UPTAKE AND PARTITIONING OF SALT BY WHEAT AND MAIZE UNDER IRRIGATION IN A SEMI-ARID CLIMATE

By

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DECLARATION

I, Cowan Chatwin Mc Lean, declare that:

• The Master's Degree research dissertation that I herewith submit for the Master's Degree qualification Magister Scientiae Agriculture at the University of the Free State is my own independent work, and that I have not previously submitted it for a qualification at another institution of higher education.

• I also agree that the University of the Free State has the sole right to the publication of this dissertation.

Cowan C. Mc Lean

Signature

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ABSTRACT

Irrigated soil is affected by salinity on a global scale, resulting in impaired crop development and reduced yields. Mitigation measures exist to decrease root zone salinity through leaching practices but this has detrimental offsite impacts. With increasing temperatures inducing water limitations, additional tactics are required to decrease root zone salinity.

Crop salt removal is a tactic often overlooked due to the generally assumed small quantity of salts removed when crops are harvested but can aid as a viable measurement when quantified, especially for precision agriculture. This study therefore presented three research aims with focus on the salinity inducing cations; potassium, calcium, magnesium and sodium. The first research aim was to quantify cation uptake and partitioning of wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and popcorn (*Zea mays everta*), while the second research aim quantified the relationship between soil cations and cation uptake by these crops. The third research aim tried to spatially characterise soil cations and thus cation uptake using apparent soil electrical conductivity (EC_a) measurements.

Electromagnetic induction (EMI) surveys were conducted on three fields under centre pivots, which were located on commercial irrigation farms in the districts of Douglas and Luckhoff. These surveys were conducted at the beginning of the wheat (June 2016) and beginning of the maize and popcorn (December 2016) season. Soil and plant sampling points were identified based on the degree of soil apparent electrical conductivity (EC_a) variability determined with the "Electrical Conductivity Sampling Assessment and Prediction" (ESAP) software and its featured "Response Surface Sampling Design" (RSSD) sampling methodology. The topsoil (0-300 mm) was sampled at the beginning of each crops' season before planting, while the crops were sampled past physiological maturity (at harvest). Standard laboratory procedures were used to analyse the soil properties; bulk density, clay, gravimetric water, $pH_{(water)}$ and electrical conductivity of the saturation extract (EC_e). Soil plant available ions were extracted with the Ambic-2 extraction method, while the closed-tube wet decomposition with acid technique was used to obtain the plant analytes. The Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES), which is an electro-spectroscopy technique, was used to analyse the cations present in the wheat, maize and popcorn plant material, as well as in the soil.

For the first aim, the cation concentrations and weighted mean of the components were determined and compared with the sufficient and critical ranges of established literature, while the biomass and yield were compared with that of commercial cereal crops. Cation uptake was then calculated by multiplying the components weight with the concentration, from which biomass uptake can then be determined. The significant partitioning of cations by crop components was determined with mean separation at the 95% confidence interval. The stem-leaf of wheat, maize and popcorn was the dominant components to remove cations, ($P \leq 0.001$). For the second aim, linear regression analysis was performed with Microsoft Excel to obtain a relationship between soil properties (EC_e, SAR and clay) and cation uptake but only the SAR had a relationship and correlated with cation uptake. A linear relationship ($R^2 = 0.7$) was then only found between SAR and Na^+ in the soil for wheat. For the third research aim, the ESAP software was used to find EC_a correlations between the afore mentioned soil properties, yield, biomass and soil cations but the results were unfavourable. Correlations for both aims were done at the 95% confidence interval.

The results revealed that the mean cation uptake for the wheat, maize and popcorn biomass was 384.2 kg ha^{-1}, 508.9 kg ha^{-1} and 359.8 kg ha^{-1}, respectively. From this biomass uptake, it can be estimated that the wheat, maize and popcorn seeds partitioned a mean 11.5%, 12.7% and 8.5% of cations, respectively which is used to suit the need of the commercial market. However, crop residue is commonly left behind as a soil cover and can induce soil salinity when re-introduced into the soil medium. The wheat, maize and popcorn stem-leaf were therefore estimated to partition a mean 80.8%, 81% and 86.8% of cations, respectively.

Crop salt removal can serve as an important mitigation measurement in minimising fertiliser applications and excessive irrigation practices when using crop components to enhance soil conditions such as organic matter, water retention and structure.

Keywords: Salinity, cations, leaching, electromagnetic induction (EMI), apparent electrical conductivity (EC_a), ESAP (Electrical Conductivity Sampling Assessment and Prediction), RSSD (Response Surface Sampling Design)

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CHAPTER 1. INTRODUCTION

1.1 Background

Soil and water resource (surface and groundwater) salinity refers to the quantity of total dissolved inorganic salts. The major soluble and readily dissolvable salts are calcium, magnesium, potassium, sodium, chloride, sulphate, nitrate, carbonate and bicarbonate and combine to form ion pairs (ionic salts) in soil (Yan *et al*., 2015). Ideally, the concentration of individual salts in water resources and soil water (i.e. over the entire field water contents) should be easily measurable *in situ* (Rhoades *et al*., 1999). At present, this is not practically possible. Instead, the ability of surface water, groundwater and soil water to conduct an electrical current (EC) is measured. The EC of these waters are directly proportional to the total dissolved salts (TDS, mg L^{-1}), which are related with a conversion factor ranging from 6.4 to 9.2 (Du Preez *et al*., 2000; Hanson *et al*., 2006). The EC of the actual soil water (EC_w) that plant roots are exposed to during the growing season would be the ideal representation of soil salinity. It has however become standard practice to assess soil salinity through laboratory measurements of the EC of the extract of a saturated soil-paste sample (EC_e) (Rhoades *et al*., 1999). Sometimes soil salinity is also measured with dilutions of 1:1, 1:2, 1:5 or 1:10 soil water ratios, i.e. $EC_{1:1}$, $EC_{1:2}$, $EC_{1:5}$ and $EC_{1:10}$. In addition, apparent soil electrical conductivity (EC_a) is a vast and reliable indirect measurement for soil salinity when a good correlation between EC_e and EC_a is established (Corwin & Scudiero, 2016 and Podwojewski *et al*., 2019). This is especially true in precision agriculture or site-specific-crop management, which requires spatial characterisation of salinity across the field (Rhoades, 1981; Rhoades *et al*., 1999; Corwin & Lesch, 2003 and 2005).

There are many systems to classify soil salinity (Shahid & Rahman, 2011). The classification suggested by the US Salinity Laboratory Staff (1954) are probably most common, where a soil is considered saline with an EC_e > 400 mS m^{-1}. In Australia a soil with EC (1:5 H_2O) > 200 mS m^{-1} is considered highly saline, while in South Africa a EC_e between 200 and 400 mS m^{-1} is considered slightly saline (Rengasamy, 2006; Nell & van Huyssteen, 2017). Soil can also be classified as sodic depending on the ratio of sodium ions in soil water, relative to calcium and magnesium ions. These ratios are expressed as the sodium adsorption ratio (SAR) or as the exchangeable sodium

percentage (ESP) and are regarded as sodic when the SAR is equal or greater than 13 or the ESP is equal or greater than 15 (US Salinity Laboratory Staff,1954; Shahid *et al*., 2018). Majority of classification systems try to link the amount of salt present in a soil to a specific soil form as opposed to the influence on crop yield, i.e. the danger of increasing EC_e on crop yield is not considered.

Soil salinity remains a growing global issue threatening the productivity of agriculture, especially irrigated soils located in arid and semi-arid regions. Natural and human induced water and salt balance changes cause approximately two million hectares of land to be uncultivable every year due to excessive salts (Hoang *et al*., 2016). The global statistics on salt-affected soils vary with different data sources. Shahid et al. (2018) for example estimated that of the earth's 1.5×10^9 ha cultivated land about 0.34×10^9 ha (23%) and 0.56×10^9 ha (37%) are affected by salinity and sodicity, respectively. In the 1990's it was estimated that approximately 18% of the then 1.3 million ha irrigated soils in South Africa were severely affected by soil salinity, waterlogging and sodicity (Backeberg *et al*., 1996). A remote sensing survey estimated that a mean 6.27% (94 050 ha) of soils located in nine irrigation schemes of South Africa showed signs of salinity and waterlogging (Nell, 2017). These salt-affected and waterlogged soils were quantified through satellite images obtained from an overhead perspective by using electromagnetic radiation in different regions of the electromagnetic spectrum which is reflected from the Earth's surface (Nell *et al*., 2015; Nell, 2017). Further deterioration of irrigation water quality could potentially see this problem rise in future due to South Africa's low mean annual rainfall and high atmospheric evaporative demand (Van Rensburg *et al*., 2011).

Salt stress is displayed through various plant symptoms; with the earliest sign a reduction in the rate of leaf surface expansion. All the major processes are affected, namely photosynthesis, protein synthesis, energy and lipid metabolism, and ultimately crop yield. These detrimental effects are attributed to i) disturbance in ion homeostasis and toxicities, ii) nutrient imbalances caused by excessive salts, and iii) a decrease in the osmotic potential of soil water, causing a reduction in root water uptake. Salt stress is most commonly caused by excessive amounts of Na^+ and Cl^-, with Na^+ also affecting soil permeability. The suppression of growth occurs in all plants, but their

tolerance levels and growth rate at excessive salt concentrations vary among different plant species (Parida & Das, 2005).

Maize (*Zea mays* L.) is an important C_4 plant from the Poaceae family; because it is the most cultivated cereal crop after rice and wheat (Farooq *et al*., 2015). It is sensitive to salinity even though a wide intraspecific genetic variation for salt resistance in maize has been developed (Mansour *et al*., 2005). Wheat (*Triticum aestivum* L.) is an important C_3 plant from the Poaceae family because it is the most widely grown cereal crop in the world. It is more tolerant to salinity than maize, but its growth is also severely affected by increasing salt concentrations (Goudarzi & Pakniyat, 2008; Banerjee *et al*., 2009). The relative yield of both wheat and maize is reduced by 10% at 4.9 and 1.7 dS m^{-1} and by 25% at 6.3 and 2.5 dS m^{-1}, respectively (Maas & Hoffman, 1977). The yield reduction of modern hybrids, however, are less as modern wheat yields only start to decline at 6 – 8 dS m^{-1} (Hasanuzzaman *et al*., 2017).

1.2 Motivation

Irrigation tends to increase individual and total salt concentrations in the root zone that negatively influence soil permeability and crop growth and yield. Plants, however, also require salts to aid in daily functional and photosynthetic activities; and therefore only absorb nutrients when they are in the form of an ionic salt (Rauscher, 2017). These nutrient salts are readily available for plant uptake and are mostly applied through fertilisers because organic forms take time to mineralise (Appendix 1). Excessive salt in the root zone is removed through leaching with water containing less salt. Leaching is more efficient when soil salinity levels are high (Barnard *et al*., 2010). The offsite consequence of leaching, however, is an increase in salt concentration of surface and groundwater resources through natural and/or artificial drainage that connect irrigated fields to these resources. In addition, drainage water can pollute these resources with leached crop nutrients, herbicides and pesticides as well as mobilise salts that occur naturally in soil (Chaudhri *et al*., 1964; Letey *et al*., 2011).

Managing salt concentration in the root zone, while minimising the consequent offsite impact, requires a definite understanding of all the salt balance components involved. Salt additions to the root zone are through irrigation, capillary rise from shallow groundwater tables, weathering of soil

minerals or salt deposits and when chemicals (e.g. fertiliser) are applied to the soil. Removal of salt from the root zone are through precipitation in the soil, natural and/or artificial drainage (leaching) and when crop biomass is harvested (Rhoades, 1974; Sandhu & Malik, 1975; Van Rensburg *et al*., 2008). The environmental impacts of leaching can possibly be limited by quantifying the removal of salts by crops to minimise the need of leaching. Crop salt removal is, however, generally assumed to be small with limited research on spatial uptake of salts and partitioning into various plant parts, especially by wheat and maize (Ammari *et al*., 2013). The primary salts chosen for this study are the cations K^+, Ca^{2+}, Mg^{2+} and Na^+ as they serve as base cations important in the soil cation exchange capacity (CEC) that affect soil pH, electrical conductivity and soil fertility. The cations K^+, Ca^{2+} and Mg^{2+} are important macro-nutrients that promote and sustain crop growth (i.e. photosynthesis, protein synthesis, grain quality). Ca^{2+} and Mg^{2+} improve soil structure, while Na^+ and K^+ to a lesser degree deteriorates the structure of soil. The aim of this study was to investigate the spatial uptake and partitioning of cations by irrigated wheat, maize and popcorn grown in a semi-arid region under various agronomic practices.

1.3 Objectives

The specific objectives were to:

i) Quantify cation uptake and partitioning of irrigated wheat, maize and popcorn.

ii) Quantify the relationship between soil cations and cation uptake by wheat, maize and popcorn.

iii) Evaluate the possibility of spatially characterising soil cations and therefore cation uptake with apparent soil electrical conductivity surveys.

1.4 Organization of the dissertation

The dissertation is organized into six chapters:

- Chapter 1 contains the background, motivation, aim and objectives
- Chapter 2 contains the literature review divided into five main topics, namely salts associated with irrigation, crop response to excessive salts, uptake of salts, use of EMI sensors and EC_a data and extraction and determination methods of salts
- Chapter 3 provides the overall materials and methods through a description of study sites, the collection of EC_a data, soil and plant sampling and soil and plant laboratory analysis

- Chapter 4 contains the results
- Chapter 5 contains the discussion
- Chapter 6 contains the conclusion and recommendations

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

"Without agriculture, man cannot live and without water, man cannot have agriculture" (Ramachandran, 2010).

Agriculture uses about 1.5 billion ha (11%) of the 13.2 billion ha global land surface for crop production and 70% of the Earth's freshwater supply to irrigate land for crop growth and promotion of high yields (FAO, 2011; Fitton *et al*., 2019; Tramberend *et al*., 2019). There are, however, on-site problems (root zone salinity and sodicity, decreases in crop yield) and offsite issues (water resource salinisation and pollution) associated with irrigation due to the salt load in water (as explained in Chapter 1). Salinisation can thus generally be defined as excessive accumulations of salinity-inducing salts (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, CO_3^{2-} and HCO_3) in the soil that hinders crop growth (Keller *et al*., 1986; Volkmar *et al*., 1998; Butcher *et al*., 2016; Desutter *et al*., 2016; Hoang *et al*., 2016; Kumar *et al*., 2017). These on-site and off-site issues caused by salinisation can be proactively managed through good on-farm water and salt management decisions before problems appear (Barnard *et al*., 2020). To aid with these on-farm decisions, it will be valuable knowing precisely how much salt crops take up. This information can also help if on-farm practices fail to proactively manage water and salt because of poor implementation or due to highly uncontrolled site-specific factors. Reclamation of saline and/or sodic soils are possible through controlled strategic leaching as well as soil and water amendments and bioremediation (calcareous soils are reclaimed without the application of amendments through the cultivation of certain salt tolerant crops).

With the ever-increasing availability and affordability of technology to support decisions within a field, the need also exists for spatial water and salt management. Hence, spatial quantification of salt uptake will assist with this. Salinised soil can be quantified and delineated with geophysical techniques of electromagnetic induction (EMI) and electrical resistivity (ER) used to measure apparent electrical conductivity (EC_a). Electromagnetic induction equipment includes the EM38, Dualem, etc., with the EM38 most widely used in agriculture (Doolittle & Brevik, 2014). Uptake

and partitioning of salts by cereal crops have been investigated in previous literature but information for modern hybrids, especially regarding the effects of management practices on partitioning, is limited (Ciampitti *et al*., 2013). The uptake and partitioning of higher yielding wheat and maize is investigated for the purpose of this study to assist in salinity management strategies, which will combat inconsistencies resulting in better crop growth responses (Ramanjineyulu *et al*., 2018). Precise knowledge regarding the uptake and partitioning by these major cereal crops will also improve prediction models as crop uptake was often only estimated.

The aim of the literature review is to understand the factors affecting the soil salt balance, the salts associated with irrigation, the threshold concentrations and effect of salts on plant growth, methods of salt removal from soil, benefits of crop salt removal, the most reliable method to extract and analyse salts in soil and plant material, how to express the uptake of salts, the uptake of salts from previous studies and also how to use an electromagnetic induction sensor as a tool to spatially quantify and characterise soil salinisation.

2.2 Salts associated with irrigation

Irrigation can be defined as an artificial systematic supply of water to increase soil moisture and promote plant growth in areas where evaporation exceeds precipitation. This can, however, induce soil salinity as salts in irrigation water often include the cations Ca^{2+}, Mg^{2+}, Na^{+} and the anions Cl^{-}, SO_4^{2-}, HCO_3^{-} (Twomlow *et al*., 2006; Scherer *et al*., 2013). Water quality is therefore an important measurement as it describes the fitness of water to be utilised or consumed and also its functionality in protecting aquatic ecosystems. It is measured by determining the physical, chemical, biological and aesthetic properties which are controlled by constitutes that are dissolved or suspended in water (Department of Water Affairs and Forestry, 1996).

Strict guidelines published in 1996 by the Department of Water Affairs (now, Department of Water and Sanitation) for water quality and application were revised by Du Plessis et al. (2017). These guidelines first only constituted the water quality criteria and the target water quality ranges (TWQR), which is the range of levels at which the presence of constituents would have no consequences or harmful effects with long-term use (Du Plessis *et al*., 2017). These guidelines,

however, were very generic and not applicable on smaller scales. The revised approach thus sought to develop a software-based decision support system (DSS), which is able to provide both generic and site-specific risk-based irrigation water quality guidelines for South Africa. The DSS operates at three tiers, where Tier 1 resembles the generic modified 1996 guidelines which provide a conservative water quality assessment and should any problems persist, a more site-specific approach, Tier 2, is used. Tier 2 is a more in-depth water quality assessment approach that takes environmental aspects such as climate and soil of a locality into consideration by making use of a sophisticated crop growth- soil water balance and chemistry model. Tier 3 constitutes site specificity using modules of the DSS and other resources. The DSS thus guides the user through a decision tree to choose the most suited route needed for assessment (Du Plessis *et al*., 2017).

2.3 Response of crops to excessive salts

A typical growth response curve can be used to describe the response of crops to nutrient supply. The curve, Figure 2.1, has three regions namely; a deficient region which indicates an increase in growth with increasing nutrient supply to meet plant deficiency, an adequate region which illustrates that growth is at its optimum and remains unaffected by changes in nutrient supply and a toxic range which indicates a decrease in growth due to increasing nutrient supply which induces ion toxicity (Römheld, 2012).

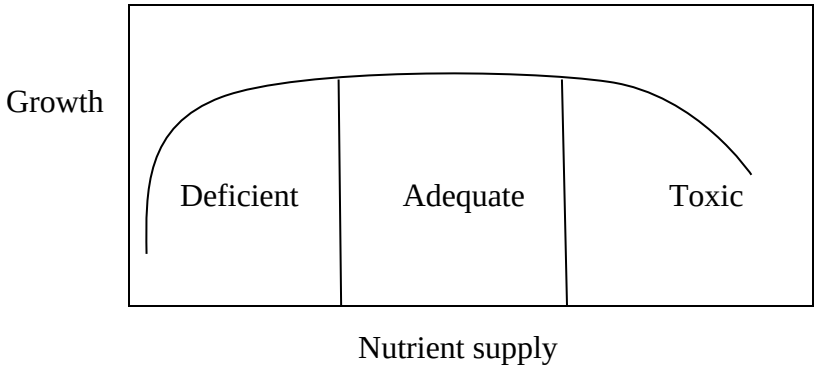

Figure 2.1 The growth response curve of nutrient supply (Römheld, 2012).

An excessive accumulation of nutrients also induce salinity and can therefore be referred to as nutrient salts (Yasutake *et al*., 2014). These excessive salts can have specific ion effects, promote

nutrient imbalances, induce oxidative stress and most importantly, decrease the osmotic potential of soil-water in the root zone (Yasutake *et al*., 2009; Puvanitha & Mahendran, 2017). The outcome of these effects on crops may lead to cell membrane damage, altered levels of growth regulators, inhibition of enzymes and also metabolic dysfunction including osmotic regulation and photosynthesis (Abbas *et al*., 2013; Puvanitha & Mahendran, 2017).

Salt-affected crops do not have homogeneous growth as salinity concentrations vary greatly over a field. Its effects can therefore be observed in the development of the crop. Salinity stress is often displayed through visual plant symptoms (necrosis at the tip or along margins of older leaves) that arise when nutrient salts are excessive, reducing the growth rate as well as crop yields (Bakht *et al*., 2011). High salt concentrations, especially chloride and sodium sulphates (ClO_4S^{-3} and Na_2SO_4), impose both osmotic and ionic stress on plants, which lead to certain morphological and physiological changes (Bernstein, 1975; Goudarzi & Pakniyat, 2008; Puvanitha & Mahendran, 2017). Excessive concentrations of sodium (Na^+) and chloride (Cl^-) hinders the uptake and translocation of potassium (K^+) and affects the K:Na ratio in crop components (Goudarzi & Pakniyat, 2008). This leads to the inability of crops to adapt tolerance mechanisms by excluding toxic Na^+ from the cytoplasm of roots and shoots and maintain a high K:Na ratio. This inability causes changes in the root, shoots and leaves as well as stunts the grain quality and yield of crops. These nutrient salts decrease root and shoot elongation, induces ion toxicity in the roots and can also increase the soil osmotic pressure in the root zone, thereby hindering the ability of roots to absorb water, causing plants to wilt as metabolic changes occur (Goudarzi & Pakniyat, 2008; Bakht *et al*., 2011; Abbas *et al*., 2013; Dadshani *et al*., 2019). Accumulation of nutrient salts in the root zone not only affects K^+ uptake but also prevents the uptake of other essential nutrients such as calcium and phosphorus (P), promoting the accumulation of toxic elements (Na^+ and Cl^-) to damaging levels. These toxicities may further inhibit photosynthesis, protein synthesis, inactivate enzymes or damage chloroplasts and other plant organelles especially in older leaves as they are more susceptible, often due to a weaker leaf tissue. The aboveground biomass of plants is thus more affected by salinity compared to the root biomass because of the photosynthetic inhibition crop components experience (Lamari & Bernier, 1991; Bakht *et al*., 2011; Machado & Serralheiro, 2017).

Osmotic stress is not the only detrimental metabolic dysfunction induced by salinity as the growth response of leaves is also affected. Plants have the ability to regulate their stomatal conductance to reduce water loss by transpiration and thus limit these osmotic stresses. This defensive mechanism in-turn affects photosynthesis as the chlorophyll content is reduced and carbon dioxide (CO_2) availability decreases due to stomatal and mesophyll diffusion limitations. Light absorbance is therefore adversely affected and further prohibited because of a decrease in leaf area expansion caused by excessive salts (Abbas *et al*., 2013; Machado & Serralheiro, 2017; Dadshani *et al*., 2019). Inhibited photosynthetic activity further enhances the overproduction of reactive oxygen species (ROS) and ultimately reduce plant growth and yield as overproduction of ROS is highly toxic and damages proteins, lipids, carbohydrates, etc. (Farooq *et al*., 2015; Dadshani *et al*., 2019).

Ions can reach toxic levels at high concentrations when nutrients have formed ionic salts by specifically binding with Cl^-, Na^+ and SO_4^{-2} ions (Ryan *et al*., 1975). Excessive ion effects on maize crops investigated by Farooq et al. (2015), showed that high Na^+ and Cl^- concentrations in the rhizosphere decrease nitrate (NO_3^-), ammonium (NH_4^+) calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and iron (Fe^{2+}) uptake. Maize seed germination and stand establishment as well as a decrease in grain weight and number are also the effects of an excess of these salts. The most toxic ion affecting maize is Na^+ as it hinders stomatal modulations leadong to water loss and necrosis (Farooq *et al*., 2015). Wheat is slightly more tolerant to salinity than maize because it increases its levels of soluble sugars, causing the stressed cells to release proteins under high salt concentrations. These adaptive responses assist wheat crops under high salinity conditions to promote growth. Wheat can also be severely affected by high levels of Na^+ and Cl^- salts. High levels of salinity also inhibit wheat root and shoot elongation due to decreasing amounts of water uptake for the osmotic adjustment of the plant body (Banerjee *et al*., 2009).

A nutrient salt that is essential but also harmful at high concentrations to both wheat and maize is sulphur (S), taken up as sulphate (SO_4^{2-}) by crops (Aula *et al*., 2019). It is mostly applied with other nutrients through fertilisers in the form of an ionic salt and hinders crop growth when in excessive concentrations. Both wheat and maize growth response is affected by SO_4^{2-} as clear signs of water stress and necrosis occur, thus causing a reduction in growth and development (Eaton, 1942; Khan *et al*., 2006). Eaton (1942) also found that maize is more sensitive to sulphate salts

compared to wheat because the crop shows immediate stress above a few milliequivalents SO_4^{2-} concentration increases. It is evident from literature that Na^+, Cl^- and SO_4^{2-} are more harmful to both wheat and maize as they indicate similar but more severe effects to crops as compared to other nutrient salts.

Plants have the ability to tolerate salinity at certain concentrations and thus undergo adaptative changes when experiencing stress. A prime example is the hormonal imbalances caused by salinity that decrease the stomatal aperture as the transport of kinetin from roots to leaves decrease and the abscisic acid (ABA) content in leaves increase (Bernstein, 1975). This, however, has its own limitation (inhibiting photosynthesis) as described above. A study by Bakht et al. (2011) further investigated the changes in ABA that protect plants from salinity stress, with focus on shoots and seeds of maize. The study found that the ABA concentrations in these components also increased as salt concentrations increased and concluded that ABA assist crops with salt tolerance. Salt tolerance of crops can be quantified as the percentage of yield decline over a range of salt concentrations and is based on parameters such as the threshold, the electrical conductivity (EC) and slope (Maas & Hoffman, 1977; Grattan *et al*., 2012). Plant growth is hindered when the threshold value of salinity is exceeded. The threshold value depends on the crop, external environmental factors such as temperature, wind speed, relative humidity and water-supplying potential of the root zone. Salt concentrations above the threshold value linearly decrease plant growth until it dies (Maas, 1986). Maas & Hoffman (1977) formulated Equation 2.1 below to determine a crop's response to soil salinity.

$$Y_r = 100 - b\,(EC_e - a) \qquad (2.1)$$

Where,

Y_r = percentage of the yield of the crop grown under saline conditions relative to that grown under non-saline conditions

a = the threshold electrical conductivity (mS m^{-1}) of the saturated soil paste at which yield decreases start

b = percentage yield loss per unit increase in the electrical conductivity of the soil extract in excess of the threshold value

EC_e = electrical conductivity of the soil extract (mS m^{-1})

The salt tolerance rating of selected crops based on their threshold value (a, mS m^{-1}) and slope of yield decline (b, % mS m^{-1}) as illustrated in Table 2.1 (Maas, 1986).

Table 2.1 Salt tolerance of specific agronomic crops (Maas, 1986)

		Electrical conductivity of saturated soil extract		
Common Name	**Botanical Name**	**Threshold (mS m^{-1})**	**Slope % per mS m^{-1}**	**Rating***
Bean	*Phaseolus vulgaris*	100	0.190	S
Cotton	*Gossypium hirsutun*	770	0.052	T
Maize	*Zea mays*	170	0.120	MS
Pea	*Pisum sativum*	-	-	S
Peanut	*Arachis hypogaea*	320	0.290	MS
Potato	*Solanum tuberosum*	170	0.120	MS
Wheat	*Triticum aestivum*	600	0.071	MT
*S=Sensitive, MS= Medium Sensitive, MT = Medium Tolerant, T= Tolerant				

(-) = no data available

Observations from a long-term experiment done in a lysimeter by the Mediterranean Agronomic Institute, Italy, in 1989 was compared with the results from Maas & Hoffmann (1977) as depicted by Katerji et al. (2000), as well as with the review done by Grattan et al. (2012) in Table 2.2.

The various crop threshold data presented in Table 2.1 and 2.2 cannot provide a fully accurate, quantitative measure of crop yield losses from salinity for every field. This is due to the change in growth response to salinity depending on the climate, irrigation management, agronomic management, cultivar genetics and crop response to saline conditions (Maas, 1986; Grattan *et al*., 2012).

Table 2.2 The threshold EC_e (dS m^{-1}) and slope (% yield reduction/ dS m^{-1}) according to the lysimeter experiment **(**Katerji *et al*., 2000), and corresponding data published by Maas & Hoffman, (1986) and Grattan et al. (2012)

Crop	Botanical name	Lysimeter experiment		Maas and Hoffman		Grattan et al.	
		EC_e	b	EC_e	b	EC_e	b
Sugarbeet	*Beta vulgaris*	0.0	0.4	7.0	5.9	7.0	5.9
Wheat	*Triticum aestivum*	-	-	5.7	3.8	6.0	7.1
Wheat Durum	*Triticum durum*	0.0	1.9	-	-	5.9	3.8
Potato	*Solanum tuberosum*	0.0	5.6	1.7	12.0	1.7	12.0
Sunflower	*Helianthus annuus*	0.5	8.7	-	-	4.8	5.0
Maize	*Zea mays*	1.3	10.5	1.7	12.0	1.7	12
Maize (forage)	*Zea mays*	-	-	-	-	1.8	7.4
Soybean	*Glycine max*	2.0	11.4	5.0	20.0	5.0	20.0
Tomato	*Solanum lycopersicum*	2.4	16.4	2.5	9.9	2.5	9.9
Broadbean	*Vicia faba*	2.8	14.4	1.6	9.6	1.6	9.6

(-) = no data available

2.4 Nutrient salt removal from the root zone

2.4.1 Uptake by crops

Plants used as biological removers of nutrients from soil have been widely investigated for decades but little focus has been given to salt removal and partitioning (Sayre, 1948; Hanway, 1962; Chaudhri *et al*. 1964; Sandhu & Malik, 1975; Francious, 1981; Karlen *et al*., 1988; Ciampitti *et al*., 2013). Agricultural crops are mostly non-halophytic and suffer under severe salinity stress, especially when threshold values are exceeded. Halophytic plants adapt easily to different environments as they can tolerate severe salt concentrations including ions such as Cl^- and Na^+, which are harmful to crops (Flowers & Colmer, 2015). The reclamation of saline soil with a halophyte was first conducted by Chaudhri *et al*. (1964), where the plant *Suaeda fruticose* was used to extract salts. The results indicated that the leaves had the highest concentration of salt removal with Na^+ salts being the most accumulative, the stems had the highest concentration of K^+ removed, followed by the roots which had the highest removal of Ca^{2+}. It was concluded that the leaves removed Na^+ while roots maintained the Ca^{2+} in the root zone to promote soil flocculation. The study also concluded that halophytic plants can be used with agricultural crops

to help aid salt removal from saline soil (Chaudhri *et al*., 1964). Plant salt removal was then investigated in a zero-leaching lysimeter to evaluate the growth response and salt removal of alfalfa *(Medicago sativa* L.) in saline soil (Francois, 1981). Alfalfa plants had a reduction in growth due to the high salinity content and absorbed more Na^+, Ca^{2+}, Mg^{2+} and Cl^- compared to K^+. Plants that grew in less saline conditions had a good growth response and thus absorbed more K^+ compared to Na^+, Cl^- and Ca^{2+} (Francois, 1981).

Various studies have been done to investigate the uptake of nutrients by higher yielding crops and where these nutrients accumulate within the plant biomass (Sayre, 1948; Hanway, 1962; Karlen *et al*., 1988; Du Preez & Bennie, 1991; Setiyono *et al*., 2010; Ammari *et al*., 2013; Bender *et al*., 2013; Ramanjineyulu *et al*., 2018). These studies have confirmed the uptake and partitioning of nutrients with a general conclusion that it promotes plant biomass production, where a higher biomass is associated with a higher grain yield. The requirement for biomass accumulation therefore acts as the driving force for mineral nutrient uptake and assimilation. Statistical analysis was used to discuss the significance (p-value) of differences in yield, uptake within the plant biomass, between crops and the different localities. Yield and total uptake of the grain was compared to that of the biomass to determine the degree of grain production and nutrient uptake, which is calculated as the harvest index (HI) and nutrient harvest index (NHI). The HI is therefore useful to calculate the percentage of grain production from the biomass produced and by using the NHI, the percentage of nutrients removed by the grain or other components from the biomass can also be determined. The range value for the HI of modern varieties of cultivated grain crops is between 0.3 - 0.6 and reflects the efficiency of dry matter partitioning to the grain. (Karlen *et al*., 1988; Hay, 1995; Setiyono *et al*., 2010; Bender *et al*., 2013; Ciampitti *et al*., 2013 and Ramanjineyulu *et al*., 2018).

The concentrations of nutrient uptake by maize crops (Table 2.3) investigated by Sayre (1948), Hanway (1962) and Karlen et al. (1988) was compared with one another in a study done by Bender et al. (2013). The study also investigated the uptake and partitioning of nutrients by hybrids of higher yielding maize (Table 2.4) to determine the degree in uptake between previous and current maize cropping practices. The biomass of the study by Karlen et al. (1988) had a nutrient uptake one-third higher as compared to the study of Bender et al. (2013), with micronutrients (B^{3+}, Zn^{2+}

and Mn^{2+}) uptake being two-thirds greater. The results thus suggest that micronutrient accumulation may differ among soil micro-environments and agronomic management, and may also be less reliable estimated on a dry weight basis, compared to macronutrients. Comparisons with the other studies have showed that nutrient removal vary greatly depending on the agronomic management practices, yield level and grain nutrient concentration (Bender *et al*., 2013).

The uptake of nutrients by winter wheat have also been investigated but not as intensively under South African growing conditions. A study by Du Preez & Bennie (1991) investigated the uptake and partitioning of nutrients at different growth stages. The study compared uptake by the grain with recalculated data (to suit the yield) of the ears (husk) obtained from a study done by Gregory et al. (1979). The uptake at harvest (Table 2.5) is of critical importance for the purpose of this study as nutrient translocation have minimum effect on the nutrient contents in crop components at this stage.

The results by Du Preez & Bennie (1991) corresponded well with the recalculated data of the ears and concluded on the high degree of nutrient uptake by the wheat components, which was sufficiently supplied by the soil and NPK fertiliser. The research also suggested that these nutrients can be re-introduced into the soil medium when crop residue is not removed.

Table 2.3 Total uptake of selected nutrients by intensively fertilized and irrigated maize (Bender *et al*., 2013)

Agronomic practice	Year published		
	1948	**1962**	**1988**
	Agronomic parameters		
Row spacing (cm)	107	107	30
Plant spacing (cm)	36	66	30
Plant density (plants ha^{-1})	25.960	42.583	111.111
Grain yield (kg ha^{-1})	6300	4600	16.300
Biomass (kg ha^{-1})	13.700	13.600	31.800
Macronutrients (kg ha^{-1})	**Nutrient uptake**		
N	159	141	386
P_2O_5	77	56	161
K_2O	131	87	446
Mg	-	-	44
S	-	-	40
Micronutrients (g ha^{-1})	**Nutrient uptake**		
Fe	-	-	1900
Mn	-	-	900
Zn	-	-	800
Cu	-	-	140
B	-	-	130

(-) = no data available

Table 2.4 Total uptake, grain partitioning and harvest index (representing the percentage of total nutrient uptake present in the grain) of 6 maize hybrids at physiological maturity (Bender *et al*., 2013)

Nutrients	Total uptake		Removal with grain		Nutrient Harvest index	
	Average	**Range**	**Average**	**Range**	**Average**	**Range**
	Macronutrients (kg ha^{-1})				**%**	
N	286	266-307	166	145-188	58	51-62
P_2O_5	114	100-133	90	73-108	79	70-82
K_2O	202	181-225	66	57-78	33	27-37
Mg	59	52-66	17	15-20	29	25-33
S	26	24-28	15	13-16	57	52-60
	Micronutrients (g ha^{-1})				**%**	
Zn	498	448-563	308	269-353	62	60-65
Mn	542	496-793	72	62-87	13	11-16
B	83	67-101	19	13-32	23	17-31
Fe	1376	1224-1569	248	218-285	18	17-22
Cu	141	132-155	41	30-49	29	21-33

Table 2.5 Uptake and partitioning of nutrients by the biomass, ears and grain of winter wheat at harvest (Du Preez & Bennie, 1991)

Nutrient	Biomass uptake	Components	
		Ears	Grain
	kg ha^{-1}		
N	213.7	86.8	99.9
P	39.9	20.3	21.1
K	326.3	26.4	25.2
Ca	32.7	2.4	2.6
Mg	20.6	5.6	6.8
S	17.8	1.1	3.9

2.4.2 Benefits

Although the quantities are small, the removal of nutrient salts by crops may be viewed as a form of bioremediation, i.e. crops also take up ions that affect the behaviour of soil. Crop uptake of nutrient salts has many positive effects on soil physical properties and is therefore very viable under non-leaching conditions. The hydraulic conductivity of soil increases with plant salt removal as compared to leaching treatments because more Na^+ than Ca^{2+} can be extracted by plants under these conditions, thereby limiting soil dispersion probabilities caused by excess Na^+. Crop uptake also retain more nutrient salts in the soil as leaching decreases soil EC, making it the preferred procedure to remove salts from the root zone (Ammari *et al*., 2013).

Another benefit is the ability of plants to reduce soil pH and cause the dissolution of lime in the form of calcite ($CaCO_3$). The dissolution process is driven through root respiration and decomposition of organic matter, releasing CO_2 and H^+ protons into the soil solution. This is a natural and cost-effective process that will supply the soil with adequate Ca^{2+}, thereby replacing Na^+ on the cation exchange complex to promote soil flocculation and aggregate stability. The replaced Na^+ is then either removed by the infiltrating water or taken up by plants and stored in the above-ground plant biomass (Qadir *et al*., 2005; Jesus *et al*., 2015). The study also concluded that plants (depending on their tolerance) removed more Na^+ when the soil was irrigated with saline-water, thus making it suitable even when poor quality irrigation water is used (Ammari *et al*., 2013).

Utilizing crops for nutrient salt uptake is a viable solution for saline soil and can be very effective in stabilizing soil structure, particularly under non-leaching conditions. The best suitable plants for remediation are plants that can absorb higher salt concentrations of Na^+ compared to Mg^{2+} and Ca^{2+}. The duration for remediating saline soil is dependent on depth, as it will take a shorter period of time to remediate the topsoil compared to the whole profile. The applicability of remediating saline soil through crops is still questionable as not enough studies have included the uptake and accumulation of nutrient salts in the aerial biomass of plants, especially under various climatic conditions (Jesus *et al*., 2015).

2.5 Measuring salts associated with irrigation

2.5.1 In-field soil measurements

Electromagnetic induction (EMI) instruments are commonly used to determine the electrical conductivity (EC) of soil properties because it does not require the need to insert electrodes into the soil (McKenzie *et al.,* 1997).

The EMI sensor, Figure 2.2, most widely used in soil science and in vadose zone hydrology is the Geonics EM38-MK2 (Corwin & Lesch, 2005). The EM-38 device is a valuable application in agriculture due to its measuring depth of up to 1500 millimeters (mm), which corresponds roughly to the root zone, when the instrument is placed in the vertical coil configuration. When the instrument is placed in the horizontal coil configuration, the depth of measurement is between 600-750 mm to 1000 mm. The instrument measures the EC_a of soil, which is then correlated to soil conducting properties (EC_e, bulk density, texture, etc) using statistical software (McKenzie *et al.*, 1997; Corwin & Lesch, 2005; Corwin & Scudiero, 2016).

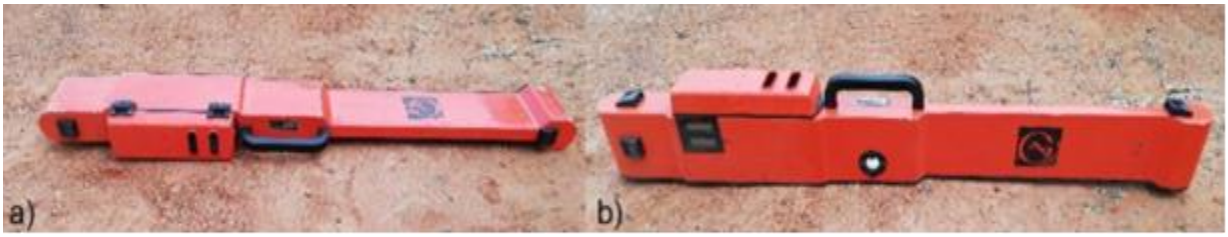

Figure 2.2 The EM38-MK2 in a) horizontal position with coils parallel to soil surface for shallow readings and b) in vertical position with coils perpendicular to soil surface for deeper readings.

Various factors need to be accounted for before an EC_a survey is conducted as not only soil properties (clay, water content) but also objects such as metal can conduct an electrical current. The most influential factor is the concentration of soluble salts in soil moisture, as an increase in soil moisture increases conductivity but as the soil moisture decline so will the EC_a. This change in soil moisture content emphasize the need to know soil moisture to ensure that the instrument measurements are reliable. A range of moisture contents, ranging from 20-30 percent of available moisture to slightly more than field capacity ($\geq$ 70% of field capacity) is required for accurate EC_a estimates and should thus not be less than one-half of the field capacity. This ensures a continuous solid-phase pathway for electrical flow between soil particles as soil structure limits particle to particle contact between aggregates (Rhoades *et al*., 1999; Corwin & Lesch, 2005). Protocols as described by Corwin & Scudiero (2016), should therefore be followed before conducting an EC_a survey with the Geonics EM38-MK2 instrument. The EC_a measurement is primarily influenced by soil water content, clay, salinity (EC_e = saturated paste electrical conductivity), bulk density, temperature and organic matter, and secondarily by metal, compaction, surface roughness, irrigation management, topography and elevation (Corwin & Lesch, 2003; Corwin *et al*., 2003; Corwin & Scudiero, 2016). Secondary influences should be minimised to ensure reliable EC_a measurements.

A Global Positioning System (GPS), which is a satellite-based three-dimensional radio-navigation system is used to obtain the locations of the EC_a measurements over a field. The accuracy of this method is increased by using the Differential GPS (DGPS) technique whereby two receivers are used. One receiver is at a fixed known position and the other in motion with the EM-38 operator. Differential GPS accuracy of a few meters can be achieved and centimetre-level accuracies can be obtained if precise carrier-phase measurements are used. The EM-38 has been successfully used in conjunction with DGPS to create accurate EC_a maps (McKenzie *et al.*, 1997). According to the literature by McKenzie *et al.* (1997) there are 4 major advantages of using the DGPS and EM-38 method namely;

- Data collection is timely and cost-effective, because a grid does not have to be pre-surveyed,

- The DGPS give an electronic record of the all-terrain vehicle (ATV) used or operators position at a rate of 1 Hz,
- Real-time DGPS can be used to adapt the grid to the nature of the salinity, and
- Crossovers or tie-lines can be used to see the repeatability of the EM-38 readings at the same location during a data-collection session or after a long period of time.

The model-based RSSD program in the (ESAP) software (ESAP-95 Version 2.01R), is a statistical program which is used to generate optimal soil sampling designs from EC_a survey information (Lesch *et al*., 2000). Sampling point selection is based on the spatial variation of geo-referenced EC_a measurements with the use of a model-based response surface sampling design (RSSD) to help minimise the number of samples needed to obtain spatial variation (Corwin & Scudiero, 2016). The program transforms the survey data through principal component analysis (PCA) and selects a response surface approach based on the transformed data to identify candidate locations on the field fitting the selected sampling design. A space-filling algorithm is then used to select a set of points from the candidate locations where soil samples are collected (Corwin & Scudiero, 2016).

Soil EC_a measurements undertaken with electrical conducting instruments can be correlated to salinity (EC_e) or other conducting properties through a stochastic or deterministic approach (Corwin & Lesch, 2003; Corwin & Scudiero, 2016). The deterministic approach is mostly used and preferred when localized variation in soil type occurs in the field. It also requires additional inputs of soil water content, saturation percentage, bulk density and temperature for the conversion. The stochastic approach is mostly applicable in studies that lack soil property information and thus makes use of statistical modelling techniques such as co-kriging and spatial regression to predict soil properties from EC_a survey data (Corwin & Lesch, 2003; Corwin & Scudiero, 2016).

The relationship between EC_a and EC_e is encompassed by the water content of the soil and is mostly used to assess soil salinity. This close relationship between EC_a and EC_e is expressed by Equations 2.2 to 2.8, which is derived from the deterministic two-pathway solid-liquid series-coupled (DPPC) model developed by Rhoades *et al*. (1989 & 1990).

$EC_a = [\frac{(\theta_s+\theta_{ws})^2\, EC_{ws}\,.\, EC_s}{\theta_s\,.EC_{ws} + \theta_{ws}\,.\, EC_s}] + (\theta_w - \theta_{ws})EC_{wc}$ (2.2)

and

$EC_e = EC_w\,(\frac{\theta_w}{P_b}\frac{100}{SP})$ (2.3)

or

$EC_w = (\frac{(EC_e\,.\,P_b\,.\,SP}{100\,.\,\theta_w})$ (2.4)

$EC_s = 0.019\ (SP) - 0.434$ (2.5)

$\theta_s = P_b/2.65$ (2.6)

$\theta_{sw} = 0.639\ \theta_w + 0.011$ (2.7)

$\theta_w = (PW\,.P_b)/100$ (2.8)

Where,

EC_a = electrical conductivity of the bulk soil (dS m^{-1})

θ_{ws} = volumetric water content in the small and large pores ($cm^3\ cm^{-3}$)

θ_w = total volumetric soil water content, determined as ($\theta_w = \theta_{ws} + \theta_{wc}$)

θ_{wc} = volumetric water content of the soil water in the continuous pathway

θ_s = volume fraction of the solids, determined as (p_b/p_s)

θ_{sw} = volumetric water content in the solid pathways ($cm^3\ cm^{-3}$)

p_b = is the soil bulk density and p_s is the particle density of mineral soils with a norm of 2.65 g cm^{-3}

EC_s = surface conductance of the soil phase (dS m^{-1})

EC_{wc} = electrical conductivity of the soil water pathway (dS m^{-1})

EC_e = electrical conductivity of the soil-paste extract (dS m^{-1})

EC_w = electrical conductivity of the soil water (dS m^{-1})

EC_s = electrical conductivity of the solid phase (dS m^{-1})

SP = gravimetric water content of the saturation paste/ saturation percentage

PW = percentage water on a gravimetric basis

The equation expresses the relationship between bulk soil EC_e, PW, SW and P_b, thus providing a tool to measure the mobile and immobile salt and water contents of the soil (Rhoades *et al*., 1989 & 1990; Corwin & Lesch, 2003). The measurements of soil EC_e, PW, SW and P_b followed by the utilisation of equations (2.2) to (2.8) can thus be used to calibrate soil EC_a and vice versa (Corwin & Lesch, 2003).

There are thus four steps to follow in the operating procedure for field-scale EC_a surveys in precision agriculture, namely (Corwin & Lesch, 2003):

i) an intensive EC_a survey
ii) a soil sample design based on the EC_a survey
iii) a stochastic or deterministic calibration of EC_a to sampled soil EC_e
iv) determining the soil properties influencing the EC_a measurement

An EC_a survey produces a large volume of spatial data, where its measurement is influenced by various properties. There are two approaches used to determine the properties influencing EC_a namely; wavelet analysis and linear regression (Corwin & Lesch, 2003; Corwin & Scudiero, 2016). Wavelet analysis is efficiently used to characterise the interrelated factors influencing EC_a measurement, however it requires the collection of soil sample data on a regular grid basis or equal-spaced transect. These two sampling methods are not very practical for determining the spatial distribution of soil salinity and other correlated soil properties from EC_a measurements. The best manner in interpreting the spatial data from a measured EC_a survey is thus by using statistical analysis and graphical display. The statistical approach relies on targeted sampling strategies and spatial regression calibration models, which can be used to estimate soil properties from EC_a survey data. This is mainly possible if calibration soil samples are obtained and the survey data correlates well with the target soil property. A suitable regression model is then specified that relates the target soil property to a transformed linear combination of conductivity signal data readings (Corwin *et al*., 2003; Corwin & Lesch, 2003 & 2005; Corwin & Scudiero, 2016).

Crop yield data and EC_a survey data can also be used for site-specific crop management to identify soil properties influencing yield and to delineate site-specific management zones. This can be achieved if crop yield and EC_a measurements are correlated within-field, followed by basic statistical analysis. A spatial linear regression is formulated that describes the soil properties as an independent variable and crop yield as the dependent variable, which is useful to established which property was the driving force behind the yield. Interpolation methods (i.e. kriging, inverse distance weighting (IDW), cubic spline) are then used to graphically display the distribution of a target property, with IDW and kriging often used. To determine which interpolation method is best suited with a spatial data set, the jackknifing statistical approach is used to establish the interpolation method that minimises the prediction error (Corwin & Scudiero, 2016).

2.5.2 Laboratory soil analyses

There are various methods to measure the ion concentration in soil. The accuracy of the results, however, depend on the protocols followed as outlined by Motsara & Roy (2008) when sampling and processing soil for analysis. The method applied to extract a composite of nutrient salts from soil without having to do individual analysis is mostly applied as it saves time and costs. The Ambic-2 method is generally applied for this purpose for ICP-OES analysis.

A study done by Thompson (1995) investigated different methods such as Olsen, Ambic, Bray No.1&2, Mehlich-3, etc., to extract exchangeable cations from soil with emphasis on K. The study concluded the Ambic method to be the most efficient and time-saving method to extract a composite of plant-available nutrient salts into solution for ICP-OES analysis. The Ambic-2 method makes use of:

- De-ionised water
- Superfloc N300 with an adjusted pH of 8 done with ammonia solution 100% (NH_4)
- Ammonium bicarbonate (NH_4HCO_3)
- Ethylene-diamine-tetra-acetic acid di-ammonium (EDTA)
- ammonium fluoride (NH_4F)
- Whatman No.1 filter paper

- pH meter with buffer solutions
- acetic acid glacial 100% (CH_3COOH)

The superfloc solution is prepared by placing 4000 ml of de-ionized water in a 5 L glass beaker and stirred using a magnetic stirrer until a vortex is formed in the solution. Thereafter 20 g of dry powder should very slowly be added to the edges of the vortex and left to stir for 2 hours until the flocculent is dissolved. The solution should then be transferred to a 5 L bottle top dispenser. The extracting solution used by the Ambic-2 method can then be prepared by weighing and transferring 395.4 g of NH_4HCO_3, 65.3 g of $(NH_4)_2EDTA$ and 7.4 g of NH_4F into a 5 L glass beaker. Approximately 800 ml of de-ionised water should then be added and stirred with a magnetic stirrer to dissolve the salts before 200 ml of the superfloc solution is added. The solution should remain stirring as more de-ionised water is added until the 5 L mark is reached. The solution should then be transferred into a 20 L plastic container, followed by adding 15 ml de-ionised water again until a final volume of 20 L is reached. The extract solution should then be left overnight in a cold room and the pH adjusted to 8 if needed, with ammonia solution before the extract is used.

The extracting can then commence by scooping 2.5 ml of soil into a plastic container and then adding 25 ml extraction solution. The suspended solution is then stirred with a magnetic stirrer for 10 minutes at 400 rpm. Set up a tray with funnels containing Whatman No. 1 filter paper and glass beakers underneath the funnels to catch the extract. After the time commenced, the extract can carefully be poured into the funnel and left to filter. When the filtering is complete, the residue can be disposed of and the extract transferred to 50 ml polypropylene greiner tubes for storage in a cold room. The extract is then diluted with 20 ml de-ionised water before it is analysed with the ICP-OES to detect the cations present in the soil (Thompson, 1995; Manson & Roberts, 2000).

Nutrient salts in the soil solution have been correlated to the amount of exchangeable soil cations (Sharpley & Kampath, 1988). The EC of the saturation extract (EC_e) is indicative of the total dissolved nutrient salts in the soil solution and often used to classify the salt hazard of soil or leaching requirements of saline soil for reclamation. The method includes; mixing 250 g of air-dry soil in a suitable container and moistened with de-ionised water while mixing with a spatula. Ensure that a saturated paste is obtained through saturation characteristics, i.e. a shiny surface or

the paste flowing slightly when tilled or no free water ponding when a trench is made. The saturated paste should then be left for at least an hour or overnight with special care given in covering the container to prevent the paste from drying out. The soil paste is then filtered by suction through Whatman No. 50 filter paper on a funnel and a clear solution should be collected in a test tube that is placed in a suction flask under the funnel. The filtrate can then be analysed with a conductivity meter and the conductivity of the saturation extract expressed in mS m^{-1} (Non-affiliated soil analysis work committee, 1990).

2.5.3 Laboratory plant nutrient analyses

Plants are analysed with different extraction methods and instruments to obtain the ion concentrations in plant material. The two main procedures of plant analysis include sap extraction and chemical analysis (Kalhoro *et al.*, 2016). The basic steps of vegetation analysis include the selection of material to be sampled, the sample and preliminary sample handling, sample preparation for proper analysis, final analysis and data treatment (Namieśnik & Zygmunt, 2003).

Analytical techniques play an important role in plant analysis and an ideal method is described as; one that provides precise, reliable information, is sensitive, rapid and inexpensive to perform (Goyal, 2002). Important techniques in biochemistry involve the measurement of emitted light intensity. In order to relate an optical measurement to the amount of a particular component in a sample, it is necessary to utilise the ability of molecules or atoms to absorb or emit light when exposed to a certain set of conditions. Optical methods of analysis entail the use of special equipment which is often simple and inexpensive (Draper, 1976). Table 2.6 illustrates the optical methods of analysis, as well as their main characteristics pertained from plant sap extractions.

Table 2.6 Optical methods of analysis (Draper, 1976)

Method	**Basis of the technique**	**Apparatus**
Molecular absorption analysis:		
Colorimetry	Absorption of visible light by molecules in solution	Colorimeter
Spectrophotometry	Absorption of light of a narrow wavelength band by molecules in solution	Spectrophotometer
Atomic absorption analysis	Absorption of light by a free atomic species	Atomic-absorption spectrometer
Atomic emission analysis	Emission of light by atoms in an excited electronic state	a) Atomic-emission spectrometer
		b) Flame photometer
Fluorimetry	Fluorescence of a solution	(a) Fluorimeter
		(b) Spectrofluorimeter

Plant materials are complex matrices and when components of very low concentration are of interest, it is important to use analytical methods that are characterised by high selectivity, sensitivity and resolution (Namieśnik & Zygmunt, 2003). There are different methods of extracting plant material for analysis namely:

Heat treatment through either wet- or dry ashing

Dry ashing is the most convenient and frequently used method to analyse plant material. Plants are grinded and digested by heating the dried and ground substance in a muffle furnace to a temperature, usually 450 ^{o}C, which is high enough to volatilise or oxidise all carbon-containing compounds. No liquid is used and white ash is produced that consist solely of inorganic salts. After the sample cools, the sample ash is taken up in acid for determination of specific elements (Okalebo *et al.*, 2002). Dry-ashing is described as a simple method by Okalebo et al. (2002), however some constraints persist such as:

- **Reactions leading to combustion** – The temperature of the sample can become 150 ^{o}C higher than that of the furnance and may set on fire, causing self-combustion. When the furnance is heated, the temperature of the sample causes a loss of analyte. The plant sample should thus first be charred carefully on a hot plate.
- **Choice of temperature** – If the temperature remains too low, the samples will not be ashed completely, which will be evident from the grey or black colour of the residue. If the

temperatures are too high, the analyte may volatilise, which is a process that cannot be directly observed. The most suited temperature range is between 450-550 ^{o}C and the actual selection of the ashing temperature depend on the composition of the matrix as many metal halides are volatile.

- **Contamination**- Some dry-ashing procedures require the addition of a reagent for better oxidation or to prevent volatilisation. The reagent should thus be pure and not contaminate the sample.
- **Inclusion**- A grey or black coloured ash indicates the presence of carbon, which may also include the analyte. After the ash is taken up in acid and filtrated, the process should then be repeated at higher temperatures limited to a maximum of 550 ^{o}C, with the ash remaining on the filter.
- **Fixation**- When porcelain crucibles are used at high temperatures metal ions such as, Al^{3+}, Cu^{2+}, Fe^{3+}, Zn^{2+} and Pb^{2+}, may be bound to the silicates of the plant and should thus be released by fuming with hydrofluoric acid. When platinum crucibles are used metals such as Cu^{2+}, Hg^{2+}, Ag^{+} and Sn^{2+} may be lost for analysis by the formation of alloys.

Wet ashing

It involves the digestion of plant material with a mixture of nitric and perchloric acid. The procedure is however not suitable for materials containing more than 10 g of fat per 100 g of dry matter as there is a risk of explosion with usage of these acids. After the plant material is digested, the acid mixture is removed through heat treatment and the residue is then treated with hydrochloric acid to obtain a solution (Draper, 1976; Okalebo *et al*., 2002). This procedure is ion specific and thus able to determine the concentration of chloride, where silver nitrate is used to aid in the precipitation of chloride, which is then followed by titration of the excess silver remaining in solution (Draper, 1976).

Closed tube extraction

Plant material is digested using acids to obtain an extract that is analysed with an inductively coupled plasma optical emission spectrometry (ICP-OES) instrument to determine the

concentrations of multiple elements. Before plants are analysed, the best extraction method is determined by the following criteria as described by Wheal et al. (2011):

- the suitability of final sample to the method of analysis,
- the ability to produce a representative sample,
- the completeness and reproducibility of recovery,
- extent of sample contamination,
- the duration of the method and
- the economic and environmental cost of operating time, including preparation, cleaning, reagent consumption, waste production and disposal.

Wet decomposition, also referred to as acid digestion mostly uses nitric acid (HNO_3) with other acids or oxidising agents, such as hydrogen peroxide (H_2O_2), to accelerate the breakdown of organic material. Open glass tubes are heated by aluminium heater blocks at atmospheric pressure to aid the digestion process, however this method is often susceptible to contamination from airborne particulates, sample loss through volatilisation and also requires longer digestion times. By sealing the digestion vessels these risks are greatly reduced and thus produce more accurate results (Wheal *et al*., 2011).

Screw-cap polypropylene (PP) tubes are most acceptable for acid digestion because it reduces sample loss, the pressure inside the tube increases the boiling point of the acids thus causing the duration of digestion to be much lower, the material of the tube (PP) is resistant to mineral acids and can tolerate temperatures of up to 130 ^{o}C. This method uses oven-dried samples with a weight of 0.30 g that is added to a 50 ml PP tube. The sample mass should not exceed 0.35 g as the pressure build-up during heating will rupture the tubes and dry out the samples during digestion. Plant digestion then follows by adding 2 ml HNO_3 and 0.5 ml H_2O_2 to the tube, where it is then hand tightened and vortexed with a centrifuge for 10 seconds to ensure the entire sample is wetted.

The samples are then pre-digested overnight at room temperature (20-22 ^{o}C), and vortexed again the following day before placed on heating blocks or in a sand-bath for final digesting. The build-up pressure in the tubes is then released and equalised by loosening the tube caps after 30 minutes

or when the heating temperatures reach 80 ºC. The samples are heated again for 2-3 hours until digestion is complete and left to cool. The extract is then diluted with de-ionised water to the 25 ml mark in the tube by using a bottle-top dispenser and vortexed again for 10 seconds. The diluted extract is then placed on an orbital mixer at 220-300 rpm for 5 minutes to ensure thorough extract dilution (Wheal *et al*., 2011).

Closed tube digestion is the best suitable method to get plant material into solution ready for ICP-OES analysis because it not only saves time and reduces the risk of sample contamination but it also makes use of less dangerous acids, require smaller sample masses, requires less intensive supervision, uses lower temperatures and samples can be conveniently stored in the tubes (Wheal *et al*., 2011).

2.6 Conclusion

Salt accumulation is a detrimental effect of irrigation practices and pose a direct threat to sustainable crop production.

Crops utilise salts as nutrients and translocate them from roots to the various plant components to aid in functioning and development. However, these salts can become harmful when in excessive concentrations, especially within the root zone, thereby limiting uptake (nutrients, water) and growth. The tolerance of crops to salinity concentrations differ, with wheat being less sensitive to salinity compared to maize. Removal of salts from the root zone is often done through leaching practices but this has negative impacts (groundwater pollution, soil deterioration, nutrient status decline). Crop salt removal is therefore a viable approach to remove salts from the root zone and can also serve as a mitigation measure to minimise salt addition from excessive fertiliser applications by re-introducing crop residue into the soil. To effectively manage salinity, the salinity status of soil needs to be spatially quantified.

Different approaches exist to examine the magnitude of salinity or soil properties influencing crop growth over a field. The most widely used approach is the spatial measurement of EC_a through EMI or ER to characterise salinity or influencing soil properties. Electromagnetic induction,

specifically the Geonics EM38-MK2, is mostly used in soil science as it is a non-invasive technique. A model-based RSSD program in the ESAP software is used to obtain a soil sampling design from the measured EC_a information where sampling points are selected from. The properties influencing EC_a are then correlated through stochastic or deterministic modelling and characterised with wavelet or linear regression statistical analysis. Interpolation methods are lastly used to graphically display the spatial distribution of the EC_a influencing soil properties.

There are different methods available to extract and analyse the salt concentration in soil and plant material. The most reliable extraction method for spectrophotometry (ICP-OES) analysis has been identified as liquid extraction with a closed tube digestion for plants and Ambic-2 method for plant available nutrient salts in soil.

The literature review indicate that research has been done to compare nutrient salt concentrations and threshold values of various cash crops along with their salinity symptoms as well as the nutrient concentrations of wheat and maize partitioned within the biomass. It was also acknowledged that there is insufficient information available regarding the spatial uptake and partitioning of salts from soil by higher yielding cereal crops and their contribution in the soil salt balance for salinity management as previous investigations mostly focused on leaching.

CHAPTER 3. MATERIALS AND METHODS

3.1 Description of study fields

Three fields from two separate farms located in two provinces were used in the study, i.e. Field 1 near Douglas in the Northern Cape and Field 2 and 3 near Luckhoff in the Free State (Figure 3.1). These fields form part of the research project "Management guidelines for technology transfer to reduce salanisation of irrigated land with precision agriculture" funded by the Water Research Commission (Project K5/2499/4), and was selected in co-operation with crop and soil specialists from GWK (Griekwaland Wes Korporatief) and the South African Sugarcane Research Institute (SASRI). Field measurements commenced in June 2016 and continued over two seasons, with final measurements taking place in May 2017.

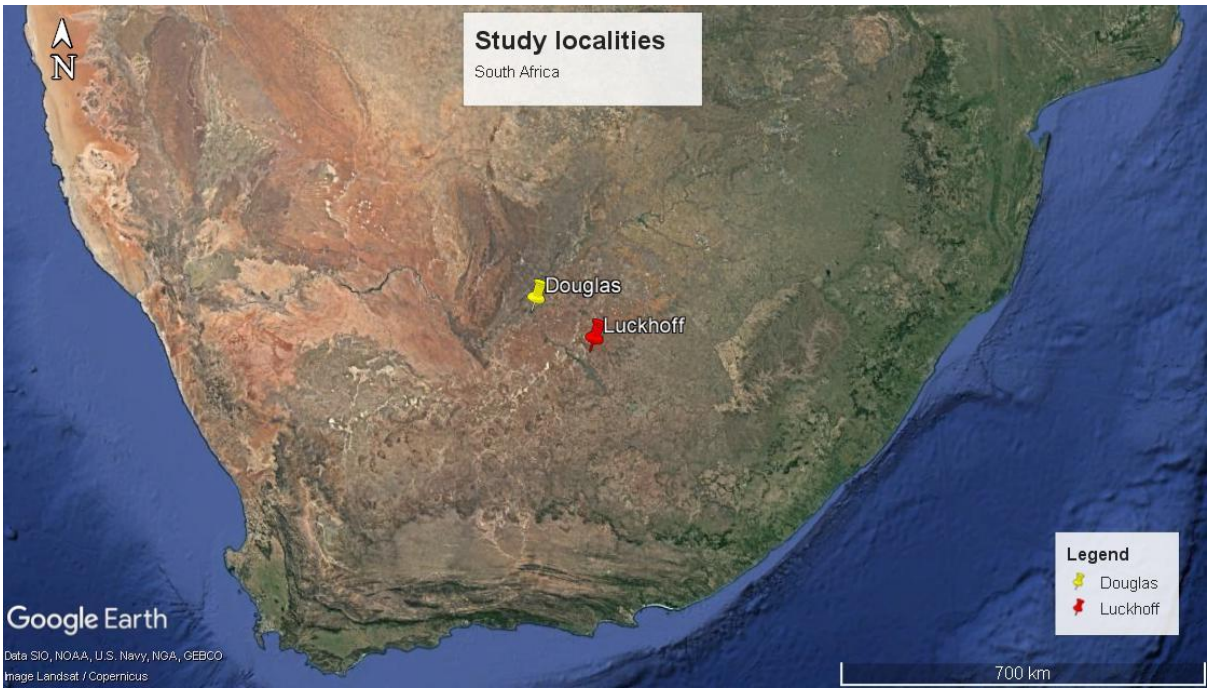

Figure 3.1 Location of the two farms (image obtained with the use of Google Earth Pro).

Long-term seasonal weather data of each farm are summarized in Table 3.1. Data from the DeHoek Weather Station was used at Field 1 near Douglas which is roughly located 34 km west of the farm. For Field 2 and 3 data from the Rust Weather Station was used, which is situated 33 km

south of the farm. All fields were irrigated by centre pivot irrigation systems with water abstracted from a prominent irrigation source.

Table 3.1 Summary of both localities' long-term climatic conditions during the wheat and maize seasons (Van Heerden and Walker, 2016)

Climate	Mean Max T (ºC)	Mean Min T (ºC)	Mean Max RH (%)	Mean Min (%)	Mean Total Radiation (MJ m^{-2})	Mean Wind Speed (m s^{-1})	Total Rainfall (mm)	Total Relative ET_o (mm day^{-1})
June to November wheat season								
Douglas	24.3	6.3	84.6	19.5	19.2	1.9	80	3.9
Luckhoff	23.0	6.7	85.4	20.6	19.9	2.0	91	5.3
December to June maize season								
Douglas	29.3	13.1	-	-	-	-	260	5.1
Luckhoff	28.7	13.5	-	-	-	-	234	4.9

ET_o = Reference evapotranspiration of well-irrigated crops
(-) = No data available

Field 1 (Figure 3.2) is a 40 ha field located about 20 km northwest of Douglas at an altitude of 1016 m and longitude and latitude of 29º01'38.01''S, 24º00'06.83''E. The field is irrigated by water from the Lower Riet River, which forms part of the Orange-Riet Irrigation Scheme. The climate is classified as hot semi-arid (BSh) according to the Köppen-Geiger classification system and thus receives limited rainfall throughout the year (climate-data.org, 2020). During the wheat season (June to November), the mean long-term reference evapotranspiration (ET_o) and minimum and maximum temperature amounted to 3.9 mm day^{-1}, and 6.3 and 24.3 ºC, respectively, with a total mean long-term rainfall of 80 mm. The mean long-term ET_o and minimum and maximum temperature during the maize season (December to June) amounted to 5.1 mm day^{-1}, and 13.1 and 29.3 ºC, respectively, with a total mean long-term rainfall of 260 mm (Van Heerden and Walker, 2016, Table 3.1). Irrigation water from the nearest stream gauge (i.e. instrument measuring water level and flow) during the wheat and maize growing seasons had a mean long-term EC of 180 (standard deviation = 152 mS m^{-1}) and 105 (standard deviation = 33 mS m^{-1}) mS m^{-1}, respectively, while the mean long-term SAR remained below 5 (Huizenga *et al*., 2013, Table 3.2).

Field 2 is a 20 ha and Field 3 a 40 ha field (Figure 3.3), which are located about 40 km south west of Luckhoff. The farm is located along the Settlement section of the Orange-Riet Irrigation Scheme

at an altitude of 1198 m and longitude and latitude of 29º38’32.23’’S, 24º42’01.69’’E. Field 2 was irrigated by blended drainage and orange river water and Field 3 with water obtained from the Orange River. The Luckhoff area also receives little annual rainfall and is classified as cold semi-arid (BSk) (Climate-data.org, 2020). Weather station data for the wheat, maize and popcorn growing seasons were similar to Field 1. The mean long-term ET_o and minimum and maximum temperature during the wheat season amounted to 3.7 mm day^{-1}, and 6.7 and 23 ºC, respectively, and 4.9 mm day^{-1}, and 13.5 and 28.7 ºC, respectively, during the maize season (Table 4.2). The mean long-term rainfall during the wheat season is 10 mm more and 30 mm less during the maize season compared to Field 1 (i.e. 91 and 234 mm for wheat and maize). The wheat and maize mean long-term EC was 17.9 (standard deviation = 2.3 mS m^{-1}) and 18.5 (standard deviation = 2.4) mS m^{-1}, respectively, while the SAR remained below 1 (Huizenga *et al*., 2013, Table 3.2). It is also evident that Douglas had a slightly higher mean temperature during the wheat and maize seasons as compared to Luckhoff but received lower rainfall during the June to November wheat season. Although the mean long-term rainfall during this season was low, the mean rainfall calculated over the two seasons for Douglas was higher (i.e. 170 mm) than Luckhoff which had a mean long-term seasonal rainfall of 162 mm.

Figure 3.2 Field 1 at Douglas, located along the Lower Riet River section of the Orange-Riet Irrigation Scheme (Image from Google Earth with the use of ArcGIS).

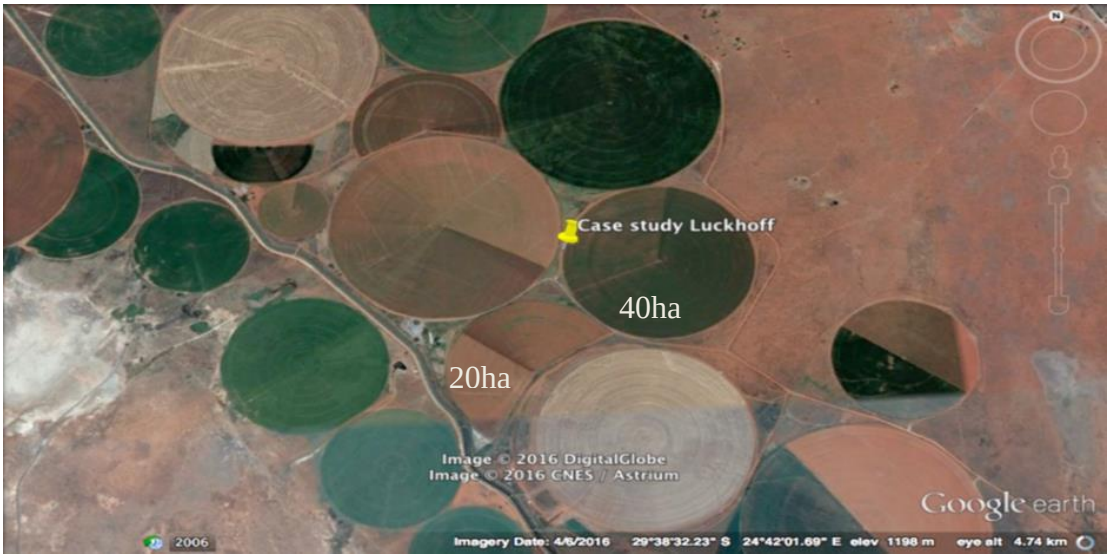

Figure 3.3 Fields 2 and 3 at Luckhoff, located along the Settlement Section of the Orange-Riet Irrigation Scheme (Image from Google earth with the use of ArcGIS).

Table 3.2 Long-term irrigation water quality at the two study localities during the wheat and maize seasons (Huizenga *et al*., 2013)

Parameters	Douglas		Luckhoff	
	June to November wheat season	**December to June maize season**	**June to November wheat season**	**December to June maize season**
EC ($mS.m^{-1}$)	180 (SD = 152)	105 (SD = 33)	17.9 (SD = 2.3)	18.5 (SD = 2.4)
SAR	< 5	< 5	< 1	< 1

EC = Electrical Conductivity

SAR = Sodium Absorption Ratio

Soil at the fields were classified with a soil auger on a grid sampling basis according to the South African Taxonomic Soil Classification System (Soil Classification Working Group, 1991). Figures 3.4 and 3.5 illustrate box and whisker plots of the surveyed soil forms (number of grid locations are shown in brackets) at the various fields with their corresponding clay content in 300 mm depth intervals up to 1.5 m from left to right. The box and whisker plots on the left representing the 0-300 mm topsoil are thus of importance for the purpose of this study. The interquartile range (body) of the box represent the difference between Q1 and Q3, where 50% of the data lies. The lower line of each box represents the first quartile (25% of the data lies below Q1) and the upper line represents the third quartile (75% of the data lies below Q3). The middle line represents the median

and the cross the mean. The upper and lower whiskers of the box represent the maximum and minimum values, excluding the outliers caused by unusual large values (Bluman, 2009).

It is evident from the results that, regarding the particle size distribution, soils between Field 1 and Field 2 and 3 are very different with clay percentage varying from approximately 3 to 52%. Soils at Field 1 have the highest clay content and are mainly hydromorphic with poor external drainage due to the presence of carbonates in the subsoil. The most dominant soil forms are Augrabies followed by Clovelly, which had a mean clay content of 23% and 22%, respectively. The clay content of the soil is spatially diverse as indicated by an interquartile range of roughly 20% (Figure 3.4). Soils at Fields 2 and 3 are uniform and dominated by a deep (± 1.5 m) sandy Hutton soil form with a 10% clay content. These soils are formed from wind-blown sand deposits and usually have good drainage within the soil profile (Soil Classification Working Group, 1991). The soil is therefore spatially very homogeneous over the field which is supported by the low interquartile range (± 5) as depicted in Figure 3.5.

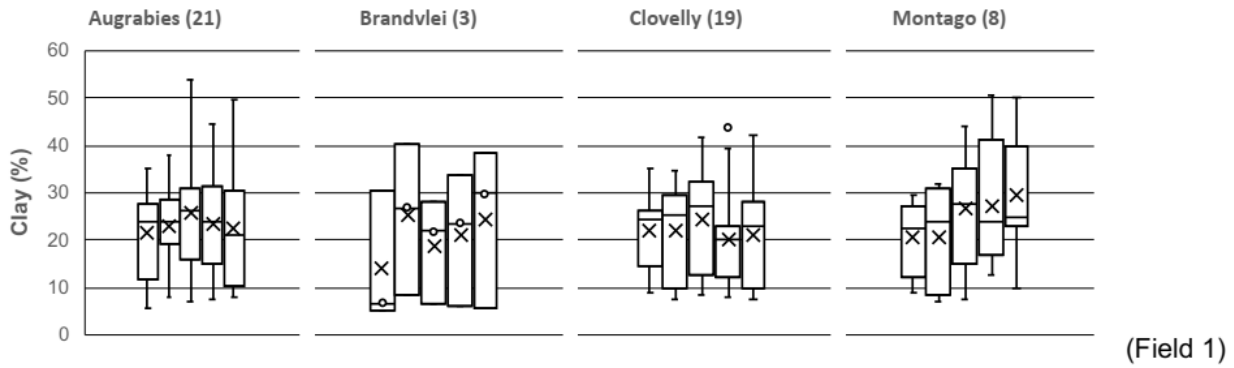

Figure 3.4 Soil classification at Field 1 (Barnard *et al*., 2020).

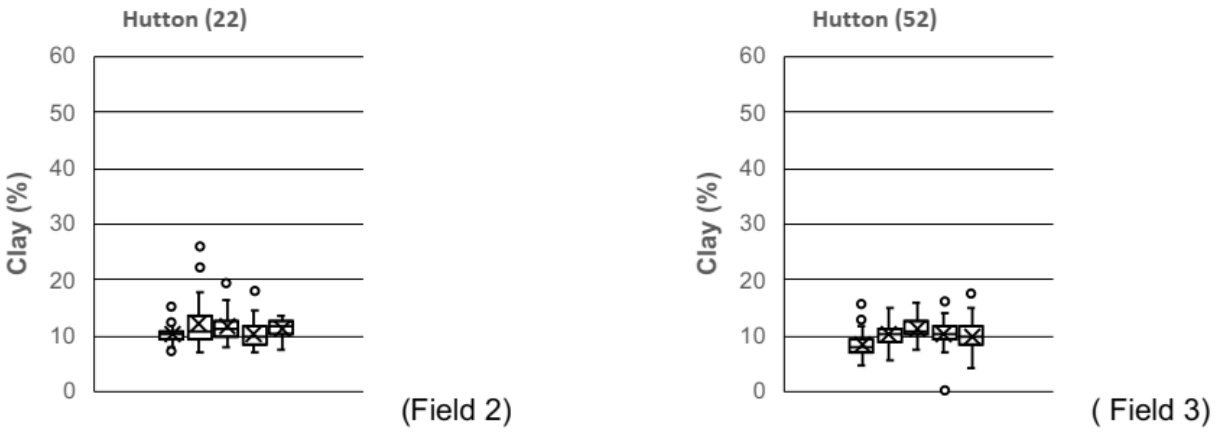

Figure 3.5 Soil classification at Field 2 and 3 (Barnard *et al*., 2020).

Winter wheat (2016) and summer maize (2017) were planted at all the fields, except for Field 3 which was planted with popcorn instead of maize. Standard agronomic management practices were followed by the producers, including fertiliser application, irrigation and pest control practices. No special amendments were made during the study period. The maize crops at Field 1 and 2 as well as popcorn at Field 3 had similar row spacings at 76 cm, respectively. The wheat crops at Field 1 was sowed and not planted in rows, while the farmer at Field 2 and 3 planted wheat with a row spacing of 20 cm. The soil and crop management practices applied during the course of the study are presented in Table 3.3 and 3.4.

Table 3.3 Agronomic practices applied at Field 1 (2016-2017)

Practices	**Field 1**	
	Jun-Dec 2016	**Dec 2016- May 2017**
Crop	Wheat	Maize
Cultivar	PAN 3497	PHB 32Y27
Planting density	80 kg ha^{-1}	88 000
Planting dates	07 July 2016	13 Dec 2016
First harvest date	07 Dec 2016	28 May 2017
Post-harvest crop residue management	Burn	Strip-till
Weed management	MCPA/Resolve	Primagram
Cultivation practices	CLG up to 450 mm	Strip-till up to 300 mm
Fertiliser type (kg ha^{-1})	Plant 350 2:3:2	Plant 350 2:3:2
Total kg N ha^{-1}	280	310
Total kg P ha^{-1}	55	65
Total kg K ha^{-1}	85	90
Method of fertiliser	Granular fertiliser with plant; Liquid fertiliser for rest of the season	Granular fertiliser with plant; Liquid fertiliser for rest of the season
Organic fertilisers	None	None
Total irrigation water applied (mm)	540	600

Table 3.4 Agronomic practices applied at Field 2 and Field 3 (2016-2017)

Practices	Field 2		Field 3	
	Jun - Dec 2016	**Dec - May 2017**	**Jun - Dec 2016**	**Dec - May 2017**
Crop	Wheat	Maize	Wheat	Popcorn
Cultivar	SST 835	PAN 6126	SST 835	427
Planting density	100 kg ha^{-1}	85 000	100 kg ha^{-1}	80 000
Planting dates	20-Jun-16	-	16-Jun-16	-
First harvest date	-	-	29-Nov-16	-
Crop residue management	Burn	Burn	Retained	Burn
Pest management	Lice sprayed	Red spider, mite and worms sprayed	Spray for lice	Red spider, mite and worms sprayed
Weed management	Spray for weeds before wheat covered soil surface	-	Spray for weeds before wheat covered soil surface	Spray for weeds; Johnson grass
Cultivation practices	Plough to 300 mm depth, followed by tillage to 300 mm depth	Plant immediately after wheat was burnt	Plough to 300 mm depth, followed by tillage to 300 mm depth	Plant immediately after wheat was burnt
Fertiliser type (kg ha^{-1})	Plant mixture and then straights	Plant mixture and then straights	Plant mixture and then straights	Plant mixture and then straights
Total kg N ha^{-1}	252	280	252	280
Total kg P ha^{-1}	42	53	42	53
Total kg K ha^{-1}	52	65	52	65
Method of fertiliser	Fertigation through centre pivot	Fertigation through centre pivot	Fertigation through centre pivot	Fertigation through centre pivot*

(-) = no data available

3.2 EC_a surveys and identification of EC_a-directed soil sampling sites

The Geonics EM38-MK2 soil sensor was used in the vertical orientation at a transect width of 10 m to conduct an initial EC_a survey at the various fields for the WRC project. A reference 50 m transect to the side of each field was measured at the beginning and end of the survey to determine instrument drift. Protocols described by Corwin & Scudiero (2016) were followed when the EC_a survey of the described fields (Figure 3.2 and 3.3) were conducted. The sensor was enclosed in a plastic container to avoid metallic interference and lifted about 80 mm above the soil surface while

being drawn 3 m behind a quad bike at a speed of approximately 8 km hour^{-1} over the respective fields (Figure 3.6).

Data collected from the EMI instrument were then logged onto a hand-held Trimble TSC3 controller that was linked to a Trimble GNSS receiver mounted on the quadbike, which received geo-referenced coordinates from a stationary Trimble GNSS SPS851 base station. Both EC_a and GPS data were recorded at one-second intervals and stored on the controller unit.

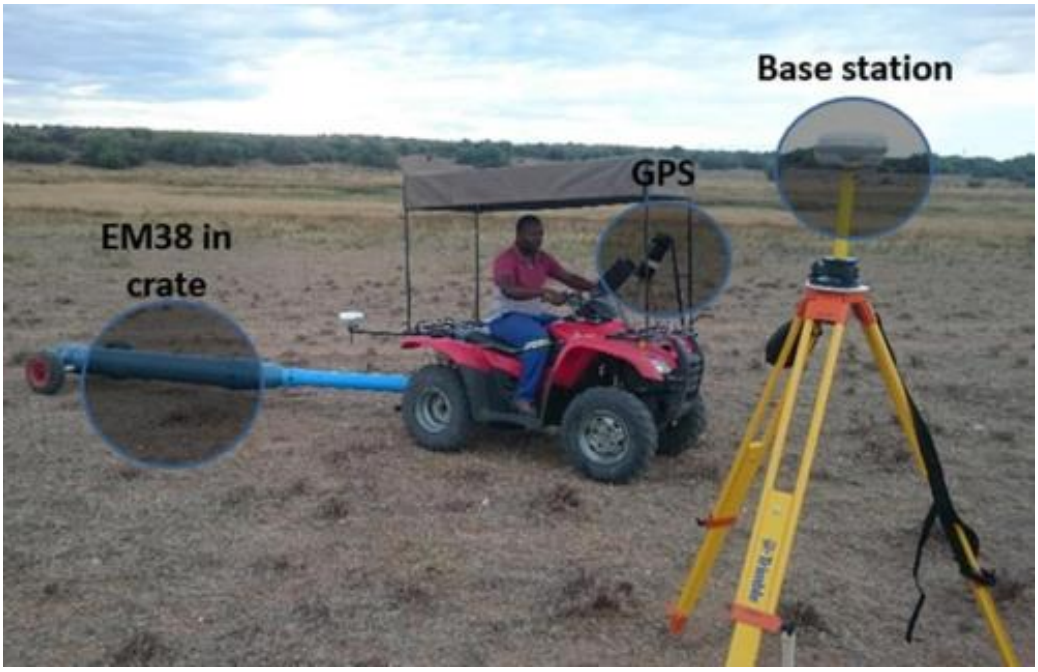

Figure 3.6 Mobile EMI soil survey unit for continuous soil measurements (Photo by Van's lab).

The spatial variation of the geo-referenced EC_a measurements were then used to identify soil sampling sites. This was achieved with the use of a model-based response surface sampling design (RSSD) to help minimise the number of samples needed to obtain spatial variation of soil properties (Corwin & Scudiero, 2016). The model-based RSSD program of the ESAP software (ESAP-95 Version 2.01R), is a statistical program which is used to generate optimal soil sampling designs from EC_a survey information (Lesch *et al*., 2000). The program transforms the survey data through principal component analysis (PCA) and selects a response surface approach based on the transformed data to identify candidate locations on the field fitting the selected sampling design (Corwin & Scudiero, 2016). A space-filling algorithm is then used to select a set of sites from the

candidate locations where soil and plant samples are collected. The program produced a sampling design consisting of twelve (12) sampling sites at Field 1, 2 and 3, respectively. The identified sampling sites represent ± 95% of the observed range in the geometric mean of the EM-38 and EM profile ratio data, and is uniformly spatially distributed (Corwin *et al*., 2003).

3.3 Soil and plant sampling

3.3.1 Soil sampling and preparation for analyses

Soil samples were collected at the 12 EC_a-directed sites at the start of the crop growing seasons, with standard sampling protocols and quality control as outlined by Motsara & Roy (2008). A 1 m x 1 m area served as the sampling site for soil samples, where four samples were collected within the 1 m^2 sampling area and mixed to create a composite sample. A soil auger and core sampler were used to sample soil in 300 mm depth increments up to 1500 mm because that is the sensor range of the EM38-MK2 when scanning in a vertical orientation (Corwin & Lesch, 2005). The soils were dried in a drying room at 35-40 ^oC and then grinded to be screened through a 2 mm sieve to obtain a homogenous representation of the sample for analysis. For the purpose of the study objectives, only the topsoil (300 mm) was used and analysed for bulk density, texture, gravimetric water, electrical conductivity of saturated paste extract (EC_e), sodium absorption ratio (SAR), pH (water) and plant available cations (Non-affiliated soil analysis work committee, 1990; Thompson, 1995; Motsara & Roy, 2008).

3.3.2 Plant sampling, measuring and preparation for analyses

A 1 m x 1 m sampling area for wheat and 2 m x 2 m sampling area for maize, with four replications each were harvested from the 12 EC_a-directed sites at the end of the 2016 winter season and 2017 summer season, respectively. The entire plant was cut at the soil surface just above the root zone with all its above-ground components in-tact. Plants were sampled early morning and moisture loss was prevented by placing the freshly harvested samples in plastic bags tied with a cable tie prior to weighing. Wet mass of each plant was measured in-field on the same day of harvesting (by mid-afternoon) to minimise moisture loss. Great care was taken during the sampling and handling process in order to prevent errors during analysis.

To ensure accurate laboratory results, samples were prepared and stored in such a manner that any changes in chemical composition were avoided. In the laboratory plants were rinsed in distilled water to remove any dust depositions that might have occurred in field. After washing, plant samples were oven-dried overnight for 24 hours at a temperature of approximately 60 to 68 ^{o}C and weighed upon drying to determine the dry mass. This temperature is ideal for drying of plant samples because it prevents volatilisation of compounds in plant tissues (Okalebo *et al*., 2002). Plants were then divided into different individual components that were used for analysis. Maize and popcorn were divided into stem-leaf, cobs, husks (cob leaves surrounding the seed) and seeds, and wheat was divided into stem-leaf, husks (consisting of glumes, paleas and lemmas) and seeds.

These individual plant components were then grinded separately into a powder form to obtain a homogenous representation of the sample (Draper, 1976; Okalebo *et al*., 2002). Powdered samples were placed in self-sealing (zipper) plastic bags placed in carton boxes and plastic crates and stored in a cold room at a temperature of -12 ^{o}C. Freezing should commence as soon as the grinded samples are available, since many biochemical transformations may become active at temperatures as low as 2 to 3 ^{o}C (Draper, 1976).

3.4 Soil and plant nutrient analyses

Standard methods are available to analyse the salt inducing cations of interest (United States Salinity Laboratory Staff, 1954; Non-affiliated soil analysis work committee, 1990; Thompson, 1995; AgriLASA, 2004). These cations include Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}.

An electro-spectroscopy technique was used to determine these analytes. The Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) method was used to analyse the cations present in the wheat, maize and popcorn plant material, as well as in the soil. The instrument uses light energy to detect the radiation emitted by the excited ions present in the extract solution (Wheal *et al*., 2011).

3.4.1 Soil analyses

Bulk density was determined by driving a coring metal ring of known mass and volume into the soil with the use of a core sampler and sampling three replications within the sampling area. Excess soil was trimmed and the sample wrapped with cling-wrap to preserve soil moisture. The soil was then first weighed in the laboratory and then dried in an oven for 24 hours at 105 ^{o}C before the dry mass was determined. The soil water content was determined using the gravimetric water content and soil texture was determined by using the pipette method as outlined by the Non-Affiliated Soil Analysis Work Committee (1990). Soil $pH_{(water)}$ was determined by using a pH meter in a 1:2.5 (v/v) soil: water suspension without temperature adjustments as outlined by AgriLASA (2004). Electrical conductivity (EC_e) and pH (pH_e) of the saturated paste was measured with a standard EC and pH meter after a saturated soil paste was prepared by mixing 250 g dry soil with distilled water. (United States Salinity Laboratory Staff, 1954; Non-affiliated soil analysis work committee, 1990).

The Ambic-2 extraction method, which makes use of an ethylene-diamine-tetra-acetic (EDTA) di-ammonium extraction solution to allow the analysis of Na^+ from the extract, was used for soil analysis. This method was modified from the original Ambic method which uses EDTA di-sodium solution for soil extracts (Thompson, 1995). The soil sample was scooped, not weighed and the extraction was done by adding a prepared solution containing superfloc N300, ammonium fluoride, ammonium bicarbonate and EDTA di-ammonium to the soil and stirring it for 10 minutes with a magnetic-stirrer at 400 rpm. The samples were then filtered with Whatman No. 1 filter paper and diluted with 20 ml de-ionised water for ICP-OES analysis. This method is fast and efficient in determining a composite of plant-available macro and micro ions in soil (Thompson., 1995; Manson & Roberts, 2000).

3.4.2 Plant nutrient analyses

A closed-tube wet decomposition with acid technique was used to obtain the analytes mentioned above from the ground plant components. The samples were digested with a mixture of nitric acid and hydrogen peroxide and left overnight for pre-digestion at room temperature (Wheal *et al*.,

2011). The closed-tubes were then placed in 200 ml water-filled beakers and heated on a sand bath at 120 ^{o}C to ensure decomposition of organic material. The method is used to obtain the analytes from the plant samples because it is highly efficient and precise, thus limiting possible loss of compounds through volatilisation (Wheal *et al*., 2011).

The procedure is as follows (Wheal *et al.*, 2011): Weighing of 0.30 g oven dried ground plant material and placing it into a labelled, dry and clean closed-cap digestion tube. Add 2 ml nitric acid and 0.5 ml hydrogen peroxide to each tube containing plant material, which is then centrifuged for 30 seconds and left overnight. The reagent was also added to 3 empty tubes to create blanks for each field of samples. The samples were centrifuged again for 10 seconds the following day and digested at 120 ^{o}C for 2-3 hours. The procedure indicated that the plant material should be digested and suspended in solution. The contents were then allowed to cool until the solution turned yellow. Exactly 25 ml of distilled water was then added and mixed well with an orbital mixer or shaker. The extracts were then diluted for ICP-OES analysis by adding water up to 50 ml and mixed again with the shaker. The extract was allowed to settle so that a clear solution could be taken from the top of the tube for analysis.

3.5 Determining cation uptake by the crops

The aboveground biomass and cation uptake by crop components are expressed in kg ha^{-1} on a dry-weight basis, while the nutrient harvest index is expressed as a percentage. The nutrient harvest index can be modified to a salt harvest index (SHI) for the purpose of this study to emphasize salt uptake. Cation uptake by each crop component was calculated by multiplying the yield of the crop component with the components' converted cation concentration to obtain the same international system (SI) unit (i.e. kg ha^{-1}). The total crop (biomass) cation uptake was then calculated by adding the cation uptake of the individual crop components together, as expressed with Equations 3.1 and 3.2. The nutrient harvest index (NHI) is calculated with Equation 3.3, which provides an estimation of partitioning and remobilization of cations in the plant (Clay & Carlson, 2010; Bender *et al*., 2013).

Wheat biomass cation uptake = ∑ [seed cation uptake + husk cation uptake + stem-leaf cation uptake] (3.1)

Maize and popcorn biomass cation uptake = ∑ [seed cation uptake + stem-leaf cation uptake + cob cation uptake + husk cation uptake] (3.2)

Salt Harvest Index = (component cation uptake) / (biomass cation uptake) x 100 (3.3)

3.6 Statistical analyses

The descriptive statistics of crop biomass and grain yield as well as clay content between the respective fields were analysed through box-and-whisker plots constructed with Microsoft Excel. General descriptive statistical analysis from Microsoft Excel were also used to interpret the cation concentrations and determine the magnitude of cation uptake between wheat and maize. The statistically significant differences in the cation uptake between crop components at each field were determined based on cation accumulative differences between means with the use of a one-way ANOVA through IBM SPSS software version 26. Significant differences ($P \leq 0.05$) in crop cation uptake by components between the respective fields were then determined with Kruskal-Wallis statistical analysis through IBM SPSS software as the data were not normally distributed. Linear regression model statistical analysis was then performed with the use of Microsoft Excel to determine a possible correlation between soil properties (EC_e, SAR and clay) and cation uptake by the crops.

CHAPTER 4. RESULTS

4.1. Cation concentrations of wheat

Concentrations of the cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) measured in the various plant components at each field are presented in Table 4.1 for wheat and Table 4.2 for maize (Field 1 and 2) and popcorn (Field 3).

The weighted mean wheat biomass K^{+}, Ca^{2+} and Mg^{2+} concentrations were similar at all three fields. At Field 1 however the weighted mean biomass Na^{+} concentration was 72% higher (i.e. 0.49 kg ton^{-1}) compared to Fields 2 and 3. Variability in the weighted mean biomass cation concentrations were generally moderate (CV < 35%). The K^{+}, Ca^{2+} and Na^{+} concentrations at Field 1 were the highest in the stem-leaf, followed by the husk (i.e. glumes, palea and lemma) and seed, while Mg^{2+} concentrations were in the order of husk > stem-leaf > seed. Variability in cation concentrations were moderate for all the wheat components, except for the high variability (CV = 153%) in Ca^{2+} concentration of seed.

Wheat biomass K^{+} and Ca^{2+} concentrations at Field 2 had a weighted mean value that was 19% and 24% higher compared to Field 1 and 3. Variability in cation concentrations in wheat biomass was moderate (CV < 35%) over the field, except for the high variability (CV = 46%) in biomass Na^{+} concentration. The K^{+} and Na^{+} concentrations between plant components at Field 2 compared well to Field 1 (i.e. stem-leaf > husk > seed), while the Ca^{2+} and Mg^{2+} concentrations compared differently (husk > stem-leaf > seed). The variation in cation concentrations between wheat components were moderate over the field, except for the high Na^{+} variability in the stem-leaf and husk and extreme variability (CV = 138%) in the seed.

Biomass K^{+} concentration at Field 3 was a weighted mean 11% higher compared to Field 1, while the biomass Ca^{2+}, Mg^{2+} and Na^{+} weighted mean concentrations were lower compared to the other fields. The variability of cation concentrations in the biomass was moderate (CV < 35%) over the field. The K^{+} and Na^{+} concentrations in wheat components at Field 3 compared well to Fields 1 and 2 (i.e. stem-leaf > husk > seed), while the Ca^{2+} and Mg^{2+} concentrations compared well to

Field 2 (husk > stem-leaf > seed). The overall degree of variation in cation concentrations between wheat components was moderate (CV < 35%) over the field.

Table 4.1 Descriptive statistics for the concentration of cations in various wheat components after harvesting

Salt (kg ton^{-1})	Field	Weighted mean	CV	Seed		Husk		Stem-Leaf	
				Mean	CV	Mean	CV	Mean	CV
K^+	1	13.81	13.4	3.93	43	9.28	46.7	22.86	13.7
	2	17.91	11.9	4.26	12.9	13.24	27.3	26.46	11.3
	3	15.37	15	4.35	10.6	9.97	31.7	23.90	10.7
Ca^{2+}	1	1.67	22.7	0.49	153.1	2.24	21.9	2.45	19.6
	2	2.14	21.2	0.46	13	3.69	23.3	2.87	24.7
	3	159	18.1	0.48	12.5	2.68	22.8	2.10	21.4
Mg^{2+}	1	1.51	12.5	1.47	25.2	1.57	16.6	1.53	15
	2	1.45	21.5	1.41	10.6	1.90	26.8	1.41	35.5
	3	1.12	15.2	1.45	11	1.20	27.5	0.88	30.7
Na^+	1	1.77	21.2	0.34	14.3	1.92	22.4	2.79	25.8
	2	0.58	45.5	0.08	137.5	0.76	50	0.88	60.2
	3	0.39	17.4	0.27	29.6	0.45	11.1	0.47	21.3

CV = 0%-15% (low variability), 15%-35% (medium variability), >35% (high variability) (Wilding *et al*., 1994; Peralta & Costa, 2013)

4.2 Cation concentrations of maize and popcorn

Maize at Field 1 had the highest biomass weighted mean Na^+ concentration (i.e. 21% higher compared to Fields 2 and 3). The highest to lowest cation concentrations of maize biomass at Field 1 was $K^+ > Ca^{2+} > Mg^{2+} > Na^+$, with a low variability (CV < 15%) over the field. The K^+ and Ca^{2+} concentrations were the highest in the stem-leaf, followed by the husk (i.e. cob leaves surrounding the seeds), cob and seed, while the order in Mg^{2+} and Na^+ concentrations between components differed from K^+ and Ca^{2+} (i.e. stem-leaf > seed > husk > cob and stem-leaf > husk > seed > cob, respectively). Variability in all maize components was moderate over the field, while an extreme variation (CV = 167%) in Ca^{2+} seed concentration was measured.

Table 4.2 Descriptive statistics for the concentration of cations in various maize (Field 1 and 2) and popcorn (Field 3) components after harvesting

Salt (kg ton^{-1})	Field	Weighted mean	CV	Seed		Cob		Husk		Stem-Leaf	
				Mean	CV	Mean	CV	Mean	CV	Mean	CV
K^+	1	14.86	10.7	3.33	10.2	4.51	14.9	8.60	18.4	38.89	12.2
	2	13.60	18.2	3.08	9.4	6.84	12.0	7.19	14.2	35.47	18.9
	3	19.03	17.5	2.67	15	5.46	14.5	6.12	35	46.93	14.6
Ca^{2+}	1	2.53	9.7	0.06	166.7	0.08	37.5	0.83	23	7.81	7.9
	2	2.58	15.1	0.04	50	0.11	36.4	0.75	18.7	8.15	12.3
	3	2.86	30.9	0.05	20	0.16	37.5	0.98	16.3	7.62	26.8
Mg^{2+}	1	2.14	9.3	1.06	17	0.26	23.1	0.84	25	4.80	18.1
	2	1.83	13.9	0.96	11.5	0.34	23.5	0.95	23.2	3.99	21.1
	3	2.32	22.1	1.33	19.5	0.48	20.8	1.34	11.9	4.26	28.9
Na^+	1	0.54	7.9	0.26	15.4	0.25	8	0.29	10.3	1.15	11.3
	2	0.44	42.8	0.11	18.2	0.26	19.2	0.12	58.3	1.16	53.5
	3	0.41	9.7	0.27	3.7	0.28	3.6	0.27	11.1	0.65	15.4

CV = 0%-15% (low variability), 15%-35% (medium variability), >35% (high variability) (Wilding *et al*., 1994; Peralta & Costa, 2013)

The cation concentrations, especially Ca^{2+}, at Field 2 compared well to Field 1, while the weighted mean biomass K^+, Mg^{2+} and Na^+ concentrations at Field 2 was 9%, 17% and 23% less compared to Field 1, respectively. Variability in weighted mean biomass K^+, Ca^{2+} and Mg^{2+} was moderate (CV < 35%) over the field, while a high variation in Na^+ concentration was measured (CV = 43%). The K^+ and Ca^{2+} concentrations at Field 2 compared well to Field 1 (i.e. stem-leaf > husk > cob > seed). This was also true for the Mg^{2+} concentrations (stem-leaf > seed > husk > cob), while Na^+ concentrations between components differed from Field 1 (i.e. stem-leaf > cob > husk > seed). The degree of variation in cation concentrations was moderate over the field, while a high variability (CV ≥ 50%) was measured for Ca^{2+} in the seed and Na^+ in the husk and stem-leaf.

The weighted mean cation concentrations of the popcorn biomass at Field 3 were generally the highest between the respective fields, except for the Na^+ concentration, which was 20% lower compared to the mean Na^+ concentration of Field 1 and 2 (i.e. 0.49 kg ton^{-1}). Popcorn cation concentrations varied moderately (CV < 35%) over the field with the highest variability measured for the Ca^{2+} concentration (CV = 31%). The order of K^+, Ca^{2+} and Mg^{2+} concentrations in popcorn components compared well to maize components at both Field 1 and 2, while the Na^+ concentration in popcorn components differed from these fields (i.e. stem-leaf > cob > seed > husk). The overall

degree of variation in the cation concentrations of popcorn components were also moderate over the field and had the least variation in Na^+ concentrations.

4.3 Biomass and grain yield of wheat, maize and popcorn

Box-and-whisker plots of grain yield and biomass production for wheat, maize and popcorn are presented in Figures 4.1 and 4.2. From Field 1 the mean wheat grain yield and biomass production was the highest (8 ton ha^{-1} and 21 ton ha^{-1}) followed by Field 3 (7 ton ha^{-1} and 18 ton ha^{-1}). The mean grain yield and biomass production at Field 2 (6 ton ha^{-1} and 16 ton ha^{-1}) was lower compared to Fields 1 and 3 (Figure 4.1). The degree of variation in the grain yield was similar between fields, while the biomass variability was similar between Fields 1 and 3. Variation in biomass was the lowest for Field 2.

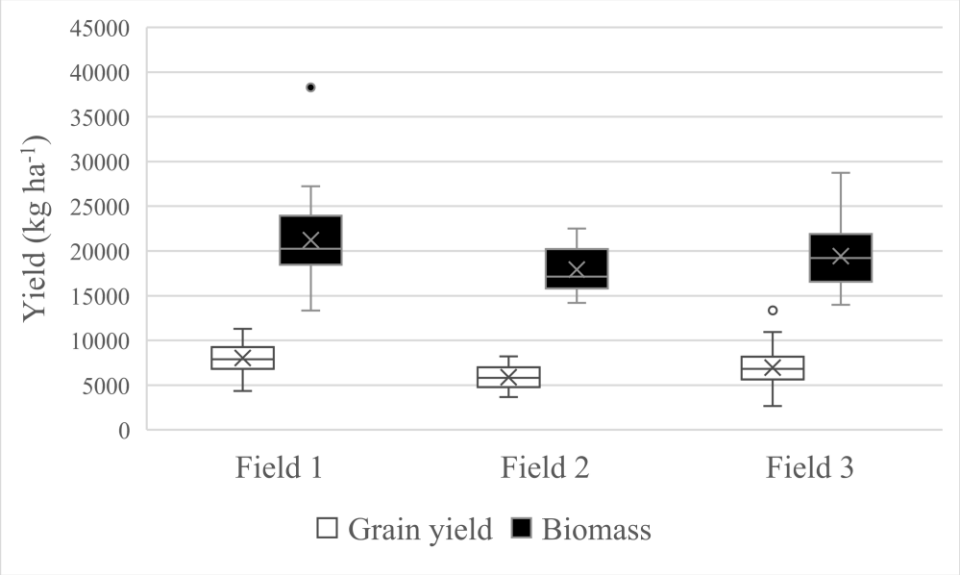

Figure 4.1 Wheat grain yield and biomass production over the various fields.

The mean maize grain yield for Field 1 (16 ton ha^{-1}) and Field 2 (14 ton ha^{-1}) and mean biomass production (29 ton ha^{-1} and 26 ton ha^{-1}, respectively) were higher compared to that of popcorn of Field 3 (Figure 4.2). Mean grain yield and biomass of popcorn was 8 ton ha^{-1} and 8.5 ton ha^{-1} less compared to that of maize. The degree of variation in grain yield and biomass production between Field 1 and 3 was similar (IQR = ± 400), while Field 2 had a higher degree of variation, especially

for the biomass. Literature states that higher biomass production act as the driving force for nutrient salt uptake to sustain higher yields (Karlen *et al*., 1988; Setiyono *et al*., 2010).

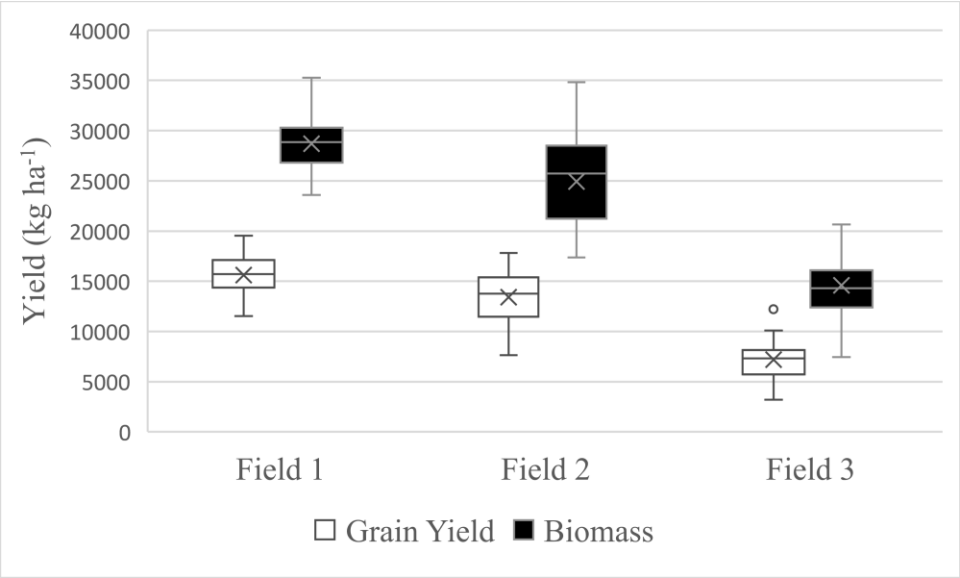

Figure 4.2 Measured maize (Field 1 and 2) and popcorn (Field 3) grain yield and biomass production over the various fields.

4.4 Cation uptake and partitioning by wheat

Results of biomass cation uptake and partitioning are presented in Table 4.3 for wheat and Table 4.4 for maize (Field 1 and 2) and popcorn (Field 3). Statistical mean separation at the 1% and 5% probability levels were also determined to establish which of these cations were significantly partitioned between the components.

Biomass Na^+ uptake followed by Mg^{2+} was the highest at Field 1. The mean wheat biomass K^+ uptake at Field 1 was 294.2 kg ha^{-1} with a moderate variability (CV = 25%), while the biomass uptake of Ca^{2+}, Mg^{2+} and Na^+ were 88%, 89% and 87% less than K^+, respectively. Variability of biomass Na^+ uptake was moderate but also the highest (CV = 32%), while Ca^{2+} and Mg^{2+} had a moderate variation (mean CV = 26%) over the field. Biomass uptake of K^+ at Field 1 was significantly ($P < 0.001$) partitioned in the stem-leaf (80% of biomass K^+), followed by the seed (11% of biomass K^+) and husk (9% of biomass K^+). Significant differences ($P \leq 0.05$) in the uptake

of Ca^{2+}, Mg^{2+} and Na^{+} were also measured between wheat components, namely stem-leaf > husk > seed for Ca^{2+} and Na^{+}, and stem-leaf > seed > husk for Mg^{2+}. Uptake by the stem-leaf amounted to 71%, 49% and 78% of biomass Ca^{2+}, Mg^{2+} and Na^{+}, while uptake by the husk and seed amounted to 18%, 14% and 15% and 11%, 37% and 7% of biomass Ca^{2+}, Mg^{2+} and Na^{2+}, respectively. The overall degree of variation in cation uptake over the field ranged from moderate to high (CV ≥ 26% - ≤ 59%). Less variability was noted in cation uptake by the stem-leaf, except for Na^{+} which had 10% more variation compared to the seed, while an extreme variation (CV = 168%) was measured for Ca^{2+} uptake by seed over the field.

The K^{+} and Ca^{2+} biomass uptake at Field 2 was the highest of all three fields. K^{+} wheat biomass uptake was 25.7 kg ha^{-1} higher with the lowest variation (CV = 19%) compared to Fields 1 and 3 (i.e. mean K^{+} = 295.8 kg ha^{-1} and mean CV = 23%). Biomass Ca^{2+}, Mg^{2+} and Na^{+} uptake was 88%, 92% and 97% less than K^{+}, respectively, which was similar to the biomass Ca^{2+} uptake at Field 1 but higher than the Mg^{2+} and Na^{+} uptake. Variability in Ca^{2+} and Mg^{2+} biomass uptake over the field was similar (mean CV = 27%) and classified as moderate (CV < 35%), while a high variation (CV = 44%) was measured for biomass Na^{+} uptake. The significant uptake of K^{+} by the stem-leaf (85% of biomass K^{+}), husk (7% of biomass K^{+}) and seed (8% of biomass K^{+}) at Field 2 was higher than the stem-leaf but lower than the husk and seed compared to Field 1. The order of significant differences ($P \leq 0.05$) in the uptake of Mg^{2+} and Na^{+} between wheat components at Field 2 compared well to Field 1 (i.e. stem-leaf > seed > husk and stem-leaf > husk > seed, respectively), while uptake of Ca^{2+} was significantly ($P \leq 0.001$) partitioned by the stem-leaf. Ca^{2+} uptake by the stem-leaf at Field 2 was higher compared to Field 1, while uptake of Ca^{2+}, Mg^{2+} and Na^{+} by the husk and seed as well as Mg^{2+} and Na^{+} by the stem-leaf was lower (Table 4.3). Uptake of biomass Ca^{2+}, Mg^{2+} and Na^{+} by the stem-leaf amounted to 78%, 56% and 83%, while uptake by the husk and seed amounted to 15%, 12% and 12% and 7%, 32% and 5%, respectively. Variability in cation uptake between wheat components at Field 2 also ranged from moderate to high (CV ≥ 22% - ≤ 62%) but was overall higher, except for seed, compared to Field 1. Seed at Field 2 had the lowest K^{+}, Ca^{2+} and Mg^{2+} variability (mean CV = 24%), while the variation in Na^{+} uptake was extreme (CV = 138%).

Wheat biomass K^+ uptake at Field 3 was 297.4 kg ha^{-1} (3.2 kg ha^{-1} higher compared to Field 1) and had a moderate variability which was 4% less compared to Field 1. The Ca^{2+}, Mg^{2+} and Na^+ biomass uptake was 90%, 93% and 97% less than K^+, respectively, which was higher compared to Field 1. This was also true compared to the biomass Ca^{2+} and Mg^{2+} uptake at Field 2 while the biomass Na^+ uptake was the same as Field 3. Variation in wheat biomass Ca^{2+}, Mg^{2+} and Na^+ uptake at Field 3 was classified as moderate (CV < 35%) with similar variability in Ca^{2+} and Mg^{2+} biomass uptake compared to Field 2. K^+ uptake by the stem-leaf, husk and seed at Field 3 differed significantly ($P \leq 0.001$). Uptake of K^+, however, was less by the stem-leaf (82% of biomass K^+) and higher by the husk (8% of biomass K^+) and seed (10% of biomass K^+) compared to Field 2. The order of significant differences in the uptake of Ca^{2+} between wheat components at Field 3 compared well to Field 1 (i.e. stem-leaf > husk > seed). The Mg^{2+} biomass uptake was significantly ($P < 0.05$) partitioned by the seed and stem-leaf followed by the husk, while the order of Na^+ partitioning differed from the other fields (i.e. stem-leaf > seed > husk). Table 4.3 show that the K^+ uptake by the stem-leaf at Field 3 was higher compared to Field 1, while uptake of K^+ by the husk was higher and uptake of Ca^{2+} the same as Field 2. The partitioning of K^+, Ca^{2+}, Mg^{2+} and Na^+ by the seed at Field 3 was also higher compared to Field 2 and slightly less (mean K^+, Ca^{2+}, Mg^{2+} and Na^+ = 1.2 kg ha^{-1}) compared to Field 1. At Field 3, the biomass uptake of Ca^{2+}, Mg^{2+} and Na^+ by the stem-leaf amounted to 70%, 42% and 62%, while the husk amounted to 19%, 12% and 13% and the seed to 11%, 46% and 25% of Ca^{2+}, Mg^{2+} and Na^+ biomass, respectively. Variability in K^+, Ca^{2+}, Mg^{2+} and Na^+ partitioning at Field 3 ranged from moderate to high but varied less overall compared to Field 2. The least degree of variation over the field was noted for the stem-leaf, followed by the seed, while extreme variation was noted for Ca^{2+} (CV = 82%) and Na^+ (CV = 72%).

Table 4.3 Descriptive statistics of cation uptake in various wheat components at the various fields after harvesting

Salt (kg ha^{-1})	Field	Biomass uptake		Seed		Husk		Stem-Leaf	
		Total	CV	Mean	CV	Mean	CV	Mean	CV
K^+	1	294.2	25.3	31.8^b	52.8	26.7^b	59.3	235.7^a	28.7
	2	321.5	18.5	24.9^b	23.7	22.1^b	57.5	274.5^a	21.9
	3	297.4	21.1	30.3^b	29.5	22.8^b	82.2	244.3^a	28.1
Ca^{2+}	1	35.2	28.5	4.0^c	167.7	6.4^b	42.4	24.8^a	25.6
	2	38.4	26.5	2.7^b	25.4	5.9^b	59.9	29.8^a	33.3
	3	30.7	22.7	3.3^c	30.9	5.9^b	51.2	21.5^a	31.5
Mg^{2+}	1	32.0	22.5	11.9^b	36.3	4.5^c	38.7	15.6^a	25.6
	2	26.0	26.6	8.2^b	22.7	3.2^c	62.2	14.6^a	42.4
	3	21.9	24.1	10.1^a	28.7	2.7^b	58.1	9.1^a	38.9
Na^+	1	37.1	32.3	2.7^c	28.9	5.5^b	39.7	28.9^a	38.9
	2	10.5	44.2	0.5^b	137.5	1.3^b	62.4	8.7^a	50.6
	3	7.7	23.7	1.9^b	42.7	1.0^c	71.6	4.8^a	30.9

CV = 0%-15% (low variability), 15%-35% (medium variability), >35% (high variability) (Wilding *et al*., 1994; Peralta & Costa, 2013)

Mean separation (abc) = significant difference in means from highest to lowest at probability levels (highly significant at 0.001 = a), (moderate significance at 0.01 = b) and (low significance at 0.05 = c)

4.5 Cation uptake and partitioning by maize and popcorn

Maize biomass at Field 1 partitioned K^+, Mg^{2+} and Na^+ the highest, while maize at Field 2 partitioned Ca^{2+} the highest. The partitioning of Ca^{2+} by the husk was higher compared to the seed across all fields. At Field 1 the mean maize biomass K^+ uptake was 427.1 kg ha^{-1} with moderate variability (CV = 15%), while biomass Ca^{2+}, Mg^{2+} and Na^+ uptake was 89%, 86% and 96% less than K^+, respectively. Biomass Ca^{2+}, Mg^{2+} and Na^+ variability at Field 1 was moderate (CV < 35%). Table 4.4 show that K^+ at Field 1 was higher partitioned between components compared to the other fields, except for cob at Field 2. The biomass K^+ uptake was significantly ($P < 0.05$) partitioned by the stem-leaf (81% of biomass K^+), followed by the seed (12% of biomass K^+), husk (4% of biomass K^+) and the cob (2% of biomass K^+), with uptake by husk amounting to twice the K^+ uptake of the cob. The partitioning of Mg^{2+} and Na^+ by the stem-leaf, Ca^{2+} and Na^+ by the husk and Ca^{2+}, Mg^{2+} and Na^+ by the seed at Field 1 was the highest, while no considerable differences were noted in Ca^{2+} and Na^+ uptake between Fields 1 and 2. Significant differences ($P \leq 0.05$) measured in the uptake of Mg^{2+} and Na^+ between maize components were similar to K^+ uptake

(i.e. stem-leaf > seed > husk > cob), while Ca^{2+} was significantly ($P < 0.001$) partitioned by the stem-leaf. Partitioning of biomass Ca^{2+}, Mg^{2+} and Na^{+} amounted to 94%, 69% and 67% by the stem-leaf, and 2%, 27% and 7% by the seed, while the cob partitioned 0.4%, 0.8% and 3%, and husk 4%, 3% and 4% of biomass Ca^{2+}, Mg^{2+} and Na^{+}, respectively. The overall degree of variation in cation partitioning between maize components was moderate (CV < 35%), except for the husk (CV > 80%), which had high variability. An extreme variation was noted for the Ca^{2+} seed uptake (CV = 194%).

The maize biomass K^{+} uptake at Field 2 was 345.2 kg ha^{-1} (81.9 kg ha^{-1} less compared to Field 1) with a moderate variation (CV = 33%) over the field, while biomass Ca^{2+}, Mg^{2+} and Na^{+} uptake was 81%, 87% and 97% less than K^{+}, respectively. Biomass Ca^{2+} and Mg^{2+} variability at Field 2 was moderate (CV < 35%) over the field with the highest variation (CV = 55%) measured for Na^{+} uptake. The biomass K^{+} partitioning at Field 2 compared well to Field 1 as significantly more K^{+} was also partitioned by the stem-leaf, followed by the seed, husk and cob (i.e. 80%, 12%, 4% and 4% of biomass K^{+}, respectively). The partitioning of K^{+} between husk and cob at Field 2 was similar, while K^{+} partitioning by the stem-leaf, however, was slightly lower (1%) and by the cob slightly higher (2%) compared to Field 1. Significant differences ($P \leq 0.05$) measured in the uptake of Mg^{2+} between maize components were similar to the K^{+} uptake (i.e. stem-leaf > seed > husk > cob), while biomass Ca^{2+} and Na^{+} was significantly ($P < 0.001$) partitioned to the stem-leaf. The order of biomass Mg^{2+} and Ca^{2+} partitioning compared well to Field 1. Table 4.4 show that only the Ca^{2+} uptake by stem-leaf and Mg^{2+} uptake by husk and cob at Field 2 was higher compared to Field 1, while Ca^{2+} and Na^{+} uptake by the cob between these fields were similar (0.2 kg ha^{-1} and 0.5 kg ha^{-1}, respectively). Partitioning of biomass Ca^{2+}, Mg^{2+} and Na^{+} amounted to 97%, 67% and 82% by stem-leaf, and 1%, 28% and 12% by the seed, while the cob partitioned 0.3%, 1% and 4% and husk 2%, 4% and 2% of biomass Ca^{2+}, Mg^{2+} and Na^{+}, respectively. The variation in biomass Ca^{2+}, Mg^{2+} and Na^{+} partitioning between maize components were moderate (CV < 35%). A high variation was measured for stem-leaf Na^{+} uptake (CV = 66%) as well as cob and seed Ca^{2+} uptake (mean CV = 55%). Variation in cation uptake by husk was also the highest at Field 2 and overall, higher compared to Field 1.

At Field 3, the popcorn K^+ biomass uptake was 278.4 kg ha^{-1} (107.8 kg ha^{-1} less than the mean K^+ biomass of maize) with a moderate variation (CV = 26%) over the field. Popcorn Ca^{2+}, Mg^{2+} and Na^+ biomass uptake was 85%, 88% and 98% less than biomass K^+, respectively, and had a moderate to slightly high variation. The highest variation was measured for Ca^{2+} uptake (CV = 37%). Biomass K^+ partitioning at Field 3 was different from the other fields as K^+ was highly significantly ($P < 0.001$) partitioned to the stem-leaf. The biomass K^+ uptake between components (i.e. 89%, 7%, 2%, 2%) however, compared well to the K^+ uptake by Fields 1 and 2 (i.e. stem-leaf > seed > husk > cob, respectively). The magnitude in K^+ uptake by popcorn components were less compared to maize, while the difference in K^+ uptake between the husk and cob was similar to Field 2. Significant differences ($P \leq 0.05$) measured in the uptake of Mg^{2+} and Na^+ between popcorn components compared well to Field 1 (i.e. stem-leaf > seed > husk > cob), while biomass Ca^{2+} partitioning compared well to both Fields 1 and 2. Table 4.4 show that although the cation uptake at Field 3 was less compared to the other fields, Ca^{2+} uptake by the seed was relatively similar between fields, while partitioning of Ca^{2+} by the cob was similar to Fields 2 and 3 (i.e. 0.2 kg ha^{-1}) and Mg^{2+} similar to Field 2 (i.e. 0.6 kg ha^{-1}). Partitioning of biomass Ca^{2+}, Mg^{2+} and Na^+ amounted to 96%, 66% and 58% by stem & leaf, and 1%, 28% and 32% by the seed, while the cob partitioned 0.5%, 2% and 5% and husk 3%, 4% and 5% of biomass Ca^{2+}, Mg^{2+} and Na^+, respectively. Variation in cation uptake between components were overall moderate with the highest variation measured for Ca^{2+} uptake by the seed (CV = 50%). Variability in uptake was considerably lower compared to uptake by maize components with no extreme variation noted over the field.

Table 4.4 Descriptive statistics of cation uptake in various maize (Field 1 and 2) and popcorn (Field 3) components after harvesting

Salt (kg ha^{-1})	Field	Biomass uptake		Seed		Cob		Husk		Stem-Leaf	
		Total	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
K^+	1	427.1	14.9	51.9^b	14.5	9.4^c	23.4	18.1^c	81.8	347.7^a	17.0
	2	345.2	32.5	41.3^b	21.1	12.1^c	21.9	14.3^c	88.1	277.5^a	38.2
	3	278.4	26.3	18.9^b	25.4	6.3^b	25.4	6.7^b	47.8	246.5^a	29.1
Ca^{2+}	1	45.5	14.8	0.8^b	193.8	0.2^b	50.0	1.8^b	83.3	42.7^a	15.3
	2	65.3	28.1	0.5^b	60.0	0.2^b	50.0	1.5^b	100.0	63.1^a	29.2
	3	41.7	37.4	0.4^b	25.0	0.2^b	50.0	1.1^b	36.4	40.0^a	39.3
Mg^{2+}	1	61.5	12.6	16.5^b	17.6	0.5^c	20.0	1.8^c	88.9	42.7^a	15.2
	2	46.2	26.4	12.9^b	22.5	0.6^c	33.3	1.9^c	94.7	30.8^a	33.1
	3	33.8	28.8	9.4^b	28.7	0.6^c	33.3	1.5^c	40.0	22.3^a	39.9
Na^+	1	15.3	10.7	4.0^b	17.5	0.5^c	20.0	0.6^c	83.3	10.2^a	13.7
	2	11.4	54.7	1.4^b	28.6	0.5^b	20.0	0.2^b	100	9.3^a	66.7
	3	5.9	21.5	1.9^b	26.3	0.3^c	33.3	0.3^c	33.3	3.4^a	29.4

CV = 0%-15% (low variability), 15%-35% (medium variability), >35% (high variability) (Wilding *et al*., 1994 & Peralta & Costa, 2013)

Mean separation (abc) = significant difference in means from highest to lowest at probability levels (highly significant at 0.001 = a), (moderate significance at 0.01 = b) and (low significance at 0.05 = c)

4.6 Cation uptake and partitioning between fields

Uptake between fields was done to verify if cation partitioning was generic due to the different agronomic practices applied. Wheat K^+ uptake by the seed was significantly different between Fields 1 & 2 and 2 & 3, which was also true for the Mg^{2+} and Na^+ uptake between all fields (Table 4.5). The Mg^{2+} and Na^+ uptake by the husk differed significantly between Fields 1 & 2 and 1 & 3, while the K^+ uptake by the straw differed significantly between Fields 1 & 2. Uptake of Ca^{2+} and Mg^{2+} by the straw was significantly different between Fields 1 & 3 and 2 & 3, while Na^+ uptake differed significantly between all fields.

Maize cation uptake by the seed was significantly different ($P \leq 0.05$) between fields, while only the K^+ and Ca^{2+} uptake by the cob, Na^+ uptake by the husk and K^+, Mg^{2+} and Na^+ uptake by the stem-leaf was significantly different between fields (Table 4.6). The K^+, Mg^{2+} and Na^+ uptake by the seed between maize and popcorn was significantly different, which was also true for Ca^{2+} uptake between Fields 2 & 3. The cob and husk K^+ uptake was significantly different between

maize and popcorn, as well as the Ca^{2+} uptake between Field 1 & 3 and Na^{+} uptake between Field 1 & 3 and 2 & 3. The cation uptake by the stem-leaf was significantly different between crops, except for the K^{+} uptake between Fields 2 & 3. Popcorn therefore had similarities in uptake and partitioning of cations compared to maize.

Table 4.5 Significant difference in wheat cation uptake and partitioning between fields

Component	Field Comparisons	K^{+}	Ca^{2+}	Mg^{2+}	Na^{+}
Seed	1 & 2	**	n.s	***	***
	1 & 3	n.s	n.s	*	***
	2 & 3	**	n.s	**	***
Husk	1 & 2	n.s	n.s	***	***
	1 & 3	n.s	n.s	***	***
	2 & 3	n.s	n.s	n.s	n.s
Stem-Leaf	1 & 2	**	n.s	n.s	***
	1 & 3	n.s	*	***	***
	2 & 3	n.s	***	***	**

Significant difference at probability levels: * (low significance at 0.05), ** (moderate significance at 0.01) and *** (highly significant at 0.001) n.s = non-significant

Table 4.6 Significant difference in maize and popcorn cation uptake and partitioning between fields

Component	Field Comparisons	K^{+}	Ca^{2+}	Mg^{2+}	Na^{+}
Seed	1 & 2	**	**	***	***
	1 & 3	***	n.s	***	***
	2 & 3	***	***	***	*
Cob	1 & 2	**	**	n.s	n.s
	1 & 3	***	*	n.s	***
	2 & 3	***	n.s	n.s	***
Husk	1 & 2	n.s	n.s	n.s	***
	1 & 3	***	n.s	n.s	***
	2 & 3	*	n.s	n.s	n.s
Stem-Leaf	1 & 2	***	n.s	***	*
	1 & 3	***	***	***	***
	2 & 3	n.s	***	**	***

Significant difference at probability levels: * (low significance at 0.05), ** (moderate significance at 0.01) and *** (highly significant at 0.001)

4.7 Relationship between wheat, maize and popcorn cation uptake and selective soil properties

Results of the linear regression analysis between cation uptake and EC_e, SAR and clay are shown in Table 4.7 for wheat and in Table 4.8 for maize and popcorn. The linear relationship between these soil properties and wheat Mg^{2+} and Na^+ uptake was significant ($P \leq 0.001$). However, no correlation ($R^2 < 0.5$) between Mg^{2+} and Na^+ uptake and EC_e was found, which was also true for Mg^{2+} uptake and clay content. The Mg^{2+} uptake correlated with an increasing SAR ($R^2 = 0.5$) but only 50% of the data fitted the regression model, while a higher correlation ($R^2 = 0.7$) was noted between Na^+ uptake and increasing SAR and clay where 70% of the data fitted the regression model. The linear regression results indicate that SAR had a minor influence on the uptake of Mg^{2+} by wheat, while SAR and clay content definitely influenced Na^+ uptake. Further analysis (Appendix 2) was conducted to determine which of the SAR influencing soil cations (i.e. Ca^{2+}, Mg^{2+}, Na^{2+}) contributed most to cation uptake by wheat. Additional linear regression results between these soil cations and the uptake thereof, indicate that only an increase of Na^+ in the soil significantly ($P < 0.001$) induces the uptake of Na^+ by wheat with a 70% correlation as no correlation ($R^2 < 0.5$) was found between the other cations.

Table 4.7 Linear regression statistics measuring the relationship between cation uptake and soil properties for wheat

Property	Parameter	Mg^{2+}	Na^+
EC_e	Depth (m)	0 – 0.3	0 – 0.3
	R^2	0.44	0.31
	P-value	< 0.001	0.001
SAR	Depth (m)	0 – 0.3	0 – 0.3
	R^2	0.49	0.70
	P-value	< 0.001	< 0.001
Clay	Depth (m)	0 – 0.3	0 – 0.3
	R^2	0.31	0.7
	P-value	0.001	< 0.001

Significant difference at probability levels: * (low significance at 0.05), ** (moderate significance at 0.01) and *** (highly significant at 0.001)

The significant relationship of the linear model between maize and popcorn Mg^{2+} and Na^+ uptake and the soil properties compared well to wheat. The linear relationship between K^+ and Ca^{2+} uptake

and EC_e and SAR, as well as between K^+ and Ca^{2+} uptake and clay was significant. Although the relationship between these variables were significant, no correlation ($R^2 < 0.5$) was measured between cation uptake and EC_e and clay as well as between the SAR and K^+ and Ca^{2+} uptake. Table 4.8, however, indicated that the SAR correlated ($R^2 = 0.5$) with maize Na^+ uptake but only 50% of the data fitted the regression model, while a higher correlation ($R^2 = 0.6$) between SAR and Mg^{2+} uptake was measured with a 60% data fit in the regression model. The SAR appear to be driving the uptake of these cations, especially Mg^{2+}, but additional linear regression results unfortunately indicates no significant relationship or correlation ($R^2 < 0.5$) between the cations influencing SAR and the uptake thereof by maize and popcorn (Appendix 2).

Table 4.8 Linear regression statistics measuring the relationship between cation uptake and soil properties for maize and popcorn

Property	Parameter	K^+	Ca^{2+}	Mg^{2+}	Na^+
EC_e	Depth (m)	0 – 0.3	0 – 0.3	0 – 0.3	0 – 0.3
	R^2	0.22	0.30	0.38	0.31
	P-value	0.008	0.002	< 0.001	0.001
SAR	Depth (m)	0 – 0.3	0 – 0.3	0 – 0.3	0 – 0.3
	R^2	0.33	0.40	0.6	0.57
	P-value	0.001	< 0.001	< 0.001	< 0.001
Clay	Depth (m)	0 – 0.3	0 – 0.3	0 – 0.3	0 – 0.3
	R^2	0.39	0.25	0.44	0.33
	P-value	< 0.001	0.005	< 0.001	0.001

Significant difference at probability levels: * (low significance at 0.05), ** (moderate significance at 0.01) and *** (highly significant at 0.001)

4.8 Relationship between crop cation uptake and soil EC_a

Sufficient literature exists regarding the spatial characterisation of soil properties (i.e. EC_e, water content, clay, bulk density) through EC_a measured with electromagnetic induction (Rhoades, 1981; Rhoades *et al.*, 1999; Corwin & Lesch, 2003 & 2005; Corwin & Scudiero, 2016).

In Table 4.9, the current study, however, attempted to correlate the salinity inducing cations (i.e. K^+, Ca^{2+}, Mg^{2+}, Na^+) with EC_a to spatially characterise cation uptake by wheat and maize. Due to the site-specific nature of this technique, calibration was done separately for each field. Attention was given to characterise Na^+ uptake by wheat and Mg^{2+} uptake by maize and popcorn because

they had the best fitted regression models but the results were unfavourable. Although a relationship can be found for some cations, the model fit is not significant. The study therefore found it unsuccessful to characterise cation uptake by crops using soil EC_a measurements at these fields.

Table 4.9 Correlation between EC_a and soil properties to characterise wheat, maize and popcorn cation uptake

Crops	Field	EC_e	SAR	Clay	Grain Yield	Biomass	K^+	Ca^{2+}	Mg^{2+}	Na^+
Wheat	1	0.146	0.108	0.006	0.268	0.143	0.495	0.886	0.415	0.341
	2	0.757	0.568	0.562	0.048	0.166	0.692	0.831	0.124	0.179
	3	0.951	0.151	0.682	0.674	0.302	0.458	0.339	0.133	0.339
Maize	2	0.244	0.918	0.682	0.034	0.000	0.325	0.014	0.097	0.005
Popcorn	3	0.722	0.153	0.009	0.030	0.014	0.184	0.042	0.055	0.007

CHAPTER 5. DISCUSSION

5.1 Cation concentrations, crop yield and biomass production

Biomass cation concentrations of wheat and maize at harvest were high compared to the critical and sufficient norms suggested by Campbell & Plank (2000) at physiological maturity (Appendix 1- Table 1.2). The mean K^+ concentration in wheat exceeded the sufficient ranges, while the Ca^{2+} and Mg^{2+} concentrations fell within the suggested optimum ranges. Maize K^+, Ca^{2+} and Mg^{2+} concentrations, however, were higher compared to the optimum concentration ranges (Campbell & Plank, 2000). Wheat seed and stem-leaf, as well as maize biomass and seed cation removal at harvest were compared with FSSA (2007) suggested norms (Appendix 1- Table 1.3). Wheat K^+ removal by the seed was relatively close to the suggested norm, while Mg^{2+} removal was 1 kg t^{-1} less and stem-leaf K^+ removal almost three times higher compared to the suggested norm for straw (FSSA, 2007). Maize biomass K^+, Ca^{2+} and Mg^{2+} removal was less, which was also true for K^+ removal by the seed, while Ca^{2+} and Mg^{2+} removal was relatively similar compared to the suggested norms (FSSA, 2007). These differences in crop concentrations and cation removal between the current study and literature suggested optimum ranges and norms could be due to the sampling time difference. A common misconception is made regarding the stoppage of cation assimilation at crop maturity as previous research suggest that dry weight cation accumulation and translocation is still ongoing at the flowering stage of maize growth and as wheat crops mature (Karlen & Whitney, 1980; Karlen *et al*., 1988; Bender *et al*., 2013).

Biomass Na^+ concentration of wheat was different between fields. The difference in wheat Na^+ concentrations may be due to differences in the Na^+ and K^+ concentrations in the soil at the respective fields (Krishnasamy *et al*., 2014). At Field 1, high Na^+ concentrations in the soil were measured that was almost within the same range as K^+ concentrations. The differences between these cations were greater at Field 2 and 3 (Appendix 3). The K^+ and Na^+ concentrations are compared because of the affinity thereof in the soil lyotropic series ($Al^{3+} > H^+ > Ca^{2+} > Mg^{2+} > NH_4^+ = K^+ > Na^+$), which is based on differences between the ion valence charge and hydrated radius; William & Norman, 2008). According to the lyotropic series ((Brady, 1984), K^+ is stronger adsorbed to soil particles compared to Na^+. The high biomass Na^+ concentrations at Field 1 may

thus be due to the high Na^+ concentrations present in the soil that competed with the absorption of K^+ as Na^+ can be substituted to aid in non-specific biophysical functions of K^+ (Goudarzi & Pakniyat, 2008; Krishnasamy *et al*., 2014; Maathuis, 2014). Unfortunately, there is limited literature available regarding the critical or sufficient norms for Na^+ uptake by wheat, maize and popcorn. Based on the current study's mean Na^+ uptake of the respective fields between crops, a suggested critical range for Na^+ uptake by wheat and maize biomass can be 18.4 kg ha^{-1} and 13.4 kg ha^{-1}, respectively, with a variation of 33%, while a critical range for popcorn biomass Na^+ uptake may be 21.5 kg ha^{-1} with a variability of 22%.

The magnitude of the grain yield for wheat, maize and popcorn fall within the ranges described for modern varieties of cereal crops (Hay, 1995 and Hütsch & Schubert, 2017). The difference in grain yield between fields are due to differences in above-ground biomass production as grain yield considerably increases with an increase in dry matter production and nutrient uptake (Malhi *et al*., 2006; Setiyono *et al*., 2010). Another possible reason may be the cultivar genetics, climatic differences or agronomic management practices applied. The high wheat and maize biomass and grain yield at Field 1, indicate the highest degree of cation uptake and partitioning, followed by Field 2 for maize and Field 3 for wheat. Kruskal-Wallis statistical results (Table 4.5 and 4.6) suggest that cation uptake was also influenced by soil conditions as the significant differences in cation uptake can be coupled with differences in soil cation concentrations between fields.

5.2 Uptake and partitioning by wheat

Wheat uptake and partitioning results show that the stem-leaf removed the highest amount of cations, followed by the seed and husk which did not differ much. The dominant uptake of K^+ by stem-leaf is due to the high availability in the soil (from fertiliser applications) and the need of this macro-nutrient to ensure crop height, improve grain quality, maintain stomata regulation to limit water stress as well as activate enzymes that regulate photosynthesis, nutrient uptake and protein building (Bahmanyar & Ranjbar, 2008; Guo *et al*., 2019). The stem-leaf was also the dominant component to remove Ca^{2+}, Mg^{2+} and Na^+ from the fields, with the exception of the seed at Field 3, which removed 1 kg ha^{-1} more Mg^{2+} compared to the stem-leaf. The Ca^{2+} and Mg^{2+} cations also accumulate in high concentrations as they are essential nutrients for crop growth (i.e. cell growth,

photosynthesis, protein production) (FSSA, 2007). The extreme variation in Ca^{2+} uptake by the seed may be due to the high Ca^{2+} concentrations in the soil (Appendix 3).

Sodium may not be classified as an essential nutrient to crops but can be beneficial in low K^+ conditions by maintaining ionic balance and cell turgor (Subbarao *et al*., 2003; Maathuis, 2014). The extreme variation of Na^+ uptake by the seed at Field 2 may be due to the high Na^+ as reflected in SAR and lower K^+ in the soil (Appendix 3). This is supported by linear regression analysis which found a strong relationship (R^2 = 0.7) between Na^+ uptake and SAR as well as Na^+ concentrations in the soil, which can be expressed with the linear model equations; Y = 27.01x – 18.05 and Y = 0.031x + 0.47, respectively. This may explain the high Na^+ accumulation in the biomass at Field 1 as the SAR and Na^+ concentration in the soil at this field was the highest. The study found that Na^+ uptake by wheat increased in soil with increasing Na^+ ranging between 0.70 to 1.62 ton ha^{-1}, which competed with K^+ uptake and was therefore significantly partitioned in the stem-leaf and husk. The stem-leaf removed about 29 kg ha^{-1} and the husk 6 kg ha^{-1} Na^+ from the soil with the highest SAR and Na^+ concentration (Field 1), while these components removed a mean 7 and 1.2 kg ha^{-1} Na^+ from the soil with lowest SAR and Na^+ concentration (Field 2 and 3), respectively.

Wheat, like most cereal crops, accumulate nutrients during the growth stages until they become relatively constant after 120 days of planting (post-anthesis) as the crop reaches physiological maturity, where the nutrient salts are then translocated to various crop organelles to complete the growth cycle (Gregory *et al*., 1979, Karlen & Whitney, 1980; Du Preez & Bennie, 1991). The current study is somewhat in agreement with the uptake of cations from previous studies although accumulative differences do occur.

The current study agrees with the investigation of cation accumulation by Gregory et al. (1979) and Karlen & Whitney (1980), which found a high uptake of K^+ by the stem and leaf as compared to the husk and seed. The study by Karlen & Whitney (1980) also found a higher degree of Ca^{2+} uptake by the stem and leaf followed by the husk, as well as similar degrees of Mg^{2+} uptake by the seed and stem-leaf which corresponded well with the current study. Although the data of Gregory et al. (1979) was recalculated by Du Preez & Bennie (1991) to meet their yielding potential,

substantial differences in uptake were noted. The recalculated data found higher degrees of K^+ uptake by the husk as compared to the seed, which was the opposite for the current study. Noticeable differences were also evident in the Ca^{2+} uptake by the husk of the current study which removed more Ca^{2+} compared to the seed, while similarities were found in the higher uptake of Mg^{2+} by the seed. The accumulative cation uptake was higher compared to previous studies. This may be due to the higher grain yields (> 5 ton ha^{-1}) over the fields, different agronomic conditions, magnitude of cation concentrations in the soil and degrees of fertiliser input that has proved to be a limiting factor when comparing uptake for higher yielding crops (Karlen & Whitney, 1980; Du Preez & Bennie, 1991).

5.3 Uptake and partitioning by maize

Maize partitioned more cation concentrations compared to popcorn, but the highest cation uptake of both these crops was by the stem-leaf, followed by the seed. Popcorn has different characteristics, e.g. thinner and taller stems, higher ear placement and hanging tassels, as compared to maize, which resulted in the lower degree of uptake measured (Rathod *et al*., 2019). The degree of variation in the uptake of cations by popcorn at Field 3 was overall lower compared to maize (Field 1 and 2) especially for the husk, suggesting a more homogenous production over the field.

Statistical results indicate that Ca^{2+} uptake over the various fields, K^+ uptake at Field 3 and Na^+ uptake at Field 2 followed a different trend compared to other cations and was significantly partitioned in the stem-leaf. The significant uptake of Ca^{2+} can be due to the need of this cation to promote cell growth in the stem-leaf however, extreme variation was measured for Ca^{2+} seed uptake that was similar to wheat and may thus be due to the high Ca^{2+} concentrations in the soil. The seed partitioned the second highest cations except for Ca^{2+} which was partitioned higher in the cob leaf due to the need of this cation to ensure cell growth (FSSA, 2007). The high K^+ uptake in popcorn stem-leaf is an essential requirement for stem strength and stomata regulation due to the thinner stems and leaf blade of this crop, while the high Na^+ uptake is however not due to the role of this cation but rather the small difference between Na^+ and K^+ concentrations in the soil (Subbarao *et al*., 2003). It may also be due the SAR in the soil as a relationship (R^2 = 0.5) was found between increasing SAR and Na^+ uptake for maize.

The cob and husk cation uptake were the lowest with no significant differences ($P > 0.05$) measured but did remove substantial amounts of K^+ and Mg^{2+} cations and are often left as residue. The Mg^{2+} uptake by the seed, husk and cob was the highest, after K^+, as it plays a key role in producing the chlorophyll molecule required for photosynthesis (FSSA, 2007; Zhang *et al*., 2020). The high Mg^{2+} uptake was strongly driven by an increasing SAR in the soil as linear regression analysis found a significantly strong relationship ($R^2 = 0.6$) between these variables, which can be expressed with the linear model equation; $Y = 29.45x + 6.34$. This explains the excessively high Mg^{2+} uptake at Field 1 as it had the highest SAR between the fields, while Mg^{2+} uptake at Field 3 was the lowest which may be due to the lower SAR measured (Appendix 3). The study found that Mg^{2+} uptake by maize and popcorn increased in soil with a low SAR ranging between 1.05 to 2.18 meq L^{-1} and is significantly partitioned by the stem-leaf followed by the seed and husk. Field 1 had the highest SAR, where maize stem-leaf removed 43 kg ha^{-1} Mg^{2+}, while the seed and husk removed 17 and 1.8 kg ha^{-1} Mg^{2+}, respectively. Field 2 had a lower SAR (1.29 meq L^{-1}) compared to Field 1, where maize stem-leaf removed 31 kg ha^{-1} Mg^{2+}, seed removed 13 kg ha^{-1} Mg^{2+} and husk removed 1.9 kg ha^{-1} Mg^{2+}. Field 3 had the lowest SAR (1.05 meq L^{-1}), where popcorn removed 22.3 kg ha^{-1} Mg^{2+} and seed and husk removed 9.4 and 1.5 kg ha^{-1} Mg^{2+}, respectively. Soil at Field 2 had a lower SAR and Mg^{2+} concentration but the husk removed more Mg^{2+} compared to Field 1, which had a higher SAR and Mg^{2+} concentration. This may mainly be due to the high sandy nature of the soil at Field 2 (Appendix 3) that retained Mg^{2+} less strongly as no significant differences were measured with Kruskal-Wallis statistical analysis for Mg^{2+} uptake by the husk between fields.

The concentrations in uptake and partitioning of these cations are greater compared to previous studies but some ranges are still in agreement with uptake and partitioning by some maize and popcorn components (Hanway, 1962; Karlen *et al*., 1988; Ciampitti *et al*., 2013; Rathod *et al*., 2019 and Ahmed *et al*., 2020). The results, however, relate more to the study by Bender et al. (2013), which also found higher uptake in seeds and stover (stem-leaf, cobs, husk) compared to other studies. The study concluded that maize production increase over the years and renewed evaluations is thus required regarding the uptake and partitioning of nutrients. The uptake of the cations was measured past physiological maturity, at harvesting, as the translocation of nutrients

during the growth period is eminent (Hanway, 1962 and Karlen *et al*., 1988). The increase in cation uptake by the stem-leaf and seed is also due to the increase in biomass as it acts as the driving force for nutrient uptake (Karlen *et al*., 1988 and Bender *et al*.,2013). The same account for the other components which had high cation concentrations in the early growth stages of the crop but then later mitigated to produce the grains, resulting in the high fractionation of cations stored by the seed (Ciampitti *et al*., 2013). The high degree of uptake by the stem-leaf, especially K^+, may be due to the controlled application of NPK fertiliser and the need of this macro-nutrient for stomata regulation and photosynthesis, as well as maintaining crop height and grain yields. The application of K^+ fertiliser to the soil also mitigates the uptake of other nutrients by maize and popcorn, especially N and P (Rathod *et al*., 2019; Ahmed *et al*., 2020).

The results of K^+ uptake is in agreement with research by Bak et al. (2016) and Ciampitti et al. (2013), which found that K^+ is mostly accumulated in the stem and leaf as compared to the other components at physiological maturity. The study is however, not in agreement with the higher degree of uptake by the cob and husk compared to grains as the results of the current study indicate the opposite. Literature states that the degree of K^+ uptake in maize and popcorn components are significantly differentiated by cultivation techniques and K^+ application modes (Vyn *et al*., 2002). This may explain the differences in K^+ partitioning as the study by Bak et al. (2016) applied different treatments of K^+ fertiliser and harvested crops earlier as compared to the current study. The high degree of Ca^{2+} and Na^+ uptake by the stem-leaf is also in agreement with results of prior studies, except for Mg^{2+} which significantly accumulated in this component and not in the ear and shank (husk and cob) as previously reported (Karlen *et al*., 1988 and Ciampitti *et al*., 2013). The uptake and partitioning of these studies was during vegetative stages and at physiological maturity of the maize crop and thus not at harvesting (post-physiological maturity), which can explain the differences in cation uptake and partitioning.

5.4 Salt harvest index of wheat, maize and popcorn

Wheat at Field 3 and maize at Field 2 removed the highest amount of cations which can be attributed to the high availability thereof from the sandy nature of the soil, which retained cations less strongly compared to the clay soil of Field 1 (Brady, 1984). The high pH of Field 1 also affected cation uptake as a pH between 6-7.5 is described as optimal for wheat and maize growth and nutrient uptake (FSSA, 2007; Yan *et al*., 2015). A salt harvest index (SHI) can be formulated from a nutrient harvest index (NHI) as it follows the same principles (i.e. uptake by grain divided by accumulative uptake of all components).

A SHI for individual components can thus be used to estimate the degree of uptake by a component. The mean cation removal by the biomass at the respective fields for wheat, maize and popcorn were 384.2 kg ha^{-1}, 508.9 kg ha^{-1} and 359.8 kg ha^{-1}, respectively. When grain is removed from a field, it can be estimated for wheat, maize and popcorn that a mean of 11.5%, 12.7% and 8.5% of cations are removed, respectively. Crop residue (leaves, stems) are often left bare and is a salt inducing factor as organic material can mineralise when reintroduced into the soil medium. The degree of salt partitioning in these residing components is thus vital to manage salinity for precision agriculture. When leaving these residues behind, a mean 80.8% of cations in the wheat stem-leaf, a mean 81% of cations in the maize stem-leaf and 86.8% of cations in popcorn stem-leaf can potentially be added to the soil, respectively. The remaining percentage of cations are partitioned in the husk. The SHI of wheat, maize and popcorn at these fields indicate that cation uptake was the highest in the stem-leaf, with popcorn removing a slightly higher degree of cations from the fields, excluding the grain.

A recent study evaluated the growth response of maize with the use of different fertilisation treatments of wheat straw and Mg^{2+} fertiliser applications. The study found an increase in maize grain yield with additions of both straw and Mg^{2+} fertiliser compared to no straw or separate Mg^{2+} and straw additions. The straw is rich in nutrients as stated by the current study (stem-leaf, section 5.3), and act as an important nutrient resource when decomposed, it promotes organic material in soil, improves soil physiochemical properties and maintains soil water (Zhang *et al*., 2020). This is evident of the use of crop residue to minimise excessive fertiliser applications.

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Leaching remain a dominant and effective tactic to remove salts from the root zone but crop salt removal is often overlooked due to the assumed small quantity of salts removed. Despite this constraint, it is still vital quantifying crop salt removal to aid in mitigating crop residue after harvest. The study undertook this task and formulated the following research questions: i) to investigate the uptake and partitioning of salinity inducing cations (i.e. K^+, Ca^{2+}, Mg^{2+}, Na^+) by wheat, maize and popcorn, ii) to determine if a relationship between soil cations and the uptake thereof can be achieved and also iii) to determine if soil cations and crop uptake can be spatially characterised using EC_a measurements.

Seeds are the most harvested crop product to suit the needs of the commercial markets. Given its high value, it was found that maize seeds partitioned the most cations followed by wheat. The first research aim concluded that cations are, however, dominantly partitioned in the stem-leaf for wheat, maize, and popcorn. These components removed about 80% of cations with stem-leaf, especially for popcorn, removing the most cations. These components are seldomly removed from a field and often left as a soil cover to stabilise soil and prevent erosion. They can thus become re-introduced into the soil medium and depending on the soil nutrient status, induce salinity conditions if excessive fertilisers containing these cations are also applied. Additionally, these components can also improve soil conditions (water retention, improved structure, increased organic material) if properly managed under controlled agronomic practices (fertilisation, irrigation) which may lead to increased grain yields.

Regarding the second research question, it was concluded that the SAR played a significant role in Na^+ uptake by wheat and Mg^{2+} uptake by maize but only Na^+ in soil correlated with SAR. Further linear regression analysis indicated that an increasing Na^+ concentration in the soil increases Na^+ uptake by wheat, while only an increasing SAR increases Mg^{2+} uptake by maize and popcorn. Wheat can therefore serve as a potential bio-accumulator to remove Na^+ from sodic soils as it is a non-essential nutrient. It was, however, also confirmed with literature that an increase of

Na^+ in the soil competes with the uptake of K^+ in K^+-deficit soils as Na^+ can substitute for non-biophysical functions of K^+. The study therefore suggested maximum critical Na^+ ranges for wheat, maize and popcorn as there is limited literature available. These ranges can serve as potential estimates as the study had the limitation of not being able to investigate the effect of fertiliser inputs and irrigation water quality on the salt balance.

For the purpose of spatially characterising soil cations and therefore crop uptake using EC_a measurements, no correlations were achieved. It was concluded that for the fields investigated, EC_a measurements were not influenced by the soil cations thereby making it impossible to spatially characterise crop cation uptake. It is known that there are many soil properties (water content, bulk density, clay, EC_e) that do influence EC_a measurements, which have not only served its efficiency in directing RSSD soil and plant sampling but also identifying the dominant property influencing grain yield. Correlation of some of these properties with EC_a is investigated in the larger WRC project.

6.2 Recommendations

The study investigated salt uptake and partitioning of salinity inducing cations, thereby creating a precedent for future research regarding uptake and partitioning of salinity inducing anions. This will better quantify the total removal of salts when crops are harvested which may aid in minimising leaching as the primary factor of salt removal in the soil salt balance. Further quantification of Na^+ removal and partitioning by more salt tolerant crops (i.e. ×*Triticosecale*, *Hordeum vulgare, Festuca perennis*) under sodic conditions can also be beneficial in salt management strategies as the quantities of salt removal by commercial crops are low. Additional research is also needed on the salt tolerance of modern hybrid maize, popcorn and wheat crops for South Africa.

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APPENDICES

Appendix 1. Ionic salt forms and crop concentration comparisons

Table 1.1 Ionic salt form of nutrients salts (Rauscher, 2017)

Salt	Nutrient
Boric Acid [H_3BO_3]	Boron
Calcium Nitrate [$Ca(NO_3)_2$]	Calcium/Nitrogen
Copper Sulfate [$Cu(SO_4)$]	Copper
Chelated Iron [$C_{10}H_{13}FeN_2O_2$]	Iron
Ferrous Sulfate [$FeSO_4$]	Iron
Magnesium Sulfate [$MgSO_4$]	Magnesium
Manganese Chloride [$MnCl_{12}$]	Manganese
Manganese Sulfate [$MnSO_4$]	Manganese
Molybdenum Trioxide [MoO_3]	Molybdenum
Monopotassium Phosphate [KH_2PO_4]	Potassium/Phosphorus
Potassium Chloride [KCl]	Potassium
Potassium Nitrate [KNO_3]	Potassium/Nitrogen
Potassium Sulfate [K_2SO_4]	Potassium
Zinc Sulfate [$ZnSO_4$]	Zinc

Table 1.2 Critical and sufficient concentration values (%) for the cations in wheat and maize at the various fields (Campbell & Plank, 2000)

Field	Crop	K	Ca	Mg	Na
		%			
Field 1	wheat	3.58	0.51	0.46	0.5
Field 2	wheat	4.4	0.7	0.47	0.17
Field 3	wheat	3.82	0.53	0.35	0.12
*Critical value	wheat	2.0	0.15	0.1	-
*Sufficient range	wheat	2.0 – 4.0	0.2 – 1.0	0.14 – 1.0	-
		%			
Field 1	maize	5.53	0.87	0.7	0.19
Field 2	maize	5.36	0.91	0.63	0.17
Field 3	maize	6.24	0.93	0.76	0.15
**Critical value	maize	2.0	0.40	0.25	-
*Sufficient range	maize	1.6 – 2.5	0.2 – 0.8	0.12 - 0.5	-

(-) = no data available; *concentration at maturity, **critical value at maize tasselling stage

Table 1.3 Suggested nutrient salt removal norms (kg t^{-1}) for the cations in wheat and maize at harvest (FSSA, 2007)

Component	Crop	K	Ca	Mg	Na
		kg t^{-1}			
Seed	wheat	4.3	-	2.5	-
Straw	wheat	8.6	-	-	-
		kg t^{-1}			
Seed	maize	4	0.5	1	-
Biomass	maize	20	5	4.5	-

(-) = no data available, maize biomass expressed per ton of grain

Appendix 2. Regression statistics for cation uptake as influenced by SAR of the study fields

Table 2.1 Relationship of the SAR influencing soil cations and wheat uptake

Soil Cation	Parameter	Ca Uptake
Ca	Depth (m)	0 – 0.3
	R^2	0.00019
	P-value	0.9431
Soil Cation	**Parameter**	**Mg Uptake**
Mg	Depth (m)	0 – 0.3
	R^2	0.33
	P-value	0.00092
Soil Cation	**Parameter**	**Na Uptake**
Na	Depth (m)	0 – 0.3
	R^2	0.70
	P-value	< 0.001

n.s = no significance

*** = significant at the 0.001 probability level

Table 2.2 Relationship of the SAR influencing soil cations and maize and popcorn uptake

Soil Cation	**Parameter**	**Ca Uptake**
Ca	Depth (m)	0 – 0.3
	R^2	0.01076
	P-value	0.68205
Soil Cation	**Parameter**	**Mg Uptake**
Mg	Depth (m)	0 – 0.3
	R^2	0.00553
	P-value	0.76931
Soil Cation	**Parameter**	**Na Uptake**
Na	Depth (m)	0 – 0.3
	R^2	0.063889
	P-value	0.31156

n.s = no significance

Appendix 3. Soil properties and cation concentrations

Table 3.1 Soil properties of the centre pivot at Field 1 over the sampling period

		Field 1 Sampling times						**P-value**
		16-Jun		**16-Dec**		**17-Jun**		
Soil Property	**Unit**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	
EC_e	mS m^{-1}	447.58^a	52.6	211.83^b	34.2	115.17^b	17.2	***
SAR	Meq L^{-1}	1.61^b	32.9	2.18^a	13.8	1.28^b	27.3	***
Grav_Water	%	13.1^a	16.6	13.3^a	20.9	9.5^b	10.5	***
Clay	%	26.5^a	19.9	26.5^a	19.9	26.5^a	19.9	n.s
p_b	g cm^{-3}	1.44^a	4.2	1.44^a	4.2	1.44^a	4.2	n.s
pH	-	8.33^a	1.7	8.27^a	2.5	8.32^a	1.6	n.s

CV = 0%-15% (low variability), 15%-35% (medium variability), >35% (high variability) (Wilding *et al*., 1994; Peralta & Costa, 2013)

Mean separation (abc) = significant difference in means from highest to lowest at probability levels (highly significant at 0.001 = a), (moderate significance at 0.01 = b) and (low significance at 0.05 = c)

P_b = Bulk density

Table3.2 Soil properties of the centre pivot at Field 2 over the sampling period

		Field 2 Sampling times						P-value
		16-Jun		16-Dec		17-Jun		
Soil Property	**Unit**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**	
EC_e	mS m^{-1}	103^b	44.4	172.5^a	29.9	104.33^b	27.3	*
SAR	Meq L^{-1}	1.19^a	19.3	1.29^a	19.4	1.33^a	12.8	n.s
Grav_Water	%	7.2^b	24.2	9.9^a	26.6	-	-	***
Clay	%	9.3^a	28.6	9.3^a	28.6	9.3^a	28.6	n.s
p_b	g cm^{-3}	1.51^a	3.9	1.51^a	3.9	1.51^a	3.9	n.s
pH	-	6.35^a	15.6	6.18^a	14.2	6.55^a	10.1	n.s

CV = 0%-15% (low variability), 15%-35% (medium variability), >35% (high variability) (Wilding *et al*., 1994; Peralta & Costa, 2013)

Mean separation (abc) = significant difference in means from highest to lowest at probability levels (highly significant at 0.001 = a), (moderate significance at 0.01 = b) and (low significance at 0.05 = c)

p_b = Bulk density

(-) = no data available

Table 3.3 Soil properties of the centre pivot at Field 3 over the sampling period

		Field 3 Sampling times						P-value
		16-Jun		16-Dec		17-Jun		
Soil Property	**Unit**	**mean**	**CV (%)**	**mean**	**CV (%)**	**mean**	**CV (%)**	
EC_e	mS/m	106.25^a	28.4	78.33^b	30.9	67.09^b	38.6	**
SAR	meq/L	0.96^b	10.4	1.05^a	9.5	1.05^a	8.6	*
Grav_Water	%	5.7^b	36.4	9.2^a	26.6	-	-	***
Clay	%	13.3^a	19.7	13.3^a	19.7	13.34^a	19.7	n.s
p_b	g/cm-3	1.48^a	4.1	1.48^a	4.1	1.48^a	4.1	n.s
pH	-	6.57^a	6.5	6.68^a	2.7	6.81^a	4.9	n.s

CV = 0%-15% (low variability), 15%-35% (medium variability), >35% (high variability) (Wilding *et al*., 1994; Peralta & Costa, 2013)

Mean separation (abc) = significant difference in means from highest to lowest at probability levels (highly significant at 0.001 = a), (moderate significance at 0.01 = b) and (low significance at 0.05 = c)

p_b = Bulk density

(-) = no data available

Table 3.4 Soil cations over the sampling period for Field 1

		Field 1 soil cations						P-value
		16-Jun		16-Dec		17-Jun		
Soil Salt	**Unit**	mean	CV (%)	mean	CV (%)	mean	CV (%)	
K^+	ton ha^{-1}	2.40[a]	29.6	1.79[b]	25.1	2.14[a]	20.6	*
Ca^{2+}	ton ha^{-1}	14.42[a]	14.2	13.21[a]	7.3	13.46[a]	9.7	n.s
Mg^{2+}	ton ha^{-1}	2.17[a]	18.4	2.39[a]	19.3	1.98[b]	13.1	*
Na^+	ton ha^{-1}	1.62[b]	32.1	2.16[a]	13.4	1.25[c]	25.6	***

n.s = no significance

* and *** = significant at the 0.05 and 0.001 probability level

Table 3.5 Soil cations over the sampling period at Field 2

		Field 2 soil cations						P-value
		16-Jun		16-Dec		17-Jun		
Soil Salt	**Unit**	mean	CV (%)	mean	CV (%)	mean	CV (%)	
K^+	ton ha^{-1}	1.40[a]	30.7	2.02[a]	27.7	1.83[a]	34.4	n.s
Ca^{2+}	ton ha^{-1}	5.34[a]	53.4	6.12[a]	30.6	6.26[a]	28.6	n.s
Mg^{2+}	ton ha^{-1}	1.20[a]	45	1.30[a]	23.1	1.28[a]	14.1	n.s
Na^+	ton ha^{-1}	0.75[b]	10.7	0.88[a]	9.1	0.92[a]	8.7	**

n.s = no significance

** = significant at the 0.01 probability level

Table 3.6 Soil cations over the sampling period at Field 3

		Soil cations at Field 3						P-value
		16-Jun		16-Dec		17-Jun		
Soil Salt	**Unit**	mean	CV (%)	mean	CV (%)	mean	CV (%)	
Ca	ton ha^{-1}	6.98[a]	21.9	6.73[a]	16.8	7.18[a]	18.8	n.s
Mg	ton ha^{-1}	1.35[a]	20	1.37[a]	18.3	1.52[a]	21.1	n.s
K	ton ha^{-1}	2.09[a]	16.3	2[a]	25.5	1.91[a]	19.4	n.s
Na	ton ha^{-1}	0.70[b]	5.7	0.76[a]	5.3	0.79[a]	7.6	***

n.s = no significance

*** = significant at the 0.001 probability level