SOIL FERTILITY CONSTRAINTS OF IRRIGATED WHEAT PRODUCTION IN SOUTH AFRICA

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ABSTRACT

There is a gradual decrease in the number of wheat (*Triticum aestivum* L.) producers in South Africa due to low profitability of the crop. As producers target higher yields to improve profits, nutrient demand and removal increases, and poor soil fertility management is inevitably a major limiting factor for wheat production. This study was aimed at exploring the soil fertility constraints of irrigated wheat producers in South Africa. The objective of this study was to determine the influence of geographical regions and crop management strategies such as tillage and crop rotation, on soil fertility status of irrigated wheat fields in relation to wheat requirements. The study was conducted across the major South African irrigated wheat production regions namely: KwaZulu-Natal, the Eastern Highveld, the Warmer Northern and the Cooler Central areas. Soil were sampled from the fields of representative producers (*n* = 130) in all the irrigated wheat production regions at 0 - 20 and 20 - 40 cm depths. The samples were analysed for soil organic carbon (SOC), sulphur (S), phosphorus (P), zinc (Zn), calcium (Ca), magnesium (Mg), potassium (K), cation exchange capacity (CEC), acidity, exchangeable sodium percentage (ESP), texture and electrical conductivity (EC). Wheat crops were also scored for visual symptoms of nitrogen (N) deficiency.

The majority of the producers (63.85%) practised conventional tillage. Conservation tillage combined with a legumes-wheat crop rotation was adopted by 88.37, 13.89, 0 and 0% of the producers in in KwaZulu-Natal, Warmer Northern, Cooler Central, and Eastern Highveld regions, respectively. Soil pH, ESP and plant available P, K, Mg and Ca varied considerably across geographical regions. Soils in KwaZulu-Natal were the most acidic (pH [KCl] 4.51 ± 0.05), followed by Eastern Highveld (pH 4.97 ± 0.08), Cooler Central (pH 5.75 ± 0.09) and Warmer Northern (pH 6.32 ± 0.12). Significant positive Pearson's correlations between pH and Mg, ESP, CEC and Ca indicated that acidity was a major factor that influenced the availability of nutrients.

The Eastern Highveld and Warmer Northern regions had a slightly lower soil pH (KCl) for rotations in which wheat was preceded by a legume than by a non-legume. Mean plant available P was below the minimum range in KwaZulu-Natal (27.49 ± 2.04 mg/kg) and Warmer Northern (36.35 ± 3.65 mg/kg) regions. Conservation tillage and rotations where wheat was preceded by legumes generally had higher acidity levels and P deficiency problems than either conventional tillage or non-legume - wheat rotations. Plant available Zn, Mg, K and S were generally adequate across all geographical regions. Electrical conductity and ESP were also acceptable across all geographical regions. Calcium to Mg ratio was low in the Warmer Northern region (1.91 ± 0.11), but was within the acceptable range of 2-8 in the other regions. Soils of the Warmer Northern region had very high Mg (634.30 ± 54.31 mg/kg). There was an indication of P stratification on all all farms, hence generally adequate P levels at 0-20 cm (mean 45.57 ± 2.54 mg/kg), but deficiency at 20 – 40 cm (34.36 ± 2.28 mg/kg).

Soil organic carbon varied considerably across the irrigated wheat production regions in the country, ranging from 0.13% to 6.02%, with a mean of 1.55% and 65.60% coefficient of variation. Overall, 42.31% farms had SOC below the critical limit of 1% at 0 – 20 cm soil depth. Geographic region, tillage and soil depth had a significant ($p<0.05$) effect on the SOC. Soils in the KwaZulu-Natal region, where the majority of producers (88.37%) use conservation practices had the highest SOC (2.00 ± 0.09%), followed by Warmer Northern (1.65 ± 0.14%), Cooler Central (0.84 ± 0.08%) and Eastern Highveld (0.82 ± 0.07%) where soils had lower SOC. Farms where conservation tillage (2.15 ± 0.10%) is practiced had more SOC at both sampling depths of 0-20 cm and 20-40 cm than farms that used conventional tillage (1.02 ±

0.05%). In Warmer Northern region, fields where wheat was preceded by a legume crop had more SOC than those where it was preceded by a non-legume crop. The opposite was true for the KwaZulu-Natal. In the Cooler Central and Eastern Highveld, crop rotation systems had no significant difference in SOC. Geographical region × soil depth ($p<0.05$) interaction was also significant and showed that in KwaZulu-Natal, the SOC was higher in the 0 - 20 cm depth than in the 20 - 40 cm while depth did not affect SOC in the other three regions. No significant correlation ($r = 0.0$) was observed between SOC and clay content in KwaZulu-Natal, while moderate positive correlations were obtained for SOC and clay in other regions. Cation exchange capacity, Ca, Mg and S were significantly related to SOC in the the Cooler Central and Eastern Highveld regions. In the Warmer Northern region, there were significant negative relationships between SOC, P and pH. Zinc did not have a significant relationship with SOC in all the geographical regions.

The findings suggested that conservation tillage and inclusion of legume crop rotation systems could be important strategies for increasing SOC and soil fertility on irrigated wheat fields. Sustainable approaches for effectively enhancing P availability and addressing pH problems under these systems need to be sought.

Keywords: conservation tillage; conventional tillage; crop rotation; organic carbon; plant available nutrients; wheat yield.

DECLARATION

I, Nondumiso Zanele Sosibo declare that:

1. The research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;
2. This dissertation has not been submitted in full or in part for any degree or examination to any other university;
3. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;
4. This dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
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5. where I have used material for which publications followed, I have indicated in detail my role in the work;
6. This dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;
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Signed:……………………………............ Date:………………………………….

Nondumiso Zanele Sosibo (Candidate)

I as the candidate’s supervisor have/have not approved this dissertation for submission

Signed:… …….. …………Date:…23rd March 2016………………………..

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Dr E. Dube (Co-supervisor)

Signed:……… Visser …………. Date:… 23rd March 2016..……………………..

Mrs L. Visser (Co-supervisor)

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LIST OF ABBREVIATIONS

ARC:	Agricultural Research Council
AS:	Acid saturation
Ca:	Calcium
CA:	Conservation agriculture
CC:	Cooler Central
CEC:	Cation exchange capacity
DAFF:	Department of Agriculture Forestry and Fisheries
DTPA:	Diethylene triamine pentaacetic acid
EC:	Electrical conductivity
EH:	Eastern Highveld
ESP:	Exchangeable sodium percentage
FAO:	Food and Agriculture Organisation
K:	Potassium
KCl:	Potassium chloride
Mg:	Magnesium
N:	Nitrogen
PDP:	Professional Development Programme
REML:	Residual (Restricted) Maximum Likelihood
S:	Sulphur
SGI:	Small Grain Institute
SOC:	Soil organic carbon
SOM:	Soil organic matter
Zn:	Zinc

PREFACE

This thesis is made up of five chapters. Chapters 1 and 2 (general introduction and literature review) introduce the reader to irrigated wheat producer constraints in South Africa with regards to soil fertility, and identifies opportunities for refinement of soil fertility management. The literature review identifies information gaps to this respect. Chapter 3 looks at plant nutrient availability on irrigated wheat producers' fields in South Africa, including the factors that influence this availability. Chapter 4 explores soil organic carbon (SOC) status of irrigated wheat fields in South Africa, including important management factors that influence the SOC levels. Good SOC management is central to sustainable soil fertility and crop yield improvement. Finally, a general discussion which ties up the findings of chapters 2, 3 and 4 to give overall conclusions and recommendations, is provided in Chapter 5.

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1 GENERAL INTRODUCTION

1.1 INTRODUCTION

South Africa currently faces a wheat (*Triticum aestivum* L.) production crisis as wheat production declined progressively from 2.5 million tons, produced on 974 000 ha, in 2002 to approximately 1.7 million tons, produced on 500 000 ha in 2013 (Agricultural Statistics, 2014). The decline in land area under wheat suggested producer disinterest in wheat production in South Africa, because of the low profitability of the crop when compared to alternative crops such as maize (*Zea mays* L.) and soyabean (*Glycine max* L.) (Lemmer and De Villiers, 2012; Brandt, 2012; Payne, 2012). Wheat producer prices in South Africa are benchmarked against the international wheat price, and in the recent past, they have not been increasing at the same rate as input costs (African Agriculture Review, 2012). Fertilizer inputs contribute 20 - 35 % of the total variable input cost of wheat in South Africa, and from 2010 to 2011, the price of urea increased by 24.3% whilst that of mono-ammonium phosphate increased by 16.6% (Agriculture Statistics, 2012). Many producers argue that they just cannot produce wheat profitably anymore in South Africa (Heydenrych, 2012).

Profitability of wheat production is a function of yield, producer price and input cost, and at the farm level, producers could improve their profits through strategies that maximize yields and/or reduce production cost. Yield potential is the economic yield of a cultivar when grown in environments in which it is adapted, with nutrients, adequate water and with pests, diseases, weeds, lodging, and other stresses effectively controlled (Evans and Fischer, 1999; Lobell *et al.*, 2009). The yield potential of irrigated wheat in South Africa is increasing progressively because of improvements in genetic yield potential of cultivars and technological advancements that enable producers to improve crop management (Smit *et al.,* 2010). Hence, in recent years, researchers and industry agronomists conducting cultivar trials in South Africa have documented a potential yields of 10 t/ha in many production areas of South Africa (ARC –SGI, 2015). When these yields are compared with the national average yield of 6 t/ha, it appears that there is opportunity for improving wheat yield in some production systems of South Africa through refinements of crop and resource management strategies. According to Armour *et al.* (2004), the environmental and management circumstances that enable the production of a 15 t/ha wheat crop are a combination of cultivar and sowing date that will lead to grain growing through the solar radiation peak, cool but sunny grain filling conditions, and most importantly, attention to agronomic detail so that no growth constraints occur.

Irrigation is an effective tool for increasing productivity of cropped lands and in South Africa. Intensive irrigation systems combining winter wheat and a summer crop (usually maize or soyabean), whereby producer's harvest eight or more crops in the course of five years are common. Nutrient demand and removal inevitably increases as producers intensify crop production and target higher yields, suggesting that it is critical for producers to refine soil fertility management practices in improving yield, production efficiency and profitability. Indeed, poor nutrient management appears as the most frequently reported yield limiting factor in wheat production systems (Tittonell *et al.*, 2008; Neumann *et al.*, 2010; Nadim *et al.*, 2013; Rani *et al.*, 2013; Tittonell and Giller, 2013; Affholder *et al.*, 2013). A FAO policy document on constraints to food production across the world identified high nutrient removal in irrigation crop production as a major basis of deterioration in soil fertility in developing countries (FAO, 2006). As a result, application rates of inorganic nitrogen (N), phosphorus (P) and potassium (K) based fertilizers have also increased, in order to meet the increased nutrient demands. These inorganic fertilizer applications at a high rate may also negatively affect soil properties such as soil pH, organic carbon, aeration and soil texture through various chemical processes, resulting in reduced soil fertility and productivity. Salinity and sodicity, which refer to the excessive concentration of soluble salts and sodium (Na), respectively are problems which can occur on irrigation soils depending on quality of the irrigation water, method of irrigation and adequacy of drainage (Warrence *et al.,* 2002).

Soil organic carbon (SOC) content is an important indicator of the fertility, quality and productivity of soils (Dlamini *et al.*, 2014; Smith *et al.,* 2014). Sandy soils, with less than 1% SOC, are prone to structural destabilization and crop yield reduction (Howard and Howard, 1990). At such SOC levels, it may not be possible to obtain the potential wheat yields irrespective of soil type (Kay and Angers, 1999). However, the SOC content in the soil is affected by a number of factors such as soil texture, climate, temperature, topography, vegetation and management (crop rotation, tillage practice and fertilization) (Lou *et al.,* 2012).

1.2 PROBLEM STATEMENT

Amidst the wheat production challeges in South Africa, there is no record of studies carried out to determine the extent to which soil fertility limits the production capacity of irrigated wheat producers. There is also a paucity of information on the effects of various environmental, crop and resource management strategies on the soil fertility of irrigated wheat fields across South Africa. There are four main geographical regions in South Africa where irrigated wheat is produced, namely: KwaZulu-Natal, Eastern Highveld, Warmer Northern and Cooler Central. These regions are distinctive in soil types, climatic conditions and in some cases, farmer crop and resource management strategies for irrigated wheat.

1.3 STUDY OBJECTIVES

The objectives of the study were:

1) To determine the soil fertility status of the four main geographical locations where irrigated wheat is produced in South Africa.
2) To determine the influence of geographical regions, tillage and crop rotation as well as interactions of these factors, on the soil fertility.

1.4 HYPOTHESES

Based on the above objectives, the hypotheses for the study were:

1) Nutrient availability on irrigated wheat fields in South Africa is significantly below the optimum range for wheat production.
2) Geographical regions, soil texture, tillage practices and crop rotation systems, as well as the interactions of these factors have a significant influence on the soil fertility status of irrigated wheat fields in South Africa.

2 LITERATURE REVIEW

2.1 BACKGROUND

Soil fertility can be defined as a measure of the soil's ability to sustain satisfactory crop growth, both in the short and longer-term, and is determined by a set of interactions between the soil's physical environment, chemical environment and biological activity (Brady and Weil, 2008). There is no standard method for measuring soil fertility, but measurements of nutrient availability, salinity, soil acidity and soil organic carbon (SOC) are generally considered as adequate to distinguish soils in terms of fertility (Tisdale *et al.,* 1993). According to Tucker (1999), plant essential nutrients are grouped into non-mineral and mineral nutrients. The former include carbon (C), oxygen and hydrogen. The latter are further divided into primary, secondary and micro-nutrients. Primary nutrients include nitrogen (N), phosphorus (P) and potassium (K). Secondary nutrients include calcium (Ca), magnesium (Mg) and sulphur (S). Essential micronutrients are boron (B), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu) and molybdenum (Mo) (Landon, 1991). Each of the nutrients plays in plant growth and quality, and there is a minimum range for each nutrient below which it is deficient, or above which it is toxic (Uchida, 2000). An important concept in chemical soil fertility is nutrient balance which based on the Liebig law of the minimum (Brady and Weil, 2008). The law states that "*if one of the essential elements is deficient or lacking, plant growth will be poor, even when all the other elements are abundant. If the deficient element is supplied, growth will be increased up to the point where the supply of that element is no longer the limiting factor*".

There are many opportunities for improving crop yields in Sub-Saharan Africa through the refinement of agronomic factors such as soil fertility, pest and disease management (Hochman *et al.,* 2012; Mueller *et al.,* 2012; Bryan *et al.,* 2014). However, more research is being done on plant breeding than on crop nutrition studies in Africa. According to Kumwenda *et al.* (1996), "*this bias is a legacy of the Green Revolution in Asia which succeeded through the use of improved germplasm under very different conditions — particularly Asia's more fertile and uniform soils — than those prevailing in Africa*". In Africa, soil fertility depletion due to poor management is generally regarded as the main limiting factor in crop production (Kimaru, 2011; Chianu *et al*., 2011; Mugendi *et al*., 2011). Soil fertility problems that the rest of Africa is facing include: soil acidity, nutrient deficiency, low SOC content and high erodibility of soils (Mills and Fey, 2003; Kolawole, 2011). On the other hand, fertilizers and lime that are used extensively by irrigated wheat (*Triticum aestivum* L.) producers in South Africa contribute the most to total variable costs on wheat enterprises (DAFF, 2013). Producers, therefore need soil fertility improvement technologies that will allow them to reduce the amount of fertilizer applied, or at least increase the profitability of fertilizer application.

As alluded in the introductory chapter, scientific information on the soil fertility constraints which limit the yield capacity of irrigated wheat producers in South Africa is required. This information will guide the formulation of research and development interventions for saving the ailing wheat industry. This literature review identifies soil fertility constraints of irrigated wheat in South Africa and opportunities for improving soil fertility management, including information gaps in this regard. It begins with an overview of irrigated wheat production in South Africa, followed by a review of soil fertility requirements of wheat, and lastly, constraints and opportunities for improving soil fertility management in South African irrigated wheat production.

2.2 DESCRIPTION OF IRRIGATED WHEAT PRODUCTION REGIONS OF SOUTH AFRICA

The irrigated wheat production area of South Africa can be divided into four main geographic regions – the cooler central irrigation region in the north eastern parts of Northern Cape, the warmer northern irrigation region in North West, Limpopo and Gauteng provinces, the Highveld region in Mpumalanga and Free State, and lastly, the KwaZulu-Natal region (Plate 2.1). The Cooler Central region is arid. It has lower average annual temperatures ranging between 15 and 31°C, and predominantly deep, loamy Hutton soil forms (Fey, 2010) that are ideal for irrigation. Irrigated wheat grows best on loamy and sandy soils that have good drainage. Average annual rainfall vary between 200 - 715 mm. Warmer northern irrigation region is semi-arid, with average temperatures ranging between 18 and 32°C. The average annual rainfall vary between 200 and 600 mm annually and the region has oxidic soils with a relatively higher clay content than the other regions. The Highveld region has a semi-arid climate and receives an average rainfall of 200 to 500 mm per year. Mean monthly temperatures range between 14°C and 26°C and the area is dominated by soils of plinthic origin (Fey, 2010). In KwaZulu-Natal, irrigated wheat is mostly grown around Bergville and Winterton localities (Plate 2.1) at high altitude areas with highly weathered, well-drained oxidic soils (Fey, 2010). The climate of KwaZulu-Natal is sub-humid and warmer, with average temperatures ranging between 15 and 32°C. Cool and moist climate is ideal for wheat growth but spring wheat can tolerate high temperatures between 22 and 34°C (DAFF, 2010). Winter wheat can tolerate temperatures between 5 and 25°C (DAFF, 2010). It most likely that temperature is a major limiting factor of wheat productivity in the warmer regions of South Africa, such as KwaZulu-Natal. There is evidence suggesting that an increase in temperature by 1°C above the optimal can reduce wheat yield by up to 50% (You *et al.,* 2009). Average rainfall of 600 to 1000 mm is received annually in KwaZulu Natal.

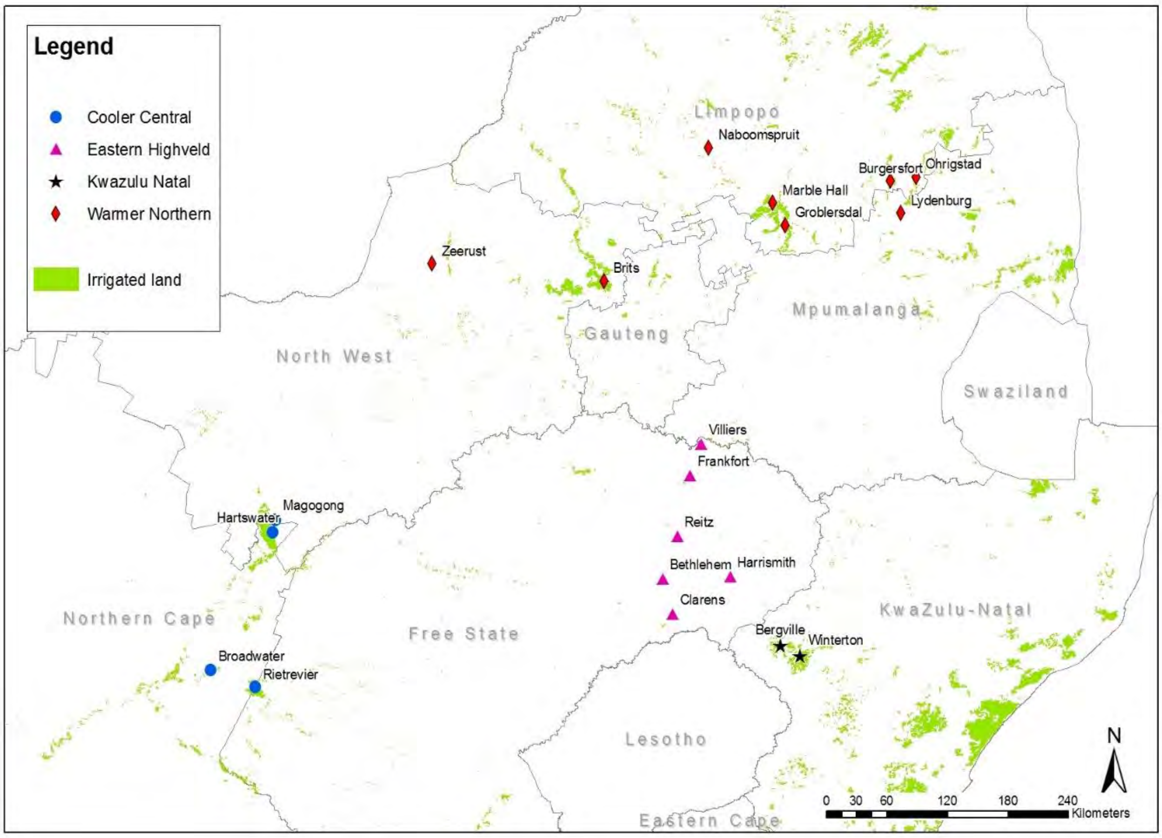

Plate 2.1 The major production regions of irrigated wheat in South Africa.

The majority (> 95%) of irrigated producers in South Africa are large-scale commercial producers (DAFF, 2013). The rest are emerging producers, who produce on a small scale mainly for household food security. The soil fertility challenges faced by smallholder producers differ from those faced by large scale commercial producers. The emerging producers use low fertilizer inputs, are nearly always located on marginal lands, are resource poor and generally lack technical expertise to handle their fields. No record could be found in the current literature about emerging producer in irrigated wheat producing areas. Therefore, this literature review focused primarily on soil fertility requirements and constraints of irrigated wheat in South Africa from a commercial producer perspective.

2.3 SOIL FERTILITY REQUIREMENTS AND CONSTRAINTS OF IRRIGATED WHEAT IN SOUTH AFRICA

2.3.1 Nitrogen

Nitrogen (N) is required in large quantities as a building block of proteins and an important component of chlorophyll in wheat (Tucker, 1999). However, N deficiency is common in South Africa, especially on sandy soils. Nitrogen is therefore the major fertilizer nutrient supplied to irrigated wheat in South Africa. Nitrogen is a mobile nutrient in the plant, and if there is insufficient N in the soil, deficiency symptoms will first appear on the older leaves (Jones and Jacobsen, 2005). If more than the required N is available, it would result in luxury uptake by the crop, which may result in rank growth and undesirable effects such as lodging. Nitrogen requires careful management because it can easily be lost through volatilization, leaching and denitrification (Brady and Weil, 2008; Lamb *et al.*, 2015). Soil sampling at planting may not provide reliable indications of the N fertility status of the soil, as nitrate-N is easily leached from soils. If the total N required by the wheat crop is applied once off, there is a risk of excessive vegetative growth and lodging and higher potential for leaching, as well as soil acidification.

The N management requirements for wheat has been reviewed extensively (e.g, Gauer *et al.,* 1992; Woodard and Bly, 1998; Raun *et al.,* 1999). Based on these reviews, it is generally agreed that early N deficiency in wheat up to the booting stage affects yield potential, while N deficiency in the later stages affect protein content. The grading and market price for wheat in South Africa is determined primarily by grain protein content. Therefore, it is important for wheat producers to ensure adequate N supply throughout the growing season. Most producers apply N in split applications at critical growth stages in order to improve N use efficiency. This is especially important on coarse textured soils that have a high N leaching potential, as those found in the Eastern Highveld. The yield potential and residual soil N status are important considerations to estimate the N requirement of irrigated wheat. In regions such as the Cooler Central and Highveld (Plate 2.1) where cool conditions during grain fill may improve yield potential, the N recommendations are usually higher. The general N fertilizer guidelines for irrigated wheat production in South Africa is based on the target yields that are presented in Table 2.1.

At flag leaf, the wheat plant must contain more than 4.2 % N if there is adequate N supply in the soil (ARC-SGI, 2015). The sources of N for a wheat crop are residual soil N, current mineral fertilizer (nitrate-N and ammonium-N), as well as soil minerals and organic matter. Residual soil N levels tend to vary considerably and are strongly influenced by the preceding crop and past N fertilization practices. Ideally, wheat should be preceded by an N-fixing legume in order to reduce the N fertilizer crops requirements. Giller *et al.* (2009) argue that N recommendations may not be reduced in situations whereby both biomass and grain material is harvested from the legume. Mineralization of N from soil organic matter (SOM) can contribute up to 40% of the total N requirements of the wheat crop (Anderson and Domsch, 2010). However, since most South African soils are typically very low in organic matter, mineralizable N is often ignored in N recommendations.

Table 2.1 General nitrogen fertilizer guidelines for irrigated wheat production in South Africa

Target wheat yield (t/ha)	Nitrogen fertilizer requirement (kg N/ha)
4-5	80-130
5-6	130-160
6-7	160-180
7-8	180-200
8+	200+

Source: ARC-SGI Irrigation wheat production guidelines (2015)

Nitrogen requirement of the crop, or N use efficiency (NUE) may also depend on several other factors such as adequacy of water supply, the wheat cultivar, adequacy of other nutritional elements, soil texture and the residue management strategy for the production system. Studies by Garabet *et al.* (1998) showed that with adequate irrigation, wheat crops removed significantly more fertilizer N than under rain-fed conditions. The wheat also had a higher N-fertilizer use efficiency. According to Elliot *et al.* (1981), cereal crop residues with a high C: N ratio that are incorporated in the soil caused serious N immobilization. That resulted in reduced growth and yield of wheat which can be overcome by higher application rates of N. Cooler temperatures in the Eastern Highveld and Cooler Central regions could slow the decomposition of crop residues. Large amounts of crop residue biomass from cereal crops preceding wheat can lock up N, especially under no-till (Jensen, 1994). Meanwhile, limited studies have been carried out to determine the extent to which N is a limiting factor for irrigated wheat yield in South Africa.

Guarda *et al.* (2004) found that wheat varieties differ in their ability to utilize N efficiently. From the same study it was concluded that cultivars that had high NUE and N uptake at high N application rates, also tend to perform better at low N-supply. Deficiency of other essential nutrients such as P can reduce NUE in wheat and applying N in combination with P, or nutrient rich farm yard manures increases wheat yield significantly compared to sole N or P applications (Table 2.2). Therefore, N fertilizer in wheat production systems is normally applied as combinations of N, P and K fertilizers. The benefits co-applications of NPK and manure on wheat are reported from several studies (Table 2.2).

2.3.2 Phosphorus

All over the world, P is considered as the second most deficient nutrient in crop production, after N, (Ortiz-Monasterio *et al.,* 2002). The element is required for seed and root development as well as crop maturity (Brady and Weil, 2008). Phosphorus deficiency causes wheat yield loss through poor tiller emergence (Rodríguez *et al.*, 1999). The symptoms of P deficiency in cereals are purplish hues on the leaves, stunted growth due to poor root development, delayed seed development and crop maturity (Brady and Weil, 2008). A minimum of 35 mg P/kg must be available in the soil for wheat under irrigation to achieve a yield of 4-5 t/ha. If a yield more than 7 t/ha is targeted, more than 50 mg P/kg must be available in the soil, of which more than 0.5% of P must be available in plant tissue at flag leaf (ARC-SGI, 2015). Otto and Kilian (2001) demonstrated that dryland wheat in the Highveld area of South Africa, where soils had an inherent P deficiency responded positively to P applications during early and late tillering growth stages. An optimum yield of >3.5 t/ha was achieved with supplementary P applications of 10 kg/ha and 15 kg/ha. It was also observed in the same study that P application benefits were better under higher rainfall conditions.

Studies on a P deficient soil in the Great Plains, USA, showed that P (0, 15, 30 kg/ha) increased yield by more than 60% due to the production of more tillers (Sweeney *et al.,* 2000). Phosphorus is highly immobile and is better band placed or applied with seed (Uchida, 2000;

Jones and Jacobsen, 2005). Many soils in South Africa have high P sorption capacities, particularly in the high rainfall areas, where the soils also tend to be very acidic. In highly weathered soils where P fixation is a problem, increases in SOM content may decrease P adsorption capacity of soils and thus increase the availability of P to plants (Iyamurenye *et al.,* 1996). Because of SOM ability to hold strongly to colloidal surfaces via fixation reactions, P does not move easily down the rooting zone through leaching.

An immediate concern of long term practice of conservation tillage on some irrigated wheat fields in South Africa could be P deficiency in the lower soil depths. Tate (1985) also argue that P may be immobilized in the organic matter that is being built up on low P soils in the first years of conservation agriculture practice. Phosphorus management problems may therefore arise under long term conservation tillage systems , not only due to the management effect of broadcasting or row applying P fertilizer rather than incorporating it, but also due to decomposition of P-containing residues on the soil surface. Based on these arguments, there is a case for P as a likely limiting factor of irrigated wheat yield in South Africa.

Table 2.2 The benefits of nitrogen, phosphorus, potassium and manure applications on wheat yield and quality.

Reference	Objective of study	Fertility treatments	Results
Metho *et al.* (1997); Pretoria, South Africa.	To determine the effect of soil nutrient availability on wheat yield and quality, as well as the nature of genotype × soil fertility interactions.	Lime (180 kg/ha), [1]N (100 kg/ha), [2]P (70 kg/ha), [3]K (50 kg/ha) and [4]FYM (15 t/ha).	Wheat biomass, harvest index, grain yield and N content increased with combined applications of NPK and FYM, from approximately 1 t/ha for the no fertilizer control up to 6 t/ha for the NPK and FYM treatment. A significant cultivar × fertility interaction under low K conditions was observed, where by *Kariega* out yielded other cultivars.
Metho *et al.* (1998); Pretoria, South Africa.	To determine the effect of soil fertility on contribution of main stems and tillers, and first, second and third kernels in the spikelets, to yield and protein content.	Lime (180 kg/ha), N (100 kg/ha), P (70 kg/ha), K (50 kg/ha) and FYM (15 t/ha).	Main stems, first tillers, second tillers and the rest of the tillers contributed an average yield per unit area of 68.6%, 24.8%, 4.4% and 2.2% respectively. Increase in application of NPK treatment to the NPK FYM treatment increased the number of main stems, first tillers and second tillers, grain number, and hence yield and grain protein content.
Otto and Killian (2001); Bethlehem, South Africa.	To determine the effect of P applications on growth and yield of wheat.	Ten levels of P (0, 5, 10, 15, 20, 25, 30, 35, 40 and 45 kg/ha) and N (30 kg/ha)	Positive response to P application was observed during early and late tillering. Yield varied with seasons and the optimum yield were achieved with P applications of 10kg/ha and 15 kg/ha.
Ming-De *et al*. (2007); Shaanxi Province, China.	To determine the long-term effects of different fertilizer application rates on winter wheat yield.	17 levels of each N and P ranging from 0 to 180 kg/ha and 0 to 79 kg/ha respectively.	Application of N and P increased yield compared to the control. Applying combination of N and P increased the yield significantly compared to sole N or P.
Hao *et al.* (2005); Shaanxi Province, China.	To determine the effects of the long-term application of fertilizer and manure on wheat yield and soil fertility in the Loess Plateau.	FYM, NP, PFYM, NFYM, and NPFYM treatments.	Precipitation greatly affected the response of wheat yield to fertilization. The increase in soil fertility increased yield in normal years more than in drought years.
Jiang *et al*. (2006); Jiangsu, China.	To determine the effects of inorganic and organic nutrient sources on yield and yield trends of both winter wheat and maize.	8 treatments. Control, N, NP, NPK, FYM, FYMN, FYMNP, FYMNPK.	NPK treatments containing manure had highest yields, of about 7 t/ha for wheat that is 1t/ha more than NPK with no manure. Wheat showed better response to manure than maize.
Metho *et al.* (1999); Pretoria, South Africa.	To determine effects of soil fertility on grain protein yield, grain protein content, flour yield and loaf volume.	Lime (180 kg/ha), N (100 kg/ha), P (70 kg/ha), K (50 kg/ha) and FYM (15 t/ha)	There was a significant interaction between cultivar and soil fertility for all the quality parameters. Grain protein increased with increasing soil fertility, however, other parameters varied with soil fertility.

[1]N, nitrogen; [2]P, phosphorus; [3]K, potassium; [4]FYM, farm yard manure with undefined elemental composition.

2.3.3 Potassium

Potassium is responsible for the opening and closing of stomatal pores to regulate water movement in the plant, among other functions (Uchida, 2000). Therefore, adequate K would be critical for the drought tolerance of crops. Potassium is generally required in large quantities by crops, ranging from 34-224 kg K/ha for the optimum crop growth with at least 250 kg K/ha required for soils that are highly depleted in K, and 300 kg/ha for soils with high base status (Miles, 2012). The minimum K required for a wheat yield of 4 - 5 t/ha is 50 mg K/kg and this can increase to 100 mg K/kg soil for a yield target of more than 7 t/ha (ARC-SGI, 2015). Most South African soils contain sufficient amounts of K (ARC-SGI, 2015). However, concerns are raised about the availability of K in soils where high rates of nutrient removal occurs due to the use of high yielding cultivars that have been developed in the recent past (Smit *et al.*, 2010). In a study conducted a study in South Africa to determine K requirements and soil acidity management for sugarcane, it was found that K might be depleted due to continuous cropping and insufficient replenishment of this nutrient to the soil (Miles, 2012). Similar findings were noted in Kenya (Kenyanya *et al.*, 2013).

2.3.4 Secondary macronutrients

Calcium is required for the replacement of cells in a growing crop, among other important functions. It is an immobile nutrient in the plant, and deficiency symptoms starts in the younger leaves (Uchida, 2000). More than 0.2 % of Ca is required in the plant tissue at flag leaf stage to support normal growth of wheat (ARC-SGI, 2015). Magnesium (Mg) is also another secondary macronutrient required for photosynthesis and its main function is to activate some enzymes required for crop growth. Unlike Ca, Mg is a mobile nutrient and its deficiency symptoms start to show in the older leaves (Uchida, 2000). Calcium and Mg are both required for crops growth but Ca: Mg ratio is more important than the respective Ca and Mg concentrations in a soil solution. The ratio of the two nutrients on the cation exchange sites of the soil is important and it can vary as a result of the soil management system used. The acceptable ratio of Ca: Mg ranges from 1:1 to 15:1 (Brady and Weil, 2008). Lower Ca: Mg ratios will inhibit the uptake of each of these nutrients and might result in the deficiency symptoms in the growing crop. Calcium to Mg ratios can influence a wheat crops susceptibility to Al toxicity. Edmeades *et al.* (1991) investigated the effects of Ca and Mg to ameliorate Al toxicity on two wheat cultivars; Waalt (Al-tolerant) and Warigal (Al-sensitive) in Hamilton, New Zealand. Calcium and Mg improved the Al tolerance of the Al sensitive cultivar. However, only Mg ameliorated Al toxicity in the tolerant cultivar. It was concluded that Ca either had no effect, or at low Mg levels, it worsened the effects of Al-toxicity.

Last of the secondary macronutrients is S, which is required for protein synthesis and the development of nodules in the roots of legumes. Sulphur is an immobile nutrient and deficiency appears firstly in the younger leaves (Uchida, 2000). According to ARC-SGI (2015) irrigation wheat production guidelines, more than 0.4 % S is required at flag leaf stage to support good growth of wheat. Added residues or SOM that contain a lower C: S ratio will increase S content in the soil, but a high C: S will lead to immobilization of S. These factors present a case for S as a possible yield limiting factor in intensive irrigated wheat systems where there is retention of high amounts of cereal residues. Sulphur may also increase in the form of SO_4^{2-} to toxic levels via N application through enahanced mineralization of SOM (Niknahad- Gharmakher *et al.*, 2012).

2.3.5 Micronutrients

Micronutrients are important in wheat nutrition. The availability of Zn, Cu, Fe, Mn and B is positively correlated to dry matter accumulation, number of tillers and grains per spike, hence wheat grain yield (Nadim *et al.,* 2013). Zinc functions as an enzyme activator in carbohydrate metabolism and protein synthesis, and is therefore critical to both grain yield and protein content of wheat. The availability of micronutrients is highly dependent on soil acidity. According to Brady and Weil (2008), Fe and Mn are more available under acidic soil conditions, while Mo is more available under alkaline soil conditions. At low pH, Mo is adsorbed by Fe and Al oxides, as well as silicate clays (Brady and Weil, 2008). Even though they are required in small amounts, micro-nutrient deficiencies in irrigated wheat production can result in poor yield according to Liebig's law of the minimum.

Micronutrients are preferably applied as foliar sprays, or as chelates (FAO, 2008). The minimum requirements of micronutrients in the soil for optimum plant growth ranges from 2 - 11 kg/ha (Tucker, 1999) and higher concentrations may cause crop toxicities. The wheat plant tissue must at least contain 10 mg Cu or B/kg, more than 100 mg/kg of Fe and Mn and more than 70 mg Zn/kg at flag leaf growth stage in order to support plant growth (ARC-SGI, 2015). Soils in Southern Africa are generally poor in plant available Zn (<1.5 ppm), and many compound fertilizers sold in South Africa are fortified with 0.5% Zn, and at times B, S, and Mg (FSSA, 1989). Micronutrients tend to be higher under zero tillage with residue retention compared to conventional tillage (Franzluebbers and Hons, 1996).

2.3.6 Soil texture

Wheat grows well in loamy to sandy loam soils (ARC-SGI, 2015). Soil texture plays an important role in water and a lower nutrient and retention. Sandy soils consists of larger particles which have less surface area have less ability to hold water and nutrients, especially N. Clay soils consist of smaller particles with a higher surface area which improves the ability to hold water and nutrients and release it slower to meet plant's needs. Furthermore, clay soils commonly have a net negative charge which is inherited from their constituents and the negative charge contribute to high ability of nutrient retention (Brady and Weil, 2008; Jones and Jacobsen, 2005). Cation exchange capacity (CEC) is a measure of a soils ability to retain nutrients and supply them to a growing crop (Brady and Weil, 2008). It ranges from 2 - 58 meq/100 g in soils depending on soil pH and soil texture. Sandy soils usually have a lower CEC and clayey soils have higher CEC. There are possible significant variations in soil texture across and within geographical regions of South Africa where irrigated wheat is produced, due to differences in parent materials and climatic conditions. Soil texture could therefore be a cause of variation in soil fertility, as well as management requirements for ameliorating the soil fertility problems.

2.3.7 Soil acidity and electrical conductivity

Wheat grows best in soils within a pH (KCl) range between 4.5 and 6, and is highly sensitive to soil acidity and Al toxicity (ARC-SGI, 2010). As mentioned previously, the availability of nutrients vary with pH, and most of the trace elements are more available at lower a pH (<7). Iron, Mn, B, Cu and Zn are more available at a pH of 5.5 (KCl). Molybdenum is more available at pH greater than 7, while most of the macronutrients are available at pH 7 (Brady and Weil, 2008). Soil pH maintenance is a major challenge in wheat production under irrigation because pH is influenced by management factors such as fertilizer usage, crop rotation, water management and tillage practices. Production practices that increase the SOM content can also decrease the soil pH (Zeng *et al.*, 2011; Mathew *et al.*, 2012). This is because the accumulation of SOM leads to a dissociation of humic material which contains carboxylic and phenolic groups. When these groups dissociated, H^+ is released which reduces soil acidity. Caires *et al.* (2008) investigated the effects of surface-applied lime in a long-term no-tillage system on the root growth and yield of wheat. Application of lime increased wheat root length by more than 100% at the 0 – 10 cm and 10 – 20 cm depths, and wheat grain yield by more 210%. Therefore, surface applied lime can be used to ameliorate acidity problems in no-tillage wheat production systems.

Salinity refers to the accumulation of soluble salts in the soil. It affects plant growth as well as water and nutrients uptake (Hu and Schmidhalter*,* 2005). Salinity was found to reduce seedling dry matter and to delay germination of the wheat crop (Akbarimoghaddam *et al.*, 2011; Kumar *et al.*, 2012). Electrical conductivity is a measure of soluble salts which may cause salinity problems such as plant water stress and wilting that will influence crop growth. According to Horneck *et al*. (2011), an EC above 1.0 mmhos/cm (mS/cm) may result in crop growth challenges. Similarly, soil sodicity, which is the accumulation of Na^+, can have some implications on soil productivity and crop growth (Warrence *et al.,* 2002). Some irrigation soils in the semi-arid areas of South Africa are susceptible to salinity because of large salt concentrations in irrigation water, rapid evaporation and poor drainage (Perret, 2002). Permanent crop residue covers, or mulches may be helpful in alleviating salinity by reducing evaporation from the soil surface and by improving percolation rates (Bezborodov *et al.,* 2010).

2.3.8 Conservation agriculture and soil organic carbon dynamics

Reliance upon inorganic fertilizers exclusively for soil fertility improvement has led to gradual soil fertility decline and is not a sustainable approach to long term soil fertility management (Dong *et al.*, 2006; Granstedt and Kjellenberg, 1997). Conventional tillage provokes an initial rapid decline in SOC, which then stabilizes at a lower level. Lobe *et al.* (2001) studied the effects of cropping period on C and N pools in coarse-textured savanna soils of the South African Highveld, predominantly the Free State Province. Long-term cultivation (98 years) reduced soil C and N concentrations by 65 and 55%, respectively when compared to native grassland. Soil organic carbon attached to silt continued to be lost to soil erosion under continuous cropping.

Conservation agriculture (CA) is increasingly gaining acceptance across the world as an alternative production approach for sustainable management of soil fertility (FAO, 2008, Rockström *et al.,* 2010; Ward *et al.,* 2012). Conservation Agriculture is defined as a concept for resource saving, agricultural crop production that strives to achieve acceptable profits along with high and sustained production levels, while concurrently conserving the environment (FAO, 2008). The three principles of CA includes namely; 1) minimal mechanical soil disturbance and controlled traffic, 2) permanent adequate organic soil cover through the combination of green manure cover crops and retention of crop residues and 3) diversified crop rotations. The need to manage fertilizer efficiently for the success of CA has been recently proposed as a fourth principle (Vanlauwe *et al.,* 2014). There are several efforts to promote CA among irrigated wheat producers in South Africa, such as the No-Till Club of KwaZulu-Natal (Strauss and Findlay, 2014).

Conservation agriculture increases SOC through increased inputs of crop residues and reduced soil disturbance (Corbeels *et al.*, 2014). Good management of SOC increases resistance to soil erosion and water retention capacity, which is associated with sustainable long term productivity (Dlamini *et al*., 2014). It is also a sustainable strategy to restore soil health and reduce the increasing reliance upon fertilizers. Fertilizer use efficiency in wheat production systems of South Africa can be improved by adding high-quality organic matter to the soil as shown by the interactions of N, P and K fertilizers with farmyard manure (Metho *et al*., 1998), as shown in Table 2.2. High quality organic manures that have low C: N ratio and a low percentage of lignin, increase soil microbial activity, nutrient cycling and reduce nutrient losses from leaching and denitrification (Snapp, 1995).

Effective micro-organisms such as photosynthetic bacteria, yeasts, actinomycetes and fermenting fungi, are likely to be increased in soil when the SOC content of a soil is increased (Hu and Yingchun, 2013). These organisms can improve crop growth and yield by producing bio-active substances such as hormones and enzymes which can controll soil diseases and accelerate decomposition of lignin material in the soil (Van Vliet *et al.,* 2006). Ideally, irrigated wheat producers should aim to provide much of their nutrients through SOC nutrient cycling, and only use inorganic fertilizers to add limiting nutrients. However the CEC on the SOC is vulnerable and can be affected by a decrease in soil pH (Brady and Weil, 2008; Jones and Jacobsen, 2005). Kay and Angers (1999) argue that it may not be possible to attain potential yield irrespective of soil type, if the SOC content is below 1%. Fenton *et al.* (2008) also concluded that for any agricultural soil to be productive it requires between 1 and 3% SOC content. The content of SOC in wheat producing regions of South Africa, and its relationship with soil fertility needs to be understood. The extent of CA adoption for improving soil productivity in South Africa remains unclear (Andersson and D'souza, 2013).

The benefits of CA practices can be highly variable, depending on the bio-physical environment, soil and crop management systems used. Limited studies have been done to determine whether the envisaged benefits of CA practices on soil fertility can be achieved by irrigated wheat producers in South Africa. According to a review by Du Preez *et al*. (2011), soil cultivation in South Africa reduces SOC significantly, but the reduction varies with soil types, crop production systems and soil management practices. Fine textured soils tend to lose slightly less SOC in comparison with coarse textured soils due to less aggregate protection in sandy soils. The loss of SOC on cultivated fields in South Africa is also closely linked to losses of some nutrients such as N and S, but N losses are minimal when legumes are included in the rotation system (Du Preez *et al.,* 2011).

2.4 Summary and Conclusions

As recap, the objective of this literature review was to identify soil fertility constraints of irrigated wheat in South Africa and opportunities for improving soil fertility management, including information gaps in this regard. Much evidence was provided in the literature analysis to show the importance of certain fertility parameters such as N, P, K, Ca, Mg, S, Zn, SOC, salinity and acidity to irrigated wheat growth and yield in South Africa. It was also ascertained that geographical regions and various crop and resource management factors may influence these soil fertility parameters. While there is overwhelming evidence in literature suggesting that N, P, K, S, Zn, SOC, soil acidity and salinity are likely to be yield limiting factors on irrigated soils in South Africa, limited research has been carried out to quantify the extend of these problems. Dedicated scientific measurements are required in order to quantify these various parameters across irrigated wheat lands in South Africa.

3 INVESTIGATING THE AVAILABILITY OF PLANT NUTRIENTS ON IRRIGATED WHEAT FIELDS IN SOUTH AFRICA

Abstract

Increases in genetic yield potential of irrigated wheat (*Triticum aestivum* L.) in South Africa have increased nutrient demand and nutrient removal by wheat crops. Availability of plant nutrients may thus be a major factor influencing irrigated wheat yield potential. The objectives of this study were to 1) determine nutrient availability in soils obtained from irrigated wheat fields of South Africa in relation to wheat requirements and 2) determine the influence of geographical region as well as tillage and crop rotations on the nutrient availability. Soils were sampled from the 0 - 20 cm and 20 - 40 cm depths during the 2015/2016 season from fields of representative producers in the major irrigated wheat production regions of South Africa. The regions were as follows: KwaZulu-Natal, Eastern Highveld, Warmer Northern and Cooler Central area. The majority of the producers (63.85%) practised conventional tillage, and 36.15% used conservation tillage. The adoption rate of conservation agriculture, which is conservation till combined with legumes-wheat crop rotation was 88.37, 13.89, 0 and 0%, in KwaZulu-Natal, Warmer Northern, Cooler Central, and Eastern Highveld regions respectively. Soil pH, exchangeable sodium percentage (ESP) and plant available P, K, Mg and Ca varied considerably across geographical regions. Soils in KwaZulu-Natal were the most acidic (pH 4.51 ± 0.05), followed by Eastern Highveld (pH 4.97 ± 0.08), Cooler Central (pH 5.75 ± 0.09) and Warmer Northern (pH 6.32 ± 0.12). There were positive Pearson's correlations between pH and available nutrients such as P, Ca and Mg. In the Eastern Highveld and Warmer Northern regions, rotations which included legumes had slightly lower soil pH than rotations with non-legumes. Mean plant available P was below the minimum range in KwaZulu-Natal (27.49 ± 2.04 mg/kg) and the Warmer Northern (36.35 ± 3.65 mg/kg) regions. Conservation tillage systems and rotations with legumes showed more acidity and P deficiency problems than either conventional tillage or wheat-non legume rotations. Plant available Zn, Mg, K, S, Mn and N were generally adequate across all geographical regions and are likely not a potential cause of yield losses in irrigated wheat production. Electrical conductity and ESP were also acceptable across all geographical regions, which indicates that the producers are managing salinity and sodicity well. Calcium to Mg ratio was low in the Warmer Northern (1.91 ± 0.11) and was within the acceptable range of 2-8 in other regions. There was evidence of P stratification on all fields, hence P was adequate in the 0-20 cm (mean 45.57 ± 2.54 mg/kg) and deficiency at 20 – 40 cm (34.36 ± 2.28 mg/kg). The findings suggested that soil pH, Ca and P varied on the irrigated wheat farms as affected by geographical region and rotations, while plant available Zn, Mg, K and S were generally adequate and may not be a major cause of concern in terms of current causes of yield loss in irrigated wheat production.

Keywords: crop rotation; geographical regions; soil fertility; tillage; wheat yield

3.1 INTRODUCTION

Improvements in genetic yield potential as well as pest and disease resistance have greatly increased the yield potential of irrigated wheat (*Triticum aestivum* L.) in South Africa over the past decades (Smit *et al.,* 2010). As the yield potential of wheat and other crops increased, nutrient demand and removal has also risen, meaning that more nutrients are being removed than ever before with successive grain harvests. An FAO policy document on constraints to food production across the world identified high nutrient removal in irrigated crop production as a major basis of deterioration in soil fertility in developing countries (FAO, 2006).

Irrigation is an effective tool for increasing productivity of cropped fields in South Africa. Intensive crop rotation systems combining irrigated wheat in winter and summer crops whereby producers harvest eight or more crops in the course of five years are common. In order to meet the increased nutrient demands, the application rate of inorganic nitrogen (N), phosphorus (P) and potassium (K) based fertilizers have also increased. These high application rates of inorganic N and P fertilizer applications under irrigation may also affect soil properties such as soil pH, organic carbon, aeration and soil texture negatively, resulting in reduced crop yields. According to Ailincăi *et al.* (2009), soil pH (H_2O) decreased from 7.8 to 5.6 at the top 40 cm soil layer after 28 years of N and P fertilizer applications.

Soil acidity is an important parameter which controls the availability of nutrients in soils (Brady and Weil, 2008; Roosevelt, 2011; Rahman *et al*., 2012). If the soil pH is not well maintained, it can cause slow soil organic matter (SOM) decomposition, stunted root growth, poor legumes nodulation and poor plant vigour (Roosevelt, 2011). It is normally recommended that soil pH (KCl) should be kept between 5 and 6 for most crops in South Africa (DAFF, 2010). However, soil pH maintenance can be a challenge because it can be influenced management factors such as fertilizer usage, crop rotation, water management and tillage practices (Brady and Weil, 2008). Irrigation water also contain various types of salts and water losses by evapotranspiration inevitably causes an increase in concentration of the salts in the root zone.

Salinity and sodicity, which refer to the excessive concentration of soluble salts and sodium (Na) respectively. These problems can occur on irrigation soils depending on the quality of irrigation water, method of irrigation and adequacy of drainage (Warrence *et al*., 2002). Nutritionally, salinity affects crops by increasing the concentration of toxic ions such as chloride, sodium, bicarbonate, sulphate and boron. Saline soils with a high Mg: Ca ratio may cause Ca deficiency in plants (Brady and Weil, 2008). High concentration of sulphate decrease Ca uptake, while promoting Na uptake and can cause Na toxicity. The removal of excess salts by leaching is essential under irrigation, but the leaching process indiscriminately removes other essential nutrients from the soil. Water logging and salinity have been previously reported as major irrigation problems in South Africa. In Vaal harts irrigation scheme in the Northern Cape (35 000 ha), 13 - 18% of the irrigation area was affected by water logging and salinization (Ojo *et al.,* 2012).

The aforementioned factors – increased nutrient demand of the crop, nutrient removal in grain and the negative effects of long term inorganic N and P applications point to the need to pay close attention to plant nutrient supply as a probable, major limiting factor of irrigated wheat yield in the present and future. In search of agronomic strategies for increasing producer yields and profitability in the country, it would be essential to determine the nutrient availability status of irrigated wheat fields as well as the agronomic management factors that influence nutrient availability.

Nutrient availability is suspected to be a major limiting factor to irrigated wheat yield potential in the major irrigated wheat regions of South Africa. It is also not clear how agronomic practices such as tillage and crop rotation influence the nutrient availability. This information is required by researchers and policy makers to identify sustainable solutions for improving wheat yields in the the country. The objectives of this study were to determine (a) the nutrient availability in soils obtained from irrigated wheat fields in South Africa and (b) the influence of geographical regions, tillage and crop rotation on the nutrient availability.

3.2 MATERIALS AND METHODS

3.2.1 Description of study sites

Most of irrigated winter wheat production in South Africa is practiced in the summer rainfall area along river banks, basins and on commercial irrigation schemes. The study was carried out in the major irrigated wheat production regions of South Africa which are the Cooler Central, Warmer Northern, Eastern Highveld and KwaZulu-Natal. Wheat producers in each geographic region have broadly similar resource bases, enterprise patterns and constraints.

3.2.1.1 The Cooler Central Region

The Cooler Central region is located on the North eastern parts of the Northern Cape Province (Plate 2.1). The Northern Cape Province has a large network of rivers and dams, including the 'mighty' Orange River that feed canals on many commercial irrigation schemes in the province. It consist of shallow sandy soils with minimal development and lime is generally present in most parts of the landscape (FAO, 2005). The climate is arid to semi-arid, with average temperatures ranging between 15°C and 31°C, and a highly variable rainfall between 200 mm and 715 mm per annum (Table 3.1).

Table 3.1 General soil and climatic characteristics of the major irrigated wheat production regions of South Africa

	Geographical region			
	Cooler Central	**Warmer Northern**	**KwaZulu-Natal**	**Eastern Highveld**
[1]Major parent materials	Sandstone	Dolerite	Dolerite	Sandstone
[2]Average annual temperature (°C)	15-31	18-32	15-32	14-26
Soil texture	sandy	Sandy clay loam	Sandy clay loam	sandy
Soil depth	shallow	deep	deep	shallow
Average annual rainfall (mm)	200-715	200-600	600-1000	200-500
Climate type	Semi-arid	Semi-arid	Sub-humid	Semi-arid

[1] Fey (2010)

[2] Based on long term data (30 year mean) from ARC-ISCW (2013)

3.2.1.2 The Warmer Northern Region

The Warmer Northern region mostly covers the North West, Limpopo and Gauteng Provinces. It consist of strongly structured deep reddish sandy clay loam soils (FAO, 2005). The climate is arid to semi-arid, with average temperatures ranging between 18°C and 32°C and a highly variable rainfall between 200 mm and 600 mm per annum (Table 3.1).

3.2.1.3 The Eastern Highveld Region

The Eastern Highveld irrigation region is found along the boundaries of the Free State and Mpumalanga provinces. This region has a semi-arid and cooler climate, with mean monthly temperatures ranging from 14°C to 26°C and an average annual rainfall of 200 mm to 500 mm. The soils consist of red, yellow and/ greyish loamy sand soils of mostly plinthic nature with low to medium base status (Hensley *et al.,* 2006).

3.2.1.4 KwaZulu–Natal Region

In KwaZulu-Natal, irrigated wheat is mostly grown at high altitudes around Bergville and Winterton. These areas generally consist of deep red to yellow well drained sandy clay loam soils, with a low to medium base status. The soils are generally acidic with low pH between 5.5 and 6.4 (FAO, 2005). The climate is sub-humid with an average temperature ranging from 15°C to 32 °C and an average rainfall of 600 mm to 1000 mm per annum (DAFF, 2010).

3.2.2 Selection of irrigated wheat farms

The fields of producers who planted irrigated wheat during the 2015 season were used for this study. Representative producers for each of the wheat production regions were identified in collaboration with the National Wheat Cultivar Evaluation Program of ARC-Small Grain Institute. The geographic regions were further sub-divided into localities of interest where most irrigated wheat producers were concentrated. Producers were contacted and only those who gave permission for sampling on their wheat fields were considered in this study. A limitation of the purposive sampling procedure used in this study is that it excluded the fields of those irrigated wheat producers who were not willing to have their fields sampled for a variety of reasons. It also excluded the fields of wheat producers who did not plant irrigated wheat during the 2015/16 season. However, the results from this study may also be indicative of the soil fertility status in the fields of these producers, as long as the soils are from the same parent materials and are managed the same way. The smallholder irrigation producer sector in South Africa is virtually non-existent. Therefore, all samples were taken from commercial producers with centre pivot irrigation systems. The details of irrigated wheat fields from each geographic region that were used for the study are shown in Table 3.2.

3.2.3 Tillage and crop rotation systems

The producers who participated in this study were unwilling to reveal their management information and business plans with regard to tillage practices and crop rotations because of confidentiality reasons. The different tillage systems were therefore identified through observation on the fields. Conventional tillage is defined ploughing prior to planting (Lou *et al.,* 2012) while conservation tillage is characterized by minimum soil disturbance, which protects soil against degradation thus improving soil sustainability (Melero *et al.,* 2009), or zero tillage and retention of crop residues all year round (Neto *et al.,* 2010). Within the context of the current study, conservation tillage fields were identified as those fields where wheat was either planted directly into the previous crop's residues with no soil disturbance, or where there were signs of slight soil disturbance and about 30% of crop residues on the soil surface. Conventional tillage fields were those with signs of complete turning of soil and less than 30%, or no residues on the soil surface. The residues of the crops which preceded wheat were used to identify the crop rotation system as either legume or non-legume.

Table 3.2 The farms surveyed within locations of the major irrigated wheat production regions of South Africa

Irrigated wheat production regions	Locations	[†]GPS Coordinates of central point in location	Number of farms surveyed (*n*)
Cooler Central	Hartswater	S27°50.175' E24°50.258'	7
	Riet rivier	S29°07.672' E24°36.257'	12
	Broadwater	S28°58.388' E23°59.573'	3
	Magogong	S27°39.212' E24°46.350'	3
Warmer Northern	Lydenburg	S24°58.612' E30°29.918'	6
	Ohrigstad	S24°47.155' E30°32.509'	4
	Burgersfort	S24°47.869' E30°21.373'	7
	Naboomspruit	S24°25.606' E28°34.573'	3
	Tuinplaas	S24°48.507' E28°47.464'	1
	Marble Hall	S25°59.813' E29°21.181'	5
	Groblersdal	S25°18.233' E29°24.583'	6
	Zeerust	S25°25.167' E26°22.072'	2
	Brits	S25°35.107' E27°42.619'	2
Eastern Highveld	Bethlehem	S28°01.441 E28°18.265'	4
	Clarens	S28°27.014' E28°22.295	3
	Rietz	S27°58.903' E28°18.862'	4
	Frankford	S27°16.700' E28°33.431'	4
	Villiers	S26°57.557' E28°46.886'	8
	Harrismith	S28°'13.211' E29°04.591'	3
KwaZulu-Natal	Bergville	S28°46.780' E29°21.953'	28
	Winterton	S28°51.561' E29°33.045'	15

[†]Global Positioning System

3.2.4 Soil sampling and analysis

Soils samples were collected after clearing the litter layer, from the 0 - 20 cm and 20 - 40 cm depths, usinga a graduated dutch auger. A simple random sampling procedure was also used. Soil sampling was carried out from May to September 2015 after emergence of the wheat crops to ensure clear identification of the wheat fields (Plate 3.1). The GPS co-ordinates of the representative location of the fields sampled were recorded (Table 3.2). At least 10 random samples were collected from each of the fields and bulked to form a composite sample. The samples were air dried (visible organic debris removed), ground (< 2 mm) and analysed at the ARC-SGI soil labolatory. The samples were analysed for the following: soil pH, exchangeable acidity, electrical conductivity, cation exchange capacity, exchangeable bases (Mg, K, Ca and Na), available P and zinc (Zn). The soil analyses were done according to the Standard Methods of the Non-Affiliated Soil Analysis Working Committee (1990). Details of each method are presented in (Table 3.3). For N deficiency symptoms, wheat was scored at the flag leaf stage (Plate 3.2) using a guide for field identification (Snowball and Robson, 1991). The level of deficiency was scored from one to five. A score of five indicated adequate nutrition, whereby a score of one indicated a very severe deficiency.

Table 3.3 Soil analysis methods used in the study according to the Non-Affiliated Soil Analysis Working Committee (1990).

Soil Parameter	Extraction Method/solution	Analysing Instrument
P (mg/kg)	Bray 1	AA3 Seal Auto Analyser
Exchangeable Mg, Na, K, Ca and S (mg/kg)	Ammonium acetate solution	Perkin Elmar Optima 5300 ICP-OES
Zn (mg/kg)	HCl	Perkin Elmar Optima 5300 ICP-OES
Electrical conductivity (mS/cm)	1:1 soil water solution	Jenway 4520 Conductivity meter
Cation exchange capacity (meq/100g)	-	[∞]Calculated from the concentration of exchangeable bases
pH	1:5 KCl (1M) suspension	Labcon pH meter.
Exchangeable acidity (meq/100g)	titrating the soil extract containing 1 M KCl with 0.01 M NaOH	titration
Acid saturation (%)	-	[∞]Calculated from the ratio of H^+ and Al^{3+} in solution against soil exchangeable bases

[∞]Details of the calculation are provided in Appendix 1

Plate 3.1 Soil sampling from a conservation tillage irrigated wheat field in Winterton, KwaZulu-Natal.

Plate 3.2 Visual assessment of irrigated wheat for nitrogen deficiency symptoms at the flag leaf stage.

3.2.5 Data Analysis

The number of sites that were sampled for the study varied across geographic regions (Table 3.2). The resulting soil fertility data was unbalanced, with some fixed (geographic regions, crop rotations, tillage systems, soil depth) and random (locations) effects. For this type of unbalanced data, a mixed model, the residual (or restricted) maximum likelihood (REML) algorithm can be used to reliably estimate means and test the significance of the fixed effects and interactions (Virk *et al.,* 2009). REML has a powerful prediction algorithm which is designed to analyse linear mixed models that contain multiple fixed and random effects (Payne *et al.,* 2013). The mixed model for the soil fertility parameter (y_{ijklm}) in the m^{th} location, l^{th} soil depth, k^{th} crop rotation system, j^{th} tillage system and i^{th} geographical region was as follows:

$$y_{\mathrm{ijklm}} = \mu + \mathrm{G_i} + \mathrm{T_j} + \mathrm{R_k} + \mathrm{D_l} + + \mathrm{G_iR_k} + + \mathrm{G_iD_l} + \mathrm{T_jD_l} + \mathrm{R_kD_l} + \mathrm{A_m} + \mathrm{S_n} + \varepsilon_{\mathrm{ijklmn}}$$

Where the fixed effects were:

μ = the grand mean
G = the main effect of geographic region
T = the main effect of tillage system
R = the main effect of crop rotation
D = the main effect of soil depth
GR = the interaction of geographic region and crop rotation system
GD = the interaction of geographic region and soil depth
TD = the interaction of tillage system and soil depth
RD = the interaction of crop rotation and soil depth

The random effects were:

A = the random effect of location

ε = Error

The REML was performed using GenStat® 17 statistical software, and restricted to second order interactions only on the main effects. Tillage practice interactions with crop rotation and geographical region were not considered in the analysis because not all tillage systems were represented in either crop rotations or geographical regions (Table 3.3). The nutrient availability results were also compared with the known nutrient requirements of wheat for optimal growth and yield (Table 3.4). Pearson's correlation coefficient (*r)* was used to determine the significance of the relationship between various nutrient parameters and pH. A two sided *t* - test was used to test the significance of the difference between *r* and 0. Nitrogen deficiency scores were also subjected to REML analysis.

Table 3.4 Soil nutrient requirements for optimal growth and yield of wheat

Nutrient parameter	Soil test	Nutrient requirement	References
Phosphorus	Bray 1	40 – 100 mg/kg	Horneck *et al.* (2011)
pH (KCl)	KCl	4.5 – 5.5	ARC-SGI (2015)
Potassium	Ammonium acetate	125 - 800 mg/kg	Horneck *et al.* (2011)
Sulphur	-	>7.5 mg/kg	Beaton and Soper (1986)
Nitrogen	Soil test nitrate (0 – 60 cm)	50-75 mg/kg	Horneck *et al.* (2011)
Calcium		>150 mg/kg	Rehm (1994)
Magnesium		60 – 300 mg/kg	Horneck *et al.* (2011)
Zinc	DTPA extraction	>1.5 mg/kg	Horneck *et al.* (2011)
ESP – exchangeable sodium percentage	Percent of the CEC occupied by Na	<10%	Horneck *et al.* (2011)
Soluble salts (Electrical conductivity)	Saturated paste soil extract	<1.0 mmhos/cm (<640 mg/kg salts)	Horneck *et al.* (2011)
Ca:Mg ratio		§2 - 15	Schulte and Kelling (1995)
Acid saturation (%)	-	<8%	ARC-SGI (2015)
Cation exchange capacity (meq/100g)	Calculated from exchangeable bases	2-58	Brady and Weil (2008)

§A Ca: Mg ratio of 1:1 is considered as acceptable in some systems

3.3 RESULTS

3.3.1 Tillage and crop rotation practices of the producers in different regions

The majority of irrigated wheat producers who participated in the study practised conventional tillage (63.85%), with 36.15% using conservation tillage. Most of the producers in KwaZulu-Natal region (88.37%) practiced some form of conservation agriculture (CA); that is conservation till combined with a legumes-wheat crop rotation system, assuming the wheat also serves as a winter cover crop for permanent cover (Table 3.5). In Warmer Northern region, only 13.89% of the farms sampled practiced conservation tillage with legume-wheat crop rotation. In the Eastern Highveld and Cooler Central regions, all the farms (100%) practiced conventional tillage. There were more farms practicing a non-legume- wheat rotation than farms practicing a legumes-wheat rotation in the Cooler Central and Warmer Northern regions (Table 3.5). The adoption rate of CA across irrigated wheat farms in KwaZulu-Natal, Warmer Northern, Cooler Central, and Eastern Highveld regions was 88.37, 13.89, 0 and 0%, respectively. The overall adoption rate of CA was 33.08%.

3.3.2 Summary statistics for nutrient availability

Summary statistics for various nutrient availability parameters of irrigated wheat fields in South Africa are presented in Table 3.6. There was considerable variation in all the parameters measured as shown by the high coefficients of variation and corresponding large difference between minimum and maximum values, outside the optimal range for wheat growth. An exception was sodicity and salinity, as all sampled farms had acceptable ESP values (< 10) and EC values < 1 mmhos/cm (or mS/cm) (Table 3.6).

Table 3.5 Tillage and crop rotation practices of the producers who participated in the study

Geographic region	Tillage system	[1]Crop rotation system	Rotation crops	Number of farms (n)
KwaZulu-Natal	Conventional tillage	Non-legume-wheat	-	-
		Legume -wheat	Soyabean	†01
	Conservation tillage	Non-legume-wheat	Maize	04
		Legume -wheat	Soyabean	38
Cooler Central	Conventional tillage	Non-legume-wheat	Maize, oats, cotton	21
		Legume -wheat	Groundnut, soyabean	04
	Conservation tillage	Non-legume-wheat	-	†0
		Legume -wheat	-	†0
Warmer Northern	Conventional tillage	Non-legume-wheat	Tobacco, maize	16
		Legume -wheat	Sugarbean, soyabean	15
	Conservation tillage	Non-legume-wheat	-	†0
		Legume -wheat	Soyabeans	05
Eastern Highveld	Conventional tillage	Non-legume-wheat	Maize, potatoes	12
		Legume -wheat	Soyabean, whitebean	14
	Conservation tillage	Non-legume-wheat	-	†0
		Legume -wheat	-	†0

[1] Based on the identification of the previous crop's residues

† Not included in the REML analysis for estimating factor effects and means because of small sample size

Table 3.6 Summary statistics of soil chemical properties on irrigated wheat fields in South Africa

Parameter	**Mean**	**Minimum**	**Median**	**Maximum**	**Standard deviation**	**Coefficient of variation**
pH (KCl)	5.33	3.81	5.08	7.51	1.01	19.01
Acid saturation (%)	3.23	0.00	0.00	54.07	6.71	207.90
Magnesium (mg/kg)	301.80	14.04	172.60	2332.00	326.20	108.10
Potassium (mg/kg)	197.20	36.80	164.20	602.90	115.70	58.69
Phosphorus (mg/kg)	39.96	3.47	34.87	128.70	27.90	69.81
Calcium (mg/kg)	1056.00	64.80	235.9	11770.00	1329.00	125.80
Sulphur (mg/kg)	24.21	0.76	18.01	122.10	21.44	88.59
Zinc (mg/kg)	4.77	0.03	2.84	127.60	8.55	179.50
Electrical conductivity (mmhos/cm)	0.28	0.08	0.23	0.91	0.16	56.97
[1]ESP	1.78	0.19	1.06	9.14	1.69	95.03
Ca: Mg	2.47	0.85	2.44	5.56	0.86	34.78
CEC (meq/100g)	8.56	1.20	5.84	73.62	9.22	107.80

[1] Exchangeable sodium percentage

3.3.3 The effect of geographical region on plant available nutrients

Soil pH, EA, AS, EC, plant available P, K, Mg, Ca, Zn, ESP, Ca: Mg ratio and CEC varied significantly ($p<0.001$) with different geographic regions as shown in Table 3.7. The means for these various parameters in different geographic regions are presented in Table 3.8. When compared to the requirements for optimum growth of wheat, plant available Zn, Ca and K were generally adequate and EC, CEC and ESP were also within the acceptable range across all geographical regions (Table 3.8).

Table 3.7 Significance of the fixed effects tested by chi-squared F- statistic (Wald statistic/d.f) values in the overall REML analysis for plant available Zn, S, P, Mg, K and EC, CEC, pH as well as Ca: Mg of irrigated wheat fields in South Africa

		F pr. for various nutrient availability parameters											
Source of variation	**d.f**	**Zn**	**S**	**P**	**AS**	**Mg**	**K**	**EC**	**Ca**	**Ca: Mg**	**CEC**	**ESP**	**pH**
Geographical regijon	3	<0.001	0.135	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Tillage	1	0.320	0.016	<0.001	0.503	0.672	0.644	0.141	0.270	0.168	0.329	<0.001	<0.001
Crop rotation	1	0.668	0.209	<0.001	0.076	0.846	0.109	0.534	0.426	0.375	0.591	0.405	<0.001
Soil depth	1	0.063	0.487	<0.001	0.446	0.753	0.005	0.234	0.883	0.141	0.928	0.325	0.910
[1]Geographical region × Tillage	3	-	-	-	-	-	-	-	-	-	-	-	-
Geographical region × Crop rotation	3	0.150	<0.001	0.283	0.229	0.839	0.491	0.958	0.291	0.383	0.369	<0.001	0.009
[1]Tillage × Crop rotation	3	-	-	-	-	-	-	-	-	-	-	-	-
Geographical Region × Soil depth	3	0.262	0.830	0.493	0.772	0.994	0.952	<0.001	0.998	0.352	0.998	0.899	0.699
Tillage × Soil depth	1	0.549	0.731	0.696	0.923	0.902	0.913	0.018	0.972	0.941	0.938	0.990	0.890
Crop rotation × Soil depth	1	0.214	0.554	0.939	0.561	0.940	0.868	0.217	0.900	0.871	0.888	0.803	0.849

[1] Tillage interactions with crop rotation and geographical region were not considered in the analysis because not all tillage systems were represented in either crop rotations or geographical regions.

Table 3.8 The effect of geographical region on soil chemical properties

				mg/kg							
Geographical region	**pH**	**[1]AS**	**EC**	**Zn**	**P**	**Ca**	**Mg**	**K**	**Ca: Mg**	**ESP**	**CEC**
KwaZulu Natal	4.51^{d}	6.50^{a}	0.18^{c}	2.26^{c}	27.49^{d}	829.80^{d}	186.30^{c}	167.30^{c}	2.90^{a}	0.74^{d}	6.49^{b}
Eastern Highveld	4.97^{c}	4.62^{b}	0.35^{a}	2.68^{c}	56.08^{a}	586.60^{c}	139.90^{d}	198.90^{b}	2.83^{a}	2.22^{b}	4.85^{d}
Warmer Northern	6.32^{a}	0.31^{c}	0.34^{a}	8.83^{a}	36.65^{c}	1961.0^{a}	634.30^{a}	262.30^{a}	1.91^{c}	1.86^{c}	15.97^{a}
Cooler Central	5.75^{b}	0.23^{c}	0.31^{b}	5.56^{b}	49.30^{b}	668.60^{b}	203.10^{b}	155.80^{d}	2.13^{b}	2.98^{a}	5.59^{c}
P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
s.e.d	0.09	0.61	0.02	0.71	3.25	39.95	24.57	12.46	0.09	0.19	0.70

[1] AS, acid saturation

For P, the Eastern Highveld (56.08 ± 4.53 mg/kg) and Cooler Central (49.30 ± 2.77 mg/kg) egions had adequate amounts, but Warmer Northern (36.65 ± 3.65 mg/kg) and KwaZulu-Natal (27.49 ± 2.04 mg/kg) showed deficiency problems (Table 3.8). Calcium to Mg ratio was low in the Warmer Northern (1.91 ± 0.11), but was within the acceptable range of 2 - 8 in the other regions (Table 8). Fields of the Warmer Northern region had significantly more K (262.30 ± 18.85 mg/kg), Zn (8.83 ± 1.81), a higher CEC (15.97 ± 1.98) and Ca (1961.00 ± 270.00) than Eastern Highveld, KwaZulu-Natal and Cooler Centralregions (Table 3.8).

Mean soil pH in all the geographical regions was in the acidic range, and outside the acceptable range of 6.5 – 7, with KwaZulu-Natal being the most acidic (pH 4.51 ± 0.05), followed by Eastern Highveld (pH 4.97 ± 0.08), Cooler Central (pH 5.75 ± 0.09) and Warmer Northern (pH 6.32 ± 0.12).

3.3.4 The effect of tillage on plant available nutrients

Soil pH, exchangeable acidity, plant available P, S and ESP varied significantly with tillage as shown in Table 3.7. Means for tillage are presented in Table 3.9. Conservation tillage had lower pH, available P and S and higher EA than conventional tillage. Conventional tillage had adequate P (48.48 ± 2.27 mg/kg), when compared to conservation till (25.58 ± 1.92 mg/kg). There was more Na in conventional tillage (45.77 ± 4.21) compared to conservation tillage (10.87 ± 0.80). Conservation tillage (0.71 ± 0.05) had lower ESP compared to conventional tillage (2.41 ± 0.14), but the ESP of both systems were within acceptable range. Conservation tillage (21.27 ± 1.37) had lower S compared to conventional tillage (25.95 ± 1.96) as shown in (Table 3.9). However, S was genereally adequate across all tillage systems when considering the optimum S requirments for irrigated wheat.

Table 3.9 The effect of tillage on various nutrient availability parameters in irrigated wheat production systems of South Africa

Tillage practice	**pH**	**P (mg/kg)**	**S (mg/kg)**	**ESP (%)**
Conservation tillage	4.51^a	25.58^a	21.27^a	0.71^a
Conventional tillage	5.82^b	48.48^b	25.95^b	2.41^b
P value	<0.001	<0.001	<0.05	<0.001
Average s.e.d	0.06	2.10	1.67	0.10

3.3.5 The effect of crop rotation on plant available nutrients

Crop rotation had a significant ($p<0.001$) effect on soil pH and P availability (Table 3.7). Rotation systems where wheat was preceded by non-legumes had acceptable plant available P (52.20 ± 3.01 mg/kg) and relatively higher soil pH (5.9) than those where wheat was preceded by legumes-wheat rotations, which had low P (31.70 ± 1.81 mg/kg) and a more acidic (4.95) pH (Table 3.10).

Table 3.10 The effect of crop rotation on soil pH and plant available phosphorus in irrigated wheat production systems of South Africa

Crop rotation system	pH	Phosphorus (mg/kg)
Legumes	4.95^a	31.70^a
Non-legumes	5.90^b	52.20^b
P value	<0.001	<0.001
s.e.d	0.08	2.41

3.3.6 The effect of soil depth on plant nutrients availability

There was significantly (Table 3.7) more plant available P (45.57 ± 2.54 mg/kg) and K (216.30 ±10.55) at the 0-20 cm depth compared to the 20-40 cm depth which had 34.36 ± 2.28 mg/kg P and 178.10 ± 9.56 mg/kg K (Table 3.11).

Table 3.11 The effect of soil depth on potassium and phosphorus in irrigated wheat production systems of South Africa

Soil depth	Potassium (mg/kg)	Phosphorus (mg/kg)
0-20 cm	216.30	45.57
20-40 cm	178.10	34.36
P value	<0.05	<0.001
Average s.e.d.	10.06	2.41

3.3.7 The interaction effect of geographical region, tillage, crop rotation and soil depth on plant available nutrients

The interaction effects of geographical region × soil depth, geographical region × crop rotation, tillage × soil depth and crop rotation × soil depth on plant available P, K, Zn, Mg, Ca, CEC and Ca: Mg ratio were not significant ($p>0.05$) (Table 3.7). The geographical region × crop rotation interaction effect on ESP, S and soil pH was significant ($p<0.001$) (Table 3.7). The nature of the interactions are shown in Figures 3.1 and 3.2. There was more ESP under a non-legume-wheat crop rotation in the Eastern Highveld region, but no significant differences in ESP across the different crop rotation systems in KwaZulu-Natal, Warmer Northern and Cooler Central regions (Figure 3.1). There was more plant available S under non-legume-wheat crop rotation in the Eastern Highveld region, but the opposite was true for the Warmer Northern region. Sulphur levels were similar across all rotation types in KwaZulu-Natal and the Cooler Central regions (Figure 3.2). The Eastern Highveld and Warmer Northern regions had slightly lower soil pH for rotations where wheat was preceded by a legume unlike when wheat was preceded by a non-legume (Figure 3.3). For KwaZulu-Natal and Cooler Central regions, the rotations had similar pH results.

The geographical region × soil depth and tillage practice × soil depth had a significant influence on EC (Table 3.7). The interaction shows that EC results of the 20-40 cm layer in the Warmer Northern region was higher in comparison with the EC results of the Cooler Central region where the 0 - 20 cm layer was higher. In KwaZulu-Natal and Eastern Highveld regions, EC was similar in both layers (Figure 3.4). The tillage practice × soil depth interaction effect on EC shows that for conventional tillage, EC was higher in the 20

- 40 cm depth than the 0 - 20 cm depth. However for conservation tillage, the EC was similar for both depths (Figure 3.5).

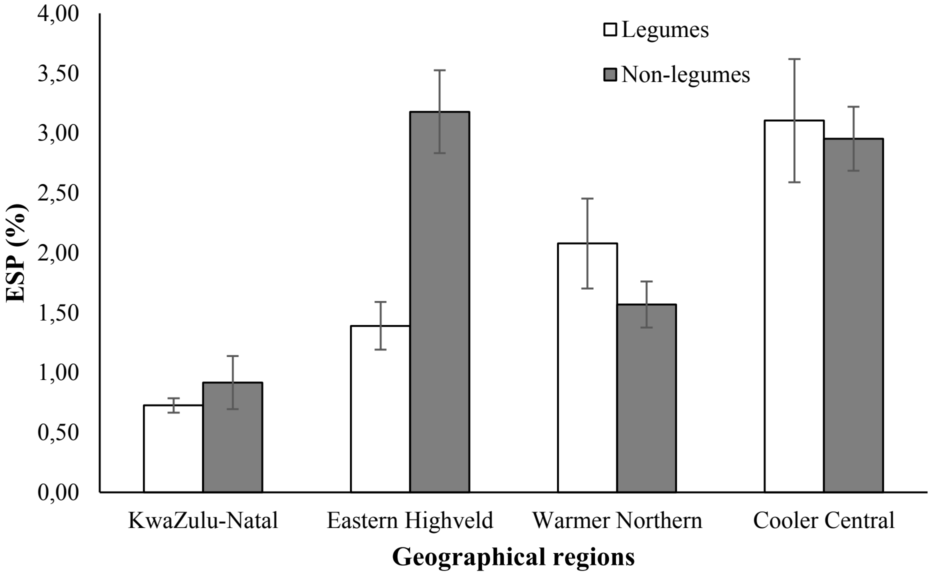

Figure 3.1 Geographical region × crop rotation effects on exchangeable sodium percentage (ESP). Means are separated by standard errors.

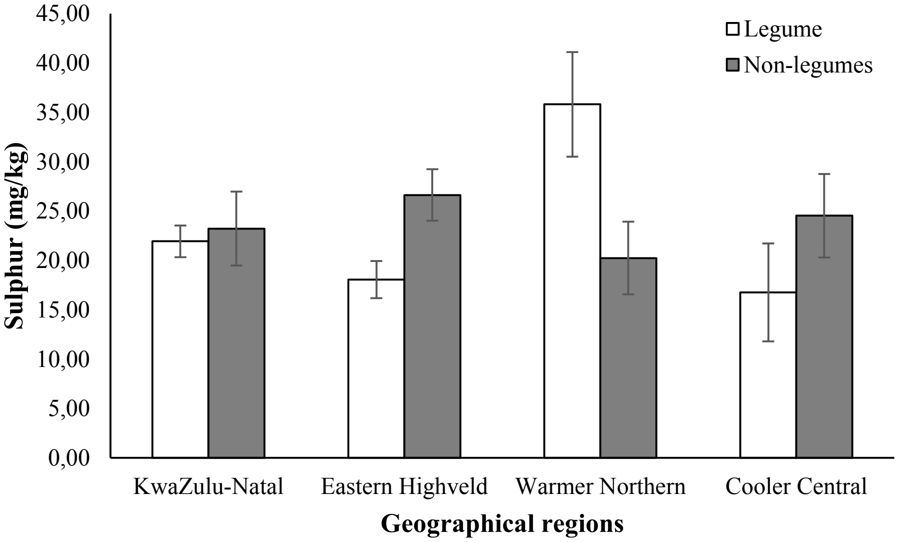

Figure 3.2 Crop rotation × geographical region effect on plant available sulphur content of irrigated wheat fields in South Africa. Means are separated by standard errors.

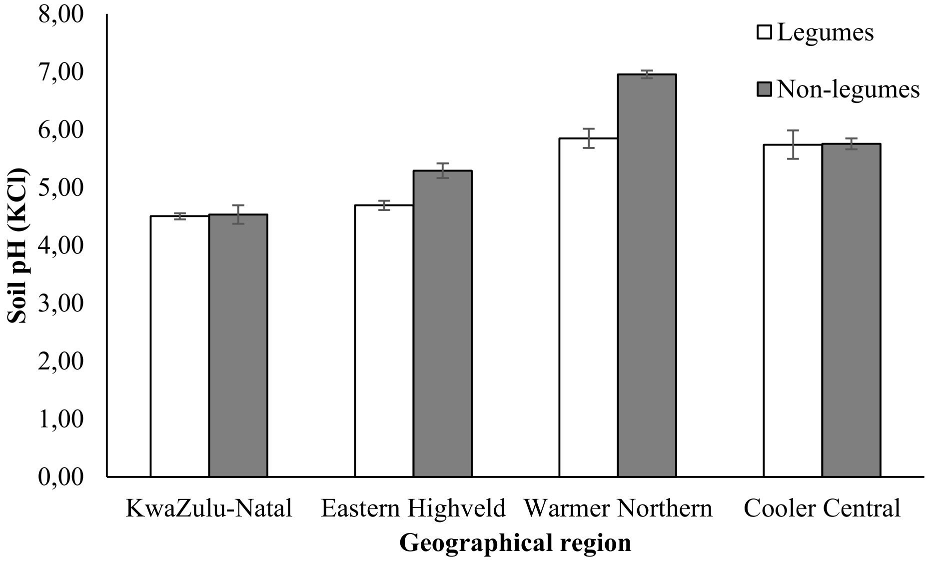

Figure 3.3 Crop rotation × geographical region effect on soil pH (KCl) of irrigated wheat fields in South Africa. Means are separated by standard errors.

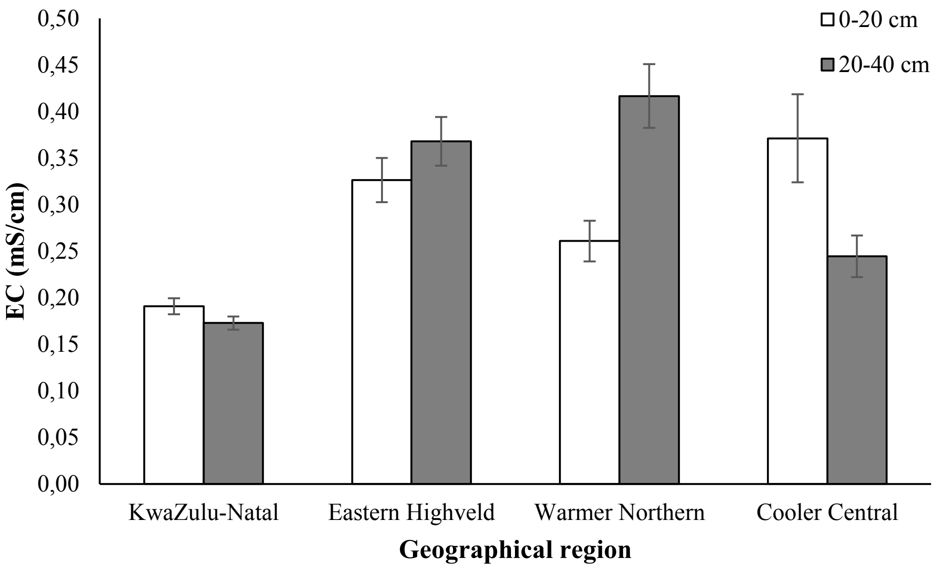

Figure 3.4 Soil depth × geographical region effect on electrical conductivity (EC) of irrigated wheat fields in South Africa. Means are separated by standard errors.

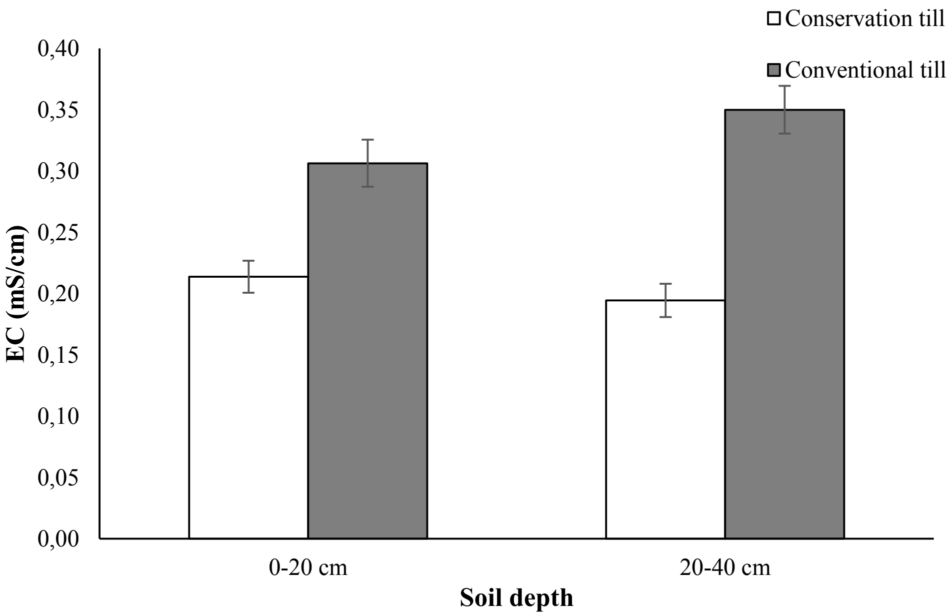

Figure 3.5 Tillage × soil depth effect on electrical conductivity (EC) of irrigated wheat fields in South Africa. Means are separated by standard errors.

3.3.8 Nitrogen deficiency scores

The N deficiency scores at flag leaf stage show that there was generally adequate N nutrition in all geographical regions (4.66/5). The mean score for KwaZulu-Natal was (4.56/5), Eastern Highveld (4.62/5), Warmer Northern (4.77/5) amd Cooler Central (4.64/5). There was no significant difference in the mean scores ($p>0.05$).

3.3.9 Relationships between nutrient availability and soil pH

There were generally significant positive relationships between pH and nutrient availability (Table 3.12). Strong relationships in particular were obtained for pH with Mg, ESP, CEC and Ca (Table 3.12).

Table 3.12 Pearson's correlation matrix for pH (KCl) and various nutrient availability parameters in irrigated wheat fields

	Pearson's *r*	**Level of significance**
CEC	0.4064	<0.001
AS	-0.5413	<0.001
Ca: Mg ratio	-0.3671	<0.001
EA	-0.684	<0.001
EC	0.1453	0.0195
K	0.3066	<0.001
Mg	0.5027	<0.001
ESP	0.5088	<0.001
P	0.1979	0.0014
S	0.2151	<0.001
Zn	0.2664	<0.001
Ca	0.3586	<0.001

3.4 DISCUSSION

The high adoption rate of conservation tillage, or some form of CA amongst irrigated wheat producers in KwaZulu-Natal (Table 3.5) is remarkable, considering that there was very low adoption of the technology elsewhere in other regions. This success can be explained in several ways. Firstly, the No Till Club of KwaZulu-Natal (http://notillclub.com), formed more than 15 years ago, may have played a huge role in the promotion of CA adoption in this region. The mission of the KwaZulu-Natal No-Till Club is "*to actively promote and facilitate environmentally friendly, economically sustainable conservation production, for the benefit of all*". At the moment, about 130 commercial producers from KwaZulu-Natal are members of the No-Till Club, and the club provides a no-till training course to these producers and any other interested parties (Strauss and Findlay, 2014). The No-Till Club also runs long term field experiments for solving some of the challenges experienced by CA producers in KwaZulu-Natal, such as the five-year trial on soil-borne diseases on Anthony Muirhead's farm in the Winterton district (Knot *et al*., 2014; Strauss and Findlay, 2014).

Another reason for wide scale adoption of CA in KwaZulu-Natal could be the fact that the heavy soils of KwaZulu-Natal generally require heavier machinery and more fuel for tillage, and CA was an obvious attraction for reducing production costs to the KwaZulu-Natal famers. They also compact easily when worked under wet conditions, such as irrigation. The KwaZulu-Natal region is also warmer, such that producers have many options for increasing biomass to obtain the benefits of CA. In the Warmer Northern and Eastern Highveld production areas where rainfall is lower, soil erosion is gradual (mainly sheet erosion) with little immediate, but rather long term impacts on soil fertility. The need to protect the land from soil erosion may therefore not be adequate to motivate producers to adopt conservation tillage there, given its other challenges.

There are many well documented challenges associated with conservation tillage under intensive irrigation such as build-up of inoculum of plant diseases in the soil, compaction, nutrient stratification and slow decomposition of crop residues, especially in the Cooler irrigation areas. The slow decomposition of the preceding summer crop’s residues presents serious planting and crop emergence challenges, especially if the producers do not have the right planting equipment. Many producers resort to the plough to solve the problems. Therefore, inability to demonstrate clear yield and economic advantage may have been the reason behind poor and slow adoption of conservation tillage amongst irrigated wheat producers in the other geographical regions. There is also no record of organizations or groups that actively promote CA in the other regions. According to Dumanski *et al.* (2006), successful CA is achieved through community driven development processes whereby local researchers, communities and producer associations identify and promote the best options for CA in their locations.

In the current study, the mean soil acidity for more than 50% of the producers (Table 3.6) was found to be below the recommended range of 6.5 – 7.5 for optimal wheat growth in all the geographical regions. Therefore soil acidity could be a major concern in the fertility of irrigated wheat fields in South Africa. The significant variation of soil acidity across geographical regions could be explained by the variation in climatic conditions. For example, KwaZulu-Natal region has relatively higher rainfall and temperatures, hence highly weathered soils with high acidity (Fey, 2010). Most of the exchangeable bases are leached by the high rainfall, this was found in a study of forest soils in Pennsylvania (Bailey *et al*., 2005). Soil pH was also influenced by the interaction of geographical region and crop rotation, where by the Warmer Northern and Eastern Highveld regions had lower soil pH on the legume-wheat crop rotations in comparison to a non-legumes-wheat crop rotations. The decrease in soil pH following legumes crop rotation can be attributed to more rapid degradation of legume residues due to favorable C: N ratio and the associated nitrification which has an acidifying (Roosevelt, 2011). During N fixation, ammonium is released and it reduces soil acidity because of its positive charge. However, it is not exactly clear why this effect was evident in some geographical regions and not in others, hence this issue requires further investigation. The importance of pH on nutrient availability is highlighted by the significant positive relationships between pH and important plant nutrients such as Mg, K, Ca, K and Zn (Table 3.12).

The decrease in soil pH and increase in exchangeable acidity on the conservation tillage systems observed in this study may be attributed to SOC accumulation. The accumulation of SOC leads to a dissociation of humic material which contains carboxylic and phenolic groups. When these groups dissociate, H^+ is released and it further reduces soil acidity. Accumulation of OM could also result in more N and S mineralisation increasing H^+ concentrations increasing acidity and lowering pH (Zeng *et al*., 2011; Mathew *et al*., 2012). However, further studies would be required to determine the SOC status of conservation tillage fields and whether it is significantly related to soil pH. The KwaZulu-Natal region had high soil exchangeable acidity than the other geographical regions, and this suggests that soils of the KwaZulu-Natal region had higher buffering capacity (more H^+ and Al^{3+} on the exchange sites) of the active acidity (Brady and Weil, 2008).

There are a number of important nutrients that appeared to be limiting on some producers fields in different irrigated wheat production regions. The low P levels which were observed on most fields in KwaZulu-Natal can be explained by the high acidity and low pH observed from the same fields. According to Brady and Weil (2008), P is adsorbed by aluminosilicates, hydrous iron or aluminium (goethite or gibbsite), amorphous Fe and Al oxides that are naturally available in the soil at low pH. This phenomenon is eminent in highly weathered (Fey, 2010) soils such as Hutton and Clovelly soil forms which were dominant in KwaZulu-Natal region. More P was available under conventional tillage in comparison to conservation tillage. As conservation tillage generally builds up organic matter in the soil surface, it is possible that P may be locked up in surface organic matter in these systems due to accumulation of SOM and mineralisation of N which could have these acidifying effects resulting in P fixation. Under conventional tillage, P is incorporated to the soil thus more P may be present in the sub surface layers. Most producers in KwaZulu-Natal have adopted conservation tillage (Table 3.5) thus there is a lack of P incorporation into the soil which may have resulted in low P availability. Nonetheless, apart from conservation till, KwaZulu-Natal soils are naturally acidic which could possibly be the reason for low P. In the current study, there was more plant available P on rotations where wheat was preceded by non-legumes compared to legumes-wheat rotations. This may be due to the fact that legumes degrade rapidly because of low C: N ratio and after decomposition of legumes, mineralization of N which have acidifying effects can occur thus resulting in P fixation hence low P availability. This view was also supported by the positive correlation of pH and available P.

Significant variations of plant nutrients with geographical regions as observed in the current study could be indicative of deference's in geological reserves of these nutrients in the different regions. This means that producers in the different regions have to manage the nutrients differently, and the geographical regions require different research agendas for refining nutrient management. Exchangeable Na content was not high enough to impair crop growth in all the geographical regions, suggesting that producers are managing sodicity well.

Zinc varied significantly across the geographical regions, but means were generally within the acceptable range (>1.5 mg/kg Zn) in all the regions (Table 3.8). These results are contradictory to findings by Herselman (2007), who reported that 91% of South African soils are Zn deficient as they contained <1.5 mg Zn/kg soil. It should be noted that most N, P and K basal fertilizers that are used in South Africa by commercial producers are fortified with 0.5% Zn, and continuous use of these fertilizers probably explains the general adequacy of Zn on these fields. There was generally adequate N nutrition on wheat fields across the geographical regions, which shows that the producers are managing N well. Much of the fertilizers promoted by fertilizer companies in South Africa are N based, hence producers are more inclined to purchase these above others. Secondly, N deficiency symptoms on wheat are relatively easy to diagnose as a characteristic yellowing of the lower leaves. Adequate N supply causes rapid growth and a dark green colour on the leaves and N deficiency is generally easy for the producers to diagnose. The high mobility of N also means that the deficiency can be corrected at any stage using ‘split-applications’ during crop growth, hence N is generally regarded by producers as a relatively easy nutrient to manage. Top dressing of N fertilizer under irrigation makes it effective because it prevents volatilization (Lamb *et al*., 2015) and enhances effective use of N fertilizer by wheat crops. From the field observations it could be inferred that producers were applying adequate N fertilizers.

Nutrient ratios of Ca and Mg observed from the current study were generally within the acceptable range in all regions except the Warmer Northern, which had a low Ca: Mg of 1.91 ± 0.11 even though it was found to decrease with soil pH suggesting a leach of Ca with decreasing soil pH (Sanchez de Cima *et al*., 2015). Edmeades *et al*. (1991) argue that wheat may not be able to tolerate aluminium toxicity if the Ca: Mg ratio is low (<2). There was very high Mg (634.30 ± 54.31) in the Warmer Northern region, possibly in the toxic range, and this caused a low Ca: Mg ratio. Because of the high Ca and Mg, contents in the Warmer Northern region, an exception can be made on the optimum nutrient ratio. This is in line with recommendations from Brady and Weil (2008), who argued that the optimum Ca: Mg ratio ranges between 1:1 and 15:1 and exceptions should be made for soils developed in the Ca or Mg rich parent materials (Brady and Weil, 2008). It is recommended that future studies must focus on sustainable approaches for effectively enhancing P availability and addressing pH problems under conservation till and legume-wheat rotations. There is also a need to investigate the staus of soil organic carbon (SOC) status of the fields, and its influence on nutrient availability.

3.5 CONCLUSIONS

There was high variation in nutrient availability on irrigated wheat fields in South Africa. The following conclusions can be made with regard to the effects of geographical regions, tillage, crop rotation and soil depth on the nutrient availability:

- Soil pH (KCl), ESP and plant available P, K, Mg and Ca varied considerably across geographical regions. Soil pH was considerably lower than the recommended range for wheat in almost all geographical regions and acidity was a major factor influencing availability of nutrients such as P, Ca and Mg.
- Mean plant available P was below the minimum range in KwaZulu-Natal and Warmer Northern regions, thus P deficiency may be a common problem of irrigated wheat crops in these regions.
- Calcium to Mg ratio was low in the Warmer Northern region, but was within the acceptable range in the other regions. There was also very high Mg in the Warmer Northern region, possibly in the toxic range.
- Conservation tillage systems and legume-wheat rotations had higher acidity and P deficiency problems than either conventional tillage or wheat-non legume rotations.
- Zinc, Mg, K, and N nutrition was generally adequate across all geographical regions, and these nutrients may not be a major cause of concern in terms of causes of yield loss in irrigated wheat production.
- Electrical conductity and ESP were also acceptable across all geographical regions.

- Plant available P and K were more available on the 0 - 20 cm soil depth which is good for plant growth.

It is recommended that future studies must focus on sustainable approaches for effectively enhancing P availability and addressing pH problems under conservation tillage and legume-wheat rotations, especially in the KwaZulu-Natal region. There is also a need to investigate the influence of geographical regions, tillage and rotation practices on soil organic carbon (SOC) status of the fields, including the relationship between the SOC and various nutrient availability parameters.

4 GEOGRAPHICAL AND CROP MANAGEMENT EFFECTS ON SOIL ORGANIC CARBON OF IRRIGATED WHEAT FIELDS IN SOUTH AFRICA

Abstract

Soil organic carbon (SOC) is central to sustainable improvement of soil fertility on cropped fields. The objectives of this study were to: (1) determine the SOC status of irrigated wheat fields in South Africa as influenced by geographic regions, tillage practices and crop rotations; and (2) determine the relationship between clay content and SOC in different geographical regions. Soils were sampled from representative, purposively selected farmlands in the four major production regions of South Africa, namely: KwaZulu-Natal (KZN), Cooler Central (CC), Eastern Highveld (EH) and Warmer Northern (WN) during the 2015/16 wheat planting season. Sampling was carried out at two soil depths of 0-20 cm and 20-40 cm. Soil organic carbon content of the samples was analysed using the Walkely Black method. Soil organic C levels varied considerably across the irrigated wheat production regions in the country, ranging from 0.13% to 6.02%, with a mean of 1.55% and 65.60% coefficient of variation. Overall, 42.31% farms had SOC content below the critical limit of 1%. Geographic region, tillage practice and soil depth had a significant ($p<0.05$) effect on the SOC. Soils in the KwaZulu-Natal region, where the majority of producers (88.37%) practiced conservation agriculture had the most SOC (2.00 ± 0.09%), followed by Warmer Northern (1.65 ± 0.14%), with Cooler Central (0.84 ± 0.08%) and Eastern Highveld (0.82 ± 0.07%) soils having lower SOC contents. Conservation tillage (2.15 ± 0.10%) farms had more SOC than conventional tillage (1.02 ± 0.05%) farms at both sampling depths. The geographical region × crop rotation interaction was significantly

($p<0.001$) related to SOC. In Warmer Northern region, fields where wheat was preceded by a legume crop had more SOC than those where wheat was preceded by a non-legume crop. The opposite was true for the KwaZulu-Natal region, while the crop rotation systems had similar SOC levels in the Cooler Central and Eastern Highveld regions. Geographical region × soil depth ($p<0.05$) interaction was significant and it showed that in KwaZulu-Natal, SOC was higher in the 0 - 20 cm soil layer than the 20-40 cm layer, while depth did not affect SOC in the other three regions. There was no significant correlations ($r = 0.0$) between SOC and clay % in KwaZulu-Natal while moderate positive correlations were observed for SOC and clay in other regions. It was concluded that conservation tillage and inclusion of legumes in crop rotation were important strategies for increasing SOC on irrigated wheat fields, although the magnitude of crop rotation was variable across geographical regions.

Keywords: crop rotation; irrigated wheat; soil organic carbon; soil texture; tillage practice

4.1 INTRODUCTION

Soil degradation is a major cause of losses in soil quality and productivity of agricultural soils. The level of soil organic carbon (SOC), which is composed of plant and animal remains at different stages of decomposition and living organisms (Bot and Benites, 2005) is considered as an important indicator of the quality and productivity of soils (Dlamini *et al.*, 2014; Smith *et al.,* 2014). Soil organic carbon influences physical, chemical and biological properties of the soil, including the formation of stable aggregates, water holding capacity and nutrient retention. In a study by Ailincăi *et al*. (2009) it was found that humus decline overtime can lead to difficulty in water uptake and soil aeration reduction due to soil texture deterioration. In addition SOC stores nutrients and acts as a habitat for soil microbial life (Smith *et al.*, 2014). Sandy (low clay) soils with less than 1% SOC are prone to structural destabilization and crop yield reduction (Howard and Howard, 1990). At such low SOC levels, it may not be possible to obtain the potential yields irrespective of soil type (Kay and Angers 1999). Therefore, it is important for producers to manage SOC responsibly for increasing productivity of their cropped lands (Srinivasarao *et al*., 2015).

According to Lou *et al.* (2012), SOC content in the soil is affected by a number of factors such as soil texture, climate, temperature, topography, vegetation as well as management practices such as crop rotation, tillage practice and fertilization. Fine textured soils are generally known to hold more stable SOC in comparison to coarse textured soils (Mtambanengwe *et al.*, 2004; Wang *et al.*, 2012). This is because humified organic matter tend to be protected in the soil aggregates, which reduces the surface area available for attack by microbes. Conventional tillage does not only deplete the readily available SOC, but also exploits sequestrated SOC, such that there is almost always more SOC in conservation tillage fields (Six *et al.,* 1999; Razafimbelo *et al.,* 2008; Shrestha *et al.,* 2015). According to Fenton *et al*. (2008), the SOC content of most highly productive agricultural soils of the world depends not only on the soil texture, but also on crop and resource management strategy.

There is agreement in the current literature about the proposition that conservation agriculture (CA) is a sustainable way of managing SOC in such a way that soil structure and fertility is well sustained for the future. The three principles of CA are no-tillage or conservation tillage, crop rotation and a permanent crop residue cover (Corbeels *et al*., 2014). The need to manage fertilizer efficiently for the success of CA has been recently proposed as a fourth principle (Vanlauwe *et al.,* 2014). While no-tillage fields tend to retain more SOC than conventional tillage fields (Corbeels *et al*., 2014; Nascente *et al.,* 2013; Naresh *et al*., 2014), the magnitude of SOC benefit from reduced tillage and crop rotation tends to be variable across different production systems, depending on many crop, soil and climatic factors (Brady and Weil, 2008). There is generally more SOC in the top soil in the conservation tillage and no-tillage fields compared to conventional tillage (Kay and VandenBygaart, 2002; Nascente *et al.,* 2013). Surface (0-5 cm) SOC is important for seedbed properties such as aggregate stability, soil moisture retention and nutrient availability (Franzluebbers, 2002). Apart from tillage practice, SOC content may also be affected by the crop rotation system. The N content of soil organic matter typically ranges from less than 0.5% to more than 6%, implying that accumulation of SOC is always be accompanied by increases in soil N (Hassink, 1997). Nitrogen fixing legumes are therefore often better contributors to SOC compared to non-legumes crop rotation (Nascente *et al.,* 2013; De Maria *et al.,* 1999). Therefore, differences in tillage, rotations and other management strategies could affect the SOC levels in different wheat production regions of South Africa.

Conservation agriculture adoption in Africa is reported as slow, as highlighted by the case of resource poor smallholder producers (Giller *et al.,* 2011; Corbeels *et al.*, 2014). In most mixed livestock and crop production systems, there is a general preference to use crop residues as fodder and not as soil cover (Andersson and D'souza, 2013; Corbeels *et al*, 2014). Irrigated winter wheat production provides an opportunity of maximizing the benefits of CA through provision of continuous soil cover in the summer rainfall areas. Limited studies have however been carried out to determine the current extent of CA adoption in many African crop production systems, especially in winter wheat production. This information is required by researchers and policy makers towards identifying strategies for improving soil quality and sustainability of crop production systems.

As alluded earlier, increased SOC levels improve soil fertility, crop yields and consequently, the amount of residues and nutrients returned to the soil. There is more efficient cycling of nutrients within the system, which eventually reduces external fertilizer requirements. *Ceteris paribus*, crop yields and the efficacy of fertilizer use, hence profitability of wheat production, will be high where the SOC of the soil is high. Identifying strategies for increasing SOC in irrigated wheat fields could increase yields and profits. The main objective of this study was to determine the SOC status of irrigated wheat fields in South Africa, as affected by geographic regions and agronomic factors such as tillage and crop rotation. The secondary objective was to determine the relationship between SOC and clay % in different geographical regions.

4.2 MATERIAL AND METHODS

4.2.1 Description of study sites

Description of the study sites in the major irrigated wheat production regions of South Africa, including producer details and soil sampling procedures, and sample handling have been described previously in sections 3.2.1, 3.2.2, 3.2.3 and 3.2.4 of Chapter 3.

4.2.2 Soil Analysis

Total organic carbon in the air-dry (visible organic debris removed) and ground (<2 mm) soil samples was determined using the Walkely-Black method (Nelson and Sommers, 1996). In this method, 0.5 g of soil and 10 ml potassium dichromate were mixed in a 500 ml Erlenmeyer flask by swirling. 20 ml of sulphuric acid (H_2SO_4) was added and mixed in gently by slowly rotating the flask under the fume hood for 1 minute. After 20 minutes, 170 ml distilled water was added in the mixture together with 10 ml (85 H_3PO_4), 0.2 g of NaF and 5 drops of ferrion indicator. The contents were again mixed by swirling. The mixture was titrated with ferrous ammonuium sulphate solution and when the end point was reached, a reading was taken, which was used to calculate the C %. Soil texture was determined using the hydrometer method (Bouyoucos, 1962).

4.2.3 Data analysis

The study design and data analysis methods have been described in Chapter 3 (section 3.3). Pearson's correlation coefficient (*r)* was used to determine the significance of the relationship between SOC and clay content. A two sided t - test was used to test the significance of the difference between *r* and 0 at the 95% confidence interval.

4.3 RESULTS

4.3.1 Soil texture

Particle size analysis showed that there were differences in mean textural class of soils in the geographical regions. Soils in the Cooler Central were predominantly sand and those of the Eastern Highveld loamy sands (Table 4.1). KwaZulu-Natal and Warmer Northern had higher clay contents, and were classified as sandy clay loam soil. There was however considerable variation in clay and silt content of the soils within geographical regions as shown by the high CV's (Table 4.1).

Table 4.1 Particle size analysis for soils in the different geographical regions

Geographical region	**Number of farms (*n*)**	**Clay**		**Sand**		**Silt**		[1]**Textural class**
		Mean	†CV%	Mean	CV%	Mean	CV%	
Cooler central	23	7.04	83.8	91.65	7.2	1.304	118.9	S
Eastern Highveld	26	11.62	62.3	86.96	10.2	1.423	175.8	LS
KwaZulu-Natal	42	23.98	26.5	71.07	11.4	4.952	75.4	SCL
Warmer Northern	35	21.91	59.6	75.03	20.3	3.057	102.5	SCL

†CV, Coefficient of variation; S, sand; LS, loamy sand; SCL, sandy clay loam

[1] Based on the USDA textural triangle

4.3.2 Soil organic carbon

The results showed that SOC content was below the critical limit of 1% on 43.85% farms surveyed in the study. Geographical region, tillage and soil depth as main factors had significant effects on SOC, while effects of crop rotation were not significant (Table 4.2). The KwaZulu-Natal (2.00 ± 0.09%) region had the highest level of SOC followed by Warmer Northern (1.65 ± 0.14%), with Cooler Central (0.84 ± 0.08%) and Eastern Highveld (0.82 ± 0.07%) having lower SOC contents (Table 4.3). Conservation tillage systems (2.15 ± 0.10%) had more SOC than conventional tillage (1.02 ± 0.05%) systems (Table 4.3). There was more SOC in the 0-20 cm (1.55 ± 0.09%) layer than in the 20-40 cm (1.33 ± 0.08%) soil layer (Table 4.3). The interaction effects of geographical region × crop rotation and tillage practice × soil depth on SOC were significant. However, the crop rotation × soil depth and tillage × soil depth interaction effects were not significant (Table 4.2). The nature of the interactions effects is described in sections 4.3.2.1 and 4.3.2.2.

4.3.2.1 The interaction effect of geographic region and crop rotation

The SOC content of crop rotation systems varied significantly ($p<0.001$) with geographical regions (Table 4.2). In KwaZulu-Natal, there was more SOC on non-legume-wheat crop rotations in comparison to the Warmer Northern region, where the opposite was true (Figure 4.1). Similar amounts of SOC were observed for legumes and non-legumes in wheat rotations in the Cooler Central and the Eastern Highveld regions (Figure 4.1).

Table 4.2 Significance of the fixed effects tested by chi-squared F- statistic (Wald statistic/d.f) values in the overall REML analysis for the soil organic matter content of irrigated wheat fields in South Africa at 95% level of confidence

Source of variation	**Wald statistic**	**d.f.**	**F statistic**	**F pr**
Geographical region	137.52	3	45.84	<0.001
Tillage practice	80.89	1	80.89	<0.001
Crop rotation	0.09	1	0.09	0.763
Soil depth	6.53	1	6.53	0.011
Geographical region × tillage practice	-	-	-	-
Geographical region × crop rotation	18.39	3	6.13	<0.001
Tillage practice × crop rotation	-	-	-	-
Geographical region × soil depth	12.17	3	4.06	0.008
Tillage practice × soil depth	3.24	1	3.24	0.073
Crop rotation × soil depth	0.03	1	0.03	0.866

[1] Tillage practice interactions with crop rotation and geographical region were not considered in the analysis because not all tillage systems were represented in either crop rotations or geographical regions

Table 4.3 Summary statistics of soil organic carbon variation with geographic region, tillage practice and soil depth

Factors		Soil organic carbon (%)						
		Minimum	**Maximum**	**Mean**	**Median**	**Standard deviation**	**Standard error of the mean**	**CV%**
Geographical region	KwaZulu-Natal	0.38	6.02	2.00	1.98	0.86	0.09	43.00
	Eastern Highveld	0.19	2.34	0.82	0.71	0.50	0.07	60.98
	Warmer Northern	0.26	5.42	1.65	1.42	1.14	0.14	69.09
	Cooler central	0.13	2.63	0.84	0.70	0.55	0.08	65.48
Tillage practice	Conservation tillage	0.38	6.02	2.15	1.99	1.00	0.10	46.51
	conventional tillage	0.13	3.16	1.02	0.78	0.68	0.05	66.67
Soil depth	0-20 cm	0.13	6.02	1.55	1.48	1.02	0.09	65.81
	20-40 cm	0.15	5.42	1.33	1.11	0.93	0.08	69.92

CV: coefficient of variation

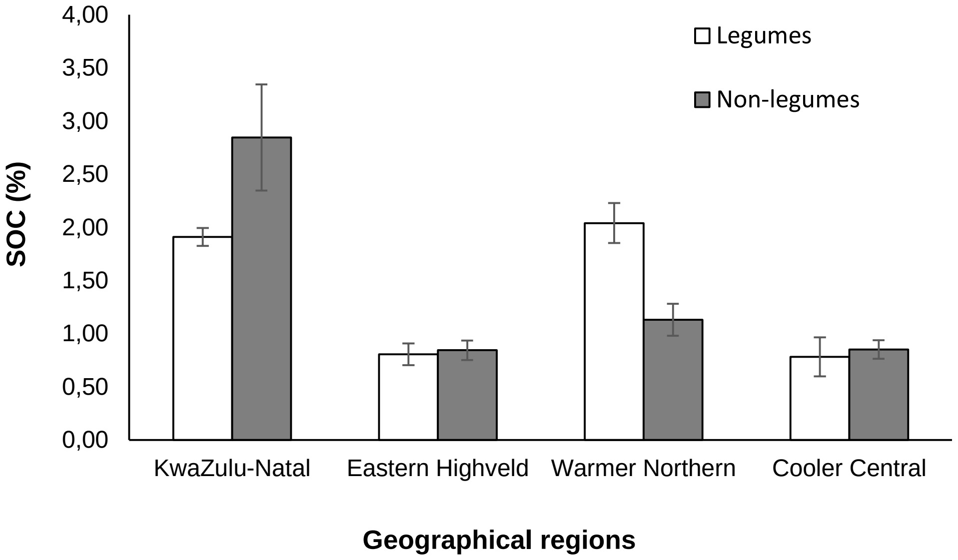

Figure 4.1 The effect of crop rotation and soil geographic region on soil organic carbon across different irrigated wheat production regions. Means are separated by standard errors.

4.3.2.2 Interaction effects of geographical region and soil depth on SOC

The interaction effect of geographical region and soil depth on SOC was significant ($p<0.05$) (Table 4.2). For producers' fields in KwaZulu-Natal, there was more SOC in the topsoil (0-20 cm) than subsoil (20-40 cm). In the Warmer Northern, Eastern Highveld and Cooler Central geographical regions, there were similar SOC levels at both depths (Figure 4.2).

4.3.3 The relationship between SOC and clay percentage

Linear correlation of overall SOC against soil clay content showed a significant moderate positive correlation (r = 0.603; $p<0.001$) as presented in (Figure 4.3). However, when correlations were done per geographical region, the results show that, there was no relationship between SOC and clay content (r = 0) in KwaZulu-Natal but all the other regions showed significant moderate positive correlations (Figure 4.4).

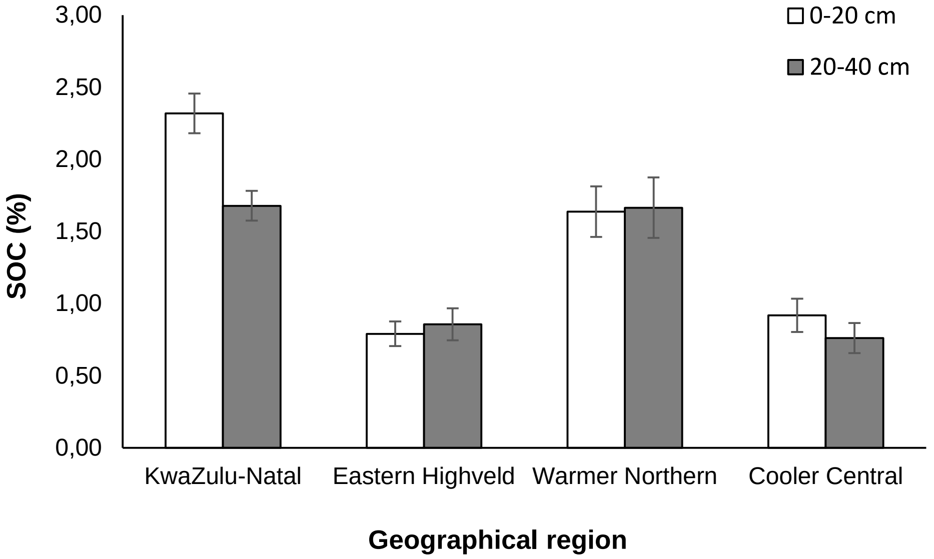

Figure 4.2 Soil organic carbon variation with soil depth in different geographical regions. Means are separated with standard errors.

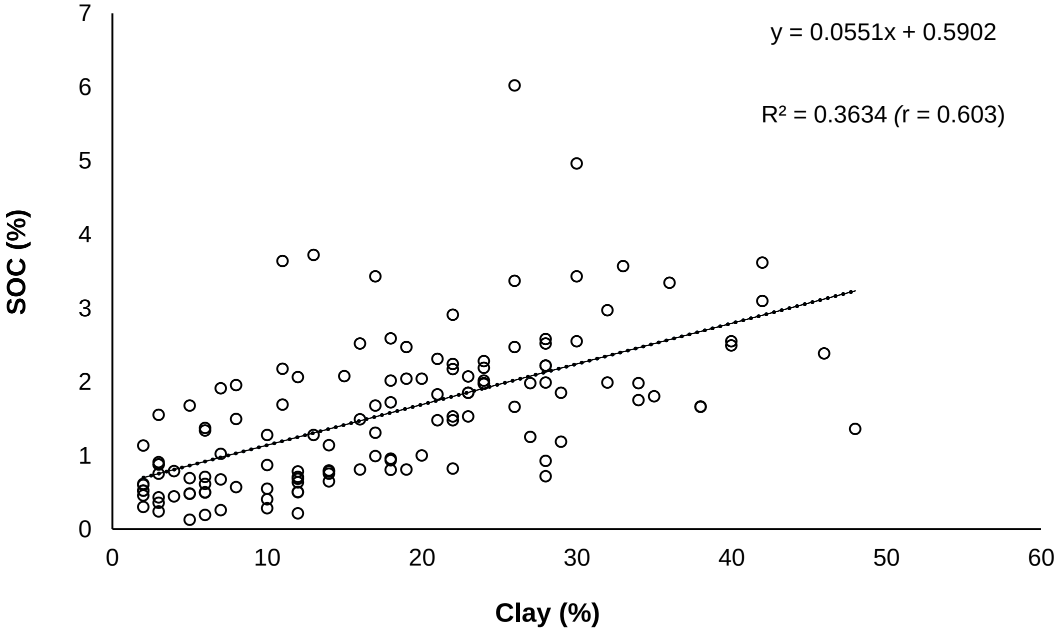

Figure 4.3 The relationship between soil organic carbon (SOC) content and clay (%) on irrigated wheat fields in South Africa

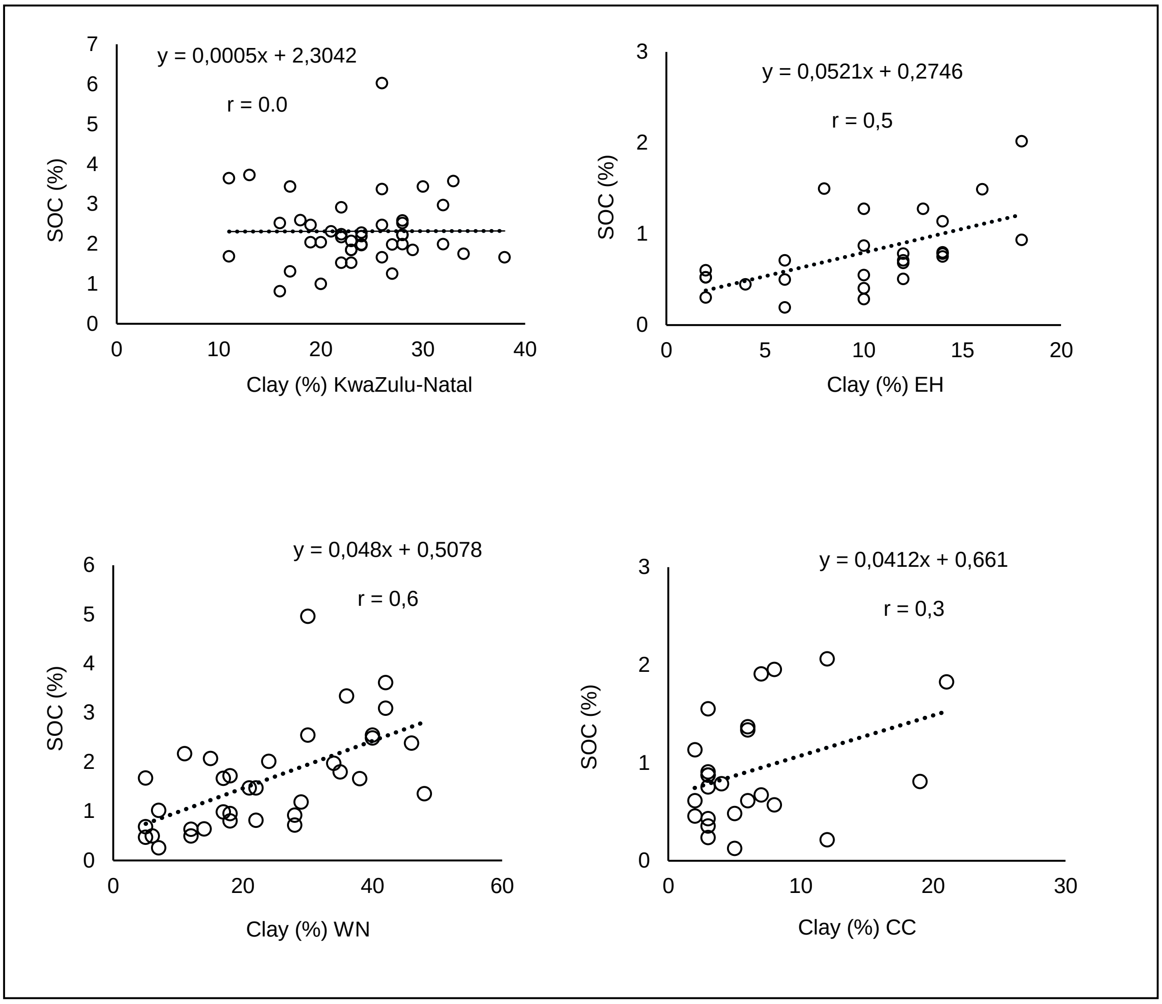

Figure 4.4 The relationship between soil organic carbon (SOC) content and clay (%) on irrigated wheat fields in different irrigation regions of South Africa

4.4 DISCUSSION

Most irrigated wheat producers who participated in the study practiced conventional tillage, and 43.85% of the sampled farms had less than 1% SOC. Kay and Angers (1999) state that when the SOC is less than 1%, yield potential of a crop is limited on most soil types. This could mean that nearly half of the irrigated wheat producers fail to achieve the yield potential of irrigated wheat on their farms due to low SOC, among other reasons. The higher levels of SOC on producers' fields in KwaZulu-Natal when compared to other production regions could be explained by the higher adoption of CA in the region (Strauss and Findlay, 2014). The activities of the No-Till Club in KwaZulu-Natal have been explained in the previous chapter (Section 3.4). In addition to management factors such as tillage practice, fertilizer application and crop rotation, the variations of SOC across the wheat production regions, as observed in this study could also be attributed to climate and soil properties (Brady and Weil, 2008). Soils in the different irrigated wheat production regions of South Africa developed from various parent materials thus they are of different soil properties and texture and have been subjected to different climatic conditions. KwaZulu-Natal and Warmer Northern regions are relatively warmer and wetter than the Eastern Highveld and CC. The soils in KwaZulu-Natal and Warmer Northern regions generally consists of well weathered fine textured soils derived from dolerite parent material. Soils of the Eastern Highveld and Cooler Central regions consists mostly of coarse textured soils derived from sandstone parent material (Fey, 2010). Weathering of soils results in high Al and Fe oxides which enables SOC to exist as organo-oxide complexes (Brady and Weil, 2008), and improvement in aggregation and aggregate stability which could protect soil carbon. High sorption, physical protection by micropores and less aeration properties of fine textured soils grants them the ability to hold more SOC in comparison with coarse textured soils (Brady and Weil, 2008). While 100% conventional tillage is practiced in the Cooler Central and Eastern Highveld regions, KwaZulu-Natal had the highest proportion of CA, followed by Warmer Northern, and the same trend was observed in terms of SOC. In addition to CA effect, KwaZulu-Natal has deeper soils, with higher clay content which could have resulted in aggregate protected C (du Preez *et al*., 2011). The higher SOC could therefore be the combined effects of clay content and CA practices.

The significant interaction of geographical region and crop rotation on SOC can be explained by the fact that non-legumes have a relatively higher C: N ratio and will degrade slower in humid areas than legumes. The similarity of legume and none-legume in the Cooler Central and Eastern Highveld could be the result of conventional tillage in which rapid breakdown of SOC cause low SOC. The higher SOC contents in the top soil (0-20 cm) of irrigated wheat fields in KwaZulu-Natal could be related to the level of adoption of CA in the region. The producers retain crop residues on their fields and the biomass is also protected from rapid decomposition through reduced, or no-tillage.

Clay content is generally thought to be the most important rate modifier of SOC accumulation, but the lack of correlation between SOC and clay content observed in KwaZulu-Natal could mean that clay content of fields in KwaZulu-Natal do not vary considerably enough to cause significant differences in effects on SOC. The variations in SOC within this region could be attributed to other factors such as rotation system, biomass input or tillage practice. Moderate correlation of SOC and clay content observed in other regions (Figure 4.4) also suggest that there are possibly other equally significant factors than just clay content which control SOC in the fields.

The variations in SOC with soil depth by geographic region and soil depth as observed in the study, can be attributed to differences in predominant tillage systems in these regions. More action is needed to increase awareness of wheat producers on the consequences of conventional tillage in terms of SOC losses, hence soil fertility depletion, and the benefits of CA. According to several researchers, SOC is more stable in the no-tillage and conservation tillage compared to conventional tillage because of the limited turnover of aggregates (Six *et al.,* 1999; de Moraes Sá *et al.,* 2013; Nascente *et al.,* 2013; Shrestha *et al.*, 2015). There is also rapid decomposition of SOC under the conventional tillage compared to conservation tillage (Kay and Vanden Bygaart, 2002). The results of the current study are also in agreement with current literature which states under conservation tillage, SOC is concentrated on the topsoil due to a limited aggregate turnover (Six *et al.,* 2000; Kay and Vanden Bygaart, 2002) while in the conventional tillage system, SOC is evenly distributed in the soil profile due to regular mixing of aggregates during tillage (Bot and Benites, 2005). Wheat producers that practice conventional tillage could benefit from reducing soil disturbance, if they could convert to CA, since many already practice rotations, permanent soil cover and proper fertiliser management, which are requirements for CA (Vanlauwe *et al*., 2014).

Soil organic matter was observed to vary with different crop rotation systems on different geographical regions. There was more SOC in KwaZulu-Natal where a non-legumes crop rotation was practiced, and this could probably be attributed to slow decomposition of the non-legumes-residues under conservation till (Chivenge *et al*., 2007). In the Warmer Northern where most producers practice conventional tillage, more SOC was measured in a legume-wheat crop rotation. These results suggest that inclusion of legumes in rotation could be offsetting some of the negative effects of conventional tillage on SOC. These unexpected findings partly agree with observations of Corbeels *et al.* (2014) and Naresh *et al.* (2014), who investigated the extent of global CA practices adoption in resource poor environments. They reported that legume crop rotations enrich soil fertility. Wheat producers in arid and semi-arid areas could benefit from adapting CA practices with legumes in rotation systems, while producers from wetter regions could benefit from including non-legumes in their rotation systems.

4.5 CONCLUSIONS

- The SOC status on many irrigated wheat producer's fields in South Africa is low (<1%) and varied considerably with geographical regions, tillage systems and crop rotation.
- The KwaZulu-Natal region had the highest SOC content of all the geographical regions.
- Conservation tillage resulted in greater SOC than conventional tillage.
- Rotation of wheat with legumes increased SOC, but the magnitude of the rotation effect varied across geographical regions.
- In the Warmer Northern region, the legume-wheat rotation had higher SOC, while the KwaZulu-Natal producers benefited even more from non-legumes crop rotation with wheat. In the Cooler Central and Eastern Highveld regions where only conventional tillage was practiced, rotations did not affect the level of SOC.
- Variations in clay content do not appear to have a significant influence on SOC in KwaZulu-Natal and only have a moderate effect on SOC in the rest of the regions.
- There was no relationship of SOC with plant available nutrients in KwaZulu-Natal but some plant available nutrients were positively related to SOC in the Cooler Central, Eastern Highveld and Warmer Northern regions.

5 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 GENERAL DISCUSSION

Poor soil fertility management is suspected to be one of the major problems that cause yield loss on irrigated wheat fields in South Africa. This study contributed to the knowledge pool through investigating the soil fertility status of irrigated wheat fields in South Africa, as well as some factors that influence this fertility. The hypotheses tested in the study were: (1) Nutrient availability on irrigated wheat fields in South Africa falls below the optimum recommended range for irrigated wheat production, (2) Low soil organic carbon (SOC) is a significant cause of poor soil fertility on irrigated wheat fields in South Africa, and (3) that geographical regions, tillage practices and crop rotations, including interactions among these factors have a significant influence on the soil fertility status of irrigated wheat fields in South Africa. There is also other important questions regarding soil fertility management for irrigated wheat in South Africa, as follows that have been addressed by the study:

1) What is the benefit of conservation practices on soil fertility?
2) What is the influence of soil texture on SOC, and the influence of SOC and acidity on nutrient availability?

The study aimed to identify opportunities to improve soil fertility management of irrigated wheat in the major irrigated wheat production areas of South Africa and provide recommendations that have a scientific basis. Nearly all the soil fertility parameters measured varied significantly across geographical regions. This chapter combines findings from different chapters in the thesis and comes up with overall conclusions and recommendations for each geographical region.

5.1.1 Correlation of SOC with plant available nutrients

It was important to correlate SOC results (Chapter 4) with plant nutrients (Chapter 3) as a means of testing whether the SOC content had a significant influence on nutrient availability. The correlations of SOC with various nutrient availability parameters per geographic region showed that the nature of the relationships between SOC and nutrient availability varied considerably across regions (Appendix 2). For example, there were no significant correlations of SOC with nutrient availability in the KwaZulu-Natal region (*r* was not significantly different from zero; Table 4.4), but significant correlations of SOC with CEC, Ca, Mg, Na and S were obtained from the Cooler Central and Eastern Highveld regions (Appendix 2). In the Warmer Northern region, there were significant negative relationships of SOC with P and pH. Zinc did not have significant relationships with SOC in all the geographical regions (Appendix 2).

Correlations of plant available nutrients with wheat yield were ommited in this study, on the logical assumption that the soil fertility results were adequate in describing the extent to which soil fertility constraints wheat yield. Nutrient availability results and other soil fertility parameters were compared with optimum requirements of irrigated wheat based on existing literature (Table 3.4). Based on these simple comparisons, the sufficiency of nutrients and SOC could be deduced. Liebig's law of minimum states that if one of the essential nutrients is inadequate, yield potential may not be achieved even if all other nutrients are adequate (Brady and Weil, 2008). Hence, it was not critical to provide correlations of soil fertility with yield in making conclusions regarding the soil fertility constraints of irrigated wheat production. It should also be noted that there is an abundance of literature which shows the relationship of different plant nutrients with wheat yield (e.g Woodard and Bly, 1998; Grant *et al.,* 2001; Orloff *et al.,* 2012). The same can also be said with the correlations of SOC with wheat yield (e.g Majumder *et al*., 2008; Lal, 2006).

5.1.2 KwaZulu-Natal region

Most of the producers from KwaZulu-Natal (97.67%) who participated in this study practised conservation till, and as elaborated previously, the KwaZulu-Natal No-Till Club may have played an important role in the promotion of no-till adoption in this region. KwaZulu-Natal had relatively high clay content thus the soil was on average classified as a sandy loam clay and these findings are in line with Fey (2010). The CA practice could explain the higher SOC (mean 2% ± 0.09%) in comparison to other regions, since no significant relationship could be established between SOC and clay content for this region (Figure 4.4). The above mentioned findings are in line with Six *et al*. (1999). However, soil P defiency and acidity problems were most severe in this region in comparison to other regions. It appears as if the adoption of CA has not addressed P deficieny and acidity problems that may be inherent to this region. The KwaZulu-Natal region has well weathered soils that are derived from dolerite (Fey, 2010). Under a humid climate, soils developed from dolerite tend to have excess sesquioxides (Brady and Weil, 2008) and the low P could possibly be attributed to the high fixation of P by sesquioxides in this region. Low soil pH, relatively high acid saturation are common in highly weathered soils. This could be another reason of low plant available P and Zn in this region. The accumulation of SOC in this region could have resulted in greater acidity, through degradation of SOM and mineralization of N under the subhumid conditions. Zinc is relatively low in this region compared to other regions but it is still within the critical limit of >1.5 mg Zn/kg soil. This implies that Zn might not necessarily be a problem, but frequent replacement of Zn in relatively higher rates than the other regions is required. It can be deduced that producers in KwaZulu-Natal have always struggled with acidity and P deficiency, therefore they were better motivated to adopt CA, which is generally purpoted to increase P availability as well as reduce acidity problems over the long term.

There is a need for dedicated research to refine the CA practice in KwaZulu-Natal to enhance P availability, reduce P stratification and reduce acidification of soils. A reasonably high CEC was observed, thus availability of exchangeable bases (Ca, K, Mg) was within the recommended range. This could be explained by the decomposition of the accumulated SOC. Calcium, Mg and K are added to the system as fertilizers thus SOC will contain these nutrients and they will be releases upon decomposition of SOC (Berg and Matzner, 1997). Exchangealbe sodium percentage (ESP) and EC were relatively low in this region and within acceptable levels. On the interactions that were considered, only geographical region × crop rotation had a significant influence on S, ESP and soil pH. Geographical region × soil depth interaction had a significant influence on EC. These interactions showed that unlike in othe regions, crop rotation had no effect on soil pH and ESP. Soil depth also had no significant effect on EC.

There was more SOC under non-legumes crop rotation in comparison to legumes crop rotation in KwaZulu-Natal, and this was attributed to the humid climatic conditions which influence the decomposition and SOC build-up rate. Non-legumes are more stable under humid conditions compared to legumes which decompose quicker. The variation of SOC with depth as observed in KwaZulu-Natal was expected under the conservation tillage systems (Six *et al.*, 1999; Kay and VandenBygaart *et al.*, 2002). It was anticipated that SOC has positive correlations with availability of nutrients (Brady and Weil, 2008) but correlations of SOC with plant available nutrients were not significant in KwaZulu-Natal. This could mean that in KwaZulu-Natal, there are other more important factors such as soil pH, clay type, e.t.c that influence nutrient availability. Lack of correlation between SOC and available nutrients could be explained by the fact that most of the SOC in KwaZulu-Natal resulted from non-legumes which generally contains low nutrients in comparison to legumes rotations which resulted in more rapid breakdown, lower OM and higher available nutrients. Therefore, the average effects of legume and non-legume rotations could have cancelled off to result in lack of correlation between SOC and nutrients (Sullivan and Andrews, 2012). Nitrogen nutrition of wheat crops, plant available S, K, Ca and Mg, including the Ca: Mg ratio were sastisfactory in KwaZulu-Natal and other regions, suggesting that these may not be considered as limiting factors to wheat growth and yield.

5.1.3 Warmer Northern region

About 13.89% of the Warmer Northern producers who participated in the current study practised conservation tillage and the rest were practicing conventional tillage. Some producers in Mpumalanga are part of the No-Till Club of KwaZulu-Natal. There was also a relatively high clay content (Brady and Weil, 2008) in the Warmer Northern soils thus they were classified as sandy clay loams according to the USDA textural triangle.The strong correlation (r = 0.60) between SOC and clay % in the Warmer Northern suggested that clay percentage was a significant determinant of the SOC status, and perhaps soil fertility in this region, this findings can be supported by Mtambanengwe *et al.* (2004) whereby more carbon was retained by fine textured soils. The mean SOC was higher than the critical limit of 1% in this region. The high clay content and SOC at higher soil pH explain the very high CEC in this region. Mean soil pH (6.35) was very close to the optimal pH for wheat cultivation (DAFF, 2010). The lower acid saturation in this region could be explained by less whethered soils and lower organic matter decomposition rate than in KwaZulu-Natal region.

The relatively higher EC and ESP in comparison to the other regions suggested that there is considerable amounts of soluble salts present, even though the salts are not adequate enough to curtail plant growth (Horneck *et al.,* 2011). Very high CEC was observed in soils of the Warmer Northern region, meaning that the soils here have a high ability to hold exchangeable cations, hence high availability of bases (Na, Ca, Mg and K) was expected. Calcium: Mg ratio was relatively lower than the recommended range (<2), such that availability of Ca and Mg might not be in sync with plant demands. A combination of young soils and higher SOC suggested that the soils could be more fertile than the soils in other regions. Although pH, SOC and other soil fertility indicators were reasonably high in this region, available P was low based on ARC-SGI (2015) production guidelines, and would only be acceptable enough for producers targeting a yield of 4 - 5 t/ha. Irrigated wheat producers normally target a yield of 7 t/ha in order to break even with production cost in this region (Prins 2013 Personal Communication[1]). Therefore, it can be concluded that P deficiency is a major factor influencing producer yields and profits in the Warmer Northern region. The reason for such low available P levels was not clear and may need further investigation.

The higher SOC and available S in legumes-wheat crop rotation in comparison to non-legumes-wheat crop rotation, suggested that the S was being released from the soil organic matter. The difference between legumes and non-legumes is mainly the C: N ratio, legumes have low C: N ratio in comparison to non-legumes thus legumes decompose and build SOC quicker than non-legumes. The significantly lower soil pH under legumes crop rotation compared to non-legumes, could be because legumes induce soil acidity through their N fixation mechanism via the nitrification process (Brady and Weil, 2008). Phosphours and soil pH correlated significantly with SOC in this region, and the results are supported by the theory which states that the accumulation of SOC results in low soil pH, and lower P availability (Brady and Weil, 2008). High availability of nutrients could mean good management of fertlizers by producers. This could also mean that under wetter conditions, conventional tillage results in faster breakdown of SOC thus faster release of nutrients hence more nutrients observed in this region.

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[1] A Prins. Griekwaland Wes Koparatief Pty LtD

5.1.4 Eastern Highveld region

Producers in this region practised 100% conventional tillage with either legumes or non-legumes crop rotation. Soil pH was acidic, and the second lowest of all the studied regions and accordingly, acid saturation was relatively higher.

Of the measured plant available nutrients, Zn was just within the recommended range probably because of low soil pH (Brady and Weil, 2008). The Eastern Highveld region showed the lowest CEC and as anticipated exchangeable bases (Na, Ca, Mg and K) were significantly lower than the other regions. Surprisingly, plant available P was on average, the highest in the Eastern Highveld, compared to other regions. This could mean that producers in this region manage P fertility status in their fields through P applications at high rates to their fields. The Ca: Mg ratio was high, enabling the unhindered uptake of Ca, Mg and K by crops.

Nevertheless, EC and ESP were relatively higher in comparison to the other regions even though they are still below the critical limits (Horneck *et al*., 2011) hence this could mean that Eastern Highveld region could be more prone to salinity and sodicity in the future. Plant available S, ESP and soil pH were significantly influenced by the interaction of geographical region × crop rotation while EC was significantly influenced by the interaction of geographical region × soil depth. There was significantly more ESP in the non-legumes crop rotation but S was significantly higher in the non-legumes crop rotation. The mechanisms behind this effect are not clear and require further study. Could it be possible that N-fixing legumes enhance solubilisation of Na in the soil or that producers whose soils have high Na knowingly include legumes in their rotations? Significantly lower soil pH which was observed under legumes-wheat crop rotation supports the common theory, that pH decreases under legumes crop rotation because of the release of H^+ ions during the nitrification process (Brady and Weil, 2008).

Under conventional tillage, it is expected that nutrient contents do not vary with depth because of the uniform mixing of soil as it can be seen with uniformly distributed EC with depth in the Eastern Highveld region. In overall, N deficiency symptoms were absent from wheat crops in this region, meaning that producers manageme N successfully.

Soils in the Eastern Highveld region were dominated by the sand fraction and were classified as sandy loams. The very low mean SOC (0.83%) in this region is probably because coarse textured soils which do not have ability to protect SOC as does fine textured soils (Mtambanengwe *et al*., 2004). It could also be because all the producers practiced conventional tillage, which is known to rapidly deplete stable SOC. The small amounts of SOC in soils of the Eastern Highveld did not vary significantly with either legumes or non-legumes-wheat crop rotation and soil depth. There was a strong positive correlation (r = 0.59) between SOC and clay %, and it is recommended that producers with low clay soils should retain residues to increase their SOC content and possibly soil fertility. When SOC was correlated with plant available nutrients, a significant correlation of SOC with CEC, Ca and Mg was observed. Positive correlation of SOC with plant available nutrients could mean that in the semi arid regions under conventional tillage, SOC decomposition is a major contributor of plant available nutrients. Soil organic matter acts as a reservoir of plant available nutrients. It has CEC that is double its own weight, so an increase in SOC would also increase CEC (Brady and Weil, 2008).

5.1.5 Cooler Central region

All participating producers in the Cooler Central region practiced conventional tillage. There was generally low SOC in the Cooler Central region (<1%) and SOC did not significantly vary with crop rotation and soil depth in this region. Soils of the region are predominantly sandy with relatively low CEC. Perhaps this could be related to the dominant use of conventional tillage. Conventional tillage could have been responsible for the uniform distribution of SOC with depth (Six *et al*., 1999; Kay and Vanden Bygaart, 2002). Conventional tillage, together with sandy texture of the soil, could explain the low SOC, CEC and soil pH levels in this region.

Although there was relatively low soil pH and acid saturation, all the plant available nutrients are relatively high given the low CEC and soil pH in this region. This could mean that producers are managing their plant essential nutrients well through additions of large amounts of inorganic fertilizers, but this might have serious implications on the profitability of wheat production in this region. The high, EC and ESP might not cause problems as yet since it is still within the critical limits (Horneck *et al*., 2011) but could cause salinity and sodicity problems in the near future if not carefully managed. A significantly high Ca: Mg ratio indicates an easy uptake of Ca and Mg, such that Ca, Mg and K could not be a problem limiting producers from achieving their yield targets in this region. Even at such low SOC levels, mean plant available Zn and P were just within the recommended range for plant growth, thus P and Zn could not be major problems hindering producers from reaching yield targets.

The moderate positive correlation of SOC with clay % in this region and the significant correlations between SOC and CEC, Ca, Mg and S were also observed. Positive correlation also suggested that good management of SOC could improve nutrient availability. As such CA may have a potential contribution.

5.2 CONCLUSIONS

- The majority of the producers practised conventional tillage, and conservation agriculture (CA) adoption among irrigated wheat producers is very low in all production regions except KwaZulu-Natal.

- Plant available Zn, Mg, K, S and N were generally adequate across all geographical regions and these nutrients may not be a major cause of concern in terms of current causes of yield loss in irrigated wheat production.
- Electrical conductivity and ESP were also acceptable across all geographical regions, suggesting that the producers are managing salinity and sodicity well.
- Soil pH, ESP and plant available P, K, Mg and Ca varied considerably across geographical regions. Acidity was a major factor influencing availability of nutrients such as P, Ca and Mg.
- Conservation tillage systems and rotations in which wheat was preceded by legumes generally had higher acidity and P deficiency problems than either conventional tillage or wheat-non legume rotations. The intensity of the problem varied across geographical regions.
- Mean plant available P was below the minimum acceptable range in KwaZulu-Natal and Warmer Northern regions, thus P deficiency may be a common problem of irrigated wheat in these regions. There was evidence of P stratification on all all farms, hence generally adequate P at 0-20 cm soil layer, but deficiency at 20 – 40 cm.
- The Ca: Mg ratio was low in the Warmer Northern due to excessively high levels of Mg, but was within the acceptable range of 2 - 8 in the other regions.
- Soil organic carbon varied considerably across the irrigated wheat production regions in the country and 42.31% of the farms had a SOC content below the critical limit of 1%.
- Soils in the KwaZulu-Natal region where the majority (88.37%) practiced conservation agriculture had the highest SOC. Conservation tillage farms had double the SOC content of conventional tillage farms at both sampling depths of 0-20 cm and 20-40 cm.

- A geographical region × crop rotation interaction effect on SOC was observed, whereby in Warmer Northern, fields where wheat was preceded by a legume crop had more SOC than those where wheat was preceded by a non-legume crop. The opposite was true in the KwaZulu-Natal region. In the Cooler Central and Eastern Highveld regions, crop rotation systems had similar SOC levels.
- On conservation tillage fields, the SOC was higher in the 0 - 20 cm depth than in the 20 - 40 cm.
- SOC and clay % in KwaZulu-Natal were not significantly related. Moderate positive correlations were observed for SOC and clay were obtained in other regions.
- Cation exchange capacity, Ca, Mg and S were significantly related to SOC in the the Cooler Central and Eastern Highveld regions.
- In the Warmer Northern region, there were significant negative relationships of SOC with P and pH.
- Zinc did not show any significant relationships with SOC in all the geographical regions.

5.3 RECOMMENDATIONS

- It is recommended that CA may need to be promoted for sustainable soil fertility in wheat production areas, particularly in Cooler Central and Eastern Highveld, where limited CA adoption has occurred.
- Conservation till and inclusion of legumes in crop rotation should be promoted as important strategies for increasing SOC on irrigated wheat fields, although the magnitude of benefit maybe variable across geographical regions.

- Future studies must focus on sustainable approaches for effectively enhancing P availability and addressing pH problems under conservation till and legume-wheat rotations.
- There is a need to further investigate the effect of each of the tillage practice on different SOC pools under wheat production over time. A crop rotation system that sustainably result in higher wheat yields may need to be investigated, considering that legumes and non-legumes encourage SOC accumulation in different wheat growing regions of South Africa

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7 APPENDICES

Appendix 1: Calculations

The formulae for calculating cation exchange capacity (CEC) is as follows:

$$\text{CEC (meq/100g)} = \text{exchangeable } [Ca^{2+}] / 200 + [Mg^{2+}] /122 + [K^{+}] /391 + [Na^{+}] /230 + \text{Exchangeable acidity (EA)}$$

That for acid saturation (AS) was;

$$AS = ([EA] / CEC) \times 100$$

Appendix 2: Pearson's correlation matrix for soil organic carbon content and various nutrient availability parameters in irrigated wheat fields per geographical region

	KwaZulu-Natal		**Eastern Highveld**		**Warmer Northern**		**Cooler Central**	
	r	p-value	*r*	p-value	*r*	p-value	*r*	p-value
CEC	0.1762	n.s	0.6143	<0.001	0.2538	0.0340	0.6435	<0.001
Ca	0.2024	n.s	0.5290	<0.001	0.1996	n.s	0.6376	<0.001
Ca: Mg ratio	0.0963	n.s	-0.2996	0.0309	-0.1212	n.s	-0.1458	n.s
EC	0.2008	n.s	0.0997	n.s	0.0283	n.s	-0.1279	n.s
K	0.0457	n.s	0.3518	0.0105	0.2180	n.s	0.2033	n.s
Mg	0.1540	n.s	0.6558	<0.001	0.3590	0.0023	0.6371	<0.001
Na	0.1356	n.s	0.3358	0.0149	0.1234	n.s	0.5788	<0.001
P	0.2077	n.s	-0.2556	n.s	-0.4144	<0.001	-0.0754	n.s
S	0.1371	n.s	0.3292	0.0172	0.1948	n.s	0.4913	<0.001
Zn	0.2570	n.s	0.0472	n.s	-0.0967	n.s	0.0855	n.s
pH	0.2457	n.s	-0.0263	n.s	-0.5439	<0.001	-0.0012	n.s