ZINC FRACTIONS IN SELECTED ZAMBIAN SOILS AND MAIZE AND WHEAT RESPONSES TO ZINC APPLICATION

By

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DECLARATION

I, **Meki Chirwa**, declare that this dissertation represents my own work and that it has not previously been submitted for a degree at this or any other university.

Signature Chirwa Meki

Date 28|04|09

APPROVAL

This dissertation of **Meki Chirwa** has been approved as a partial fulfilment of the requirements for the award of the degree of Master of Science in Agronomy (Soil Science) by the University of Zambia.

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ABSTRACT

Incidences of plant and soil zinc (Zn) deficiency have been reported in many countries. The University of Zambia soil analysis laboratory has observed that a high percentage of soil samples analyzed fall below the critical limits for Zn. Field experiments were conducted at the University of Zambia School of Agricultural Sciences Field Station to assess the response of one crop of wheat and two crops maize to soil and foliar application of Zn fertilizer. One half of each plot was assigned to treatments to receive soil application of Zn while the other half received foliar application. Zinc treatments were applied to designated plots at 25, 50, 75 or 100 kg $ZnSO_4$ ha^{-1} in a randomized complete block design with three replications. At seven weeks after planting maize (*Zea mays* MRI 724) or wheat (UNZA *WV* 1), foliar application of Zn fertilizer at 2.5, 5.0, 10 or 20 kg $ZnSO_4$ ha^{-1} was made to designated plots, again in a randomized complete block design with three replications. Grain yield and uptake were determined. Laboratory experiments were conducted to define various pools of soil Zn. Twenty two different soils were fractionated using batch extraction schemes. These soils were further cropped in the greenhouse to determine Zn uptake by wheat at six weeks. Plant uptake and soil Zn pools were used in the correlation analysis. The results showed that methods of application were significantly different for both maize and wheat, ($P = 0.0001$) and ($P = 0.0043$), respectively. The maize grain yield from the soil applied fields were higher (1.78 t ha^{-1}) than from the foliar applied fields (1.14 t ha^{-1}). The wheat grain yield was higher in the soil applied fields (3.69 t ha^{-1}) than in the foliar applied fields (2.74 t ha^{-1}). Both crops responded to Zn application and the Zn concentrations of the crops were more in the treated fields than in the controls except for the wheat foliar applied field. The mean uptake of Zn by maize in the plots with soil applied Zn ranged from 31.97 to 77.23 mg while that from foliar application ranged from 22.74 to 80.52 mg. The mean uptake of Zn by wheat in the plots with foliar applied Zn ranged from 5.13 to 10.11 mg while that of the soil applied Zn ranged from 8.89 to 14.63 mg. Results from fractionation study showed that the distribution of Zn was as follows: sesquioxide (45.5 percent) > residual (34.1 percent) > carbonate bound Zn (17.1 percent) > organically bound (9.5 percent) > exchangeable pool (5.5 percent). The sesquioxide bound Zn supplied significantly more Zn ($P = 0.056$; $R^2 = 0.19$) to wheat crop. The supply of Zn by other pools was non significant. The results obtained showed that soil application of Zn fertilizer could be more effective than foliar application. It was also observed that higher rates of Zn fertilizer application induced lower yields. In addition, the DTPA soil test method appears to be week in detecting plant available Zn from the sesquioxide Zn pool which was the major supplier of Zn in this study.

DEDICATION

To my sons, Taonga and Kalasa and my daughter Temwanani, with my deepest love.

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LIST OF ABBREVIATIONS

DTPA	Diethylene triamine penta acetic acid
BCR	Community Bureau of Reference
AAS	Atomic Absorption Spectrophotometer
UNZA	University of Zambia
CRD	Complete Randomized Design
RCBD	Randomized Complete Block Design
CEC	Cation Exchange Capacity
Redox	Reduction and Oxidation

CHAPTER ONE

1.0 INTRODUCTION

The requirement for zinc (Zn) as an essential element in plant nutrition has been adequately established (Mengel and Kirkby, 1987; Tisdale *et al.*, 1985). Consequently reduced crop productivity has occasionally been reported when it is deficient in the soil (Alloway, 2007). The problem of Zn deficiency is a global one.

Incidences of plant and soil Zn deficiency have been reported in many countries. Karak *et al.* (2006) reported that 60 percent of the soils in India were Zn deficient. The soils in Savanna under intense cultivation have low soil Zn levels (Agbenin, 2003). Cakmak *et al.* (1999) observed that 14 Mha of land in Turkey was Zn deficient. The Zn deficiency symptoms have been observed in the acidic sandy soils of Spain (Rico *et al.*, 2007). Furlani *et al.* (2005) observed that the acidic soils of Brazil were prone to Zn deficiency. The calcareous soils of Australia were observed to have low soil Zn levels (McDonald *et al.*, 2001). Maftoun and Karimian (1989) also observed that the calcareous soils of Iran were deficient in soil Zn.

In Zambia, Banda and Singh (1989) reported that high rainfall areas of Zambia have low soil Zn levels. Since then the University of Zambia soil analysis laboratory has observed that a high percentage of soil samples analyzed fall below the critical limits for Zn (O. A. Yerokun, personal communication, 2007). The reasons for such high incidences of low soil Zn in Zambia have not been elucidated. Despite the reporting of low Zn in soils, Zn deficiency symptoms have not been documented (Banda and Singh, 1989). This may be because the effects of low nitrogen, phosphorus and potassium are probably observed much sooner than Zn deficiencies. Such latent Zn deficiency symptoms (which are not easily observed) cause about 40 percent reductions in yields (Alloway, 2007).

In order to avoid yield losses due to Zn deficiency, Zn fertilizers may be applied as corrective measures through foliar application in season or at planting to the soil if the soil tests show deficiencies (Follet and Westfall, 2004). Sharma *et al.* (1988)

recommended soil application of Zn sulphate within 45 days of planting. The suitable rates of Zn soil application for maize-mungbean-rice system were observed to be 4-0-2 kg ha^{-1} in the first year and 2-0-2 kg ha^{-1} Zn for the years that follow (Hossain *et al.*, 2008). Panhwar *et al.* (2003) observed that foliar application of Zn sulphate was more effective than soil application. Soleimani (2006) combined both soil and foliar application at 0.3 and 0.6 percent Zn rate and observed that the yields were higher than just the soil application. The application of foliar spray of Zn in inorganic or organic form was comparatively suitable to provide the much needed Zn nutrient for wheat (Haslett *et al.*, 2000). Maftoun and Karimian (1989) also observed that soil application of $ZnSO_4$ (inorganic) and ZnEDTA (organic) fertilizers produced the same dry matter of maize plants.

In the extraction of Zn for analysis, Srivastava *et al.* (2008) used two different reagents to determine the critical limits of Zn in Indian mollisols and found out that it was 0.57 mg kg^{-1} for 0.005 M diethylene triamine penta acetic acid (DTPA) and 1.72 mg kg^{-1} for Mehlich 3. According to Brennan and Bolland (2002) spring wheat and durum wheat only produced optimum yields when the youngest leaf tissues contained 14 mg kg^{-1} and 20 mg kg^{-1}, respectively. The critical limits of Zn in soils for wheat were 0.6 mg kg^{-1} for DTPA-$CaCl_2$ and 0.7 mg kg^{-1} for NH_4HCO_3-DTPA (Sharma *et al.*, 1996). Potatoes grown in India responded to Zn application if soils contained below 0.75 mg kg^{-1} DTPA extractable Zn (Trehan and Grewal, 1995). Zinc fertilizer application was recommended only when soils contained below 0.65 mg kg^{-1} and plants contained below 18 mg kg^{-1} Zn (Singh and Karwasra, 1988). Singh (1986) observed that the critical limit of Zn in soils was 0.54 ppm and that it was 15.4 ppm in plants. The critical levels of Zn for wheat grown on non calcareous soils were observed to be 1.75 mg kg^{-1} soil Zn (0.1N HCl extractable Zn) and 1.7 mg kg^{-1} in wheat plant tissues (Singh and Shukla, 1985). Rice grown on calcareous soils of India was observed to respond to Zn fertilizer application when soils and plants contained below 0.78 ppm and 19 ppm, respectively (Sakal *et al.*, 1982). Banda and Singh (1989) in Zambia concluded that the critical levels of soil Zn for maize were 0.70, 2.00, 1.50 ppm for 0.005 M DTPA, 0.1N HCl and NH_4OAc-EDTA, respectively.

Fractionation schemes are used to determine the behaviour and mobilization of minerals species in soils (Hseu, 2006). Voegelin *et al.* (2008) used sequential extraction schemes and observed that when the pH of the soil decreased from 6 to 5, the exchangeable pool increased. Fedotov and Spivakov (2008) characterized the following fractions: water and exchangeable; acid soluble; oxidizable; reducible and the residual pools. Savonia *et al.* (2006) only defined three pools: the exchangeable, reducible and acid soluble pools. According to Dvorak *et al.* (2003) Zn could be bound by organic matter, clay particles and sesquioxides. Zerbe *et al.* (1999) defined the exchangeable, carbonate, sesquioxide, organic and residual bound Zn. The pools which contain Zn that was readily available for uptake by plants included the water soluble and exchangeable forms (Rico *et al.*, 2007; Covelo *et al.*, 2004; Dvorak *et al.*, 2003; Johnson and Petras., 1998). Both single and sequential procedures have been used to define and characterize various Zn fractions in soils (Margui *et al.*, 2007). There is no report to show that Zn fractions have ever been defined and characterized in Zambia to improve the understanding of Zn availability to plants. Defining the various Zn pools in soils and quantifying them may provide information on the distribution of Zn in the soils and these can be related to Zn soil test levels. This information could help improve soil Zn management and consequently increase crop productivity of the soils.

Therefore, the objectives of the study were to: (1) characterize the distribution of Zn in its various fractions in soils; (2) establish the relationship between the various Zn fractions and uptake by wheat from the soil, and (3) determine the response of wheat and maize to different rates of foliar or soil applied Zn.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 The Role of Zinc in Plants

Zinc is an essential micronutrient required by plants in relatively small amounts ranging from 5-100 mg kg^{-1} (Tisdale *et al.*, 1985). It is as a functional, structural and regulatory cofactor in many enzyme systems in plants (Tisdale *et al.*, 1985; Mengel and Kirkby, 1987). The synthesis of growth hormones such as indoleacetic acid is impaired in Zn deficient crops (Vitosh *et al.*, 1994; Marschner, 1995). This disturbs the normal growth of a plant leading to stunted growth, a characteristic symptom of Zn deficiency (Mengel and Kirkby, 1987).

Zinc activates carbonic anhydrase-an enzyme that catalyses the hydrolysis and hydration reactions of carbonyl groups (Marschner, 1995; Mengel and Kirkby, 1987). Zinc deficiency results in reduced activity of this enzyme that consequently causes a reduction in net photosynthesis by about 50 to 70 percent (Alloway, 2007).However, contrary to this notion, Marschner (1995) proposed that maximum net photosynthesis takes place even in the absence of carbonic anhydrase though the pool of carbon dioxide declines. Nonetheless, if the pool of carbon dioxide decreases, assimilation of it declines and consequently affects photosynthesis negatively. Other enzymes that are activated by Zn and are involved in carbohydrate metabolism include aldolases and fructose-1, 6-bisphosphatase, which are involved in the synthesis of sucrose and fructose, respectively (Alloway, 2007; Marschner, 1995). Absence of Zn therefore, disturbs the production of carbohydrates necessary for normal healthy growth of crops.

Zinc deficiency reduces protein synthesis in crops (Alloway, 2007). It activates RNA polymerase, enhances the structural integrity of ribosomes, and reduces the activity of RNAse thus protecting RNA from degradation (Mengel and Kirkby, 1987). Under conditions of Zn deficiency therefore, the crop will lack sufficient proteins. This will affect the stability and functions of generic materials and enzymes. If the functions of enzymes are impaired, metabolic pathways will be impaired too. The growth and health of the plant suffers too. Zinc is also important in fertilization and its absence leads to reduced grain and seed yield (Marschner, 1995). Diagnosis of Zn problems is, therefore, of utmost importance.

2.2 Availability of Zinc

The availability of micronutrients to the plant is strongly influenced by weather and soil conditions. *The availability of Zn in soils is, therefore, closely related to both the physical and chemical properties* of the soil.

2.2.1 Conditions and factors influencing availability of zinc to plants

2.2.1.1 Soil pH

Zinc is highly sensitive to changes in pH (Tisdale *et al.*, 1985). Thom *et al.*, (2007) analyzed soils in Kentucky and showed that Zn deficiencies were highly affected by high pH levels. Vitosh *et al.* (1994) observed that because of their high pH values (usually above 8.0), calcareous soils were prone to Zn deficiency. If the pH of the soil decreases, the concentration of Zn in soil solutions increases and becomes more readily available for uptake (Dvorak *et al.*, 2003). Voegelin *et al.* (2008) observed that when the pH of the soil decreased from pH 6 to pH 5, the quantity of the mobilizable fraction increased. This means that solubility of Zn decreases as the pH of the soil increases. This is partly due to formation of insoluble compounds of Zn such as $Zn(OH)_2$ and $ZnCO_3$ at pH values above 8.0 (Tisdale *et al* , 1985; Mengel and Kirkby, 1987; Alloway, 2007). The same reasons could be extended to explain high incidences of Zn deficiency in over limed soils. Over Liming of acidic soils raises soil pH thus affecting Zn solubility because Zn could be precipitated by liming agents such as magnesium containing carbonates (Alloway, 2007; Tisdale *et al.*, 1985; Brady, 1984). Over liming thus depresses Zn uptake. According to Hanc *et al.* (2002) the addition of lime to soils reduced Zn mobility. In Zambia, there has been increasing recommendations to use lime in small holder farms. This could potentially induce Zn deficiency if the soils are over limed.

2.2.1.2 Adsorption

Adsorption of Zn by soil components such as clay minerals, sesquioxides and organic compounds depends on pH (Covelo *et al.*, 2004; Dvorak *et al.*, 2003; Fontes *et al.*, 2001; Tisdale *et al.*, 1985). At near neutral pH, Zn was bound by organic matter while under acidic conditions it was bound by sesquioxides (Covelo *et al.*, 2004).

The bioavailability of micronutrients in the soil was governed by sorption/desorption phenomena at the soil-colloid solution interface (Dhanwinder *et al.*, 2006). Alvarez *et al.* (2003) reported that through isomorphous substitution or solid state diffusion, Zn^{2+} cations may enter layer silicates and be fixed irreversibly. This means that Zn could be fixed in clay minerals such as illite and kaolinite. If Zn replaces aluminium or magnesium in the crystal lattice irreversibly, it would not be desorbed. However, if fixed reversibly, it is an exchangeable cation and could be taken by plants once released into the soil solution. Dvorak *et al.* (2003) observed that organically bound Zn and Zn bound in sesquioxides could be potentially available while the residual pool may not be available for plant uptake. The organically bound form is potentially available because it can be released into the soil solution when organic matter decomposes and when released as an exchangeable cation (Donahue, *et al.*, 1983).

Udom *et al.* (2004) in SE Nigeria observed that the binding of minerals by organic matter minimized mobility of these minerals and reduced the chances of toxic effects on crops and soils. Covelo *et al.* (2004) in Galicia (Spain) and Udom *et al.* (2004) concluded that high organic matter contents of the soils together with corresponding low pH values favoured formation of zinc-organic complexes. These complexes reduce mobility of the minerals such as Zn and, therefore, prevent phytotoxicity. It is, therefore, important to assess pH changes and soil organic matter frequently because these two significantly affect the ability of the soils to retain minerals (Andersen *et al.*, 2002). Organic matter controls the mobility and solubility of Zn in some soils. Catlett *et al.* (2002) analyzed 18 alkaline soils from three farms in eastern Colorado. They concluded that free Zn ions may adsorb on organic matter in regions of low pH and precipitate as franklinite ($ZnFe_2O_4$), or as other Zn containing minerals such as kerolite at high pH. In calcareous soils, Zn precipitates as $Zn(OH)_2$ or $ZnCO_3$ (Alloway, 2007; Tisdale *et al.*, 1985). Formation of such compounds makes access of the cation (Zn^{2+}) by plants difficult. Kumar and Basavaraj (2008) concluded that low Zn levels were observed in soils which had high pH values (as a result of free calcium carbonate) and low organic matter content.

Fontes *et al.* (2001) analyzed Brazilian soils to assess how the mobility of minerals was affected by chemical and mineralogical properties of soils. They concluded that soil chemical properties were better estimators than mineralogical characteristics to predict the mobility and retention of minerals. Muhammad *et al.* (2006), working on alkaline soils from Pakistan and acidic soils from UK showed that soils with high cation exchange capacity, calcium carbonate content, organic matter, and heavy texture adsorbed more Zn. They also observed that alkaline soils from Pakistan adsorbed more Zn than the acidic soils from England; and that the solubility of Zn was high in acidic soils than in alkaline soils.

2.2.1.3 Other factors

Studies have shown that the availability of Zn decreased drastically due to either one or all of the following: intensive farming, growing of high yielding varieties, application of high analysis NPK fertilizers against non use of Zn fertilizers and reduced or non use of sewerage sludge and organic manures (Behera *et al.*, 2008, and Maftoun and Karimian, 1989). According to Rico *et al.* (2007) and Agbenin (2003) intensive cropping of high yielding varieties usually leads to a reduction in nutritional status of the soils and consequently a reduction in crop productivity. Unlike super phosphate which contains Zn as an impurity, high analysis fertilizers such as mono-ammonium phosphate are pure and do not contain Zn as an impurity. Continued use of pure fertilizers has increased incidences of Zn deficiency (Behera *et al.*, 2008; Alloway, 2007).

Other factors that influence Zn availability include its interactions with other ions (competition, antagonism and synergism), flooding and climatic conditions (Tisdale *et al.*, 1985). The P induced Zn deficiency is not because of the formation of

$Zn_3(PO_4)_2 4H_2O$ (which is soluble) but because of the physiological interactions of P and Zn in the plant (Alloway, 2007; Mengel and Kirkby, 1987). It is also believed that P inhibits mycorrhizal uptake of Zn (Tisdale *et al.*, 1985).

2.2.2 Methods of extraction of plant available zinc

Different reagents are used to extract Zn that is available for uptake by plants. Srivastava *et al.* (2008) used different reagents to extract Zn and determine the critical limits of Zn in soils and found out that it was 0.57 mg kg^{-1} for 0.005 M diethylene triamine penta acetic acid (DTPA) and 1.72 mg kg^{-1} for Mehlich 3. Srivastava *et al.* (2008) also concluded that Mehlich 3 was the suitable extractant for available Zn. They observed that the order of the ability of the reagents to extract plant available Zn from the soils was: Mehlich 3 > 0.005 M DTPA + 1 M ammonium bicarbonate > 0.01 M EDTA + 0.05 M ammonium carbonate > 0.005 M DTPA> $MgCl_2$. The critical limits of Zn in soils for wheat were 0.6 mg kg^{-1} for DTPA-$CaCl_2$ and 0.7 mg kg^{-1} for NH_4HCO_3-DTPA (Sharma *et al.*, 1996). They also concluded that DTPA-$CaCl_2$ was a suitable reagent for extracting Zn followed by NH_4HCO_3-DTPA. Potatoes responded to Zn application in soils that had 0.75 mg kg^{-1} DTPA extractable Zn (Trehan and Grewal, 1995). Banda and Singh (1989) concluded that the critical levels of Zn for maize in the soils were 0.70, 2.00, 1.50 ppm for 0.005 M DTPA, 0.1 N HCl and NH_4OAc-EDTA, respectively. They recommended 0.005 M DTPA and 0.1 N HCl for extracting Zn from the soils and for digesting plant samples. Singh and Karwasra (1988) used DTPA to extract Zn that was available for uptake by millet. They concluded that Zn fertilizer application could only be recommended when soils contained below 0.65 mg kg^{-1} and only if plants had below 18 mg kg^{-1} Zn. Singh (1986) observed that the critical limit of Zn in soils was 0.54 ppm and that it was 15.4 ppm in plants. The critical levels of Zn for wheat grown on non calcareous soils were observed to be 1.75 mg kg^{-1} soil Zn and 1.7 mg kg^{-1} in wheat plant tissue (Singh and Shukla, 1985). They used 0.1 N HCl to extract Zn from the soils and to digest plant samples.

2.2.3 Relation of the available zinc to plant uptake

The soil solution levels of Zn are indicative of its availability to plants and soil microorganisms (Meers *et al.*, 2006). Hseu (2006) analyzed three tropical soils of Taiwan and found out that the labile fractions available to the plant were the soluble, exchangeable and chelated minerals species in the soils. Similarly, Dvorak *et al.* (2003) in Czech Republic found out that water and exchangeable pools of Zn were readily available for plants. Yin *et al.* (2002) observed that organic matter bound minerals (such as Zn) and made their mobility and bioavailability difficult to the plant. The different Zn fractions are in a dynamic equilibrium with the Zn in the soil solution. Once the organic matter decomposes, it releases the nutrients to be taken up by plants. Alvarez *et al.* (2003) reported that pH, type of soil minerals, and anions present in the soil solution strongly affected the availability of Zn in calcareous soils. The Zn that is available to the plant is that which can easily be desorbed or exchanged. Zinc bound reversibly by silicate clay minerals is an exchangeable cation and is potentially available to the plant once released into the soil solution.

2.3 Fractions of Zinc in Soils

Fractionation of soils is very useful to understand the chemistry of minerals in the soils (Rico *et al.*, 2007). Fertilizer programs can only succeed if the fertility status of the soils and indeed the chemistry of minerals that control the availability of these nutrients is known.

2.3.1 Fractionation of zinc in soils into various pools

Single (or batch) and sequential extraction procedures have been used to define different pools of Zn in different soils (Hseu, 2006; Soon and Bates, 1982; Sposito *et al.*, 1982). According to Margui *et al.* (2007) sequential extraction involves the use of various extractants and extraction procedures successfully. In sequential extraction, each extractant is supposed to be chemically more active than the preceding one (Rico *et al.*, 2007). Though used widely by most researchers, sequential extraction schemes are surrounded by the problem of poor selectivity and redistribution (and readsorption) of the target mineral into various pools (Shiowatana *et al.*, 2001). The overlapping effects of reagents used caused poor selectivity of the scheme (Alvarez *et al.*, 2003). Sequential procedures are highly influenced by pH, sample weight to reagent volume ratio, extraction times, temperature and methods of shaking and phase separation (Shiowatana *et al.*, 2001). All these affect readsorption and redistribution of the target elements. According to Shiowatana *et al.* (2001) the pH of the preceding reagents affected the extraction of the target elements from the subsequent pools. They observed that readsorption occurred. Fuentes *et al.* (2004) recommended the use of the DTPA method of extraction as compared to sequential extraction of Zn supplied by biosolids to the soils.

In single or batch extraction procedures, separate aliquots were analyzed and fractions obtained by difference (Johnson and Petras, 1998). Researchers should note that the two fractionation techniques are operationally defined and therefore no procedure can discriminate against another (Johnson and Petras, 1998). However, the time taken to carry out extractions is shorter for batch analysis; it is not subjected to poor selectivity and is not affected by the pH of different reagents (Rico *et al.*, 2007). Extraction procedures are shorter than sequential ones. This minimizes the chances of readsorption.

2.3.2 Defined fractions of zinc found in soils

Both the single and sequential methods have been used by laboratories throughout the world to define the water soluble (present in the soil solution), exchangeable (ions bonded to soil by electrical charges), inorganically bound (bonded to secondary clay minerals), organically bound (bonded or chelated to organic ligands), oxides bound (bonded to metallic oxides of iron, aluminium or manganese) and the residual fractions of Zn in soils (adsorbed, precipitated, fixed or complexed) (Hseu, 2006 and Alvarez *et al.*, 2003). According to Margui *et al.* (2007) and Hseu (2006) the first two extractions included the soluble and easily exchangeable pools. The distribution of minerals in soils helps to determine the potential of the soils to supply enough nutrients for the plant (Rico *et al.*, 2007). Tehrain (2005) assessed the mobility of Zn and its distribution in soils among different pools in Iran. He concluded that the relative abundance of Zn fractions in soils was in the following order: water soluble < exchangeable < specifically adsorbed < amorphous FeO < acid soluble < MnO occluded < organic matter occluded < crystalline

FeO < residual fractions. He concluded that the residual fraction had the highest content of Zn. Milivojevic *et al.* (2005) also made the same observation and conclusions when they fractionated twenty different soils in Serbia. They concluded that the residual fraction was highest at 89 percent Zn while the exchangeable was lowest at 1.08 percent.

2.3.3 Methods of extraction of various fractions in soils

The Community Bureau of Reference is a three step sequential technique that involves the defining of the exchangeable and acidic pool by 0.11 M acetic acid; the reducible pool by 0.5 M hydroxylamine hydrochloride at pH 1.5 and the oxidizable fraction by 30 percent hydrogen peroxide followed by 1 M ammonium acetate at pH 2. Kubova *et al.* (2004) concluded that the Community Bureau of Reference scheme could be used in combination with the single extraction procedures to define pools. Savonia *et al.* (2006) modified the Community Bureau of Reference (BCR) into a five step sequential scheme.

Bakhsh *et al.* (1990) in Glasgow (UK) observed that the calcium chloride extractable Zn in the soil increased in the soil over 48 weeks of observing ryegrass while the amount of the acetic acid, EDTA and oxalate extractable Zn decreased. Either EDTA or DTPA can be used to assess and characterize the labile pool (Margui *et al.*, 2007). Voegelin *et al.* (2008) and Fedotov and Spivakov (2008) used a combination of NH_4Oxalate and ascorbic acid to define the reducible pool. While Voegelin *et al.* (2008) used NH_4NO_3, Fedotov and Spivakov (2008) used $Ca(NO_3)_2$ to define the exchangeable pool. Hseu (2005) used a mixture of nitric and hydrochloric acid to characterize the residual pool. Zerbe *et al.* (1999) defined the residual fraction by subjecting the soils to a mixture of ammonium acetate and nitric acid. The organically bound Zn was extracted using 0.1 M $K_4P_2O_7$ (Johnson and Petras, 1998). In most sequential techniques, a mixture of 30 percent H_2O_2 and nitric acid was employed to define and characterize the organic pool (Zerbe *et al.*, 1999; Hseu., 2005; Leleyter and Baraud., 2006).

2.3.4 Relation of the various fractions in soils to plant uptake

Studies have shown that pools defined in laboratories can be related directly to concentrations of nutrient elements in soils that are either available or not available for plant uptake. According to Kabata (1993) availability of micronutrients to plants depends on the reactions of these elements in the rhizosphere. He concluded that the soluble, exchangeable and organically bound pools provided the available micronutrients for uptake by plants. Both the first and second pools of either a single or sequential extraction procedure was mobile and available for uptake by plants (Margui *et al*., 2007). The organically bound Zn is an exchangeable cation and therefore available for uptake. The residual pool is strongly bound and not available for uptake.

2.4 Response of Crops to Zinc Fertilizer Application and Method of Application

Zinc can be applied either to the soil or directly to the leaves of the plants (Alloway, 2007). The availability of Zn in calcareous soils was low and as such soil application of Zn did not always correct deficiencies (McDonald *et al*., 2001). The application of Zn fertilizers to soils had not been successful because Zn was fixed, complexed or converted into forms that were not easily desorbed (Maftoun and Karimian., 1989). Karak *et al.* (2006) observed that soil applied inorganic $ZnSO_4$ fertilizer did not supply Zn needed by plants as compared to chelated forms (ZnEDTA) because it was either complexed with or fixed in clay, sesquioxide and organic matter of the soils. Formation of these complexes that reduce or minimize availability of Zn once applied to soils may be favoured by high pH values and low soil temperatures. Brennan (1991) compared foliar spray of $ZnSO_4$ and ZnEDTA and concluded that they both produced the same grain yield and were both effective. However, Follet and Westfall (2004) recommended $ZnSO_4$ soil application to be plowed down at planting. They also observed that foliar application worked more effectively as a corrective measure against deficiencies. Karak *et al.* (2006) observed that split soil application of ZnEDTA produced more grain and straw yields as compared to the same application of $ZnSO_4$. They recommended the split (first at grand tillering and then at panicle initiation stage) soil application of 1 kg Zn ha^{-1} as ZnEDTA for rice.

Sharma *et al.* (1988) observed that optimum yields were obtained when Zn fertilizers were applied to the soil within 45 days of planting than when applied to the leaves. Trehan and Grewal (1995) concluded that applying micronutrients within 30 and 50 days of planting as foliar spray was as effective as soil application. Like Follet and Westfall

(2004), Trehan and Grewal (1995) recommended the use of foliar application as an emergency measure.

Soleimani (2006) combined both soil and foliar application at 0.3 and 0.6 percent Zn rate in Iran and observed that the wheat grain yields were higher than just the soil application. Ranjbar and Bahmaniar (2007) combined soil application of Zn sulphate (at planting of wheat) and foliar application (at booting) of: Rate1as 5 kg ha^{-1} soil and 300 g ha^{-1} foliar; Rate 2 as 10 kg ha^{-1} soil and 600 g ha^{-1} foliar and rate 3 as 15 kg ha^{-1} soil and 900 g ha^{-1} foliar. In all the three cases they observed that yield, total dry matter and other yield components increased compared to the controls. Panhwar *et al.* (2003) compared foliar and soil application of $ZnSO_4.7H_2O$ and concluded that a full dose of NPK as 275,112, 175 kg ha^{-1} in combination with 1.5 kg $ZnSO_4.7H_2O$ ha^{-1} foliar application produced higher yields (114.2 t ha^{-1}) of sugarcane than the same full dose of NPK but with 10 kg $ZnSO_4.7H_2O$ ha^{-1} soil application (110.0 t ha^{-1}). The Department of Agriculture of Canada discourages applying Zn to soil and encourages the use of foliar application of 8.5 kg Zn ha^{-1} since zinc sulphate is water soluble (Thompson, 2007). Bahadur *et al.* (1998) used different rates of foliar and soil application of $ZnSO_4.7H_2O$ to mango trees of 0.25, 0.50, 1.00 percent and 0.50, 1.00, 2.00 kg $ZnSO_4$ tree^{-1}, respectively. They observed that the Zn concentration of the fruit pulp increased in all the treatments except for the 0.25 percent one. According to Dvorak *et al.* (2003) though Zn is an essential nutrient, its high levels are detrimental to plant life as it leads to a reduction in crop biomass.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Experiment one: Crop Response to Zinc Sulphate Fertilizer Application

3.1.1 Experimental site

The experiment was conducted at the University of Zambia School of Agricultural Sciences Field Station which is located 15.25° S and 28.20° E in Lusaka. The site is 1260m above sea level. The soil is described as sandy loam mixed isohyperthermic paleustalf (Msoni, 1985).

3.1.2 Weather

The rainfall and temperature as compiled by the Meteorological Department from 1990 to 2008 for Lusaka Station is as shown in Table 1.

Table1: Mean monthly rainfall and mean monthly maximum and minimum temperature for Lusaka Station (1990 – 2008)

Month	Monthly Rainfall (mm)	Maximum	Minimum	Mean
		(-------------------------	°C-------------------------	---)
Oct	10.0	31.2	17.9	24.4
Nov	72.0	30.2	17.4	24.1
Dec	184.1	27.3	17.4	22.4
Jan	227.5	26.8	17.2	22.0
Feb	171.3	26.8	16.9	21.9
Mar	87.4	26.8	16.8	21.8
Apr	30.4	26.7	15.1	20.9
May	1.3	25.5	12.8	19.1
Jun	0.4	23.6	10.6	17.1
Jul	0.0	23.5	10.3	16.9
Aug	0.0	26.2	12.6	19.4
Sep	0.6	29.7	15.5	22.6

3.1. 3 Soil analysis

Soil samples were collected from 0 – 20 cm depth of the ten random locations per field site. These were mixed together and one composite sample per location was obtained.

The composite sample was then cleaned free of large pieces residues and air dried for 48 hours. The soils used for soil analysis were crushed to pass through a 2 mm sieve and packed in black plastic bags. The soil pH was measured in a 1:2.5 (w/v) ratio of soil to 0.01 M $CaCl_2$ solution. Ten grams of the soil was weighed into 50 ml plastic containers in triplicates and 25 ml 0.01 M $CaCl_2$ was added to each. The mixture was shaken for 30 minutes and then the pH of the supernatant was measured using a glass electrode. Soil texture was determined by sedimentation using the hydrometer. Cation exchange capacity (CEC), was determined by leaching 5 g soil sample with 150 ml 1 M NH_4OAc buffered at pH 7; this was followed by steam distillation and then titration of the distillate with 0.1 N HCl. The Walkley and Black method was used to estimate the organic matter of the soils. Total N was measured using the Kjeldhal digestion method. To measure the P concentration of the soils, Bray 1 method with slight modifications was used. Three grams of the soil sample was extracted in 20 ml 0.025 M HCl and 0.03 M NH_4F in triplicates. The complex developed was then read on the UV-VIS spectrophotometer (Model: Genesys 10 UV).

The trace elements Fe, Zn, Cu, and Mn were extracted using DTPA. Twenty grams of the soil was weighed and extracted in 40 ml DTPA in triplicates. To determine calcium, magnesium, potassium and sodium, ten grams of the soil sample was weighed into 100 ml plastic bottles and 50 ml ammonium acetate added. The mixture was shaken for 30 minutes and then filtered. For magnesium and calcium, 1 ml of the filtrate was transferred to 25 ml volumetric flasks, 5 ml strontium chloride added and diluted to volume. Both trace elements and cations were read on the atomic absorption spectrophotometer (AAS), Analyst 400 Perkin Elmer (Songolo and Pauwelyn., 1993; Van Ranst *et al.*, 1999).

3.1.4 Field study

Maize and wheat were grown at the University of Zambia School of Agricultural Sciences Field Station to assess the yield and uptake of the crops following foliar or soil application of Zn sulphate fertilizer. Each crop was grown on a separate plot.

3.1.4.1 Maize crop

The plots selected for each of the two crops were cleared and prepared using hand tools. Each plot covered 10 X 18 m which were then demarcated into 2 X 6 m plots. For convenience, one half of each plot was assigned to treatments to receive soil application of Zn while the other half received foliar application. A basal fertilizer application of 200 kg ha^{-1} equivalent of 'D' compound (10: 20: 10) was applied to each plot. This resulted in applying 4.5 g fertilizer per planting station. Zinc treatments were thereafter applied to designated plots at 25, 50, 75 or 100 kg $ZnSO_4$ ha^{-1}. Treatments were assigned to plots in a randomized complete block design with three replications. Maize (*Zea mays,* variety MRI 724) was planted on 15th December, 2007. At seven weeks after planting, foliar application of Zn fertilizer at 2.5, 5.0, 10 or 20 kg $ZnSO_4$ ha^{-1} was made to designated plots, again in a randomized complete block design with three replications.

Following planting of the maize crop, there were heavy down pours of rain, which was suspected to have washed away a significant portion of the basal fertilizer. Therefore, a second application of 'D' compound was made on 11th January, 2008. This, however, delayed the application of urea. Approximately ten weeks after planting, a top dressing application of 150 kg ha^{-1} equivalent of urea (46% N) was made to each plot. This was done by placing 3.38 g urea at each planting station, 5 cm away from the plant. The crop was rain fed. After three weeks of growth, weeds were removed. At six weeks, the crops were sprayed with monocrotophos to kill the stalk borers that had attacked the field. Approximately after eight weeks of growth and just before top dressing, weeding was carried out for the second time.

Two border lines were removed from either side of the plot to reduce the harvest area to 6 X 1.2 m. The maize was harvested in the last week of April, from 25th to 30th. The grains were air dried for a week, weighed and corrected for moisture. The stovers were dried in the greenhouse for one week, then in an oven for 24 hours at 65 – 70 °C and weighed. To determine the Zn concentration of maize meal and ground stover, 0.5 g of the plant tissues was digested in an acid mixture of 6 parts H_2SO_4 and 5 parts H_2O_2 in triplicates, a modification of the method used by Parkinson and Allen, (1975). The Zn concentration of both the maize meal and the ground stover was measured on the atomic absorption spectrophotomer (AAS) (Model: Analyst 400 Perkin Elmer)

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3.1.4.2 Wheat crop

Each of the 10 X 18 m plots were demarcated into 1.2 X 10 m plots. A basal fertilizer application of 500 kg ha^{-1} equivalent of 'D' compound (10: 20: 10) was applied to each plot. Zinc treatments were thereafter applied to soil in designated plots at 25, 50, 75 or 100 kg $ZnSO_4$ ha^{-1}. Treatments were assigned to plots in a randomized complete block design with three replications. A hand made planter was used to drill the lines before planting. Wheat, University of Zambia *Wheat Variety* 1 (UNZA *WV* 1) was planted on 1st May, 2008. After seven weeks of growth, foliar application at 2.5, 5.0, 10 or 20 kg $ZnSO_4$ ha^{-1} was made to designated plots, again in a randomized complete block design with three replications. A top dressing of 200 kg ha^{-1} equivalent of urea was applied by drilling. The application was divided into two where the first 100 kg ha^{-1} urea was applied when the crop was six weeks old, and the second 100 kg ha $^{-1}$ of urea at booting. Weeding was done twice when the crop was two weeks old and when it was five weeks old. Monocrotophos was used to kill the aphids that attacked the crop when the crop was twelve weeks old. Rat traps did not work very effectively to trap and kill the rats that were cutting wheat heads. The crop was irrigated throughout its 120 days of growth.

The harvest areas were reduced to 0.4 X 10 m after removing the border lines. The wheat was allowed to dry in the field. It was ready for harvest on 4th September but was only harvested a month later on 4th to 10th October. Ten plants from each harvest area were used for dry matter yield and to measure the concentration of Zn in the plant tissues. The 1000 grain weight and grain yield were measured. To determine the Zn concentration of the plant tissues, wheat meal and wheat straw were digested in the H_2SO_4/H_2O_2 acid mixture as described by Parkinson and Allen, (1975). The filtrates were then read on the AAS (Model Analyst 400 Perkin Elmer). Zinc uptake for both crops was determined as the product of tissue weight and Zn concentration. Yield of both wheat and maize was determined as follows:

$$\text{Yield ton ha}^{-1} = \frac{\text{Yield ton X 10,000 m}^2}{\text{Plot or Harvest Area m}^2}$$

3.1.4.3 Statistics

Analysis of variance and the Duncan's multiple range tests to separate the means were carried out using the SAS Statistical Package.

3.2 Experiment Two: Greenhouse Pot Study

3.2.1 Soil analysis

Composite samples were collected from selected areas in Zambia: Chalimbana SADC Gene bank, Kashima Farm, York Farm, Huntley Farm (Kalundu bottom) in Chisamba, Liempe Farm, UNZA Field Station, Kabwe Research Station, Mazabuka Syringa Farm and Mpongwe Farm. Misamfu red and Mfulira soil series were collected from Kasama Misamfu Research Station. The samples were each collected from both the cultivated and fallow areas. The length of cultivation of crops was not uniform but maize was common to most of the farms. Wheat is grown on Mpongwe and Kalundu Bottom Farms. The cultivated fields had received fertilizer within the previous five years. Laboratory analysis was carried out as described in 3.1.3.

3.2.2 Pot study

About 3 kg of each of the 22 air dried soils were placed in polyethylene pots with filter papers placed at the bottom to prevent any loss of the soils. Each soil was replicated three times. The soils used in the pot experiment were not sieved but were mixed thoroughly and cleaned free of large residues. Basal dressing, 5.6 g of 'D' compound per pot was added at planting. Eight seeds of UNZA WV1 were sown in each pot and thinned to five plants per pot after two weeks of germination. The pots were then arranged in a CRD design. The pots were irrigated with appropriate amounts of tap water and moisture maintained to field capacity for six weeks. The above ground part of the plant was harvested after six weeks of growth, washed with tap water and then distilled water and dried at 65 -70 °C for 48 hours. To determine the dry matter yield, the dried plant tissues were weighed. The plant tissues were ground and digested in the H_2SO_4/H_2O_2 acid mixture (Parkinson and Allen, 1975). The AAS (Model Analyst 400 Perkin Elmer) was used to determine the Zn concentration. Zinc uptake for wheat was determined as the product of tissue weight and Zn concentration.

3.2.3 Statistics

Correlation analysis was carried out using the SAS Statistical Package.

3.3 Experiment Three: Soil Fractionation for Zinc Pools

Sieved soils that were used for experiment two were also used for this study. The batch or single extraction scheme used by Johnson and Petras (1998) was used with slight modifications to define various Zn fractions in the soils. Separate sets of the soil samples were extracted by various reagents as follows:

(a) Water soluble and exchangeable fraction (F1): Twenty grams of soil was extracted in 40 ml 0.005 M DTPA for 2 hours and then filtered.

(b) Carbonate bound Zn or the inorganically bound Zn (F2): One gram soil was extracted in 20 ml 1 M CH_3COONH_4/ CH_3COOH mixture at pH 5 for 5 hours.

(c) Organic bound Zn (F3): one gram soil extracted in 40 ml 0.1 M $K_2P_2O_7$ for 17 hours and then filtered.

(d) Amorphous bound Zn (F4): This was characterized using acid Oxalate at pH 3, which was prepared by mixing four parts 0.2 M ammonium oxalate and three parts 0.23 M oxalic acid. The pH was adjusted to pH 3 by using either of the two reagents used in the preparation of acid oxalate. The sample mixtures were shaken for 17 hours.

(e) Residual Zn (F5): This was determined after digesting one gram soil sample in 25 ml aqua regia (one part HNO_3 to three parts HCl) for twenty minutes on a hot plate, cooled and then filtered.

All the soils were analyzed in triplicates. The Zn concentration in the extracts was determined using the atomic absorption spectrophotometer (AAS), (Model: Analyst 400 Perkin Elmer).

3.4 Statistical analysis

The SAS Statistical Package was used to estimate the means, standard deviations, maximum and minimum Zn concentration in different pools. It was also used for the regression analysis.

CHAPTER FOUR

4.1 RESULTS AND DISCUSSION

4.1.1 Properties of Soils from Selected Areas in Zambia

The pH $_{(CaCl_2)}$ of the soils ranged from 4.1 to 7.5 (Table 2). It was observed that 30 percent of the soils were strongly acidic; 22 percent slightly acidic and 48 percent were slightly alkaline. Of these, the following were observed to be strongly acidic: Mpongwe fallow, Misamfu red cultivated and fallow, Mfulira cultivated and fallow, Mazabuka cultivated, and Liempe field H. Mapiki and Phiri (1995) and Banda and Singh (1989) also observed that Misamfu red and Mfulira were strongly acidic. Mapiki and Phiri (1995) observed that acidic soils were prone to aluminium and manganese toxicity and this causes reduction in crop productivity. Johnson and Petras, (1998) made similar observations and concluded that at low pH the solubility of most micronutrients increases causing toxicity problems for many crops. On the other hand if the pH of the soil is too high or if the soil is over limed, has low organic matter and is light to medium textured, the nutrient status is generally poor because the solubility of most micronutrients reduces (Modaihsh, 1997).

The iron and manganese levels of most of the soils analyzed were high. The Fe levels of the soil samples ranged from 4.0 to 45.7 mg kg^{-1} and that of Mn ranged from 5.8 to 19.1 mg kg^{-1}. The DTPA extractable Zn ranged from 0 to 9.1 mg kg^{-1}. The highest DTPA extractable Zn was observed in the fallow field of York farm (9.1 mg kg^{-1}) followed by Mpongwe cultivated soil (7.5 mg kg^{-1}). The critical level of Zn in soils was observed to be 0.7 ppm for 0.005 M DTPA by Banda and Singh (1989). While Srivastavia *et al.* (2008) concluded that the critical limit of Zn for 0.005 M DTPA was 0.57 mg kg^{-1}. Trehan and Grewal (1995) and Singh and Karwasra (1988) observed that the 0.005 M DTPA critical limit was 0.75 and 0.65 mg kg^{-1}, respectively. It was observed that 52 percent of the soils analyzed were below the critical limits (Table 2).

Mapiki and Phiri (1995) reported that low CEC ranged from 6 to 13 cmol/kg while high CEC ranged from 12 to 20 cmol/kg. From this background, the CEC was generally high for the 22 soils analyzed. The CEC which were high ranged from 13.8 to 44.8 cmol/kg. York Farm fallow field had the highest CEC (44.8 cmol/kg). The lowest ranged from 4.86 to 12.6 cmol/kg. The lowest was observed to be 4.9 cmol/kg for Mfulira fallow. Soil N concentration in these soils ranged from 0.03 to 0.46 percent. The lowest P value observed was 1.0 mg kg^{-1}. Generally the organic matter content of the fallow fields were higher than the cultivated ones. The highest organic matter was observed in the fallow fields of York Farm (8.9 percent) and Liempe Farm Field H (6.7 percent).

Analysis of the soils showed that 61 percent were sandy loam, 21 percent were loamy sand and 17 percent of the soils analyzed were loam (Table 3). The coarse textured soils had the lowest DTPA extractable (Table 2) and total Zn (Table 4) probably because of their poor ability to adsorb nutrients (Brady, 1984). The low ability of the loamy sand soils to adsorb nutrients could be because of the high sand content (which was above 73.2 percent) with their corresponding low organic matter (Donahue *et al.*, 1983). The total Zn of these soils ranged from 13.1 to 43.3 mg kg^{-1}. Their DTPA extractable Zn were low: Kabwe Research Station (0.4 mg kg^{-1}), Kabwe Research Station fallow (0.7 mg kg^{-1}), Misamfu red fallow (0.4 mg kg^{-1}) and Mfulira (0.9 mg kg^{-1}). The moderately coarse soils had sand above 55 percent and clay below 17.7 percent. It was observed that 5 of the 14 sandy loam soils had trace amounts of DTPA extractable Zn. The medium textured soils with their corresponding high organic matter had the highest DTPA extractable Zn of the 22 soils analyzed. The total Zn of the loam soils ranged from 73.4 to 108 mg kg^{-1}. The adsorption of Zn by these loam soils was favoured by the high amounts of the organic matter which was important in the formation of the organo-Zn complexes that acted as buffer zones for Zn (Udom *et al.*, 2003).

Table 2: Chemical properties of 11 Zambian soils collected from various locations

IDENTITY	pH $CaCl_2$	% Org. Matter	% N	CEC	Mg	Ca	K	Na	P	Zn	Fe	Cu	Mn
				(………………	………	cmol/kg………	………	………)	(………	………mg/kg	………	………	………)
UNZA Field A	7.2	1.3	0.05	14.6	2.3	5.6	0.7	0.4	7.8	0.5	4.0	0.5	22.4
UNZA Field B	7.1	1.3	0.06	13.8	2.3	5.3	1.3	0.9	11.4	2.2	4.8	1.1	18.5
UNZA Field C	7.5	1.7	0.06	10.7	2.6	8.7	1.0	0.5	7.2	3.2	6.7	0.8	6.8
Liempe H	4.7	6.7	0.05	6.0	1.0	1.3	0.9	0.4	4.7	T	29.1	0.2	10.2
Liempe H Fallow	5.3	6.6	0.05	4.9	0.9	1.9	0.9	0.3	4.7	T	39.0	0.2	14.6
Liempe former orch.	7.0	6.6	0.06	12.6	2.1	6.8	0.8	0.4	6.9	T	14.0	1.1	16.7
Gene B. M. Area	7.1	0.5	0.03	7.9	0.5	3.6	0.9	0.4	11.4	0.1	6.8	0.4	8.2
Gene Bank Fallow	5.4	1.4	0.06	7.6	0.9	2.1	1.0	0.3	1.0	T	12.7	0.4	13.5
Kabwe R. St.	5.7	1.3	0.05	6.1	0.5	1.6	1.1	0.3	1.6	0.4	14.8	0.1	19.1
Kabwe R. St. Fallow	5.7	1.4	0.11	7.1	1.3	1.7	0.7	0.3	2.3	0.7	18.1	0.1	17.5
Kalundu Bottom	6.7	2.6	0.15	15.9	2.8	5.9	1.0	0.6	2.3	1.0	10.0	0.7	13.6
Kalundu Bottom M.P.	6.8	2.8	0.19	11.3	2.6	4.7	1.1	0.6	1.6	1.2	9.7	0.4	9.9
York Farm 11 North	7.0	3.9	0.22	35.5	3.0	10.1	1.9	0.8	16.1	2.3	10.2	1.1	13.8
York Farm Fallow	6.6	8.9	0.46	44.8	3.0	10.3	2.1	0.8	5.0	9.1	20.9	1.8	18.2
Mpongwe NP1	6.5	4.6	0.27	34.0	2.6	6.1	1.3	0.4	28.2	7.5	6.5	0.8	13.7
Mpongwe NP1 Fallow	4.4	3.2	0.21	21.4	1.7	1.8	1.0	0.3	1.5	T	16.6	1.0	9.0
Kashima	7.2	2.6	0.18	15.1	2.8	8.9	1.2	0.4	14.1	2.8	4.7	2.3	7.0
Mazabuka Syringa	4.8	3.7	0.17	28.8	2.6	8.5	1.5	0.5	2.5	1.4	31.0	1.5	19.7
Mazabuka S. Fallow	5.6	5.1	0.22	34.8	3.0	9.9	1.5	1.5	1.6	0.5	30.0	2.0	10.7
Mufulira	4.1	1.3	0.09	5.3	0.0	0.2	0.4	0.4	3.6	0.9	46.0	0.5	9.6
Mufulira Fallow	4.2	1.6	0.13	4.9	1.0	0.3	0.5	0.5	1.3	0.4	21.7	0.2	7.6
Misamfu Red	4.2	1.6	0.12	6.0	1.4	0.4	0.3	0.4	4.8	0.5	32.2	0.3	6.1
Misamfu Red fallow	4.7	2.6	0.24	7.3	0.2	0.9	0.5	0.3	1.4	0.4	45.7	0.1	5.8

T = Trace amount

Table3: Physical properties of the 11 Zambian soils collected from various locations

	%			
Soil	**Sand**	**Clay**	**Silt**	**Texture**
UNZA Field A	55.20	13.60	31.20	Sandy loam
UNZA Field B	51.20	13.60	35.20	Sandy loam
UNZA Field C	61.20	9.60	29.20	Sandy loam
Liempe H	63.20	3.60	33.20	Sandy loam
Liempe H Fallow	67.20	3.60	29.20	Sandy loam
Liempe former orchard	56.20	9.60	34.20	Sandy loam
Gene Bank. M. Area	61.20	7.60	31.20	Sandy loam
Gene Bank Fallow	57.20	5.60	37.20	Sandy loam
Kabwe R. Station.	75.20	3.60	21.20	Loamy sand
Kabwe R. St. Fallow	73.20	3.60	23.20	Loamy sand
Kalundu Bottom	65.20	8.60	26.20	Sandy loam
Kalundu Bottom M.P.	77.20	9.60	13.20	Sandy loam
York Farm 11 North	33.20	28.60	38.20	Loam
York Farm Fallow	47.20	14.60	38.20	Loam
Mpongwe NP1	47.20	19.60	33.20	Loam
Mpongwe NP1 Fallow	55.20	15.60	29.20	Sandy loam
Kashima	53.20	17.60	29.20	Sandy loam
Mazabuka Syringa	37.20	25.60	37.20	Loam
Mazabuka Syringa Fallow	39.20	21.60	39.20	Loam
Mufulira	83.60	8.80	7.60	Loamy sand
Mufulira Fallow	73.60	8.80	17.60	Sandy loam
Misamfu Red	75.60	12.80	11.60	Sandy loam
Misamfu Red fallow	81.60	6.80	11.60	Loamy sand

4.1.2 Characterization of the distribution of zinc in its various fractions in the soil

The batch fractionation scheme was used to define the following five different pools of soil Zn of the 22 soils analyzed: the exchangeable pool (F1), carbonate bound Zn (F2), organic Zn pool (F3), sesquioxide bound Zn (F4) and the residual Zn pool (F5). The soil Zn pools were in the order: exchangeable (5.5 %) < organic Zn (9.5 %) < carbonate bound Zn (17.1 %) < residual Zn (34.1 %) < sesquioxide bound Zn (45.5 %). Similarly Hseu (2006) in the study of three tropical soils from Taiwan, it was concluded that the highest concentration of Zn fractions in the soils analyzed was the iron and manganese oxide bound Zn. Zerbe *et al.* (1999) reported that the soil Zn pools were in the order: sesquioxide (58 percent) > carbonate = organic (16 percent) > exchangeable (8.6 percent) > residual (1.9 percent). Margui *et al.* (2007) also observed that the manganese and iron oxide bound zinc was the highest. According to Ramos *et al.* (1999) Zn tends to form compounds with high stability constants with oxides of iron and manganese. Dvorak *et al.* (2003) also concluded that Zn has a high affinity for both organic matter and sesquioxide. This probably explains why the sesquioxide bound Zn was higher in this study. Behera *et al.* (2008) however, concluded that the highest Zn concentration was observed in the residual pool. Similar observations that the relative abundance of Zn was more in the residual pool were made by Tehrain (2005) in Iran. Unlike in this study, Milivojevic *et al.* (2005) in Serbia concluded that the highest soil Zn pool was the residual one at 89 percent.

The DTPA extractable Zn was the lowest pool and it was observed to be 5.49 percent (Table 4). Similarly, Milivojevic *et al.* (2005) in Serbia concluded that the lowest pool was the exchangeable pool which was 1.08 percent. This was also in agreement with Dvorak *et al.* (2003); they analyzed soils in Czech Republic and concluded that the exchangeable pool was the lowest. They defined the following pools: exchangeable (5 percent); Fe-Mn oxide (9 percent); organic (44 percent) and residual (42 percent). Margui *et al.* (2007) and Elsokkary (1979) also made similar observations and concluded that the exchangeable pool was the lowest of the fractions they defined. The exchangeable pool was below detection (trace amount) in some of the samples analyzed. Johnson and Petras (1998) encountered the same problem and attributed it to the use of buffered extracting reagents at pH 7. The exchangeable pool was extracted with DTPA which was buffered at pH 7. However, other researchers observed that in contaminated soils or soils that were treated with biosolids, the exchangeable pool contributed the highest content of Zn (Ramos *et al*, 1999; Hseu 2006).

Table 4: Soil Zn fractions (mg kg^{-1}) of the 11 Zambian soils collected from different locations

SOIL	Exch F1	Carbo F2	Org F3	Sesq F4	Resi F5	Total
UNZA Field A	0.52	28.00	1.84	4.32	9.55	44.23
UNZA Field B	2.15	7.75	6.16	11.95	72.40	100.41
UNZA Field C	3.16	9.40	7.61	11.55	17.9	49.62
Liempe H	T	3.03	1.43	11.15	6.55	22.16
Liempe H Fallow	T	2.95	Nd	30.45	5.35	38.75
Liempe former orchard	T	8.95	Nd	31.34	13.25	53.54
Gene B. M. Area	0.09	1.95	2.38	22.65	5.85	32.92
Gene Bank Fallow	T	2.28	1.97	49.65	7.60	61.50
Kabwe R. Station.	0.44	0.78	0.74	0.55	10.60	13.11
Kabwe R. St. Fallow	0.73	15.78	10.86	0.00	7.77	35.14
Kalundu Bottom	1.00	4.13	5.29	1.55	10.85	22.82
York Farm 11 North	2.28	20.13	5.71	17.55	22.00	67.67
York Farm Fallow	9.08	16.60	Nd	57.27	13.08	96.03
Mpongwe NP1	7.45	12.18	16.06	25.75	28.27	89.71
Mpongwe NP1 Fallow	T	3.00	2.14	4.80	10.59	20.53
Kashima	2.77	4.73	4.38	7.45	14.95	34.28
Mazabuka Syringa	1.43	6.80	6.33	74.5	18.96	108.02
Mazabuka S. Fallow	0.52	2.68	2.66	44.23	23.30	73.39
Mufulira	0.86	2.13	7.72	27.36	5.30	43.37
Mufulira Fallow	0.39	1.40	2.68	9.80	6.35	20.62
Misamfu Red	0.48	8.53	0.72	34.54	7.25	51.52
Misamfu Red fallow	0.42	1.95	4.73	15.50	11.60	34.20
Mean	3.84	7.19	5.60	22.43	18.45	51.27
Standard Deviation	5.68	5.83	4.16	20.02	17.20	32.09
Minimum	0.09	0.78	0.72	0.00	5.85	1.84
Maximum	9.08	28.00	16.06	74.50	72.40	108.02

Key: Nd = Not determined; T = Trace Amount

The total Zn concentration of the soils was positively correlated with pH, organic matter, CEC, P and clay. It was significantly correlated with CEC and clay (Table 5). This agrees with the study by Elsokkary (1979) in Egypt who showed that Zn adsorption was highly associated with CEC, Fe_2O_3 and clay. Mclaren *et al.* (1997) also concluded that CEC and organic matter influenced the adsorption and desorption of Zn. The sesquioxide bound Zn was negatively correlated with the soil pH. This suggests that reducing the soil pH increases the availability of Zn. Shiowatana *et al.* (2005) made similar observation when they analyzed soils in Thailand. They concluded that soil pH significantly determined the adsorption and sorption of minerals and that reducing it increases the concentration of minerals in the soil solution. The sesquioxide bound Zn and organic matter, clay, and P were poorly correlated. Correlation analysis showed that the carbonate bound Zn was highly and positively correlated (0.68) with the CEC of the soil. It was also positively correlated (0.47) with the soil P. This shows that there was a dynamic relationship between the Zn in the soil and CEC and P of these soils. Zinc forms complexes such as $CaCO_3$: $ZnCO_3$, a double salt, with calcium carbonate (Ramos *et al.*, 1999). They also noted that calcium carbonate tends to adsorb the Zn under favourably high pH values. There was a positive relationship between pH and carbonate bound Zn.

The organic Zn was highly correlated to the soil P. Unlike this study, Udom *et al.* (2004) and Catlett *et al.* (2002) observed that the correlation between organic matter and Zn concentration was significant. However, both this study and Udom *et al.* (2004) showed that the correlation was positive. This means that the higher the organic matter the higher the adsorption of Zn in the organic pool. Reducible and oxidizable pools were not sensitive to pH changes but were highly affected by redox conditions and microorganism activity (Shiowatana *et al.*, 2001; Leleyter and Baraud, 2006). This could explain why the correlation between the carbonate and organic pools and the pH were non significant.

Because of the heterogeneous nature of the soils, results reported by other researchers could be very different. It was observed that only residual Zn pool and the total Zn of the soils analyzed was significantly correlated with clay (Table 5). However, many researchers have reported a significant correlation between clay and Zn fractions

(Johnson and Petras, 1998; Sinha *et al.*, 1978). This means that the higher the amount of clay in a particular soil the higher the amount of Zn adsorbed. The correlation coefficient between pH and the exchangeable soil Zn was 0.42, showing a positive relationship. Though low, the correlation between the exchangeable pool with the CEC, organic matter, clay and P of the soils was positive. These results show that the correlation coefficients of CEC were generally twice those of the organic matter in relation to the forms of soil Zn. This similarity shows the close relationship between the organic matter and the exchange sites of the soil micelle. It shows that the combined contributions from organic matter and clay content of soils provides the cation reservoirs of the soils (Johnson and Petras, 1998; Brady, 1984).

Table 5: Correlation coefficients between soil zinc fractions and some properties of selected Zambian soils

Zinc Fraction	pH	OC	CEC	P	CLAY
Exchangeable	0.42	0.14	0.29	0.33	0.31
Carbonate	0.43	0.19	0.68*	0.47*	0.35
Organic	0.27	0.23	0.41	0.52*	0.39
Sesquioxide	-0.03	0.20	0.40	0.009	0.23
Residual	0.32	0.11	0.19	0.32	0.53*
Total	0.30	0.20	0.60*	0.40	0.50*

* = Significant at 0.05

4.1.3. Response of maize and wheat to different rates of soil or foliar zinc fertilizer application

The yields of maize obtained from the two methods of application were significantly different (P = 0.0001). It was observed that mean maize grain yield from the soil applied plots was higher (1.78 t ha^{-1}) than that obtained from foliar applied plots (1.14 t ha^{-1}), (Table 6). Hossain *et al.* (2008) also observed that the soil application of Zn lead to an increase in the grain yields of maize. Similar results were obtained by Abunyema and Mercer-Quarshie (2004) in Ghana who reported an increase in the maize grain yield from 1.16 t ha^{-1} (0 kg Zn ha^{-1}) to 2.18 t ha^{-1} (5 kg Zn ha^{-1}). Harris *et al.* (2007) in Pakistan reported that there was a 25 percent increase (about 0.7 t ha^{-1} increase) in the grain yield when they applied 2.75 kg Zn ha^{-1} to the soil of the maize field. They observed that increasing the rate to 5.5 kg Zn ha^{-1} produced the same results but with much lower cob weights. The maize grain yield from the soil applied fields was not different between the rates of Zn used and that it ranged from 1.48 t ha^{-1} (100 kg $ZnSO_4$ ha^{-1}) to 2.15 t ha^{-1} (25 kg $ZnSO_4$ ha^{-1}). By contrast, the grain yield of maize in the NPK + Zn soil applied field in India was 2.05 t ha $^{-1}$ (Behera *et al.*, 2008). The maize grain yields obtained from fields that received foliar spray were not different and that the lowest yield was observed in the 5 kg Zn ha^{-1} (1.05 t ha^{-1}) field.

The grain yield of wheat obtained from the two methods of application, foliar and soil application, were significantly different (P = 0.0043). It was higher in the soil applied plots (3.69 t ha^{-1}) than in the foliar applied plots (2.74 t ha^{-1}). Unlike in this study, Modaihsh (1997) observed that foliar spray of Zn at 1.8 kg ha^{-1} significantly increased grain yield of wheat grown on a calcareous sandy loam soil of Saudi Arabia. Haslett *et al.* (2000) concluded that foliar application of inorganic or organic Zn fertilizers were efficient in providing the Zn required by wheat for growth. The wheat grain yield obtained from rates of foliar application ranged from 2.21 t ha^{-1} (20 kg $ZnSO_4$ ha^{-1}) to 4.12 t ha^{-1} (5 kg $ZnSO_4$ ha^{-1}). Though the crop did not show any sign of Zn poisoning and leaf burning, it was possible that higher rates induced the low yields observed. The wheat grain yield from rates of soil applied plots ranged from 2.98 t ha^{-1} (50 kg $ZnSO_4$ ha^{-1}) to 4.26 t ha^{-1} (75 kg $ZnSO_4$ ha^{-1}). Similar results were reported by Behera *et al.* (2008) in

India when they applied 10 kg zinc sulphate ha^{-1} to the soil. The grain yield of wheat they got was 4.69 t ha^{-1}. There was, however, non significant difference in the 1000 grain weights of wheat and it was, therefore, observed that the method of application was not a factor in the 1000 grain weight, (Table 7).

Table 6: Mean grain yields of maize and wheat treated with four rates of zinc using foliar or soil application on a sandy loam soil at UNZA Field Station

	Mean Yield (t ha^{-1})	
Method	Maize	Wheat
Soil	1.78	3.69
Foliar	1. 14	2.74
LSD (0.05)	0.31	0.62

Table 7: Mean 1000 grain weight for wheat treated with four rates of zinc using foliar or soil application on a sandy loam soil at UNZA Field Station

	Mean weight (g)
Method	Wheat
Soil	45.13
Foliar	42.99
LSD (0.05)	2.277

The maize crop responded to both soil and foliar application of zinc sulphate. The highest uptake of Zn by maize plant was observed in the plots that were sprayed with 10 kg $ZnSO_4$ ha^{-1} and the lowest were seen in the control. It was observed that there was non significant difference between 10 kg $ZnSO_4$ ha^{-1} and 20 kg $ZnSO_4$ ha $^{-1}$. There was also non significant difference among 0, 2.5 and 20 kg $ZnSO_4$ ha^{-1}. The mean uptake ranged from 22.74 mg (0 kg $ZnSO_4$ ha^{-1}) to 80.52 mg (10 kg $ZnSO_4$ ha^{-1}) (Table 8). Increasing the concentration of foliar spray increased uptake up to 10 kg $ZnSO_4$ ha^{-1} when it started to drop at 20 kg $ZnSO_4$ ha^{-1}. This was also observed in the soil applied fields of maize. This may be because of Zn poisoning at higher rates though no sign of leaf burns were noticed. Correlation analysis showed that there was a highly significant relationship between the rate of soil application of Zn and uptake by maize. The mean uptake ranged from 31.97 mg (0 kg $ZnSO_4$ ha^{-1}) to 77.23 mg (75 kg $ZnSO_4$ ha^{-1}). The uptake of Zn by maize was highest in the 75 kg $ZnSO_4$ ha^{-1} plots and lowest in the control (Table 8).

The mean uptake of Zn by wheat from foliar application ranged from 5.13 to 10.11 mg. The highest uptake was observed in the field sprayed with 5 kg $ZnSO_4$ ha^{-1} though it was non statistically different from the uptake observed in the 0 and 10 kg $ZnSO_4$ ha^{-1} plots (Table 8). The control was third highest probably because the inherent soil Zn was above the threshold. Uptake of Zn by wheat from the soil applied plots did not depend on the rate of application. There was non significant difference in the uptake of Zn from different rates applied to the soil. The mean uptake from soil applied plots ranged from 8.89 mg to 14.64 mg. Sharma *et al.* (1988), however, observed that both zinc sulphate and zinc oxide increased yield and uptake of Zn by wheat when applied within 45 days of planting.

Table 8: Yield and mean uptake of zinc by maize and wheat treated with four rates of zinc using foliar or soil application on a sandy loam soil at the UNZA Field Station

		Maize		Wheat	
Method	Rate (kg ha^{-1})	Yield (t ha^{-1})	Uptake (mg)	Yield (t ha^{-1})	Uptake (mg)
Soil	0	1.54i	31.97a	3.49k	8.89f
	25	2.15i	37.97a	4.03k	14.63f
	50	1.69i	41.48a	2.98k	9.83f
	75	2.05i	77.23b	4.26k	12.72f
	100	1.48i	71.34b	3.68k	10.48f
Foliar	0	1.31j	22.74c	2.45l	7.29g
	2.5	1.10j	35.29c	2.33l	5.24h
	5.0	1.05j	42.64cd	4.12m	10.11g
	10	1.12j	80.52e	2.59l	8.49g
	20	1.10j	75.77ed	2.21l	5.13h

Key: a, b, c, d, e, f, g, h, i, j, k, l, m = the difference between mean values with the same letters are statistically non significant at 0.05

4.1.4 The relationships between the various soil zinc pools and zinc uptake in the greenhouse

There was a non significant relationship between Zn uptake by wheat grown for six weeks and the organic, exchangeable, residual and carbonate Zn pool in the soil. The sesquioxide bound Zn contributed significantly more than other pools to Zn uptake by wheat (Table 9). Similarly, Singh and Abrol. (1985) observed that the sesquioxide contributed significantly more to the Zn taken up by wheat and rice grown on alkaline soils. Sinha *et al.* (1977), however, concluded that the organic and clay bound Zn contributed positively (R^2=0.78) and significantly to the Zn taken up by maize and wheat crops. In this study the organic pool contributed a very small amount (R^2=0.056) though it was positive. Rico *et al.* (2009) analyzed 29 soils in Spain and also observed low R^2 values for organic matter. Behera *et al.* (2008) observed that most of the Zn from organic pool and the sorbed Zn were taken up by wheat and maize; but there was a negative relationship between uptake and sesquioxide bound Zn. They also noted that all individual pools could contribute to the overall uptake of the plant since the various fractions exist in a dynamic equilibrium.

Table 9: Relation between zinc uptake by wheat grown during six weeks in the greenhouse and zinc fraction in 11 Zambian soils with corresponding coefficient of determination (R^2) and level of significance

Soil Zn Pool	Regression Equation	Significance	R^2	P
Organic Zinc	Uptake = 0.0388 + 0.0011org. Zn	Ns	0.056	0.3437
Exchangeable Zn	Uptake = 0.0444 + 0.00053 Exch. Zn	Ns	0.037	0.4033
Residual Zn	Uptake = 0.0440 + 0.00011Residual Zn	Ns	0.015	0.6009
Sesquioxide Zn	Uptake = 0.0390 + 0.00036 Sesquiox Zn	*	0.188	0.0564
Carbonate Zn	Uptake = 0.0447 + 0.00014 Carbonate Zn	Ns	0.006	0.7433

KEY

ns = non significant at 0.05

* = significant at 0.05

CHAPTER FIVE

5.0 SUMMARY AND CONCLUSION AND RECOMMENDATIONS

5.1 SUMMARY

The distribution of zinc was characterized into five different fractions: F1 the exchangeable pool (5.5 percent); F2 the carbonate bound Zn (17.1 percent); F3 organic bound (9.5 percent); F4 sesquioxide bound Zn (45.5 percent) and F5 the residual pool (34.1 percent). The sesquioxide bound Zn was observed to be the largest fraction. The sesquioxide bound Zn contributed significantly ($P = 0.0564$) to the Zn required for uptake. The contribution of the other pools was non significant.

The mean maize grain yields from the soil and foliar applied fields were 1.78 t ha^{-1} and 1.14 t ha^{-1}, respectively. The mean wheat grain yield obtained from the soil applied fields was 3.69 t ha^{-1} while that from foliar applied fields was observed to be 2.74 t ha^{-1}.

5.2 CONCLUSION

Extractable soil Zn of Zambian soils is very low. Most of the soil Zn is partitioned into the sesquioxide pool which appears to be the pool supplying most of the plant Zn taken from soil. Application of Zn has a beneficial effect, with soil application seemingly better. It was observed that soil applied zinc increased the grain yield of maize and wheat significantly as compared to the foliar applied zinc.

5.3 RECOMMENDATIONS

The following recommendations for further study may be considered:

1. Investigative studies on the rates of Zn application using various rates must continue so that eventually fertilizer recommendations that are conclusive could be made.
2. Studies to compare sequential and batch extraction schemes to define Zn pools might be interesting.

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APPENDICES

Appendix 1: Contribution of the residual pool to the zinc taken up by wheat grown for six weeks in the green house pot study

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.00005	0.00005	0.283	0.6009^{ns}
Error	19	0.00366	0.00019		
C Total	20	0.00371			
C.V.		30.36%			

Appendix 2: Contribution of the sesquioxide pool to the zinc taken up by wheat grown for six weeks in the green house pot study

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.00069	0.00069	4.159	0.0564*
Error	18	0.00300	0.00017		
C Total	19	0.00369			
C.V.		28.38%			

Appendix 3: Contribution of the organic pool to the zinc taken up by wheat grown for six weeks in the green house pot study

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.00016	0.00016	0.952	0.3437^{ns}
Error	16	0.00264	0.00017		
C Total	17	0.00280			
C.V.		29.66%			

Appendix 4: Contribution of the exchangeable pool to the zinc taken up by wheat grown for six weeks in the green house pot study

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.00014	0.00014	0.731	0.4033^{ns}
Error	19	0.00358	0.00019		
C Total	20	0.00371			
C.V.		30.01%			

Appendix 5: Contribution of the carbonate pool to the zinc taken up by wheat grown for six weeks in the green house pot study

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.00002	0.00002	0.110	0.7433^{ns}
Error	19	0.00369	0.00019		
C Total	20	0.00371			
C.V.		30.50%			

Appendix 6: Analysis of variance for maize grain yield grown on a sandy loam soil at UNZA Field Station using foliar or soil application of zinc sulphate

Model: Grain Yield = Method of application + other factors not considered (error)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	6.2484	6.2484	17.03	0.0001*
Error	58	21.2847	0.3669		
C.Total	59	27.5331			
C.V.		41.51%			

Appendix 7: Analysis of variance for maize grain yield grown on a sandy loam soil at UNZA Field Station under foliar zinc sulphate application

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.2523	0.0631	0.30	0.8749^{ns}
Error	25	5.2477	0.2099		
C.Total	29	5.4999			
C.V.		40.31%			

Appendix 8: Duncan's Multiple Range Test for maize grain yield grown on a sandy loam soil at UNZA Field Station under foliar zinc sulphate application

Duncan Grouping	Mean	N	RATE
A	1.3142	6	0
A			
A	1.1189	6	10
A			
A	1.1016	6	20
A			
A	1.0977	6	2.5
A			
A	1.0503	6	5
LSD (0.05)	0.5448		

*** Means with the same letter are not significantly different.

Appendix 9: Analysis of variance for maize grain yield grown on a sandy loam soil at UNZA Field Station under soil zinc sulphate application

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	2.16018	0.54004	0.99	0.4307^{ns}
Error	25	13.6246	0.54498		
C.Total	29	15.7848			
C.V.		41.43%			

Appendix 10: Duncan's Multiple Range Test for maize grain yield grown on a sandy loam soil at UNZA Field Station under soil zinc sulphate application

Duncan Grouping	Mean	N	RATE
A	2.1476	6	25
A			
A	2.0467	6	75
A			
A	1.6932	6	50
A			
A	1.5410	6	0
A			
A	1.4814	6	100
LSD (0.05)	0.8778		

*** Means with the same letter are not significantly different.

Appendix 11: Analysis of variance for wheat grain yield grown on a sandy loam soil at UNZA Field Station using foliar or soil application of zinc sulphate

Model: Grain Yield = Method of application + other factors not considered (error)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	6.750	6.750	9.68	0.0043*
Error	28	19.535	0.698		
C.Total	29	26.285			
C.V.		25.98%			

Appendix 12: Analysis of variance for wheat grain yield grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	7.358	1.839	7.91	0.0038*
Error	10	2.326	0.233		
C.Total	14	9.684			
C.V.		17.60%			

Appendix 13: Duncan's Multiple Range Test for wheat grain yield grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

Duncan Grouping	Mean	N	RATE
A	4.1190	3	5
B	2.5935	3	10
B			
B	2.4463	3	0
B			
B	2.3324	3	2.5
B			
B	2.2136	3	20
LSD (0.05)	0.8774		

*** Means with the same letter are not significantly different.

Appendix 14: Analysis of variance for wheat grain yield grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	2.951	0.738	1.07	0.4212^{ns}
Error	10	6.901	0.690		
C.Total	14	9.851			
C.V.		22.51%			

Appendix 15: Duncan's Multiple Range Test for wheat grain yield grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

Duncan Grouping	Mean	N	RATE
A	4.2589	3	75
A			
A	4.0319	3	25
A			
A	3.6848	3	100
A			
A	3.4926	3	0
A			
A	2.9801	3	50
LSD (0.05)	1.511		

*** Means with the same letter are not significantly different.

Appendix 16: Analysis of variance for 1000 grain yield of wheat grown on a sandy loam soil at UNZA Field Station using foliar or soil application of zinc sulphate

Model: Grain Yield = Method of application + other factors not considered (error)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	34.52	34.52	3.72	0.0638^{ns}
Error	28	259.50	9.27		
C.Total	29	294.01			
C.V.		6.91%			

Appendix 17: Analysis of variance for uptake by maize grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	15599.02	3899.76	4.51	0.0070*
Error	25	21627.40	865.10		
C.Total	29	37226.42			
C.V.		57.23%			

Appendix 18: Duncan's Multiple Range Test for uptake by maize grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

Duncan Grouping		Mean	N	RATE
	A	80.52	6	10
B	A	75.77	6	20
B	C	42.64	6	5
	C	35.29	6	2.5
	C	22.74	6	0
LSD (0.05)		37.06		

*** Means with the same letter are not significantly different.

Appendix 19: Analysis of variance for uptake by maize grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	10315.37	2578.84	6.05	0.0015*
Error	25	10652.67	426.11		
C.d Total	29	20968.04			
C.V.		39.70%			

Appendix 20: Duncan's Multiple Range Test for uptake by maize grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

	Duncan Grouping	Mean	N	RATE
	A	77.23	6	75
	A			
	A	71.34	6	100
	B	41.48	6	50
	B			
	B	37.97	6	25
	B			
	B	31.97	6	0
LSD (0.05)		26.01		

*** Means with the same letter are not significantly different.

Appendix 21: Analysis of variance for uptake by wheat grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	54.76	13.67	2.98	0.0735^{ns}
Error	10	45.95	4.59		
C.Total	14	100.70			
C.V.		29.56%			

Appendix 22: Duncan's Multiple Range Test for uptake by wheat grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

	Duncan Grouping		Mean	N	RATE
		A	10.108	3	5
		A			
	B	A	8.487	3	10
	B	A			
	B	A	7.289	3	0
	B				
	B		5.239	3	2.5
	B				
	B		5.127	3	20
LSD (0.05)			4.099		

Appendix 23: Analysis of variance for uptake by wheat grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	65.21	16.30	1.76	0.2126^{ns}
Error	10	92.41	9.24		
C.Total	14	157.62			
C.V.		26.87%			

Appendix 24: Duncan's Multiple Range Test for uptake by wheat grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

	Duncan Grouping	Mean	N	RATE
	A	14.633	3	25
	A			
	A	12.718	3	75
	A			
	A	10.481	3	100
	A			
	A	9.832	3	50
	A			
	A	8.894	3	0
LSD (0.05)		5.814		

*** Means with the same letter are not significantly different.

Appendix 25: Analysis of variance for number of spikelets of wheat grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.933	0.233	0.39	0.8120^{ns}
Error	10	6.000	0.600		
C.Total	14	6.933			
C.V.		4.09%			

Appendix 26: Duncan's Multiple Range Test for spikelets of wheat grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

	Duncan Grouping	Mean	N	RATE
	A	19.3333	3	10
	A			
	A	19.0000	3	0
	A			
	A	19.0000	3	5
	A			
	A	18.6667	3	20
	A			
	A	18.6667	3	2.5
LSD (0.05)		1.4815		

*** Means with the same letter are not significantly different.

Appendix 27: Analysis of variance for number of spikelets of wheat grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	6.667	1.667	0.81	0.5485^{ns}
Error	10	20.667	2.067		
C.Total	14	27.333			
C.V.		7.44%			

Appendix 28: Duncan's Multiple Range Test for number of spikelets of wheat grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

	Duncan Grouping	Mean	N	RATE
	A	20.333	3	25
	A			
	A	19.667	3	0
	A			
	A	19.333	3	75
	A			
	A	19.000	3	50
	A			
	A	18.333	3	100
LSD (0.05)		2.7493		

*** Means with the same letter are not significantly different.

Appendix 29: Analysis of variance for plant height of wheat grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

Source	DF	Sum of Square	Mean Square	F Value	Pr > F
Model	4	15.953	3.988	2.18	0.1443^{ns}
Error	10	18.260	1.826		
C.Total	14	34.213			
C.V		1.32%			

Appendix 30: Duncan's Multiple Range Test for plant height of wheat grown on a sandy loam soil at UNZA Field Station under foliar application of zinc sulphate

Plant height

Duncan Grouping	Mean	N	RATE
A	103.533	3	5
A			
B A	102.967	3	0
B A			
B A	101.900	3	10
B A			
B A	101.900	3	20
B			
B	100.533	3	2.5
LSD (0.05)	2.5843		

*** Means with the same letter are not significantly different.

Appendix 31: Analysis of variance for plant height of wheat grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	15.1267	3.782	0.95	0.4758^{ns}
Error	10	39.887	3.989		
C.Total	14	55.013			
C.V.		1.95%			

KEY: C.V. = Coefficient of Variance

Appendix 32: Duncan's Multiple Range Test for plant height of wheat grown on a sandy loam soil at UNZA Field Station under soil application of zinc sulphate

	Duncan Grouping	Mean	N	RATE
	A	104.167	3	0
	A			
	A	103.167	3	100
	A			
	A	102.400	3	25
	A			
	A	101.667	3	75
	A			
	A	101.433	3	50
LSD (0.05)		3.8195		

Appendix 33: Ear Length of Wheat

Rate kg ha^{-1}	Method	Mean Ear Length(cm)
0	Soil	10.93
25	"	11.33
50	"	10.43
75	"	10.83
100	"	10.60
0	Foliar	9.93
2.5	"	9.93
5	"	10.03
10	"	10.30
20	"	9.97