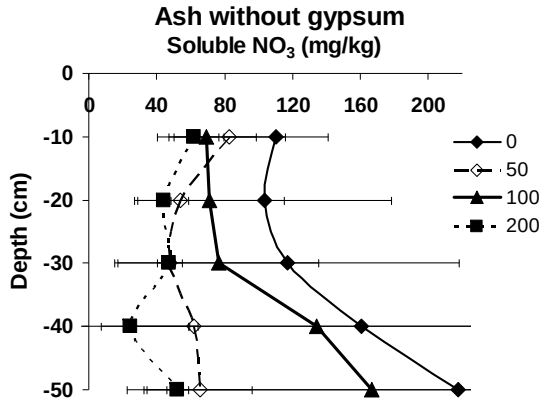

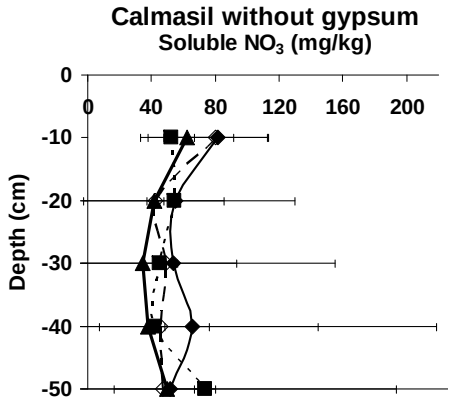

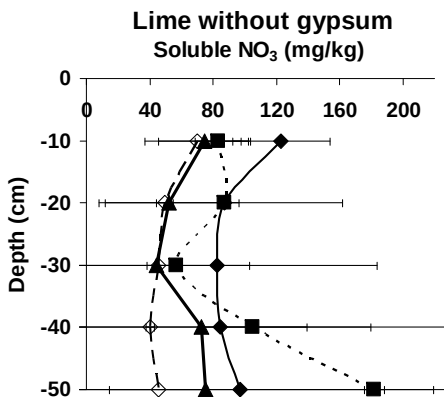

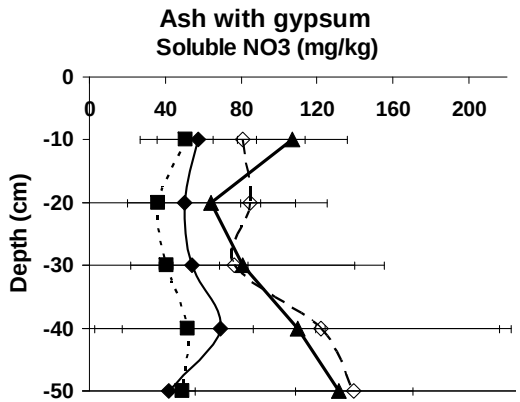

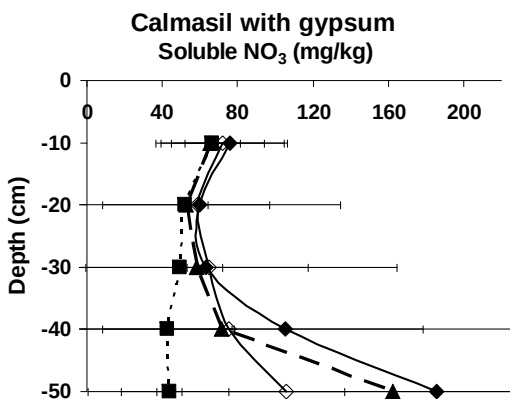

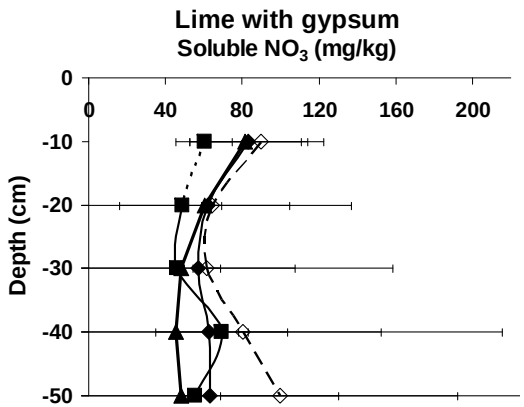

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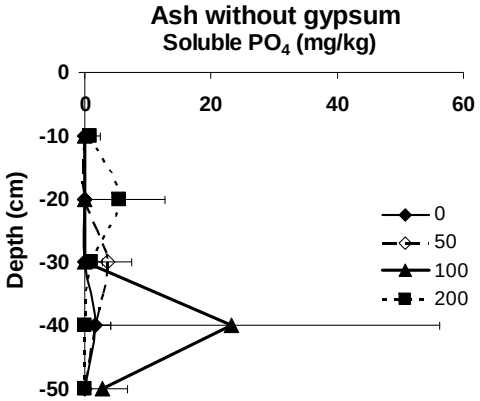

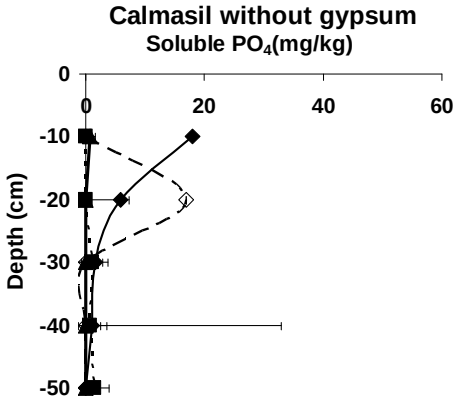

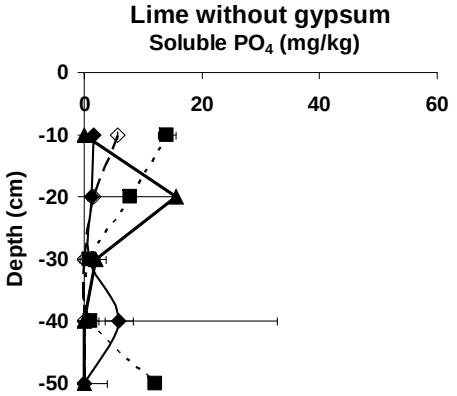

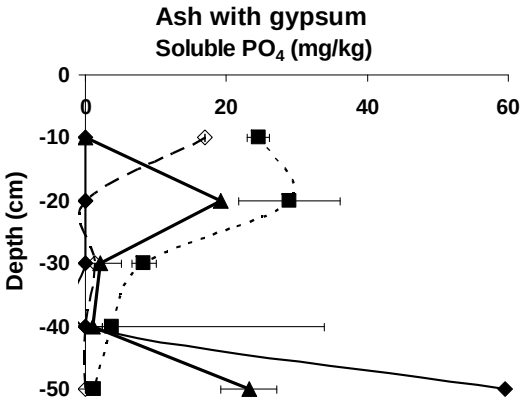

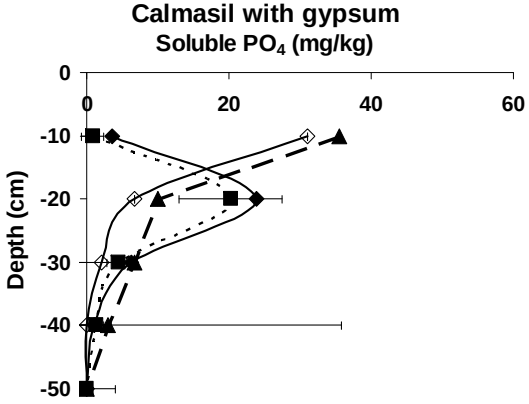

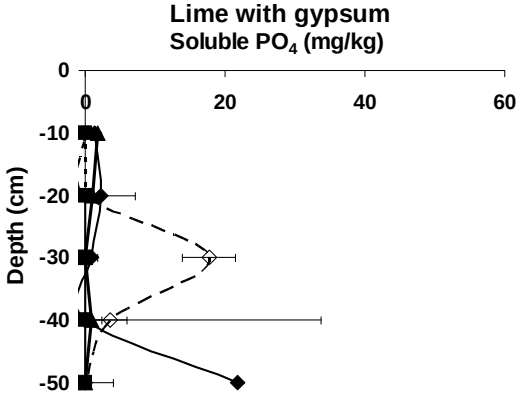

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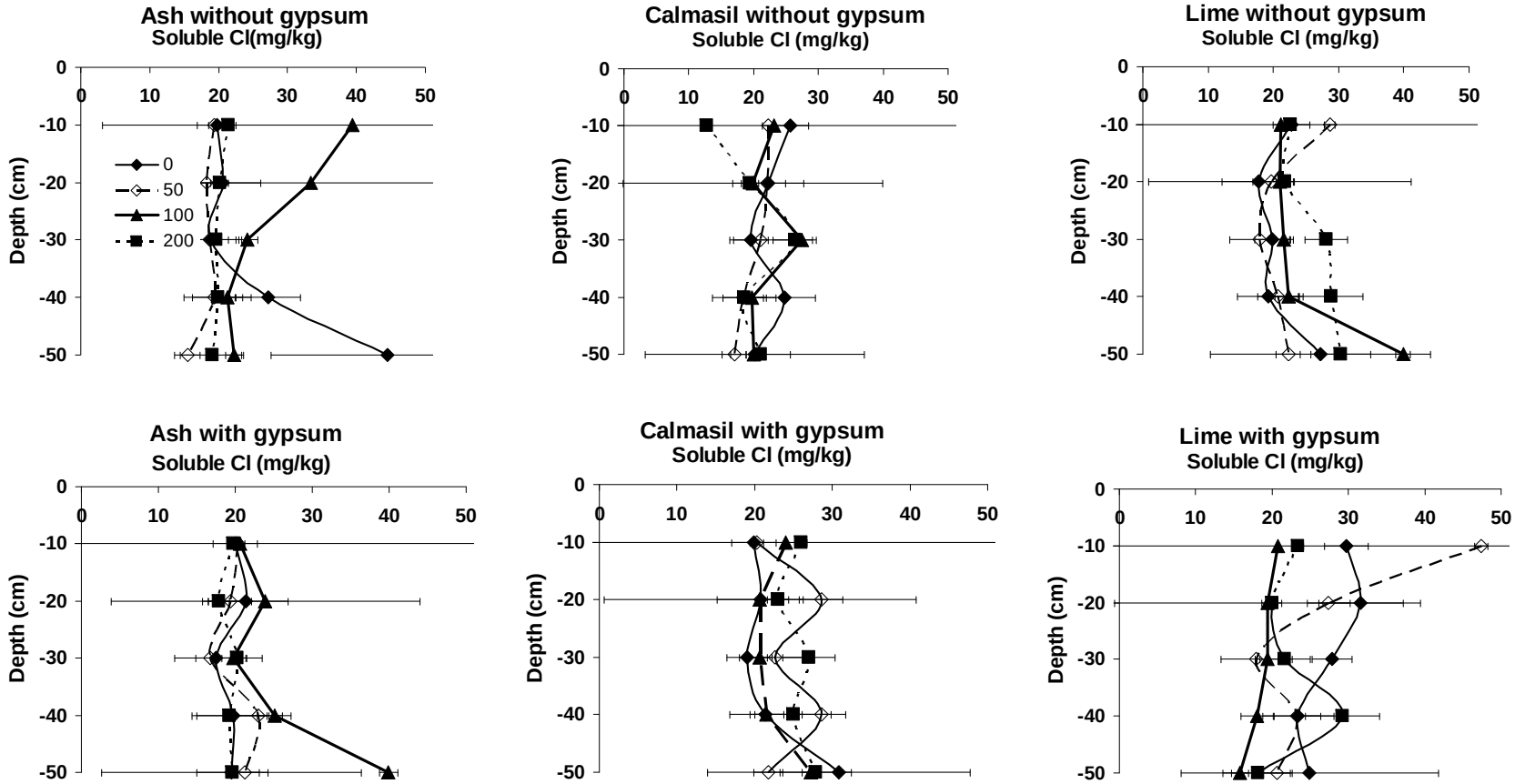

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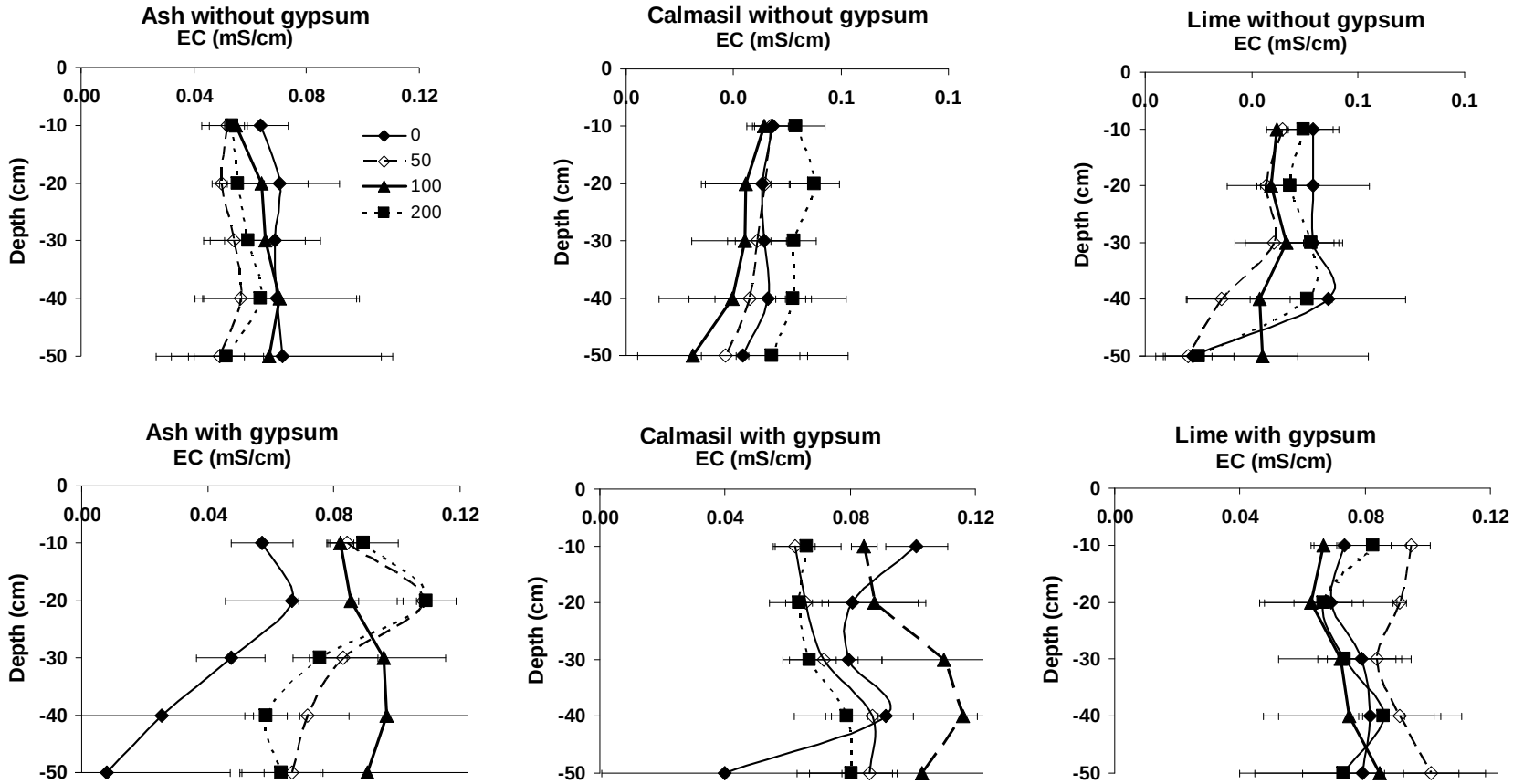
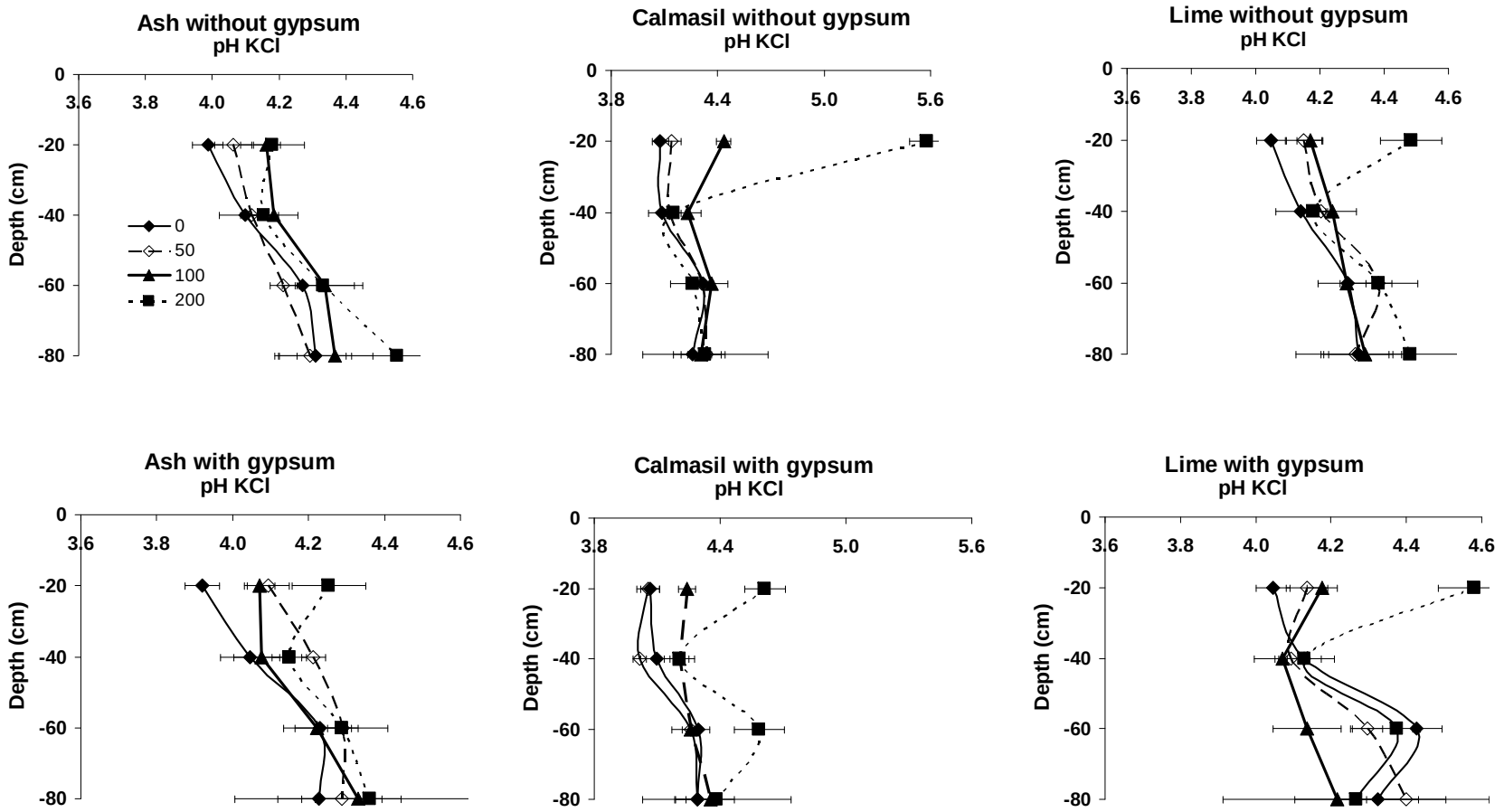


Appendix 5: Graphical representation of chemical analyses data of June 2009 soil samples
pH_{KCl}, acidity, acid saturation, extractable Ca, Mg, Na and K, water soluble Ca, Mg, Na, K, SO_4, NO_3, Cl and EC with analytical error estimates, down the soil profile



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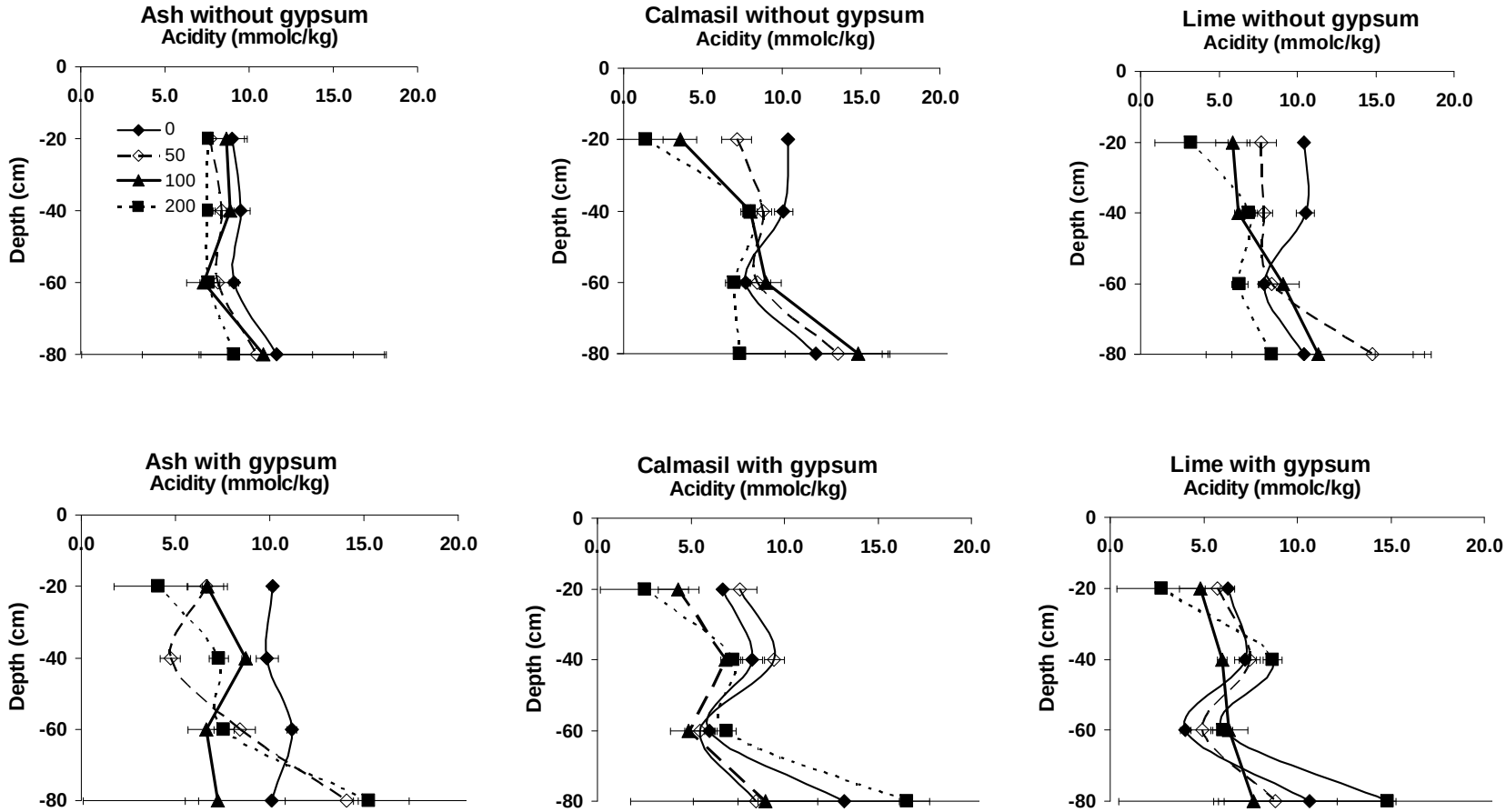

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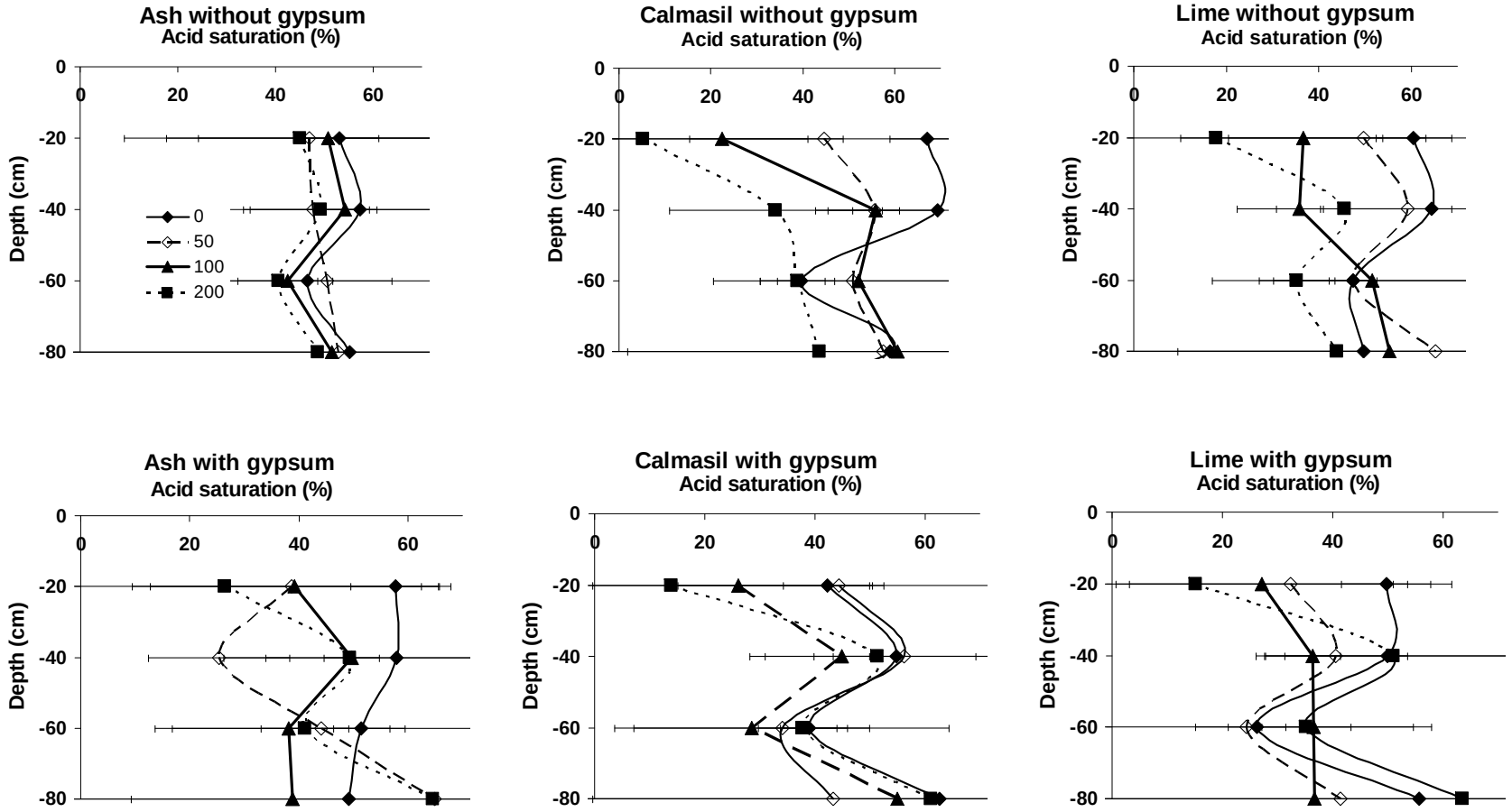

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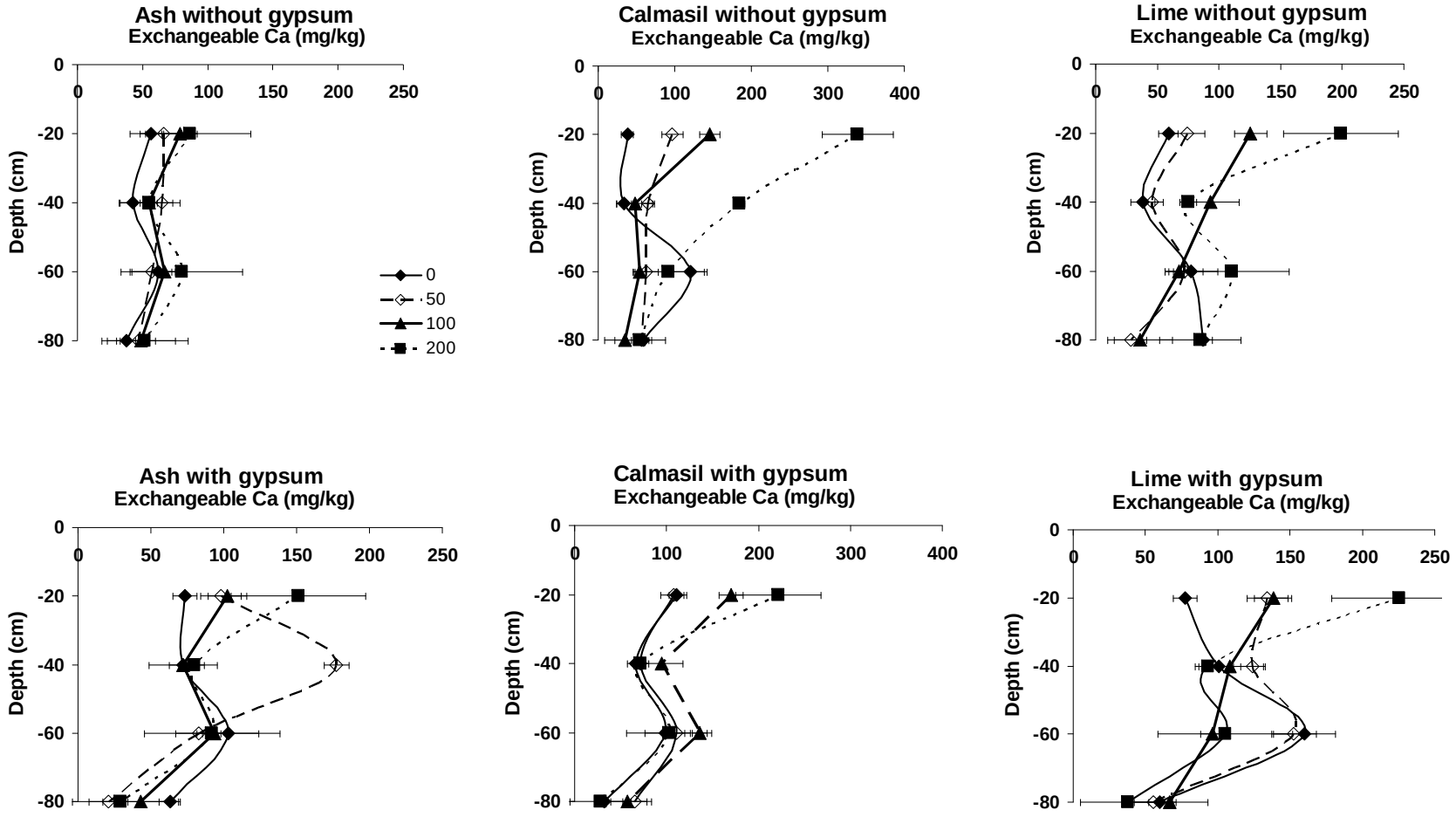

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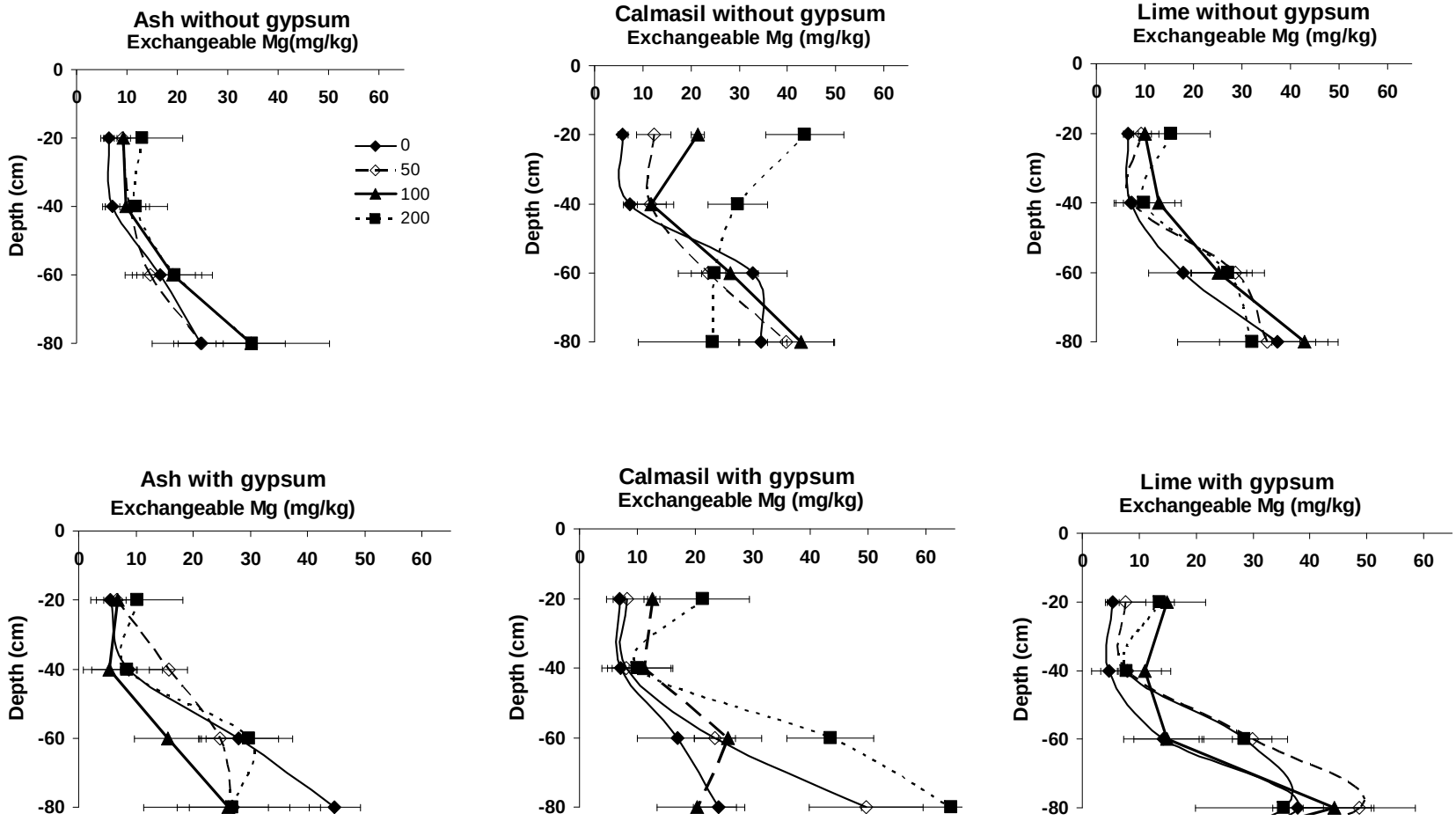

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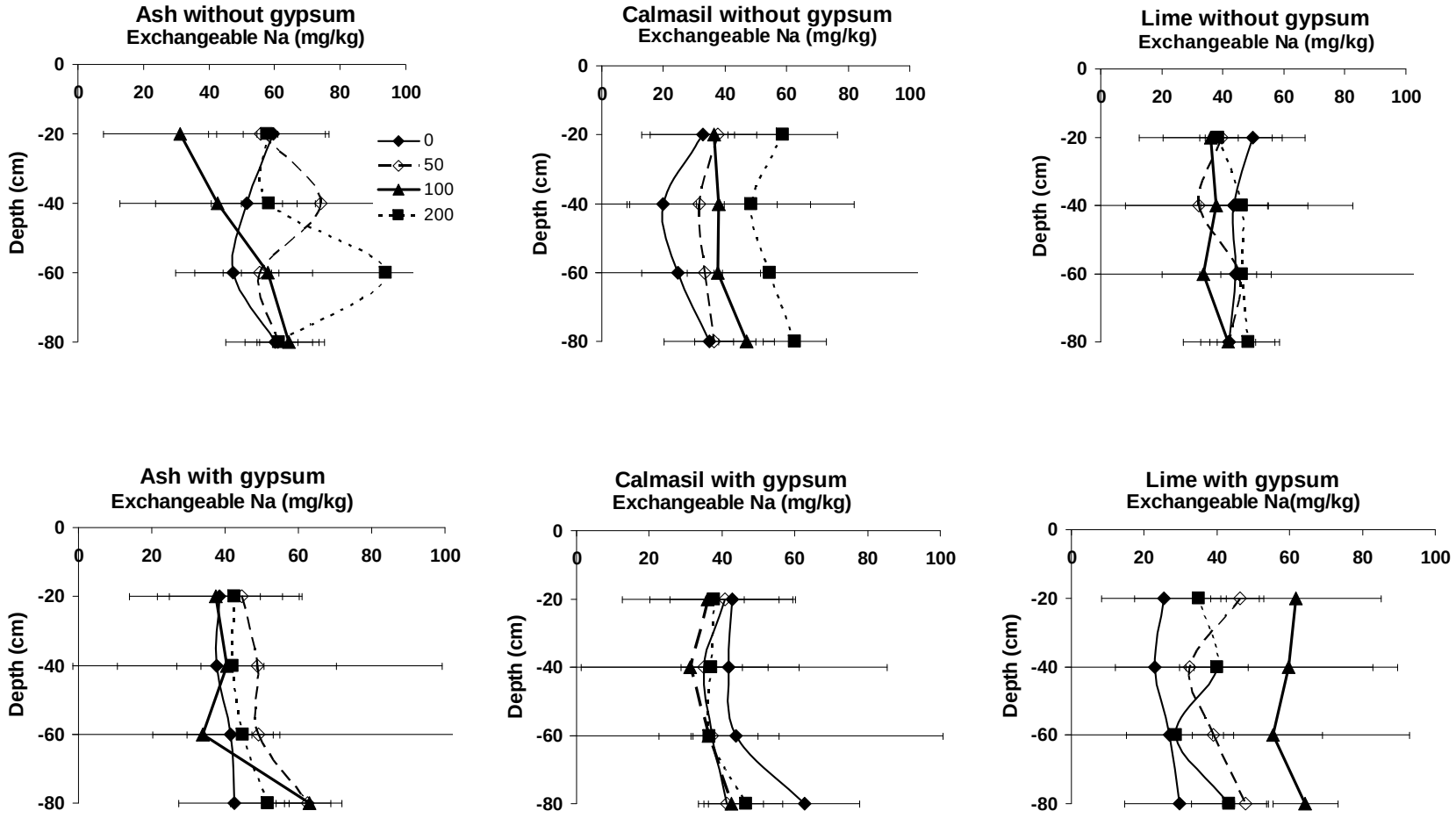

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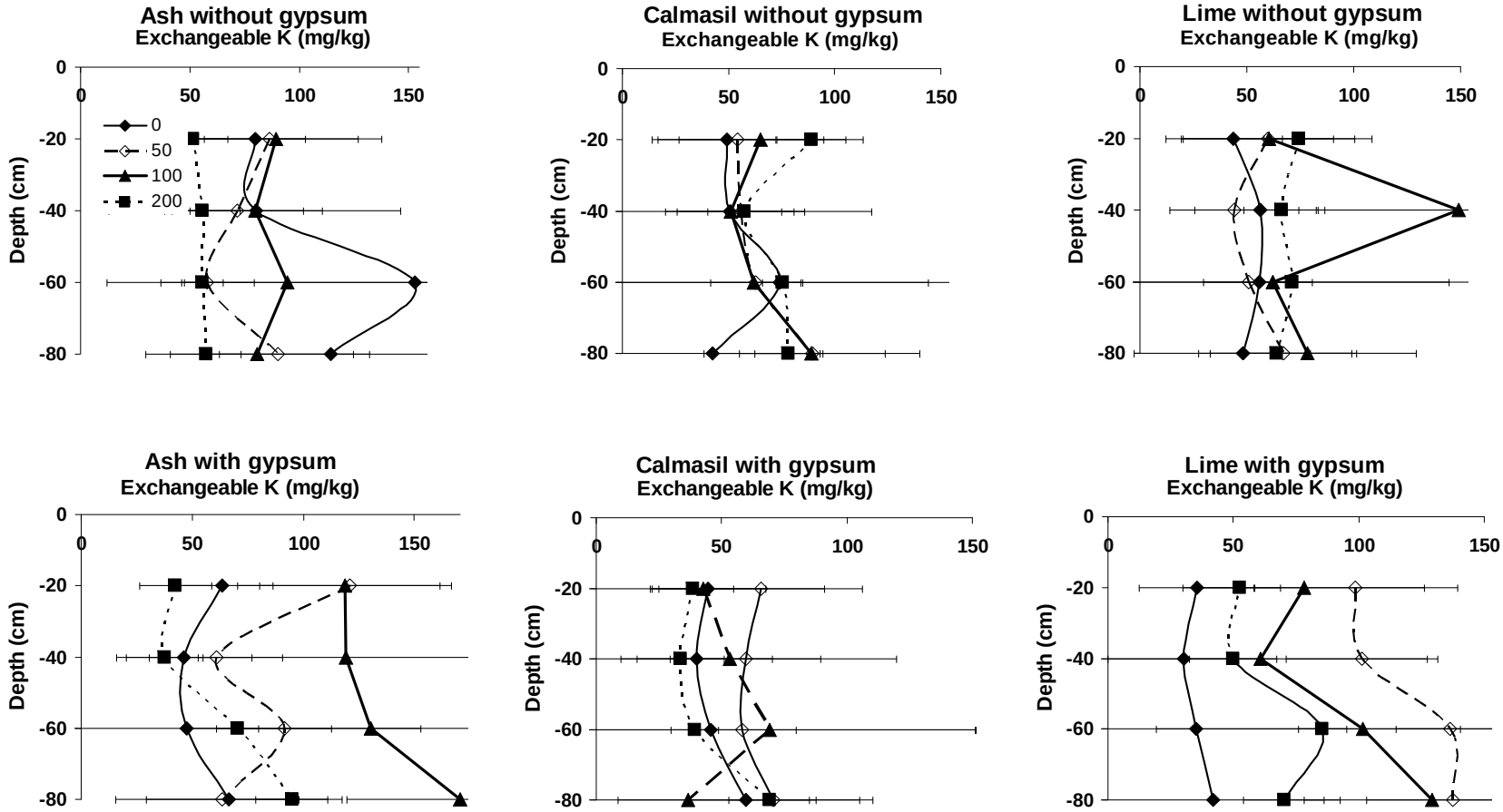

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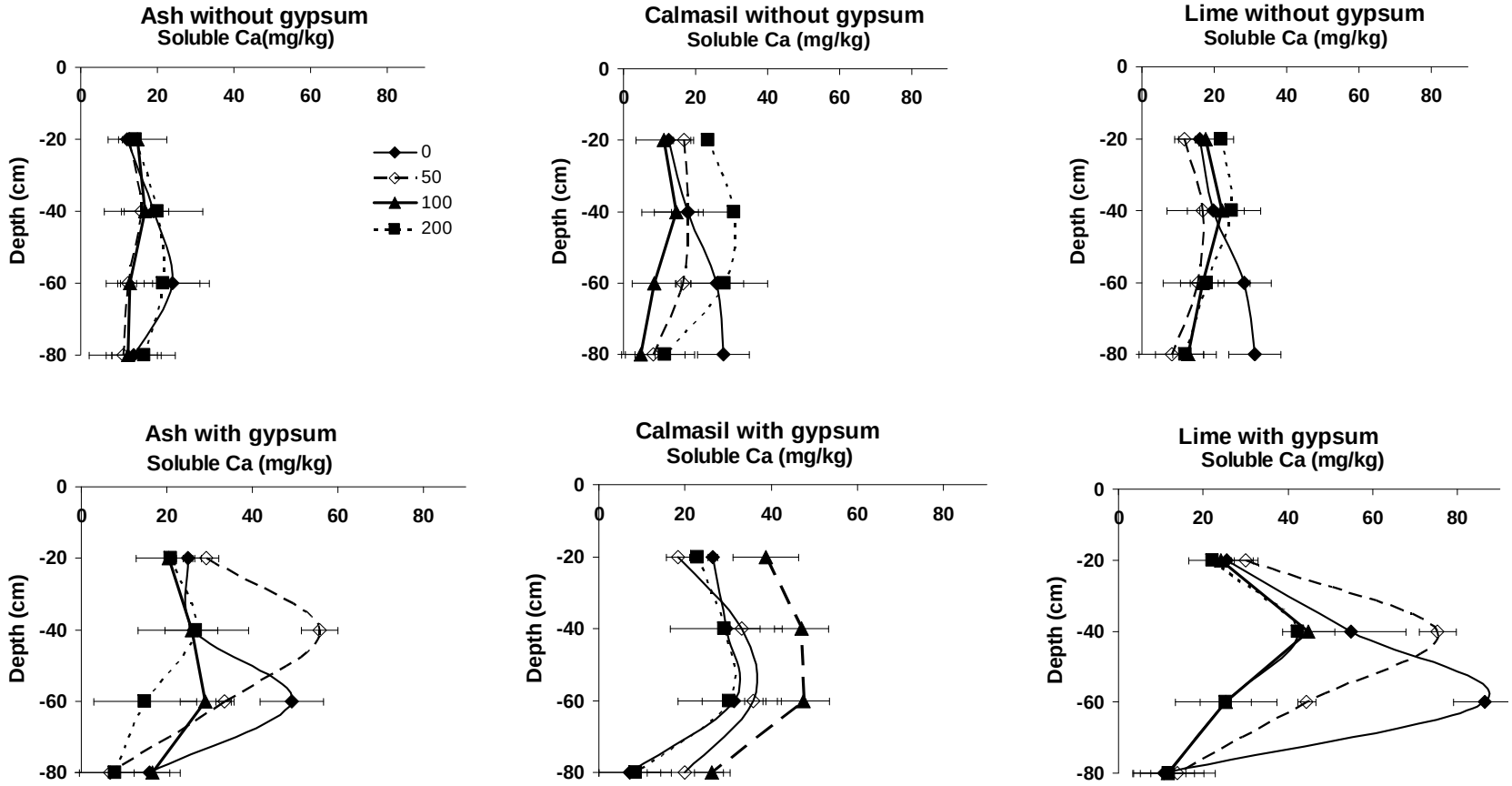

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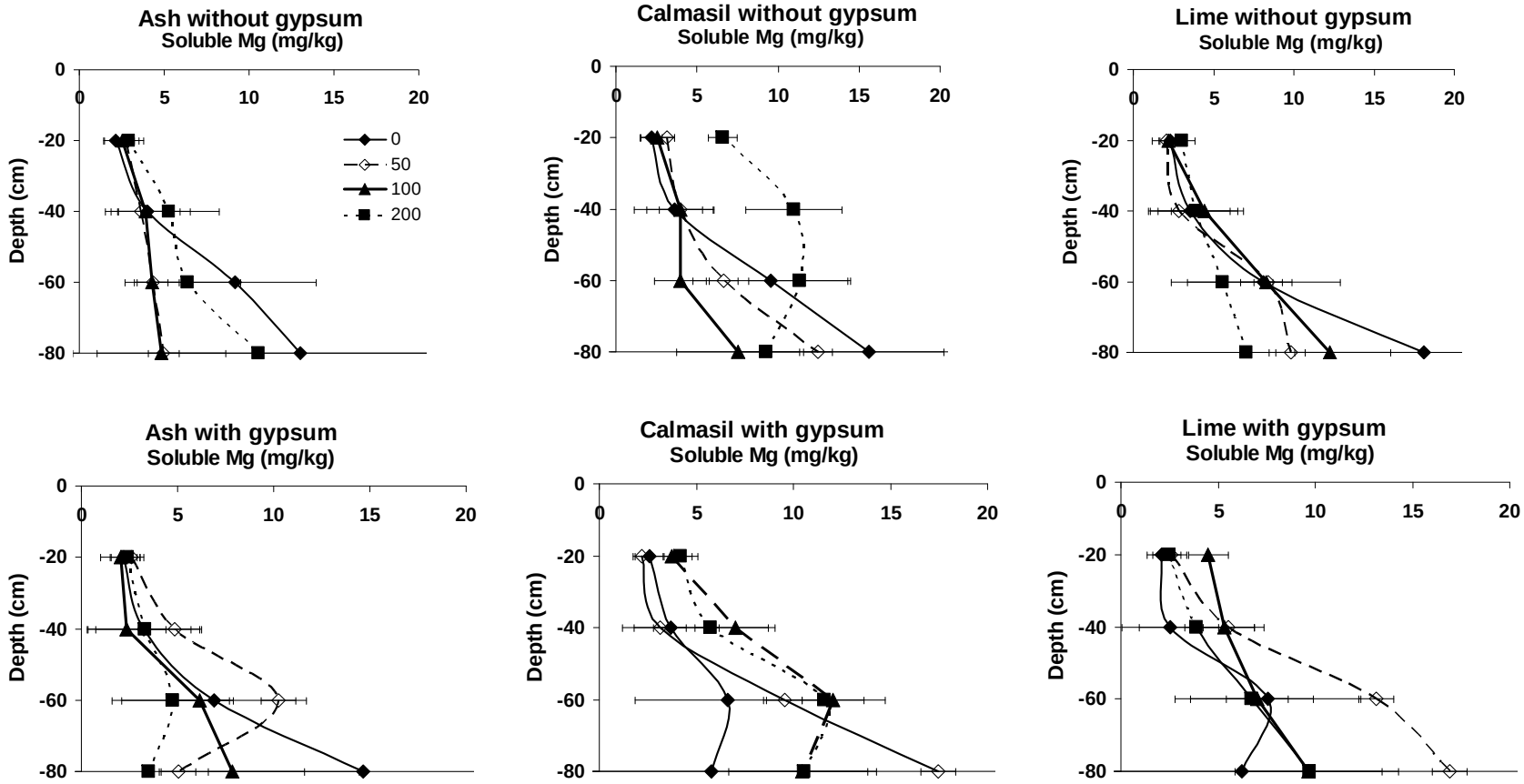

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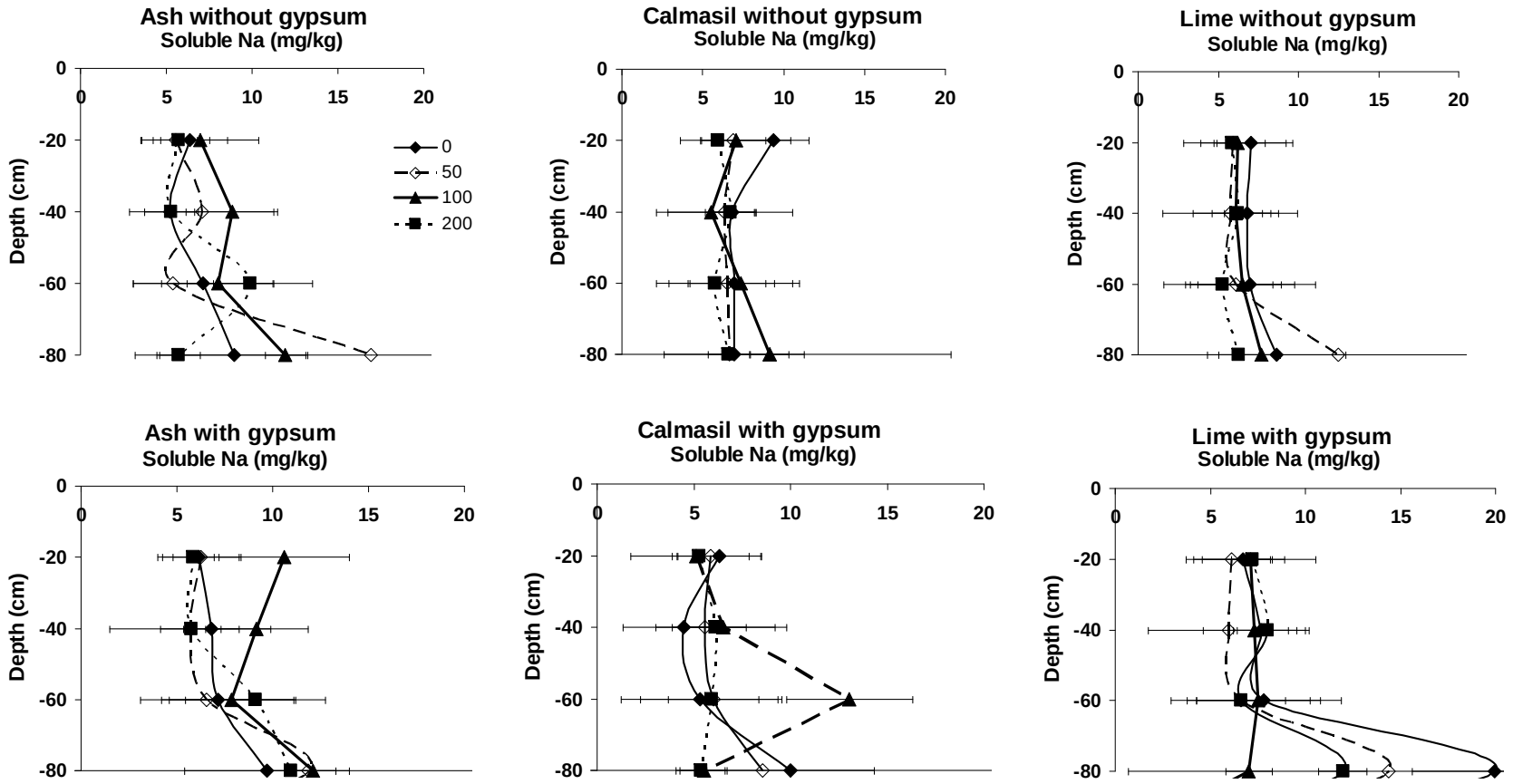

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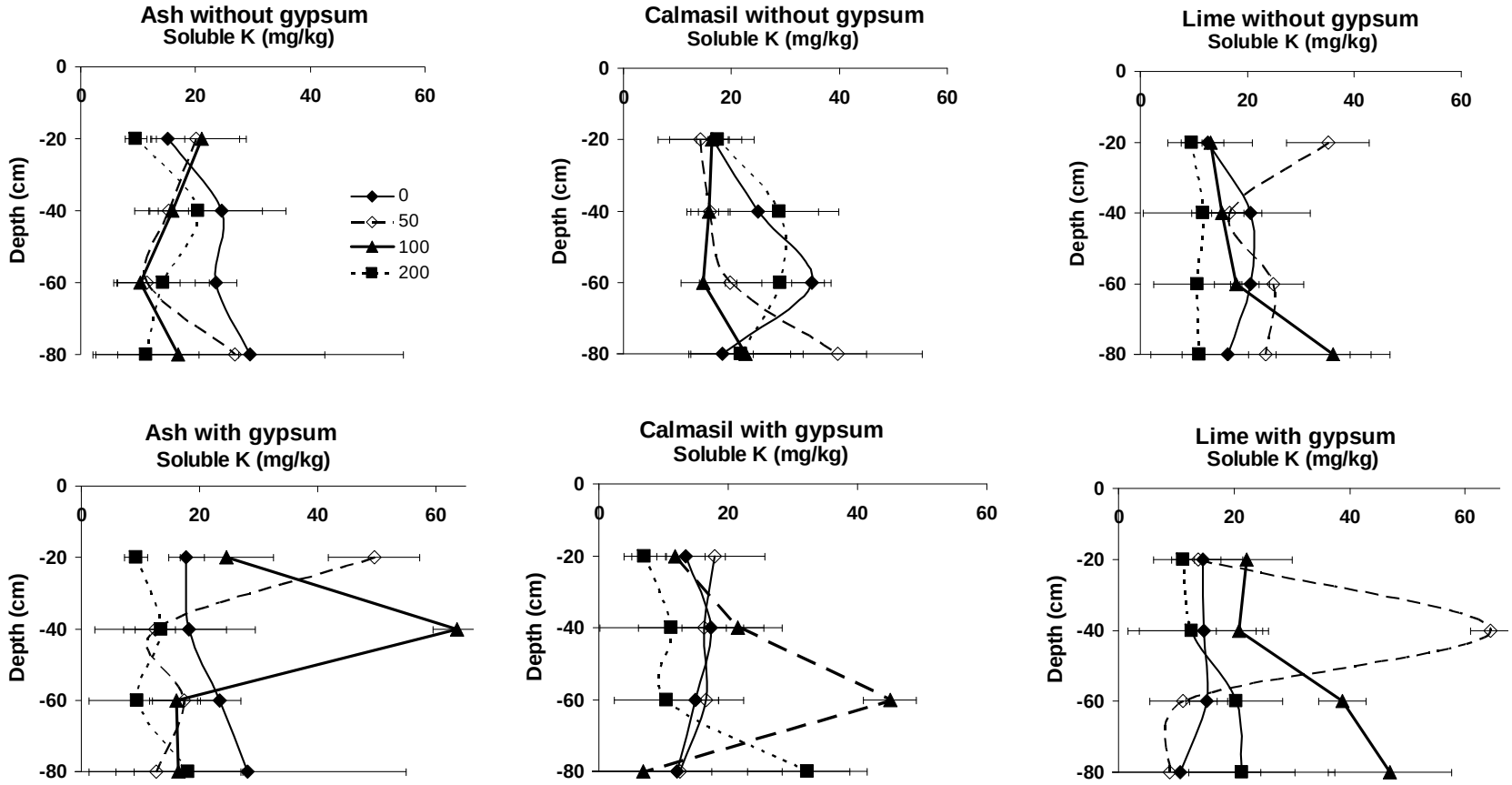

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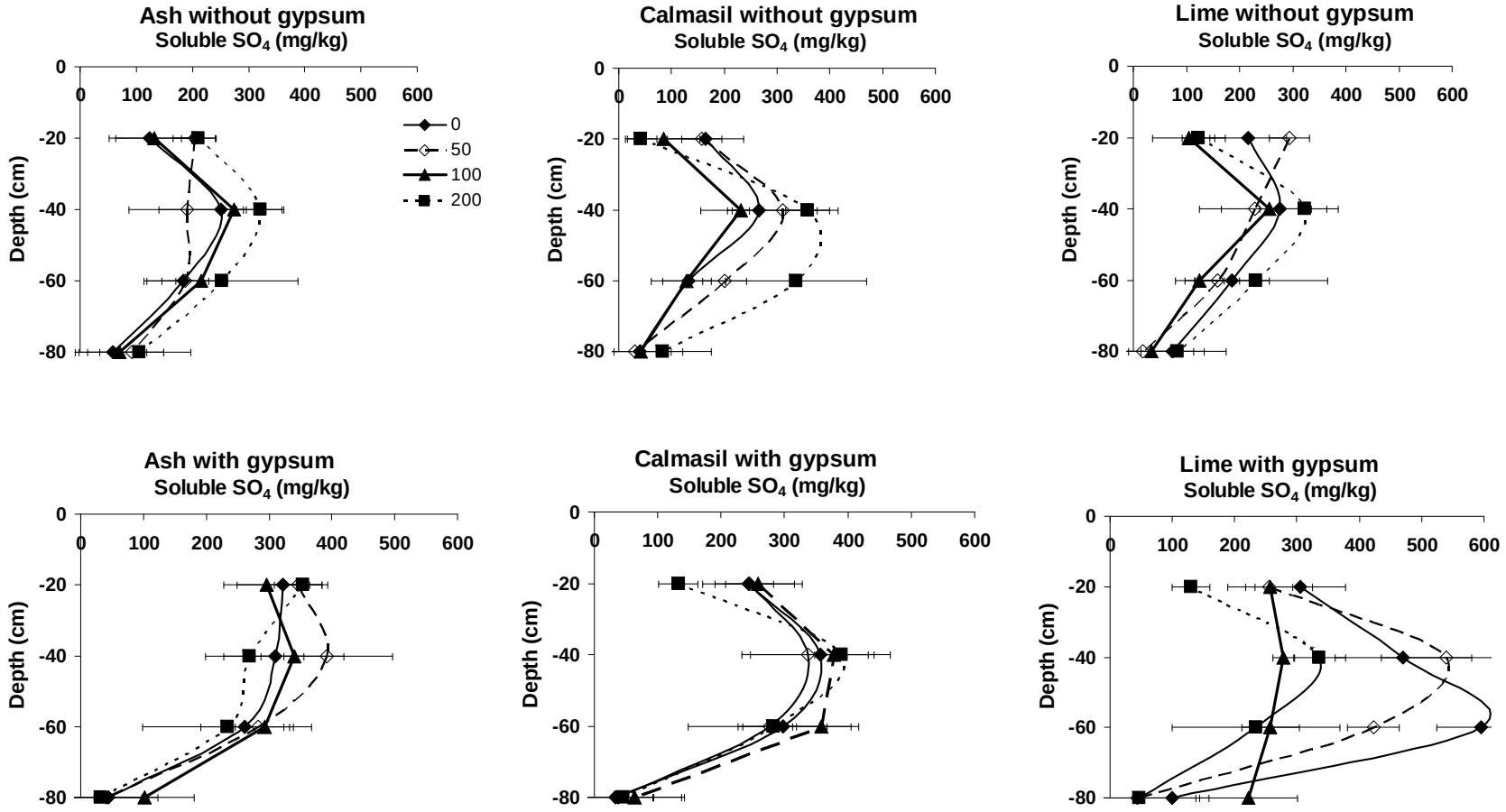

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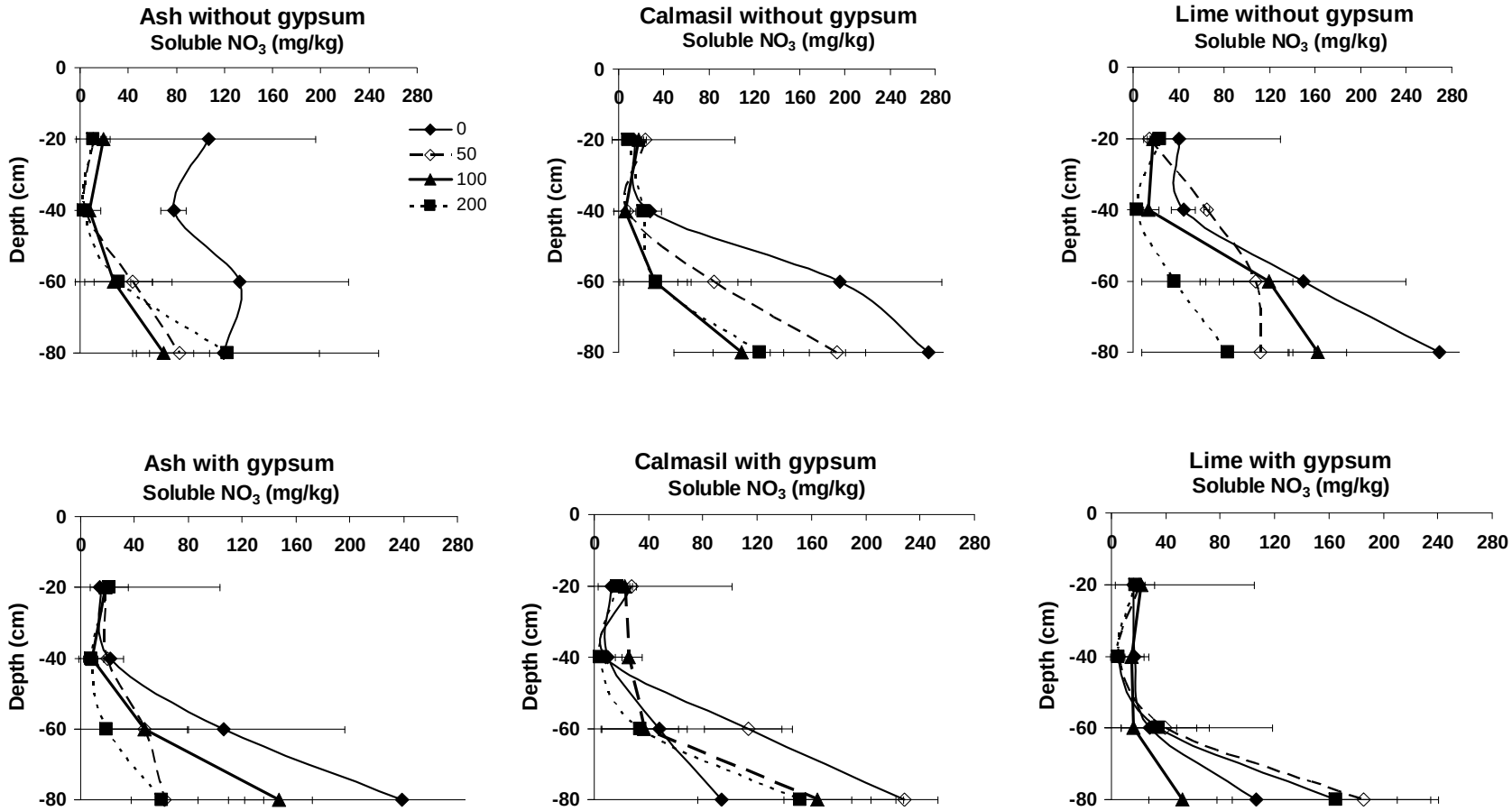

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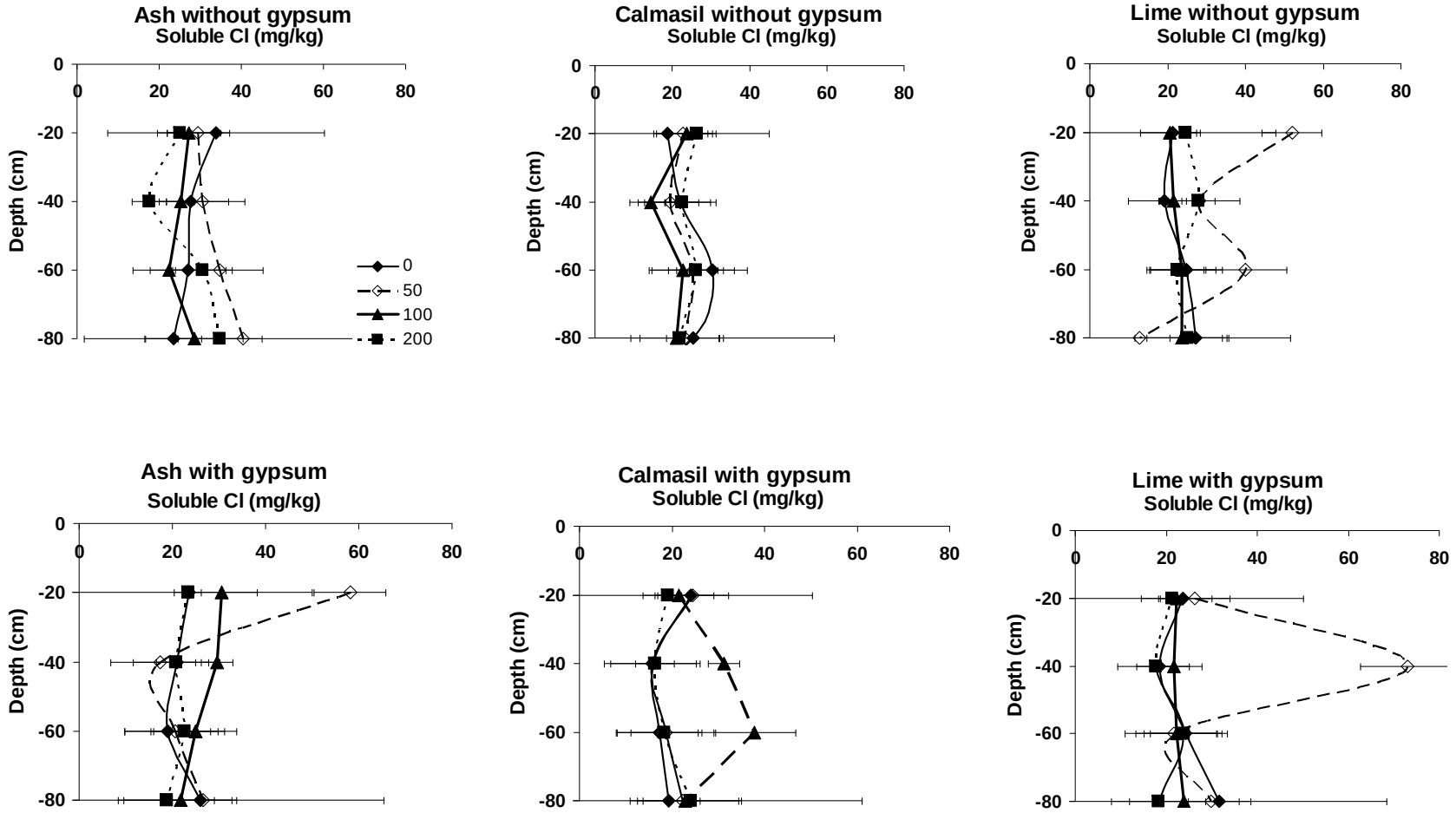

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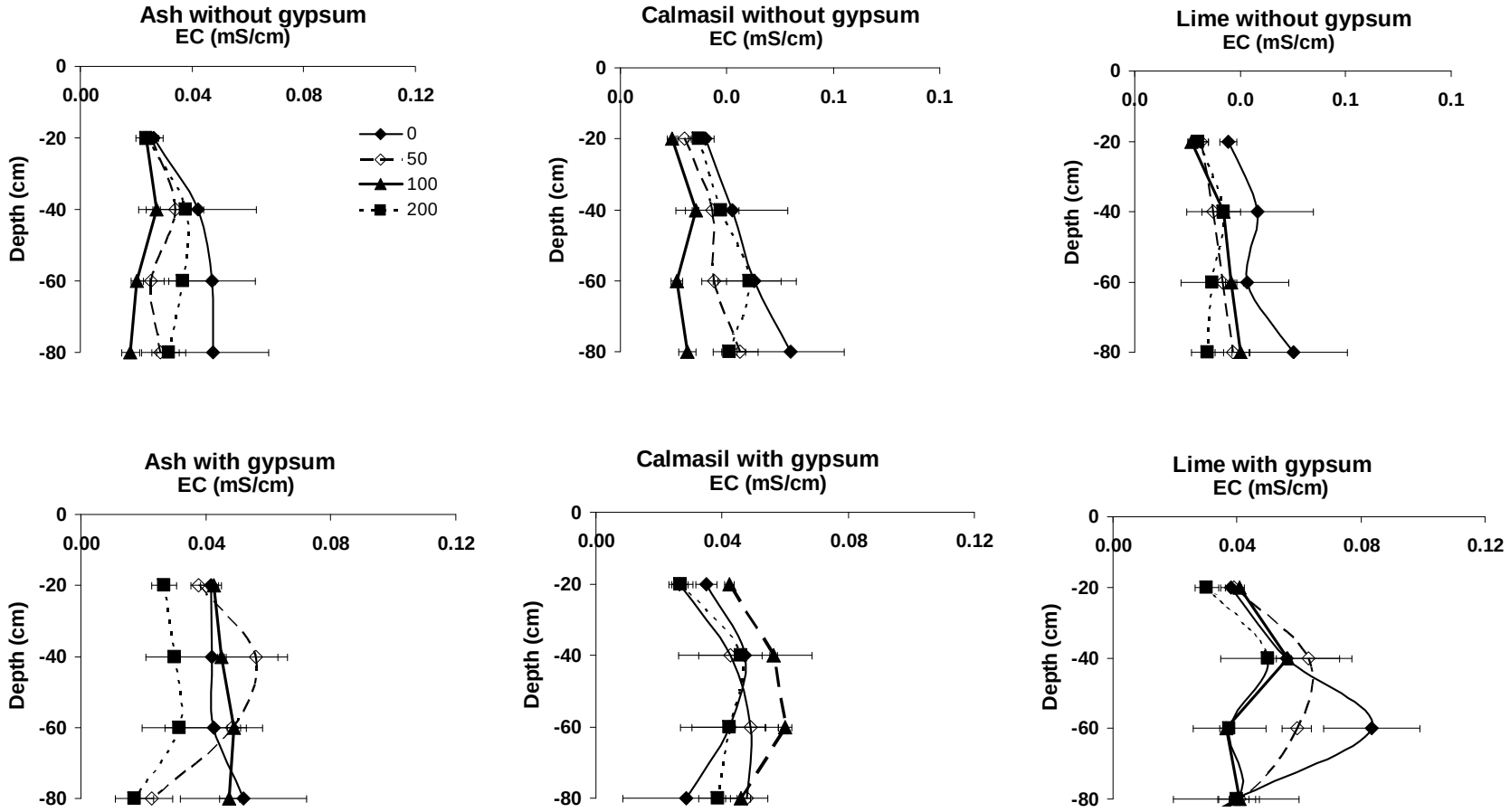

Appendix 6 Analytical data of dissolution batch experiments

Table 1 Soluble elements released from fly ash with batch dissolution experiment 1

		Al	Si	Fe	Ca	Mg	K	Na	P	As	B	Ba	Be
Initial pH and days of leachate agitation	**Final pH of leachate**	**mg/kg element in each leachate**											
pH 2 2d	2.38	4263.00	4728.00	492.90	14947.38	1781.87	1610.10	15263.97	947.70	23.21	71.40	296.07	0.96
pH 2 4d	2.38	5253.00	5877.00	519.90	14501.34	1968.39	1541.40	14976.12	942.90	22.79	77.88	325.80	1.16
pH 2 6d	2.37	5217.00	5751.00	563.70	13693.08	1815.37	816.90	14608.08	880.80	20.93	81.03	317.70	1.16
pH 2 8d	2.37	5406.00	5826.00	555.90	14189.46	1882.91	1159.50	15144.06	839.70	20.12	76.11	348.30	1.17
pH 2 10d	2.75	6225.00	6738.00	563.40	16642.38	2175.58	816.30	15187.14	864.30	21.15	86.40	371.40	1.37
pH 3 2d	8.37	20.75	967.20	0.56	9423.24	846.00	1660.50	63897.60	498.60	22.70	71.01	26.93	0.00
pH 3 4d	8.54	6.95	1096.50	0.27	8923.14	910.31	1465.50	62405.10	604.50	26.24	76.20	27.11	0.00
pH 3 6d	7.63	3.55	1320.00	0.44	9160.41	1043.00	1384.50	62229.30	449.70	22.77	81.93	38.28	0.00
pH 3 8d	7.40	2.18	1510.20	0.29	9072.33	1062.51	1604.40	62031.00	424.50	21.70	76.68	42.96	0.01
pH 3 10d	7.51	9.60	1470.30	0.32	10444.38	1151.73	1532.70	62219.10	536.40	27.66	90.39	35.64	0.00
pH 4 2d	10.08	128.61	744.00	0.58	4514.16	289.00	2792.10	63402.60	68.82	12.24	51.51	24.33	0.00
pH 4 4d	9.84	540.30	960.30	2.07	4949.82	347.41	1553.40	63170.70	117.30	13.07	53.85	26.20	0.00
pH 4 6d	10.07	508.50	1062.30	0.37	4951.80	326.88	1178.70	62732.40	58.71	11.13	53.91	29.26	0.01
pH 4 8d	9.42	554.40	1028.40	0.34	5030.88	410.03	1359.90	63534.00	92.13	13.83	56.49	27.18	0.01
pH 4 10d	9.79	514.50	1071.90	0.63	5208.93	382.04	1613.70	63592.20	91.62	14.59	57.54	29.68	0.00
pH 5 2d	9.99	373.80	930.60	1.20	4362.06	240.95	1257.60	62619.00	78.09	9.17	44.16	31.11	0.00
pH 5 4d	9.01	248.37	858.30	0.33	4874.46	356.89	1011.90	62913.00	54.54	11.54	48.66	25.55	0.00
pH 5 6d	10.21	525.30	1151.10	1.00	4758.90	285.55	1210.50	63608.70	50.34	10.25	57.81	29.45	0.01
pH 5 8d	10.11	600.90	1192.80	1.85	4747.14	369.56	1499.10	65505.30	64.20	11.40	54.18	31.20	0.00
pH 5 10d	10.25	426.00	1146.60	0.18	5006.19	351.20	1300.80	64907.10	37.35	12.26	61.14	30.42	0.01
pH 6 2d	9.81	341.70	799.20	1.74	4294.59	288.93	5013.00	63744.60	108.36	10.60	43.47	29.63	0.00
pH 6 4d	9.01	511.50	971.70	1.38	4807.20	335.61	7713.00	62811.60	79.83	12.75	49.41	30.72	0.01
pH 6 6d	9.96	457.20	1099.50	0.84	4736.43	305.67	2566.20	62706.60	60.63	8.39	46.23	31.59	0.01
pH 6 8d	10.17	571.80	1139.10	1.07	4621.50	359.93	2377.20	63408.00	84.66	11.49	43.68	31.92	0.01
pH 6 10d	9.87	477.90	1154.40	1.19	4951.26	413.30	2830.80	64949.70	70.38	8.99	46.80	32.40	0.00
pH 7 2d	9.50	284.34	675.30	4.60	4767.48	379.42	16701.00	63292.80	189.33	14.03	50.67	32.37	0.01
pH 7 4d	9.73	432.00	913.20	0.72	4723.71	382.73	8643.00	64246.20	105.96	12.05	52.05	30.27	0.00
pH 7 6d	10.13	453.90	1023.60	0.45	4673.19	340.53	3495.00	63100.80	78.42	9.89	58.44	31.77	0.00
pH 7 8d	10.07	583.20	1164.00	0.72	4464.93	341.00	3633.00	63890.40	66.36	10.91	49.74	31.11	0.00
pH 7 10d	10.13	609.60	1250.40	0.46	4799.25	389.78	3807.00	64139.70	53.31	11.56	52.80	34.35	0.01

Table 1 continues…

		Cd	Co	Cr	Cu	Mn	Mo	Ni	Pb	Se	Sr	Ti	V	Zn
Initial pH and days of leachate agitation	**Final pH of leachate**	**mg/kg element in each leachate**												
pH 2 2d	2.38	0.72	1.94	12.46	22.48	51.78	5.01	7.50	13.07	2.19	209.96	27.25	53.76	21.80
pH 2 4d	2.38	0.36	2.36	13.66	27.29	60.72	4.85	9.54	13.24	2.73	221.72	18.16	57.42	24.99
pH 2 6d	2.37	0.36	2.35	13.03	43.89	59.19	9.97	8.51	13.95	2.39	215.72	20.63	53.94	68.61
pH 2 8d	2.37	0.90	2.43	12.68	30.42	58.56	4.60	9.95	15.60	2.37	226.26	19.58	53.67	57.66
pH 2 10d	2.75	1.04	2.90	14.46	37.29	73.02	6.19	11.24	15.88	2.58	264.61	11.77	61.11	43.56
pH 3 2d	8.37	0.18		5.93	0.88	2.49	9.27	1.20	0.00	1.97	60.85	0.10	33.54	3.16
pH 3 4d	8.54	0.17		6.77	0.86	2.07	9.29	0.78	0.00	2.68	63.62	0.08	38.91	1.19
pH 3 6d	7.63	0.28	0.19	6.26	1.85	8.01	9.81	1.91	0.02	2.03	66.50	0.07	34.59	4.74
pH 3 8d	7.4	0.14	0.30	5.64	1.05	11.64	20.73	2.29	nd	1.87	68.82	0.10	34.77	3.20
pH 3 10d	7.51	0.53	0.02	7.54	1.17	5.54	15.86	0.69	0.00	2.39	74.27	0.08	40.89	4.26
pH 4 2d	10.08	0.10	nd	3.28	1.07	0.25	5.36	0.53	0.04	1.92	36.04	0.03	17.68	0.70
pH 4 4d	9.84	0.01	nd	3.40	0.83	0.93	5.40	0.12	nd	1.70	40.94	0.02	18.89	0.59
pH 4 6d	10.07	0.01	nd	3.56	2.36	0.07	6.11	0.06	0.01	1.60	44.17	0.06	19.93	0.30
pH 4 8d	9.42	0.06	nd	3.58	4.31	0.46	5.78	0.31	0.00	1.51	44.33	0.05	20.50	0.66
pH 4 10d	9.79	0.02	nd	3.86	1.25	0.35	19.56	0.14	nd	1.24	46.49	0.04	22.67	1.18
pH 5 2d	9.99	0.02	nd	3.26	0.17	0.84	5.77	0.12	nd	1.67	36.25	0.07	16.44	0.50
pH 5 4d	9.01	0.01	nd	3.25	0.66	0.28	5.06	0.54	nd	1.84	38.34	0.03	17.23	0.43
pH 5 6d	10.21	0.04	nd	3.62	1.21	0.14	6.61	0.27	0.02	1.92	44.38	0.03	19.59	1.16
pH 5 8d	10.11	0.14	nd	3.46	3.65	0.55	10.17	0.58	0.12	1.58	46.00	0.06	19.32	24.53
pH 5 10d	10.25	0.02	nd	3.55	0.97	0.41	23.10	0.08	nd	1.56	48.24	0.05	20.78	1.28
pH 6 2d	9.81	0.01	nd	3.41	0.55	0.39	5.42	0.15	nd	1.72	35.45	0.09	17.33	2.99
pH 6 4d	9.01	0.02	nd	3.62	0.26	0.89	6.26	0.19	0.01	1.93	41.63	0.01	19.58	0.90
pH 6 6d	9.96	0.13	nd	3.26	2.00	0.30	5.70	0.41	0.08	1.48	41.42	0.03	17.68	1.28
pH 6 8d	10.17	0.14	nd	3.36	1.83	0.17	5.70	0.45	0.10	1.34	42.37	0.01	18.96	11.22
pH 6 10d	9.87	0.10	nd	3.57	1.60	0.24	10.13	0.46	0.08	1.74	45.70	0.05	19.37	0.88
pH 7 2d	9.5	0.02	nd	3.54	0.79	0.42	6.24	0.42	0.01	1.83	38.05	0.09	18.89	2.37
pH 7 4d	9.73	0.11	nd	3.72	1.43	0.35	6.52	0.41	0.05	1.87	40.44	0.04	19.21	1.84
pH 7 6d	10.13	0.02	nd	3.45	1.08	1.49	9.87	0.12	nd	1.53	42.16	0.04	18.72	5.43
pH 7 8d	10.07	0.01	nd	3.46	2.66	0.22	6.61	0.11	0.03	1.62	43.03	0.02	19.38	1.51
pH 7 10d	10.13	0.01	nd	3.69	2.01	0.65	14.93	0.13	nd	1.77	48.43	0.03	20.66	3.99

Table 2 Soluble elements released from Calmasil and lime with batch dissolution experiment 1

	Days		Al	Fe	Si	Ca	Mg	Na	K	P	As	B	Ba
Initial pH of leachate		**Final pH**	**mg/kg element in each leachate**										
Calmasil													
pH 2	2	10.15	n.d	n.d	10249.02	62224.20	4365.54	732.47	680.40	11.11	0.08	10.40	20.13
pH 2	6	9.8	n.d	n.d	10298.10	55195.50	6792.81	442.62	362.40	0.69	0.03	7.16	14.89
pH 2	10	9.81	n.d	n.d	10753.05	107931.90	10126.11	372.03	493.20	n.d	0.03	15.83	29.54
pH 2	28	4.16	7.52	n.d	6961.17	42995.10	16.73	247.20	328.80	n.d	0.02	14.10	25.72
pH 4	2	11.45	46.77	n.d	3683.43	16244.91	37.18	66087.90	374.40	n.d	0.05	14.42	16.13
pH 4	6	11.54	53.70	n.d	4059.30	21319.11	16.60	65331.90	473.70	1.79	0.04	16.91	20.51
pH 4	10	11.51	48.15	n.d	4572.57	20484.42	17.59	63798.60	282.51	0.39	0.02	13.88	16.65
pH 4	28	11.51	60.27	n.d	5074.53	21846.75	6.20	61292.10	316.20	3.47	0.02	17.53	19.97
pH 6	2	11.42	51.66	n.d	3726.12	17196.87	39.89	64605.60	1051.80	1.05	0.10	13.49	19.79
pH 6	6	11.51	42.42	0.25	4215.36	21548.13	20.39	63054.60	1709.70	n.d	0.10	21.77	29.45
pH 6	10	11.42	45.54	0.04	4988.82	17981.64	27.10	62185.50	282.57	2.89	0.07	14.12	20.86
pH 6	28	11.59	58.47	n.d	4870.65	22782.33	3.39	61759.80	762.60	n.d	0.03	16.38	20.91
Lime													
pH 2	2	6.82	n.d	n.d	167.41	88641.30	4019.37	636.59	858.60	n.d	0.08	n.d	7.13
pH 2	6	6.91	8.15	7.39	236.65	82814.70	4635.63	1078.63	545.70	0.54	0.13	n.d	8.88
pH 2	10	6.62	n.d	0.34	401.85	144699.60	9234.87	285.24	471.90	6.52	0.10	n.d	12.53
pH 2	28	7.48	0.79	0.71	756.77	46252.80	2321.94	321.76	1060.20	n.d	0.11	n.d	4.43
pH 4	2	10	2.58	0.21	217.23	2327.37	395.90	62296.80	452.40	n.d	0.09	4.34	1.40
pH 4	6	9.6	6.25	n.d	166.20	2405.35	408.86	61666.50	793.20	5.91	0.36	5.03	1.79
pH 4	10	10.03	4.19	0.17	885.21	2981.25	467.76	60317.70	363.30	0.13	0.06	n.d	1.00
pH 4	28	8.92	4.64	0.27	632.35	3568.41	663.38	61057.50	528.30	1.29	0.16	1.19	1.80
pH 6	2	9.88	3.14	0.19	257.27	2038.38	416.82	58905.00	900.30	0.67	0.28	1.81	3.17
pH 6	6	9.42	3.36	n.d	324.72	3132.30	476.76	60663.00	1910.70	n.d	0.55	7.28	8.17
pH 6	10	9.76	5.91	0.59	397.09	2060.64	378.26	58908.00	315.60	n.d	0.36	2.44	3.19
pH 6	28	9.35	6.30	0.22	531.74	2303.32	540.19	62187.30	1032.30	n.d	0.17	n.d	1.28

Table 2 continues…

	Days	Cd	Co	Cr	Cu	Li	Mo	Mn	Ni	Pb	Se	Sr	Ti	V	Zn
Initial pH of leachate		**mg/kg element in each leachate**													
Calmasil															
pH 2	2	n.d	n.d	9.88	n.d	1.72	6.29	n.d	0.14	0.00	0.53	16.79	0.01	9.94	n.d
pH 2	6	0.01	n.d	1.64	n.d	0.87	3.35	0.06	0.75	0.00	0.30	12.32	n.d	5.88	n.d
pH 2	10	n.d	n.d	2.67	n.d	2.33	5.09	0.10	0.60	n.d	0.24	30.51	0.00	7.54	n.d
pH 2	28	n.d	n.d	17.15	n.d	1.53	5.25	n.d	0.04	n.d	0.67	14.66	n.d	9.95	n.d
pH 4	2	n.d	n.d	12.26	n.d	0.57	4.01	n.d	0.01	0.00	0.64	6.20	n.d	5.06	n.d
pH 4	6	n.d	n.d	16.46	n.d	0.89	5.40	n.d	0.01	0.00	0.75	8.85	n.d	6.43	n.d
pH 4	10	n.d	n.d	14.97	2.01	0.93	4.72	n.d	0.02	0.00	0.46	8.71	n.d	6.82	n.d
pH 4	28	n.d	0.00	15.13	n.d	1.21	4.22	n.d	0.03	n.d	0.49	9.06	n.d	6.72	n.d
pH 6	2	n.d	n.d	12.27	n.d	0.75	7.29	n.d	0.04	0.00	0.36	6.58	n.d	5.02	n.d
pH 6	6	n.d	n.d	14.54	n.d	0.64	6.72	n.d	0.06	0.00	0.52	7.85	n.d	6.28	n.d
pH 6	10	0.01	n.d	13.29	0.19	0.98	4.66	0.05	0.03	n.d	0.54	7.41	0.05	6.19	n.d
pH 6	28	n.d	n.d	16.43	0.29	1.17	15.01	n.d	0.03	n.d	0.51	9.15	n.d	7.64	n.d
Lime															
pH 2	2	n.d	n.d	0.20	n.d	0.34	0.46	0.65	0.51	n.d	0.15	36.78	n.d	7.43	n.d
pH 2	6	0.05	n.d	0.19	n.d	0.40	0.50	11.49	0.61	0.02	0.16	40.71	0.52	7.79	0.04
pH 2	10	0.09	0.05	0.69	n.d	0.79	0.67	37.20	1.37	0.00	0.19	74.28	n.d	7.55	0.09
pH 2	28	n.d	n.d	0.19	n.d	0.75	0.31	1.55	0.09	n.d	0.12	24.57	0.06	6.87	n.d
pH 4	2	n.d	n.d	0.10	n.d	0.83	0.10	0.07	0.01	n.d	0.36	5.08	n.d	10.31	n.d
pH 4	6	n.d	n.d	0.07	n.d	0.78	0.40	n.d	0.00	n.d	0.42	6.40	n.d	10.92	n.d
pH 4	10	n.d	n.d	0.57	n.d	0.64	0.46	n.d	0.01	n.d	0.23	6.46	n.d	16.26	n.d
pH 4	28	n.d	n.d	0.08	n.d	1.07	0.08	0.28	0.01	n.d	0.34	9.50	n.d	11.66	n.d
pH 6	2	n.d	n.d	0.09	n.d	0.68	2.65	0.01	0.05	n.d	0.13	5.59	n.d	12.10	n.d
pH 6	6	n.d	n.d	0.09	n.d	0.89	1.80	0.18	0.12	0.00	0.18	6.88	n.d	10.69	0.07
pH 6	10	n.d	n.d	0.18	n.d	0.87	0.41	n.d	0.00	n.d	0.16	5.51	n.d	12.61	n.d
pH 6	28	n.d	n.d	0.07	n.d	0.87	1.40	n.d	0.01	n.d	0.16	9.69	n.d	15.56	n.d

Table 3 Soluble elements released from fly ash with batch dissolution experiment 2

			Al	Si	Fe	Ca	Mg	Na	K	P	As	Be	Ba	B
Cumulative volume leachate (ml)	**Initial adjusted pH**	**Final pH**	**Cumulative soluble element concentration (mg/kg)**											
30	pH 2	2.27	7035.00	7341.00	865.50	2793.47	392.36	28945.38	1519.20	1146.00	24.29	1.20	394.50	79.26
55	pH 2	1.99	8655.50	8840.50	1516.50	3965.57	554.44	36424.16	7654.20	1545.75	30.74	1.45	538.60	100.41
80	pH 2	2.1	9758.50	9741.25	2645.50	4527.90	628.31	50536.58	12719.20	1988.00	36.07	1.62	606.60	111.30
105	pH 2	2.02	10205.75	10270.50	2877.63	78613.15	1289.77	54117.16	16826.70	2063.48	37.25	1.67	663.63	126.93
30	pH 3	8.38	7.74	1554.90	0.28	9265.29	1064.29	62249.70	1798.50	602.70	28.15	0.00	30.72	83.01
55	pH 3	3.96	1019.99	3266.65	14.02	12418.84	1576.67	113902.70	8308.50	725.93	32.01	0.43	169.27	109.41
80	pH 3	3.85	2349.99	4743.40	67.75	13548.55	1756.85	166503.45	11631.00	866.10	33.92	0.68	244.60	119.20
105	pH 3	3.56	3442.49	5810.90	147.62	25481.57	3370.14	191316.55	14666.00	973.55	34.86	0.84	289.27	124.06
30	pH 4	10.09	73.38	1009.50	0.25	4916.82	477.89	64217.10	1123.80	34.05	14.44	0.00	23.81	56.79
55	pH 4	7.79	80.15	1766.50	0.51	8591.12	912.35	116383.10	4681.30	376.80	25.34	0.01	47.10	88.24
80	pH 4	6.63	80.86	2379.00	0.79	10450.82	1195.66	168856.10	11853.80	518.90	29.43	0.02	91.78	102.77
105	pH 4	5.02	87.25	2749.75	1.49	11202.44	1336.80	221256.85	15528.80	526.58	29.93	0.12	138.95	110.30
30	pH 5	10.41	589.80	1415.40	0.39	4883.49	346.30	63292.50	1017.00	36.84	9.80	0.00	33.03	57.03
55	pH 5	8.64	614.15	2109.90	0.60	8403.59	831.27	115272.50	3579.50	399.09	22.27	0.01	55.28	88.68
80	pH 5	7.07	615.66	2837.90	1.01	10486.03	1160.20	166290.25	5430.00	682.59	28.03	0.01	90.13	112.40
105	pH 5	6.15	616.36	3195.40	1.30	11292.22	1304.91	219723.50	7887.50	758.49	29.59	0.01	131.66	120.01
30	pH 6	10.34	657.00	1417.80	0.62	4939.32	344.66	62112.60	2271.00	31.41	11.16	0.00	33.24	52.20
55	pH 6	8.89	674.57	2056.05	0.76	8281.22	799.88	114315.10	4061.00	277.46	22.24	0.01	59.44	75.39
80	pH 6	8.47	695.28	2550.80	0.96	10226.98	1044.56	167636.10	6355.00	537.46	27.87	0.01	77.91	87.83
105	pH 6	7.42	702.00	2942.05	1.40	11261.77	1191.23	221261.60	9415.00	746.44	30.72	0.01	95.30	95.55
30	pH 7	10.36	502.20	1356.60	0.74	4765.56	320.93	63452.10	1196.70	34.17	8.81	0.01	29.20	49.71
55	pH 7	8.39	521.44	1985.60	1.11	7995.71	765.72	115106.85	4549.20	317.17	19.04	0.01	59.65	74.71
80	pH 7	7.25	528.27	2483.35	1.47	9825.95	1004.27	167495.85	29324.20	565.57	23.97	0.01	84.54	88.87
105	pH 7	7.02	529.55	2831.10	1.78	10735.07	1156.36	219974.85	32999.20	681.45	26.05	0.01	113.89	96.21

Table 3 continues..

			Cd	Co	Cr	Cu	Mn	Mo	Ni	Pb	Se	Sr	Ti	V	Zn
Cumulative volume leachate (ml)	**Initial adjusted pH**	**Final pH**	**Cumulative soluble element concentration (mg/kg)**												
30	pH 2	2.27	0.64	2.83	14.93	43.41	79.05	4.83	12.95	7.82	2.82	57.53	43.14	62.40	29.81
55	pH 2	1.99	0.86	3.49	18.10	55.37	97.08	6.54	16.07	12.60	3.54	84.71	161.97	72.36	41.75
80	pH 2	2.1	1.16	4.06	21.07	69.68	111.57	7.92	18.38	24.55	5.03	93.87	407.62	77.58	57.37
105	pH 2	2.02	1.38	4.23	21.78	84.14	116.03	11.45	19.61	33.40	5.38	936.13	460.04	78.65	69.56
30	pH 3	8.38	0.03	0.02	7.47	0.26	5.44	10.81	0.83	0.00	2.92	66.82	0.04	42.90	1.14
55	pH 3	3.96	0.37	0.99	8.99	17.83	31.84	11.46	6.00	0.75	3.46	113.10	0.11	48.11	21.22
80	pH 3	3.85	0.51	1.54	9.94	28.30	45.42	11.79	8.94	1.98	3.79	142.54	0.45	52.26	33.39
105	pH 3	3.56	0.89	1.90	10.60	42.47	54.49	12.00	11.37	3.85	4.05	336.70	1.21	55.09	42.33
30	pH 4	10.09	0.02	0.00	3.98	1.11	0.47	6.05	0.23	0.00	1.91	45.64	0.01	22.63	0.41
55	pH 4	7.79	0.04	0.00	6.66	1.21	2.46	9.54	0.49	0.00	2.67	73.43	0.02	38.60	5.05
80	pH 4	6.63	0.19	0.21	7.96	2.35	11.03	11.91	1.62	0.04	3.13	90.65	0.05	45.83	14.29
105	pH 4	5.02	0.76	0.44	8.07	7.64	19.27	12.36	3.58	0.25	3.37	99.31	0.06	47.02	29.01
30	pH 5	10.41	0.03	0.00	3.95	1.28	0.02	5.96	0.08	0.00	1.73	49.70	0.02	21.26	0.16
55	pH 5	8.64	0.12	0.00	6.58	2.34	0.60	13.38	0.44	0.09	2.73	76.60	0.05	37.45	0.63
80	pH 5	7.07	0.18	0.04	8.20	3.60	6.70	17.23	1.42	0.09	3.13	94.51	0.09	45.81	2.70
105	pH 5	6.15	0.34	0.17	8.54	4.88	14.28	18.51	2.94	0.10	3.29	102.89	0.18	48.69	6.35
30	pH 6	10.34	0.01	0.00	4.05	0.22	0.06	6.02	0.09	0.00	1.89	48.60	0.01	22.19	0.46
55	pH 6	8.89	0.03	0.00	6.33	0.83	0.59	10.36	0.40	0.02	2.67	75.18	0.03	36.39	1.52
80	pH 6	8.47	0.04	0.00	7.65	1.27	1.33	11.98	0.59	0.03	3.10	90.62	0.08	43.78	2.85
105	pH 6	7.42	0.22	0.00	8.41	2.79	2.54	13.34	1.91	0.04	3.27	100.74	0.16	47.87	5.22
30	pH 7	10.36	0.01	0.00	3.90	3.09	0.53	6.49	0.14	0.00	1.66	47.54	0.05	20.38	2.20
55	pH 7	8.39	0.03	0.00	6.06	4.38	1.51	11.02	0.51	0.01	2.15	71.94	0.09	33.53	2.86
80	pH 7	7.25	0.28	0.00	7.26	6.29	3.63	13.04	1.21	0.06	2.52	86.57	0.13	40.07	7.94
105	pH 7	7.02	0.36	0.00	7.93	7.49	6.90	14.31	1.63	0.06	2.72	95.02	0.15	43.41	9.90