THE EFFECTS OF LONG-TERM TILLAGE AND CROP ROTATION PRACTICES ON NUTRIENT STRATIFICATION IN THE WESTERN CAPE

By

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Thesis presented in partial fulfilment of the requirements for the degree

Master of Science in Agriculture Sciences

at

Stellenbosch University

Department of Soil Science, Faculty of AgriScience

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April 2022

DECLARATION

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April 2022

ABSTRACT

The Western Cape is one of the most successful provinces in South Africa in converting to Conservation Agriculture (CA), with an adoption rate of around 80%. CA is a production system that promotes minimal soil disturbance, maintaining crop residues on the soil surface combined, with crop rotation with different species, including legumes. The absence of soil mixing in CA systems can lead to the stratification of immobile nutrients at the surface of the soil profile. Rapid drying of top soil layers may prevent roots from absorbing nutrients from these layers. Up until now, little was known regarding the extent of nutrient stratification in CA systems in the Western Cape.

The first objective of this study was to determine the vertical distribution of plant-available nutrients under different tillage practices and rotation sequences at Tygerhoek (34˚29'32" S, 19˚54'30"E) and Langgewens (33˚16'34" S, 18˚45'51" E) Research Farms. Soil samples were collected at 0-5, 5-10, 10-15, 15-20 and 20-30 cm depth intervals in zero-till (ZT), no-tillage (NT), minimum tillage (MT) and conventional tillage (CT) treatments combined with 4 crop rotation sequences - wheat monoculture (WWWW), wheat and medics rotation (WMWM and MWMW) and canola/wheat/lupine/wheat (CWLW). Crop rotation and its interaction with tillage and soil depth did not influence ($p < 0.05$) the distribution of nutrients in the soil at Tygerhoek, but the distribution of K and S in the soil at Langgewens was influenced. Tillage significantly influenced nutrient stratification at both sites. The amount of extractable Ca, Mg, P, K and C were significantly higher in the surface 0-5 cm of the soil under ZT and NT compared to CT. The higher soil organic carbon (SOC) in the topsoil under CA (ZT, NT and MT), may be due to reduced soil disturbance and retention of crop residues. The organic C in the 0-5 cm layer decreased as degree of soil disturbance was increased (ZT2.6%>NT 2.23%> MT 2.15% > CT 1.96%). The percentage difference in soil exchangeable K at Langgewens between 0-5 cm (308 mg kg^{-1}) and 5-10 cm (172 mg kg^{-1}) layers were the most at 79% for ZT.

The second objective was to evaluate the extent of soil nutrient stratification in a wide range of CA systems on commercial farms. Stratification was observed in both the natural veld and the cultivated soil. The cultivation and addition of ameliorates (fertiliser and lime) in the cultivated soil have accentuated the stratification compared to the natural

veld. The use of incremental soil sampling identified layers with levels of deficiency for K, S, Zn as well as the occurrence of subsoil acidity. On farms where CA was practiced for more than 25 years, C was built up and the highest values of Ca, K, P and S were present.

The third objective was to determine the adoption rate of CA principles and awareness of soil nutrient stratification through a questionnaire. Most of the respondents (63%) indicated that they used CA as farming system. Minimum soil disturbance (47%) was indicated as the most important CA principle, followed by crop rotation (37%) and stubble retention (10%). More than half of the respondents (54%) indicated that the carbon content in the soil were higher than 1.5 %. This could be influenced by the fact that 82% of the respondents were from the southern Cape.

More attention to sampling depth is required in conservation agriculture when sampling for lime and fertiliser recommendations to reflect the nutrient status of the soil. In the shallow soil of the Western Cape, soil increments of 0-10 cm and 10-30 cm are recommended for a better reflection of the nutrient status of the soil.

OPSOMMING

Ongeveer 80% van die produsente in die Wes-Kaap maak gebruik van bewaringlandbou. Bewaringslandbou behels die gebruik van minimum grondversteuring, bewaring van oesreste op die grondoppervlak en wisselbou met verskillende spesies, insluitende peulgewasse. Die afwesigheid van grondvermenging in die bewaringslandboustelsel kan lei tot die stratifikasie van immobiele nutrient in die grond. Wanneer die grond droog word, kan dit die opname van nutrient deur die wortels verhoed. Daar bestaan beperkte kennis van die stratifikasie van nutrient in bewaringslandboustelsels in die Wes-Kaap.

Die eerste doelwit van die studie was om die vertikale verspreiding van plantbeskikbare nutiente te bepaal by verskillende bewerkingspraktyke en wisselboustelsels by Tygerhoek (34˚29'32" S, 19˚54'30"O) en Langgewens (33˚16'34" S, 18˚45'51" O) Proefplase. Grondmonsters is geneem by diepte intervalle van 0-5, 5-10, 10-15, 15-20 en 20-30 cm in nulbewerking (ZT), geenbewerking (NT), minimumbewerking (MT) en konvensionele bewerking (CT). Hierdie is gekombineer met vier wisselboustelsels van koringmonokultuur (WWWW), medics-koring (WMWM en MWMW) en canola/koring/lupine/koring (CWLW). Wisselbou en die interaksie daarvan met bewerking en grondiepte het geen betekenisvolle effek ($P<0.05$) op die verspreiding van nutrient in die grond by Tygerhoek gehad nie. Op Langgewens is die verspreiding van K en S wel deur wisselbou beïnvloed. By biede die proefplase het bewerking 'n betekenisvolle invloed op die stratifikasie van nutrient gehad. Die hoeveelheid uitruilbare Ca, Mg, P, K en C was betekenisvol hoër in vergelyking met CT. Die hoër konsentrasie van C by bewaringslandbou (ZT, NT en MT) in die bogrond kan toegeskryf word aan die verminderde grondversteuring en bewaring van stoppel op die grondoppervlakte. Die organiese C in die 0-5 cm laag neem af met 'n toename in grondversteuring (ZT 2.6% > NT 2.23% > MT 2.15% > CT 1.96%). Die persentasie verskil tussen die uitruilbare K by Langgewens tussen die 0-5 cm (308 mg kg^{-1}) en die 5-10 cm laag (172 mg kg^{-1}) was die meeste by nulbewerking (79%).

Die tweede doelwit van die studie was die evaluasie van die stratifikasie van nutrient in die grond van 'n wye reeks bewaringsboerdery op kommersiële plase. Stratifikasie is gevind op beide die natuurlike veld en bewerkte grond. Die toevoeging van

grondverbeteraars (kunsmis en kalk) in die bewerkte grond het die stratifikasie meer geklemtoon in vergelyking met natuurlike veld. Die neem van grondmonsters op verskillende dieptes het tekorte van K, S, Zn en ondergrondversuring getoon. Op die plase waar bewaringslandbou vir meer as 25 jaar toegepas word, is die C opgebou en die hoogste waardes van Ca, K, P en S is gevind.

Die derde doelwit is om die toepassing van die beginsels van bewaringslandbou te bepaal en die bewustheid van stratifikasie te toets deur middel van 'n vraelys. Die meeste deelnemers (63%) het aangedui dat hulle boer volgens bewaringslanbou metodes. Minimum grondversteuring (47%) is aangedui as die belangrikste beginsel, gevolg deur wisselbou (37%) en stoppelbewaring (10%). Meer as die helfde van die deelnemers (54%) het aangedui dat die C persentasie in die grond meer as 1.5 % is. Hierdie resultaat kan gedeeltelik verklaar word omdat 82% van die deelnemers van die Suid-Kaap afkomstig is. Die klimaat is meer gematig en die opbou van koolstof in die grond bevorder in vergelyking met die warm en droë somers van die Swartland waartydens die koolstof in die grond afgebreek word.

In bewaringslandbou behoort meer aandag gegee te word aan die diepte van monsternemings wanneer grondmonsters vir kalk- en kunsmisaanbevelings geneem word sodat dit die voedingstofstatus van die grond meer akkuraat weerspieël. In die vlak grond van die Wes-Kaap word grondmonster op die dieptes van 0-10 cm en 10-30 cm aanbeveel.

ACKNOWLEDGEMENTS

- God, The Almighty, for giving me the strength and courage to finish this project
- My supervisors, Dr Hardie-Pieters and Dr Labuschagne for their encouragement and patience
- My family for their love and support
- Dr Booyse for the statistical analysis
- Anélia Marias for proofreading and editing
- Anelda Bowker for solving all my typing emergencies
- Lucy, my loving bull terrier, laying at my feet for hours while working
- The late Jack Human for showing me the restoration power of Conservation Agriculture in the early nineties.
- The farmers who made their time available to help with the project
- The Western Cape Department of Agriculture for the availability of the long-term data used in this research and the opportunity to study
- The Winter Cereal Trust for funding the long-term trials at Tygerhoek and Langgewens
- The staff at Elsenburg Soil Laboratory for analysing the samples

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LIST OF ABBREVIATIONS

C	Carbon
Ca	Calcium
CA	Conservation Agriculture
C: N	Carbon: Nitrogen-ratio
CT	Conventional tillage
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Mn	Manganese
MT	Minimum tillage
N	Nitrogen
Na	Sodium
NT	No-tillage
OM	Organic matter
P	Phosphorus
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
S	Sulphur
Zn	Zinc
ZT	Zero tillage

CHAPTER 1 GENERAL INTRODUCTION AND PROJECT AIMS

1.1 BACKGROUND

The winter rainfall region of the Swartland and the southern Cape provide a unique stable region for wheat, barley and canola production under rainfed conditions in rotation with cultivated pastures and fodder grains (Vink & Tregurtha, 2005).

Before conservation agriculture, traditional tillage in the winter rainfall areas of the Western Cape consisted of a primary tillage operation with a disk, mouldboard or chisel plough followed by a secondary action with a disk or tine for weeding and seedbed preparation before planting. Tillage has long been used by farmers to loosen soil, seedbed preparation and weed control. Tillage or conventional tillage generally refers to inversion ploughing to a depth of at least 20 cm or more (Kassam *et al*., 2009). Conventional tillage causes decreases in soil fertility due to a loss of soil organic matter (Hobbs *et al.,* 2008; Lal, 2001) and accompanying increase of water and wind erosion (Derpsch, 2004; Swanepoel *et al*., 2015).

Farmers are now using less tillage intensive production methods. Increased input costs (particularly diesel and agro-chemicals), exposure to international commodity prices, as well as variable rainfall combined with a lack of economic support from government, stimulated the adoption of conservation agriculture (CA). The adoption of CA in the region was also made possible by the simultaneous development of robust no-till planters able to plant successfully in stony soils. Other new technologies included the use of pre-plant herbicides to control herbicide resistant ryegrass (Anonymous, 2014).

CA is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (FAO, 2016). CA is characterised by three linked principles, namely; as minimal soil disturbance, maintaining crop residue on the soil surface combined with crop rotation with different species, including legumes. CA has found great appeal worldwide and has been adopted in many countries (Li *et al*., 2011). According to Findlater (2015) and Modiselle *et al*. (2015), farmers in the winter rainfall regions of the Western Cape are the most successful in South Africa in converting to CA, with an adoption rate of around 80% for CA. According to Sithole *et al.* (2016,) more than

70% of farmers in Western and southern Cape have adopted one or more principles of CA. As management practices change from conventional winter wheat production to CA, the soil properties, distribution of nutrients and soil organic matter in the soil profile are altered.

Fertile soil is the basis of sustainable agriculture, especially in arid and semi-arid conditions. Long-term trials are the primary source of information to determine the effects of cropping systems and soil management on soil productivity (Mrabet *et al.,* 2001). It is also important for explaining tillage and rotation effects on soil fertility and to develop management strategies.

Crop management practices, especially tillage and rotation, can impact soil nutrient stratification, crop growth and yield (Wright *et al*., 2007). Stratification of nutrients occurs in all cropping systems and seems likely to be accentuated in no-till systems (Jennings, 2013). The concern about nutrient stratification is driven by the idea that crops may not be able to access nutrients concentrated in the surface layer of soils, because this is the first layer to dry out and plant roots cannot extract nutrients from dry soil. Nutrient stratification is where nutrients such as phosphorus (P), potassium (K) and sulphur (S) occur naturally as layers or bands through the soil profile as a result of pedological processes or through anthropogenic (man-made) processes (Wheaton & Mason, 2016).

The availability of nutrients may become less predictable within a CA system because of less tillage, more stubble retention and crop diversity. We need to evaluate the status of the soil nutrients under these new conditions to see if the current norms are still applicable. Research results still vary, especially between locations on the effect of agricultural practices on soil chemical properties. Agricultural practices should be carefully monitored for long-term impacts on soil quality to avoid further deterioration of soil ecosystems (Celick *et al*., 2021). Long-term tillage and rotation trials were initiated at Langgewens and Tygerhoek in 2007 to investigate the effect of different tillage and crop/pasture systems on soil quality. These sites provided the ideal settings to study soil nutrient stratification under different tillage and crop rotation practices.

1.2 PROBLEM STATEMENT

Du Preez *et al.* (2001) found that after only 10 years of CA, the residue management practices used in some instances caused significant stratification of soil fertility indicators, which may influence crop growth and development. CA is characterised by minimal soil disturbance or mixing. This means that the crop residues are often left on the soil surface and relatively immobile nutrients released from them remain on or near the soil surface. Differences in the frequency and intensity of tillage can strongly influence the distribution and availability of the soil nutrients studied. Conventional tillage incorporates crop residues throughout the upper soil layers. In contrast, CA does not incorporate the crop residues, resulting in higher concentration of soil nutrients and soil organic carbon (SOC) in the soil surface, before decreasing sharply with depth (Vu *et al*., 2009). Nutrient stratification is a common occurrence and can potentially reduce the ability of crops to access soil nutrients and as a result reduce grain production.

The expected accumulation of nutrients in the top few centimeters may render it unavailable under dry conditions as water is required for absorption of most nutrients. Almost all nitrogen-uptake (99%) is by mass flow (FSSA, 2016) that needs soil moisture. Smit (2004) suggested that in the Swartland soil, reduced tillage practices resulted in an accumulation of several nutrients in the upper 5 to 10 cm soil. The uptake of the nutrients by crops seems not as efficient as it should be and this aspect warrants a thorough investigation into the effects of long-term CA in the Western Cape wheat production areas. Nutrient stratification can result in reduced nutrient uptake by plants when surface soil dries or when roots reach lower soil layers. Therefore, it is important to characterise nutrient stratification for producers to make appropriate fertiliser management decisions (Lupwayi *et al*., 2006).

Extensive research has been conducted in America, Latin-America and Australia on nutrient stratification in the last four decades (Wright *et al*., 2007; Kassam *et al*., 2009). The research states that CA is a sustainable agricultural practice (Pretty, 2008; Corsi *et al.,* 2012; Chattterjee *et al.,* 2020)) and stratification occurs (Holanda *et al*., 1998; Radford & Cowie, 2011; Kirkegaard *et al.,* 2014). Very little research has been conducted in South African's Mediterranean climate.

Many farmers consider no-tillage as the new norm for crop production in Western Cape (Botha, 2013). Understanding the effects of tillage and rotation on plant available nutrients is critical to developing nutrient management strategies to optimise yield while maintaining cropping system sustainability (Houx *et al*., 2011).

1.3 AIM AND OBJECTIVES

The aim of the study was to determine the extent and effect of CA on nutrient stratification in the grain producing areas of the Western Cape Province. The first objective of this study was to determine the long-term effect of conservation agriculture on topsoil stratification with different tillage practices and rotation sequences under controlled research settings. Changes in frequency and intensity of tillage practices alter the soil properties, distribution of nutrients and soil organic matter (SOM) in the soil profile (Hussain *et al.*, 1999). The hypothesis of the study is that, after more than a decade of conservation tillage and rotation practices, the distribution and concentration of pH, nutrients and organic matter in soil could be affected on the long-term trials at Langgewens and Tygerhoek Research Farms, Western Cape Province.

The second objective was to gain additional knowledge on the extent of soil nutrient stratification in a wide range of CA systems on commercial farms in grain producing areas in the Western Cape. Quantifying the rate and development of depth stratification of soil properties should lead to a better understanding of how conservation tillage systems might contribute to agriculture sustainability (Franzluebbers, 2002).

The third objective was to determine the extent of CA adoption, on-farm practices, and awareness of soil chemical stratification in the Western Cape Province grain producing area through a questionnaire.

1.4 THESIS LAYOUT

This thesis consists of six chapters. Chapter 1 is the Introduction, which addresses context of the study and states the aims and objectives. Chapter 2 is a literature review on CA and nutrient stratification. Chapter 3 discusses the long-term tillage and rotation trials at Langgewens and Tygerhoek Research Farms. Chapter 4 gives a review of the extent of soil nutrient stratification on commercial farms in the grain producing areas in the Western

Cape. Chapter 5 deals with the results of the questionnaire testing the adoption of CA and farmers' management practices. The thesis is concluded with Conclusions and Recommendations in Chapter 6.

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CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

The largest challenge of this century will be to increase annual cereal production to ensure food security on shrinking land and limited resources, while maintaining and improving soil fertility and minimising environment risk (Jat *et al*., 2014). Soil fertility is a measure of the ability of soil to sustain satisfactory crop growth in the long-term (Bhupinderpal-Singh & Rengel, 2007). Tillage and crop rotation are crucial factors that influence soil quality, crop production and the sustainability of cropping practices (Munkholm *et al*., 2013).

Excessive tillage can lead to soil degradation by reducing organic matter (OM) content and increasing soil susceptibility to wind and water erosion. SOM is oxidised when it is exposed to the air by tillage which results in a reduction of the OM in the soil (Hobbs, 2007). Conservation tillage systems are becoming increasingly popular as a way to reduce erosion and soil degradation (Dick, 1984; Wright *et al*., 2007). Conservation agricultural systems often result in greater stratification of soil properties than conventional tillage (Lupwayi *et al*., 2006). Research has shown that the less mobile elements in the soil, such as P, K and Zn, become stratified in the surface 5 cm of soil after several years of continuous no-tillage (NT) cropping. This causes nutritional constraints to productivity when the surface soil becomes dry (Radford & Cowie, 2011). Hiel *et al.* (2018) observed a clear stratification of the C, P and K between the different soil depths (0-10, 10-20 and 20-30 cm, respectively) in the reduced tillage treatment.

Conservation agriculture(CA) is promoted as one of the best soil management practices to achieve sustainable intensification required by increasing nutrient use efficiency, minimising erosion and increasing crop yield at the same time (Kassam *et al*., 2009; Lal, 2015). Sustainable agriculture is the management and utilisation of the agricultural ecosystem in a way that maintains its biological diversity, productivity, regeneration capacity, vitality and ability to function today and in the future (Lewandowski *et al*. 1999).

Crop residues left on the soil surface and relatively immobile nutrients released from them (and other nutrient sources, including fertilisers) remain on or near the soil surface (Wright *et al.,* 2005).

Tillage, residue retention and crop rotation have a significant impact on nutrient distribution and transformation in soils (Galantini *et al*., 2000; Etana *et al*., 1999), usually related to the effect of conservation agriculture on SOC content. Similar to the findings on SOC, distribution of nutrients in a soil under zero tillage is different to that in tilled soil. Increased stratification of nutrients is generally observed with enhanced conservation and availability of nutrients near the soil surface under zero tillage as compared to conventional tillage (Duiker & Beegle, 2006; Franzluebbers & Hons 1996; Follet & Peterson, 1988). This may be due to surface placement of crop residues in comparison with incorporation of crop residues with tillage (Blevins *et al*., 1977; Ismail *et al*, 1994).

Usually less than 10% of the soil surface is disturbed with no-tillage practice. As a result, distribution of OM, nutrients and pH in no-tillage (NT) soil is expected to be different than in CT soil. Several researchers concluded that CA leads to the stratification of nutrients in the surface soil layers (Dick, 1983; Blevins & Frye, 1993; Franzluebbers, 2002; Blanco-Canqui and Lal, 2008; Vu *et al*., 2009; Deubel *et al*., 2011). In NT systems, there is a problem of accumulation of nutrients, especially the ones that are immobile in soil (e.g. P), and pH increases close to the soil surface, following the application of limestone without incorporation, (Cade-Menun *et al*., 2010; Barth *et al.*, 2018).

Increased stratification of OM is likely to improve water efficiency by reducing runoff and increasing retention in soil, improving nutrient cycling by slowing mineralisation and immobilising nutrients in organic fraction rather than losing them in runoff and leachate, resisting degradation forces of wind and water erosion and mechanical compaction, improving soil biological diversity and enhancing long-term productivity of soils (Franzluebbers, 2002).

2.2 CONSERVATION AGRICULTURE

Jat *et al.* (2014) described CA as a coherent set of principles to guide the global adoption of sustainable, reliable and climate-resilient grain farming practices. Conservation tillage can be any tillage system that leaves at least 30% of the soil surface covered with crop residue after planting. Conservation tillage can provide several benefits such as soil and water conservation (Verhulst *et al*., 2011; Page *et al*.,2019), improved soil structure, decreased fluctuations in soil temperature, saved time and fuel as well as providing other environmental benefits like reduction of nitrogen use, retention of soil organic matter and improvement of soil quality (Jat *et al*., 2018. In Table 1, some of the distinguishing features of conventional and CA are shown. It has the potential to conserve soil and water by reducing their loss relative to some form of conventional tillage (Carter, 2005).

Table 2.1 Some of the distinguishing features of conventional and CA (Bhan, 2014)

Conventional Agriculture	**Conservation Agriculture**
Cultivating the land using science and technology to dominate nature	Least interference with natural processes
Excessive mechanical tillage and soil erosion	No-till or drastically reduced tillage
Residue burning or removal	Permanent surface retention of residue
Farm machinery increased soil compaction	Controlled traffic, compaction in tramline, no compaction in crop area
Mono cropping, less efficient rotations	Diversified and more efficient rotation
Poor adaptation to stresses, yield losses greater under stress conditions	More resilience to stresses, yield losses are less under stress conditions
Heavy reliance on manual labour, the uncertainty of operations	Mechanised operations, ensure timelines of operations
Productivity gains in long-run are in declining order	Productivity gains in long-run are in incremental order
Water infiltration is low	Water infiltration is high

CA tends to exclude the unsustainable parts (e.g. mono-cropping, tillage and residue removal mainly through burning) of the conventional tillage system (Marongwe *et al.*, 2011).

Conservation agriculture has three key components:

1. Maintaining a cover over the soil of at least 30%, by retaining residues from the previous crop or introducing a cover crop. It provides protection to the surface against erosion, conserves soil moisture and provides substrate for the organisms beneath.
2. Minimising soil disturbance from tillage by seeding directly into the soil or with minimum disturbance with a tine to open the soil for seed placement.
3. Diversifying crops in rotation and including nitrogen-fixing legumes. This will contribute to biodiversity in and above the soil and provide *in situ* nitrogen. Crop

rotation is practised to facilitate the control of weeds and break the disease cycle which are more prevalent in monoculture cropping (Kirkegaard *et al*., 2008).

Conservation agriculture is not a single component technology, but a system that includes the cumulative effect of all its three basic components (Verhulst *et al.,* 2010). Although the CA concept initially did not include an integration of livestock, the inclusion of pasture and forage crops have led to further improvements of the system. Integration of livestock with crop systems has been associated with increased diversification, increased financial stability and increased profitability (Basson, 2017).

2.3. THE IMPACT OF CA ON THE SOIL

2.3.1 The impact of CA on soil physical properties

Where CA increases soil organic carbon (SOC), associated improvements in soil aggregate stability are typically observed (Blanco-Canqui & Ruis, 2018; Li *et al*., 2019). Improved aggregate stability, combined with residue retention often have a positive impact on soil water storage (Page *et al*., 2020). The increase typically occurs due to a combination of greater infiltration and decreased soil water evaporation (Li *et al.*, 2019). Better infiltration is attributed to the improved aggregate stability and greater number of macro pores to let water into the soil profile in the absence of tillage (Blanco-Canqui & Ruis, 2018; Li *et al*., 2019).

High infiltration capacity is important for transporting water from the soil surface to deeper layers during rainfall or irrigation, thereby decreasing runoff/erosion and improving soil aeration in the upper part of the profile (Chan & Heenen, 1993; Zeleke *et al*., 2004). One of the major advantages associated with conservation tillage systems where residue is retained, is the greater availability of soil water, especially in years with low rainfall (Chan & Heenen, 1996). It has been shown that soils under CA generally had higher soil water content in the shallow layers of the profile than conventionally tilled soil (Bradford & Peterson, 2000; Govaerts *et al*., 2009).

Bulk density has been observed to increase (Li *et al*., 2018; Blanco-Canqui & Ruis, 2018), decrease (Mrabet *et al.,* 2012; Blanco-Canqui & Ruis, 2018; Zeleke *et al*., 2004) or be no different under CA system. Bulk density can be used as a measure of a soil's compaction and indicates the effect a soil is likely to have on seedling emergence, root growth and thus crop production (Blanco-Canqui & Ruis, 2018).

Crop residue cover on the soil surface provides an insulation effect that causes a decrease in temperature fluctuations, compared with bare soil (Unger, 1978). Application of crop residues to soil minimises soil surface erosion because a surface cover protects the soil aggregates from raindrop impact (Michels *et al.,* 1995). It may also protect the surface from wind erosion. Yield variations are thus reduced and crops can better withstand a drought through increased and consistent soil moisture and structure. These factors all lead to higher yields over the long term that cannot be achieved through conventional agricultural practices (Knott, 2015).

2.3.2. The impact of CA on soil chemical properties

The larger amount of SOC at the surface of the profile in CA is commonly associated with greater acidity relative to conventionally tilled systems. This is typically associated with the accumulation of plant residues and organic acids at the soil surface and greater nitrogen mineralisation (Franzluebbers & Hons, 1996; Sithole & Magwaza, 2019; Mrabet *et al*., 2012). Soil cation exchange capacity (CEC) impacts soil fertility, soil structural stability and soil pH buffer capacity (McBride, 1994). While CEC is largely an inherent soil characteristic dependent on mineralogy and clay content, it can also be influenced by changes to SOM and pH (Mc Bride, 1994). The results under CA are varied, Duiker and Beegle (2006) found increases and decreases, while Qin *et al.* (2010) observed no changes. Several studies have shown an increase in nutrients in the soil under CA in a response to increases in organic matter. Greater nitrogen (N) (Li *et al*., 2007; Page *et al*., 2019), P (Ismail *et al*., 1994; Qin *et al*., 2010; Sithole & Magwaza, 2019), calcium (Ca) (Chan *et al.,* 1992), magnesium (Mg) (Chan *et al*., 1992), K (Duiker & Beegle, 2006; Sithole & Magwaza, 2019), manganese (Mn) and zinc (Zn) (Rhoton, 2000) were observed in CA systems. In many instances, increases in nutrients in the soil will lead to greater plant nutrient availability, but not always. The absence of soil mixing in CA can also lead to the stratification of immobile nutrients at the surface of the soil profile. This can be a problem in more arid regions, where drying at the surface may prevent plant roots from accessing nutrients from surface layers (Mrabet *et al*., 2012; Dang *et al*., 2015).

Stratification refers to the accumulation of soil nutrients in certain areas more than in others (Dinkins *et al.*, 2014) or distribution of nutrients that is non-uniform with soil depth and especially situations with higher concentration of nutrients (such as P or K) near the soil surface (Grové *et al.*, 2007).

2.3.3. The impact of CA on soil biological properties

Additional SOC in a CA system can provide an energy source for soil microorganisms and lead to a greater microbial biomass relative to conventional agricultural systems (Gonzalez-Chavez *et al.,* 2010; Manglassery *et al*., 2015). Microorganisms include bacteria, fungi, algae and protozoa, mesofauna (nematodes) and macrofauna, like earthworms, arthropods and termites (Roper and Gupta, 1995). Increases in SOC and residue retention create a more favourable environment for the microbial populations due to improvements in soil aggregation, soil moisture and more favourable soil temperature, which can improve microbial abundance (Lupwayi *et al*., 2001; Govaerts *et al*., 2007). CA can also be associated with an improvement in the diversity of both fungal and bacterial populations, especially in the presence of more diversified crop rotations (Lupwayi *et al*., 2001; Gonzalez-Chavez *et al*., 2010; Yang *et al*., 2012).

Microorganisms play a key role in the decomposition of organic residues and thus in cycling of N, S and P (Balota *et al*., 2003). Microorganisms can also act as direct sources and sinks for nutrients (Singh *et al*., 1989). Balota *et al*. (2003) found that reduction of tillage had a much bigger effect on the microbial biomass, particularly in the 0-5 cm depth than did crop rotation. Tillage-induced differences in the soil nutrient status may also have a significant impact on root growth. The density of crop roots is usually greater near the soil surface under zero tillage compared to conventional tillage (Qin *et al*., 2004).

2.4. THE EFFECT OF RESIDUE RETENTION ON NUTRIENT STRATIFICATION

Farmers in most developing countries remove crop residues for use as fodder and/or bedding for animals, building material or fuel, resulting in great nutrient exports from agro-ecosystems (Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007; Bakht *et al*., 2009). Crop stubble is a main agricultural waste material as well as a renewable resource, due to it being rich in N, P and K (Huang *et al*., 2012). According to Scott *et al*. (2010), stubble retention implies standing stubble or surface-applied stubble or mulch. Crop residues are an important source of OM that can be returned to soil for nutrient recycling and to improve soil physical, chemical and biological properties (Kumar & Goh, 2000). Crop residues can be defined as biomass remaining on the soil's surface after harvest (Page *et al*., 2020).

Retention of plant residue has been found to have many long-term benefits like decreased soil erosion, increased soil water content and increase in soil biological activity. Soil water content increase is due to greater rate of infiltration and decreased soil water evaporation (Li *et al.,* 2019). Historically, stubble has been burnt because it improves weed control and creates easier passage for seeding equipment. The practice of stubble burning declined in the region due to concerns of soil and water erosion, loss of SOM and air pollution.

Crop stubble acts as a mulch that protects the soil against run-off and erosion. Retained stubble decreases erosion by reducing the raindrop energy at the soil surface and decrease run-off (Freebairn & Boughton, 1985; Dormaar & Carfoot, 1996). Nutrient loss due to runoff is also decreased (Smart & Bradford, 1999). Retained stubble increases the input of carbon to the soil. Mulching also reduces temperature extremes (Radford *et al.,* 1995) and direct evaporation which often results in improved crop production.

Where improvements in SOC are observed in CA systems, this can have significant effect on plant nutrient availability due to both changes to the quantity of nutrients available and their distribution in the soil profile (Li *et al*., 2019). According to this research, the total P and K concentration was significantly ($P<0.05$) greater in the top 5 cm depth of stubble retention treatments compared to stubble removal treatments. In the 10-30 cm depth, there was no difference in soil total P concentration among residue management systems. Stubble retention resulted in significantly greater SOM at the 0-30 cm depth (Huang *et al*., 2012).

Crop residues left on the soil surface and relatively immobile nutrients released from them (and other nutrient sources, including fertilisers) remain on or near the soil surface. Therefore, CA systems often result in greater stratification of soil properties than conventional tillage (Lupwayi *et al*., 2006). Differences in climatic conditions, local edaphic conditions, crop rotation systems and crop yield cause differences in the amount of crop residue that are returned to the soil (Chan *et al*., 2003; Franzluebbers & Steiner, 2002).

Plant characteristics like tissue stoichiometry, biomass cycling rates, above- and belowground allocation, root distributions and maximum rooting depth may all play an important role in shaping nutrient profiles (Jobbagy & Jackson, 2001). Easily decomposable plant residue, such as high-N leaf residues from lucerne, medics, pea and clover, can be mineralised relatively quickly (Bhupinderpal-Singh & Rengel, 2007). Non-legume crop residues (such as wheat, barley, maize and canola) with high C: N ratio may require more time (Bhupinderpal-Singh & Rengel, 2007).

Nutrient cycling in the soil-plant ecosystem is an essential component of sustainable productive agriculture. Knowledge of the effects of residue management e.g. residues left on the surface or mixed into the soil is essential when assessing effects of tillage practices resulting in different degrees of residue-soil contact (Yadvinder-Singh *et al*., 2005). The increase of C increases the number and activity of microorganisms (Huang *et al*., 2012).

2.5. THE EFFECT OF TILLAGE ON NUTRIENT STRATIFICATION

Tillage is defined as the mechanical manipulation of the soil for the purpose of crop production. Tillage can significantly affect the soil characteristics such as soil water conservation, soil temperature, infiltration and evapotranspiration processes (Busari *et al*., 2015). Tillage has been shown to affect the physical and biological processes in soils such as water conservation, microbial activity and earthworm population (Li *et al*, 2007). Tillage is used to prepare seedbeds that allow seed to be placed easily at a suitable depth when planting. Tillage helps release soil nutrients needed for crop growth through mineralisation and oxidation after exposure of SOM to air (Doran & Smith, 1987). Tillage is used to incorporate crop residues and ameliorants (lime & fertiliser) into the soil, making it more available to roots. Tillage gives temporary relief from soil compaction, and was critical in managing soil-borne diseases in the past and some insects (Hobbs *et al*., 2008).

Reduced tillage with appropriate crop rotation could increase the viability of dryland agriculture in semiarid zones (Martin-Ruenda *et al*., 2007). Maintaining and building soil quality is necessary for sustainable crop production in a conservation agriculture practices (Badagliacca et al., 2021). CA functions best when all three key features are adequately combined together in the field. In zero tillage (ZT), seed is put in the soil without any prior soil disturbance through any kind of tillage activity or only with minimum soil mechanical disturbance (Jat *et al*., 2014). No-tillage (NT) is the complete elimination of soil disturbance, except for seeding (Lal, 1997) or can be defined as a crop production system where weed control is accomplished entirely by herbicides and tillage is limited to the opening of a small slot for seed placement (Dick, 1983).

2.6 THE EFFECT OF CROP ROTATION ON NUTRIENT STRATIFICATION

Crop rotation is the agronomic practice of growing crops on the same paddock in sequence (Asseng *et al*., 2014). Crop rotation is an essential component of CA systems. Crop residues are an important source of soil organic matter and plant nutrients (Kumar & Goh, 2000). This significant carbon pool was traditionally lost when burnt or removed to feed farm animals (Kushwah et al., 2016). Legumes convert atmospheric N top plant available nitrate for their own use. Besides C, crop residues contain all mineral nutrients, the content of which varies among crop species (Brennan *et al*., 2004).

Diverse crop rotations can change soil habitat by affecting nutrient status, depth of rooting, amount and quality of residue, aggregation/microbial habitat and can stimulate soil microbial diversity and activity (Balota *et al*., 2004). The rotation of different rooting patterns combined with minimal soil disturbance in ZT promote a more extensive network of root channels and macro pores in the soil. This helps in water infiltration to deeper depths. Because rotations increase microbial diversity, the risk of pests and disease outbreaks for pathogenic organisms is reduced, since the biological diversity helps keep pathogenic organisms in check (Leake, 2003). Crop rotation and tillage impact microbial C dynamics, which are important for sequestering C to offset global climate change and to promote sustainable crop production (Balota *et al*., 2004). Crop rotation can change the quantity and quality of residues relative to monoculture cropping (Wright & Hons, 2005b).

Research results vary, especially between locations, on the effect of crop rotation on soil chemical properties. Balota *et al.* (2004) found few differences due to crop rotation on total C concentration in the soil.

The nutrients returned to the soil are affected by the amount and quality of the crop residues. Leguminous crops have low C/N ratios and this favours nitrogen mineralisation by soil microorganisms (Martin-Rueda *et al*., 2007; Haruna & Nkongolo, 2019). Wheat residues contain more lignin and decompose slowly due to the high lignin content. Legumes can add both organic C and N to the soil. SOM content and its mineralisation rate can influence levels of K, P and micronutrients in soil (Martin-Ruenda *et al*., 2007). Haruna & Nkongolo (2019) found higher OM within rotation compared with monoculture. Smith *et al.* (2020) found the largest difference between rotations in the top 0-10 cm of soil under no-till practices. An increase in OM can improve soil CEC and nutrient availability and environmental sustainability by increasing the nutrient retention. On the other hand, Martin-Ruenda *et al*. (2007) found that SOC and N were not affected by crop rotation.

The rate and extent of the stratification when changing from CT to CA depend not only on residue management, but also on climatic conditions, soil properties, cropping systems and fertiliser applications (Lal, 1997). Plant root geometry and morphology are important for maximising P uptake, because root systems that have higher ratios of surface area to volume will more effectively explore a larger volume of soil (Lynch, 1995). For this reason, mycorrhizae are also important for plant P acquisition, since fungal hyphae greatly increase the volume of soil that plant roots explore (Smith and Read, 1997).

CA can also be associated with an improvement in the diversity of both fungal and bacterial populations, especially in the presence of more diversified crop rotation (Lupwayi *et al*., 2001; Gonzalez-Chavez *et al*., 2010; Yang *et al*., 2012). Rotations of crops inhibit the build-up of weeds, insect pests and pathogens by interrupting their life-cycles, making them more vulnerable to natural predator species (Derpsch *et al*., 2010).

2.7 NUTRIENT STRATIFICATION

Changes in organic matter content are probably the most important long-term effect of CA and an important indicator of soil quality. Positively charged ions, like K, Mg, Ca and aluminum (Al) are held loosely in soil by attraction to the negatively-charged surface of soil particles. Organic matter is important to fertility because it provides many negatively-charged sites for holding exchangeable soil cations.

SOM is naturally very low in South Africa. It is estimated that 60% of the soils contain less than 0.5% SOM (Du Preez *et al*., 2011). Dick (1983) found that the organic C concentration in the 0-7.5 cm depth were significantly higher ($P< 0.001$) in the NT plots (3.01%) than the ploughed plots (2.02%). This accumulation was due to less soil-residue interaction, a lower rate of biological interaction and less erosion of soil high in organic matter. Quincke *et al.* (2007) reported that SOC accumulation occurred mostly in the top 5 cm of soil under continuous NT, while SOC losses often occurred at deeper depths.

In the sandy loam soil of the eastern Free State, tillage methods had a significant effect on organic C in the two upper soil layers, but no significant effect on the four deeper layers (Kotzé & Du Preez, 2007). The organic carbon in the 0-5 cm layer ranged from 0.6% in the ploughed plots to 0.84% in the no-tilled plots and in the 5-10 cm layer from 0.59% in the ploughed plots to 0.68% in the no-tilled plots (Kotzé & du Preez, 2007). In Spain under similar Mediterranean climatic conditions, SOC was significantly higher in the 0-5 and 5-10 cm layers under NT than CT (Hernanz *et al*., 2002). At the depths of 10-20 and 20-30 cm, no significant differences appeared between tillage systems. The organic C and N in the 0-5 cm depth were greater in NT than in CT soil, due to slower decomposition of organic matter (Ismail *et al.,* 1994).

In numerous studies, the pH of the non-limed topsoil was found to be lower for ZT than for CT (Franzluebbers & Hons, 1996; Dick, 1983; Blevins *et al*., 1983). Most differences in pH were only found in the topsoil (0-5 cm), although some authors observed a decline (Roldan *et al.,* 2007) in soil pH under ZT to a greater depth. Du Preez *et al*. (2001) found that the pH decreased as the degree of tillage intensified. Changes in soil pH are important for determining P and micronutrient availability, root growth and microbial activity (Franzluebbers & Hons, 1996). The most significant changes occurred in the surface layer where soil under no tillage had a lower pH, with less plant available iron (Fe) and copper (Cu) under CT, but more plant available P, K, Zn and Mn (Lal, 1997). The major problem with soil acidity is Al toxicity. When soil pH drops, Al becomes more soluble and the amount of aluminum (Al) in the soil solution increases. Toxic levels of Al in the soil solution affects root cell division and the ability of the root to elongate. Poor crop and pasture growth and yield reduction as a result of inadequate water and nutrition (Gazey & Davies, 2009).

On the other hand, Thomas *et al*. (2007) found that soil pH and exchangeable Mg was not affected by tillage or stubble treatments in the 0-10 cm depth, after nine years of NT, CT and reduced tillage in Queensland. Soil pH under NT was 0.1-0.2 units lower than under CT at a depth of 0-5 cm, but was not different between tillage regimes at other depths (Franzluebbers & Hons, 1996). Faba bean, lentil and chickpea are known to be sensitive to soil acidity and are successfully grown in pH $_{(KCl)}$ 5-6 (Anon, 2015).

Hussain *et al*. (1999) found that exchangeable Ca was significantly (P=0.05) higher under NT in the 0-5 cm layer compared to conventional tillage, attributed to the lack of tillage and concentration of crop residues at the soil surface.

Kotzé & du Preez (2008) reported that NT resulted in an accumulation of K, P, Ca and Mg in the upper 10-15 cm soil when ploughing served as reference. Bauer *et al.*, (2002) found 25% higher Mg under NT in the surface 0-5 cm. On the other hand, Thomas *et al*. (2007) found more exchangeable Mg and sodium (Na) in soil under CT than NT in the 0-10 cm depth and unaffected by stubble retention.

Nutrient stratification produces greater soil fertility near the surface which cause an increase in root length density near the soil surface under CT (Cannell & Hawes, 1994). Frequently, root growth is greater from 0-5 cm in conservation and no-tillage systems than in conventional tillage systems (Chan & Mead, 1992; Wulfsohn *et al*., 1996). NT causes greater and deeper water accumulation in the soil profile and greater root growth (Lampurlanes *et al*., 2001). Merrill *et al*. (1996) observed that wheat roots penetrated to greater soil depths under no tillage than under disc tilling, with larger root length density due to the cooler soil and superior soil water conservation in the near-surface zone.

There are several reasons why P is often highly stratified near the soil surface. P is highly reactive in soils binding with Fe, Al and Mn at low pH and Ca at high pH (Duiker & Beegle, 2006). Farming systems have shifted from intensive cultivation prior to sowing to no-till or minimum-till systems and this has reduced soil mixing and P in stubble retained systems is recycled to the soil surface.

In the 0-5 cm layer ploughed plots had lower P content than the mulched and no-tilled plots (Du Preez *et al.*, 2001). Extractable P was highest at the soil surface and decreased rapidly with depth (Franzluebbers & Hons, 1996). Extractable K exhibited a similar soil profile distribution as that observed for extractable P by Franzluebbers & Hons (1996). Selles *et al.* (1997) reported that total P in the surface 10 cm of soil increased significantly by 15% when soil inversion and disturbance were reduced by adoption of conservation agriculture.

Selles *et al.* (1997) also found that after 5 years in the ZT system, the total phosphorus showed a strong stratification with much higher levels at the surface layer than the layers below 4 cm ($P < 0.05$). In contrast, Holanda *et al*. (1998) found a greater concentration of P in the first layers of the soil regardless of the tillage system used. Neugschwandtner *et al*. (2014) found an accumulation of P and K with reduced tillage in the upper soil layers and depletion in the deepest soil layers over time. The surface 0-5 cm layer had 63% higher concentration of P than the 5-10 cm layer at the end of 8 years of NT in Queensland (Asghar *et al*., 1996).

Significant interactions between tillage and soil depth showed that it was particularly in the 0-5 cm soil layer that soil K was higher under ZT than CT (Lupwayi *et al*. 2006). Thomas *et al.* (2007) reported significantly higher exchangeable K in 0-10 cm soil depth under NT as compared to conventional tillage. The accumulation of K in the surface layers under NT may adversely affect the availability of K to plant roots, especially under dry spells during the growing season (Grant & Bailey, 1994; Deubel *et al*., 2011).

Nutrients like N (nitrate) and S (sulphate) are more mobile nutrients and soluble in the soil water (Johnston, 2002). CA could affect the distribution of these nutrients due to less soil mixing, soil water content, soil porosity and organic matter breakdown (Doran & Smith, 1987). Lupwayi *et al*. (2006) reported higher surface (0-5 cm depth) concentration of nitrate and ammonium-N and K under ZT than CT. The C: N ratio differed significantly in the 0-5 cm layer as a result of tillage (Kotzé & du Preez, 2007). Thomas *et al*. (2007) reported significantly higher total nitrogen in 0-30 cm soil depth under NT as compared to CT plots.

Organic matter is the main supplier of S in soil. Sulphur exists as mineral sulphates (such as calcium sulphate, magnesium sulphate and potassium sulphate), sulphide gas and elemental sulphur. In the soil solution, sulphate is replenished by mass flow and diffusion. Sulphates are easily leached (Yadvinder-Singh *et al*., 2005) and significantly increased with depth for all cropping systems and few differences between tillage regimes were observed (Wright *et al*., 2007).

Franzluebbers and Hons (1996) found significantly lower pH and extractable Cu and Fe under NT compared to CT in the upper 5 cm of soil whereas extractable P, K, Zn and Mn were higher. These researchers also found micronutrient cations (Zn, Fe, Cu and Mn) tended to be present in higher levels under ZT with residue retention compared to conventional tillage, especially extractable Zn and Mn near the soil surface due to surface placement of crop residues. In contrast, Govaerts *et al*. (2007) reported that tillage practice had no significant effect on the concentration of extractable Fe, Mn and Cu, but the concentration of extractable Zn was significantly higher in the 0-5 cm layer compared to conventionally tilled soil. The relative immobility of Zn in the soil could contribute to its stratification (Motta *et al*. 2002). Tillage systems did not affect the concentration of Cu in the soil (Shiwakoti *et al*., 2019).

Manganese decreased with depth, but no effect of tillage on Mn was observed by Wright *et al*. (2007). No significant effects of tillage on Cu were observed (Wright *et al*., 2007). Martin-Ruenda *et al.* (2007) found lower amounts of Fe, Mn, Cu and Zn under CT than MT and NT. In the 15-30 cm depth, soils under CT had a lower amounts of Fe and Zn than under MT and NT. Similar results were reported by Du Preez *et al.* (2001) and Franzluebbers & Hons (1996). Higher amounts of Mn, Cu and Zn were extracted by Santiago *et al*. (2008) under NT than CT or MT.

Nutrients get to plants in two ways, either the roots grow to the nutrient or the nutrient gets to the roots via soil water. Roots grow throughout the soil profile and use up nutrients directly around the root system and root hairs. As the concentration of nutrients around the root system drops, nutrients from higher concentration areas move (or diffuse) towards lower concentration areas towards the roots (FSSA, 2016). Potassium and phosphorus move in soil by diffusion. It needs a high concentration throughout the soil. Roots only come into contact with 1% of the soil volume (Fageria & Moreira, 2011).

In semi-arid Mediterranean environments, long-term NT, compared to CT, improves soil quality by increasing SOC and microbial biomass, thus potentially enhancing the contribution of the agroecosystem to mitigating and adapting to climate change (Badagliacca *et al*., 2021).

2.8 CONCLUSION

Tillage, residue retention and crop rotation as the principles of CA has a significant impact on pH, organic C and nutrient distribution. An increase in SOC leads to an increase in microbial biomass that on their part increase nutrient cycling of N, S and P. Nutrient cycling is an essential component of sustainable productive agriculture. Crop rotation with diverse species can change soil habitat by affecting microbial biomass. Research has shown that less mobile nutrients, like P, K and Zn becomes stratified in the top 5 cm of the soil.

Small grains have a limited rooting system that reduce their capacity to explore soil. They are also short-season crops that often are grown in cooler temperatures. Limited information is available to the effect of different degrees of soil disturbance and crop rotations on soil nutrient stratification in the Swartland and Overberg wheat producing areas and the contribution to sustainable agriculture.

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CHAPTER 3 STRATIFICATION UNDER CONSERVATION AGRICULTURE ON RESEARCH FARMS

3.1 INTRODUCTION

Conservation agriculture (CA) is gaining popularity because of, amongst others, the potential for C sequestration and beneficial effects on soil fertility and nutrient cycling (Wright, *et al*., 2007). The rapid growth in the adoption of conservation tillage is associated with the increasing pressures for food production around the world and the continuing concern about soil degradation by erosion, compaction and reduced fertility (Blevins and Frye, 1993). CA can provide positive environmental gain such as increased biodiversity, enhanced carbon sequestration and improved soil quality through an increase in soil organic matter (Michler *et al.,* 2019; Page *et al*., 2020). The absence of soil mixing in CA systems, especially those using NT, can also lead to the stratification of immobile nutrients at the surface of the soil profile. This can became a problem when drying at the surface may prevent plant roots from accessing nutrients from surface layers (Mrabet *et al.,* 2012; Dang *et al*., 2015).

In soil under CA, relatively immobile nutrients usually accumulate at the surface and decrease with depth (Franzluebbers and Hons, 1996; Holanda *et al*., 1998). Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), zinc (Zn) and manganese (Mn) all have limited mobility in the soil. When applied to the soil surface, it will remain in the top few centimeters, unless it is incorporated. The roots in the NT system mostly grow in the 0 to 5 cm layer compared to the roots in the CT system (Wulfsohn *et al*., 1996), while the opposite was true in lower layers (Chan & Mead, 1992; Rasmussen, 1991). Merrill *et al.* (1996) observed that spring wheat roots penetrated to greater soil depths under no tillage than under soil that was disc in spring, with larger root length density due to the cooler soil and superior soil water conservation in the near-surface zone. Mobile nutrients include nitrogen (N), sulphur (S), chloride (Cl) and boron (B), will move down the soil profile more easily. Nutrients in soil are replenished by mass flow and diffusion. In mass flow, water transpiring out of the leaves causes water to be drawn in through the roots, carrying nutrients along with it. In diffusion, nutrients move from an area of high concentration into one of lower concentration (Havlin *et al*., 2013). The greatest stratification or differences between surface and subsurface soils occurred for P, followed by Zn and K (Wright *et al*., 2007).

Currently little is known regarding the extent of nutrient stratification under CA in the southern Cape and Swartland regions. Long-term experiments are the primary source of information to determine the effects of cropping systems and soil management on soil productivity (Mrabet *et al.,* 2012). The aim of the study was to determine the extent and effect of CA on chemical stratification in the grain producing areas of the Western Cape. The objective of this study was to determine the long-term effect of conservation agriculture on topsoil stratification with different degrees of tillage and rotation sequences under controlled research conditions.

3.2 MATERIALS AND METHODS

3.2.1 Study sites

The research was conducted during 2018 as a component study on existing long-term crop rotation and tillage trials at the Tygerhoek (34˚29'32" S, 19˚54'30"E, altitude 158 m) near Riviersonderend and Langgewens Research Farms (33˚16'34" S, 18˚45'51" E; altitiude191 m) near Moorreesburg in the Western Cape Province of South Africa.

The soils at Tygerhoek are presented in Figure 3.1. Soil forms generally found at Tygerhoek are Mispah (Orthic A-Hard rock), Glenrosa and Swartland (Soil Classification Working Group, 1991). These are all poorly developed soils derived from Bokkeveld shale (Schloms *et al*., 1983) and very shallow, characterised by a very high stone content. The dominant clay minerals in the soil clay fraction are kaolinite and illite (Smith *et al*., 2020).

Figure 3.1 Soil map of trial area at Tygerhoek Research Farm (Vorster, 2015). Gs=Glenrosa, Km= Klapmuts, Oa=Oakleaf, Sw=Swartland, Tu=Tukulu soil form.

The soils form distribution at the Langgewens Research Farm are mainly derived from Malmesbury and Bokkeveld shales with Swartland (Orthic A-Pedocutanic B-saprolite) and Glenrosa (Orthic A-Litocutanic B, the dominant soil forms (Botha, 2013) as shown in Figure 3.2. These soils are hard and shallow (250-300 mm) in the dry state with weak structured A horizons (Maali & Agenbag, 2003). The clay content of the upper 0 – 300 mm was between 10-15% and classified as a sandy loam soil (Swiegelaar, 2014) with a gravel and stone content of 45% in the A horizon (Agenbag, 2012). The effective rooting depth is between 30 and 90 cm.

The average annual rainfall at Tygerhoek is 450 mm with 70% of the total rain occurring in April to October. Langgewens has a typical semi-arid Mediterranean climate with a mean annual temperature of 18.2 ˚C. The rainfall varies from 250 mm to 600 mm per annum of which about 80% occurs during the winter months April to September. Summer months are warm and dry, while the winter is cool and wet (ARC-ISCW, 2013).

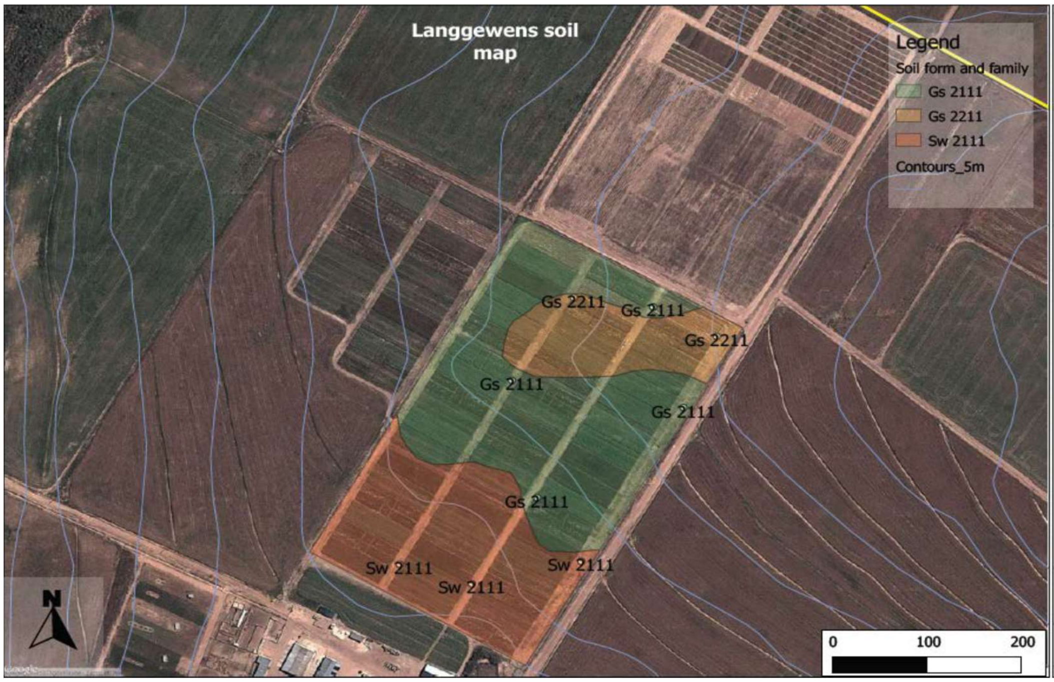

Figure 3.2 Soil map of trial area at Langgewens Research Farm (Swiegelaar, 2014).Gs=Glenrosa, Sw=Swartland soil form

3.3 EXPERIMENTAL DESIGN AND TREATMENTS

The long term field trials at Langgewens and Tygerhoek were designed to examine the effect of different rotation and tillage practices on soil quality and crop yield. Initial plots were all ZT (2000-2006) and in 2007 the current trial was initiated. The past 5 years, planting was done in the first week of May at Tygerhoek, except in 2019 when planting took place in the second week of May. At Langgewens planting took place in the third week of May in 2016 and in 2019 and 2020 planting was done in the second week of May. The other years planting took place in the first week of May. The experiment was designed as a randomised complete block with a split-plot arrangement and four replicates. The crops included in the study were: wheat (*Triticum aestivum*), canola (*Brassica napus*), lupine (*Dolichos* spp.) and medics-mix (*Medicago* spp.) grown in various crop rotations and cropping sequences and allocated to main plots.

The following four crop sequences were selected for this study:

1. Continuous wheat (WWW<u>W</u>),
2. Medic/wheat/medic/wheat (MWM<u>W</u>),
3. Wheat/medic/wheat/medic (WMW<u>M</u>) and

4. Lupine/wheat/canola/wheat (LWCW)

Last letter (underlined) in rotation code represents the crop residue on the field at time of sampling. Each main plot was subdivided into four sub-plots allocated to four tillage treatments, ranging from zero to maximum soil disturbance, namely:

1. Zero-till (ZT) – soil left undisturbed and planted with a star-wheel planter that places seed with minimal soil disturbance,
2. No-till (NT) – soil left undisturbed until planting and then planted with a tined planter that results in a maximum soil disturbance of 20% to a depth of 100 mm to 150 mm in the planting row,
3. Minimum till (MT) – soil scarified to a depth of ± 100-150 mm in late March/early April and then planted with an Ausplow no-till planter, and
4. Conventional tillage (CT)– soil scarified to a depth of ± 100 - 150 mm late March/early April, then disc ploughed (Tygerhoek) or ploughed (Langgewens) to a depth of ± 200 mm before planting with an Ausplow no-till planter.

The main plots at Tygerhoek are 80 m x 20 m with sub-plots of 35 m X 7.5 m and at Langgewens the plots are 60 m x 25 m with subplots of 25 m x 10 m. All straw, chaff and stubble remained on the soil surface and no grazing was allowed on any tillage treatments. Best practices were used on the trial. Disease, pest and weed control practices were carried out according to general local recommendations when necessary during the growing season. The star-wheel planter deposits the fertiliser at 3-4 cm deep. The no-till planter deposits the fertiliser 8-10 cm below the soil surface.

3.4 DATA COLLECTION

3.4.1 Soil samples

Ten soil samples were collected with a 40 cm diameter tube in February 2019 at 0-5, 5-10, 10-15, 15-20 and 20-30 cm depth increments and bulked per depth before the annual tillage treatments commenced in March. All sites that were sampled, were under wheat rotation in the previous year, except the WMWM crop sequence that was medic. At each replicate site 10 cores using a steel pipe (4 cm in diameter) and hammer were collected. The pipe was marked at the particular depth increments. When the pipe had been inserted into the desired depth, the pipe was pulled out of the ground and the soil collected in a plastic bag. After being transferred to the laboratory, the composite soil samples were air-dried and passed through a 2 mm sieve prior to chemical analyses at Elsenburg Analytical Laboratory. All chemical analyses were done according to standard methods: (The Non-Affiliated Soil Analysis Work Committee, 1990): organic C (Walkley-Black method), pH (1:2.5 soil to water suspension), exchangeable Ca, Mg, K and P (citric acid), extractable Cu, Fe, Mn and Zn (DTPA method) and B (hot water method).

3.4.2 Statistical analyses

The data were subjected to analysis of variance (ANOVA) using General Linear Models Procedure (PROC GLM) of SAS software (Version 9.2: SAS Institute Inc., Cary). The Shapiro-Wilk test on the standardised residuals from the model verified normality after outliers were removed (Shapiro and Wilk, 1965). Fisher's least significant difference was calculated at the 5% level to compare treatment means (Ott and Longnecker, 2010). A probability level of 5% was considered significant for all significance tests. In the tables and graphs, the small letters indicate significant differences among soil depths among the treatments ($p < 0.05$). Means followed by at least one common letter are not significantly different.

3.5 RESULTS AND DISCUSSION

In all the graphs (Fig 3.1 to Fig 3.21), the following abbreviations are used zero tillage (ZT), no tillage (NT), minimum tillage (MT) and conventional tillage (CT). The different letters on top of the bars denote a significant difference ($P < 0.05$).

3.5.1 Interaction effects

Crop rotation and its interaction with Tillage and soil Depth did not influence ($p < 0.05$) the distribution of nutrients in the soil at Tygerhoek Research farm (Appendix A1). The Tillage x Depth interaction was highly significant ($p < 0.05$) for pH, Ca, Na, Cu, S and Mn.

Crop rotation influenced ($p < 0.05$) the distribution of K and S in the soil at Langgewens Research Farm (Appendix A2). Only P and Zn were significantly ($p < 0.05$) influenced by Tillage at Langgewens. Sulphur showed no significant interactions between Crop rotation, Tillage and Depth, only the main effect of crop rotation was significant. The Tillage x Depth interaction was highly significant ($p < 0.05$) for all the nutrients, except Na, Mn and S. Furthermore, the parameters pH, K, Ca, Mg, P and B were significantly influenced by the rotation with tillage and depth interaction. Soil depth significantly influenced all the nutrient parameters at both Tygerhoek and Langgewens.

3.5.2 Soil organic carbon (SOC)

Figures 3.3 and 3.4 show SOC distribution with depth at Tygerhoek and Langgewens experimental sites, respectively. The Tygerhoek soils tended to have higher C contents than those at Langgewens. Typically, soil organic carbon (SOC) in the southern Cape tends to be above 1.5% compared to 1.0% or less in the Swartland. Summer rainfall and milder climatic conditions result in a more rapid breakdown of crop residues that are then incorporated into the soils of the southern Cape than is the case in the Swartland (Hardy *et al*., 2011).

At Tygerhoek, the organic C content decreased with depth, irrespective of tillage treatment, although this was not always significant. The least disturbed treatment (ZT) had significantly higher C (2.6%) in the 0-5 cm depth and as the degree of soil disturbance increased, the C content decreased (NT 2.23%> MT 2.15% > CT 1.96%). Soil C stratification was more severe between the 0-5 cm and 5-10 cm layers in ZT (37%) compared to NT (15%), MT (19%) and CT (11%) at Tygerhoek. The sharp decrease in C between ZT 0-5 cm and 5 - 10 cm was the result of little soil disturbance by the discs during the planting process. Only soil available P (0.35) was significantly ($P<0.01$) correlated to organic C (Appendix A5).

The influence of the tillage treatments on the soil organic C at Langgewens was similar to those observed at Tygerhoek. The 0-5 cm soil C level of ZT treatment was significantly higher than all the other treatments. The soil C levels under CT were more evenly distributed with depth. Increased soil disturbance resulted in lower C content in the 0 -15 cm layers. In the ZT system, the SOC significantly decreased with soil depth from 0 - 15 cm. Distribution of SOC under MT was intermediately stratified between CT and ZT. Hernanz *et al.* (2002) found, under similar Mediterranean conditions in Spain, that the interaction of tillage and soil depth on SOC revealed that CT was the most uniform distribution of SOC within the soil profile. At the same trial site, Cooper (2017) found soil C levels of 1.8% under NT, 1.7% under MT and 0.9% under CT in the 0-5 cm depth of the WMWM system. Organic matter is a reservoir of several nutrients, including P, Cu, Fe, Mn and Zn. It chelates micronutrients and thus increases their availability to plants through reduced precipitation with P (Ndiaye & Krishna, 2002) and oxides (Havlin *et al*., 2013). The soil organic C had a significant ($P<0.001$) positive correlation with Ca (0.65), Mg (0.68), P (0.51), Zn (0.64) and B (0.49) in the 0-5 cm layer at Langgewens (Appendix A8). Soil K (0.39) was significant ($P<0.01$) correlated with soil organic C in the 0-5 cm layer.

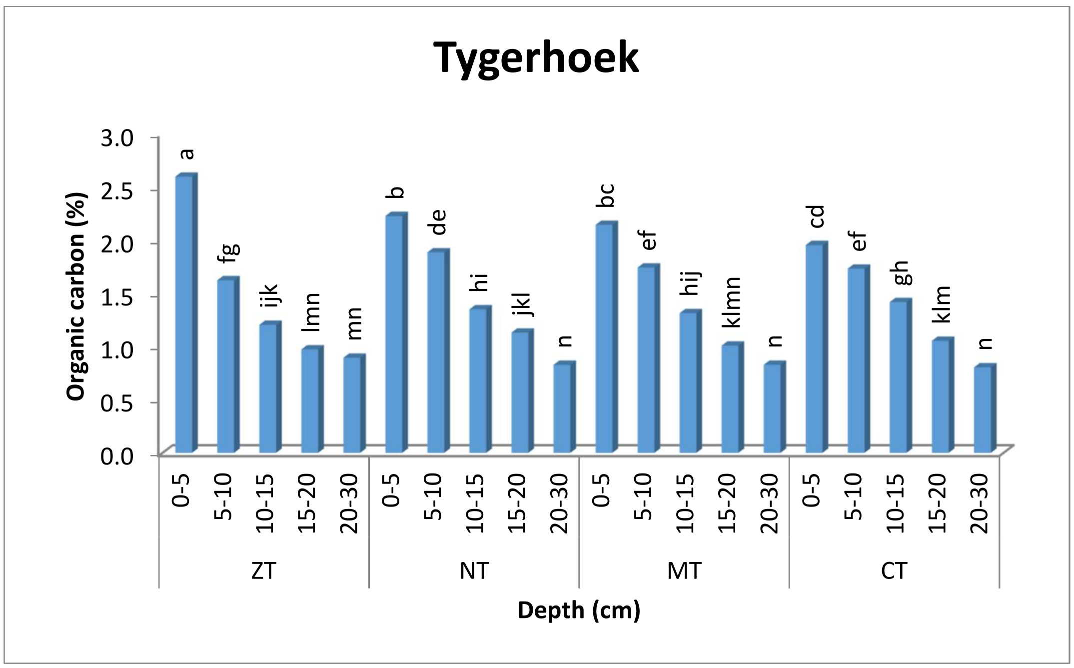

Figure 3.3 Depth distribution of soil organic carbon from 0 - 30 cm as influenced by tillage treatments and sampling depth at Tygerhoek long-term trial in 2018. Different letters on top of the bars denote a significant difference ($P < 0.05$).

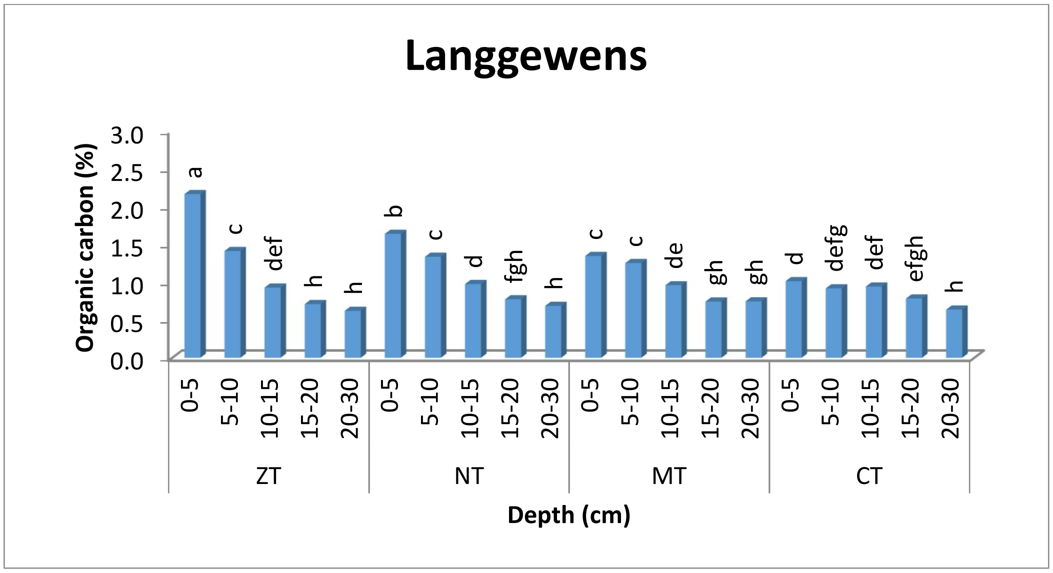

Figure 3.4 Depth distribution of soil organic carbon from 0-30 cm as influenced by tillage and sampling depth at Langgewens long-term trial in 2018. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

Several studies have indicated that stratification ratio (SR) for SOC range from 1.1 to 1.9 for conventional tillage and 2.1 to 4.1 for no-tillage (Díaz-Zorita & Grove, 2002). Stratification ratio (SR) has been shown to be an effective technique for monitoring soil C responses to climate, land use, tillage and other management effects. Therefore, the SR of SOC is frequently used as an indicator of soil quality (Diaz-Zorita & Grove, 2002; Franzluebbers, 2002; Sa & Lal, 2009). An SR of SOC > 2 indicated a high soil quality, with < 2 frequently found in degraded soils (Franzluebbers, 2002). Changes in the SR can show changes in the rate of SOC sequestration (Franzluebbers, 2002; Moreno *et al*., 2006). High SR of SOC reflect undisturbed soil and high soil quality of the surface layer. Table 3.1 shows the SR of the nutrients at Tygerhoek and Langgewens.

Soils with a stratification ratio greater than 2 are low in inherent levels of OM. The ratio could be improved with conservation tillage, despite modest or no change in total soil organic carbon within the rooting zone (Franzluebbers, 2002). The SR-values of 0 - 5 cm at Tygerhoek were all above 2, and decreased with increase in soil disturbance [ZT (2.9)> NT (2.7)>MT (2.6)>CT (2.4)]. At Langgewens, the SR for the top 5 cm showed a decrease with increase in soil disturbance as follows: ZT (3.48)> NT (2.39)>(1.81)>CT(1.59). In another long-term tillage trial at Langgewens, Tshuma *et al.* (2021) found a SR for SOC of 3.86 for NT compared to 1.12 for CT.

Table 3.1 Stratification ratio values for SOC at Tygerhoek and Langgewens Research Farms. ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

		Tillage treatment			
	Soil depth ratio	**ZT**	**NT**	**MT**	**CT**
Tygerhoek	0-5: 20-30	2.90	2.69	2.59	2.43
	5-10: 20-30	1.81	2.28	2.10	2.15
	10-15: 20-30	1.35	1.63	1.59	1.76
Langgewens	0-5: 20-30	3.48	2.39	1.81	1.59
	5-10: 20-30	2.27	1.95	1.68	1.44
	10-15: 20-30	1.49	1.42	1.29	1.48

3.5.3 Soil pH, exchangeable calcium and magnesium

Soil pH as a measure of soil acidity is one of the most important soil fertility indicators, as it influences several soil processes including nutrient dynamics (Loke & Kotzé, 2013). The levels of Ca and Mg in soils are related to pH (Barnard & Du Preez, 2004). Soils under continuous no-till often produce stratified soil acidification due to surface fertiliser or lime placement and subsequent lack of mixing (Barth *et al.* 2018). Figures 3.5 and 3.6 show soil pH distribution with depth at Tygerhoek and Langgewens experimental sites, respectively. At Tygerhoek the $pH_{(KCl)}$ values never dropped below 5.5, but at Langgewens the $pH_{(KCl)}$ values went as low as 5.1 in the ZT in the 15-20 cm zone. Low pH becomes a problem when it is below the critical level for optimal levels for cereals (pH 5.2-5.4) or legumes (pH 5.4-5.6) (Tang *et al.*, 2003). The soil pH difference between the southern Cape and Swartland soils is likely due to the lower base saturation of Swartland due to differences in parent material (Liebenberg *et al.*, 2020).

At Tygerhoek, the pH of the 0-5 cm layer (pH 6.2) under NT was significantly higher than those of the other depths under NT, but not significantly higher than 0-5 cm under ZT. The pH of the MT and ZT 0-5 cm layers were significantly higher than those of the deeper depths. Unlike the CA systems, under CT, there were no significant differences in soil pH between the 0-5 and 5-10 cm layers. Similarly, at Langgewens, all the CA treatments showed significant differences in soil pH between 0-5 cm and deeper soil depths, while CT showed no significant difference in pH values between 0-5 cm and 5-10 cm layers. The distinct 0-5 cm pH stratification observed in the CA sites is likely due to little or no mixing of surface applied lime. The soils at Tygerhoek and Langgewens were limed in 2012 at a rate of 1 ton.ha^{-1} calcite. Lime is highly immobile in soils due to its low solubility (Manson & Findlay, 2015). It is further clear that, as the extent of soil disturbance increases from ZT to MT, so the extent of pH stratification decreases at both sites.

At Langgewens, the 5-30 cm soil layers under CT had a significantly higher soil pH than the other tillage treatments, further illustrating the effect of tillage on lime incorporation. Soil pH stratification due to surface lime application in CA grain production systems has recently been shown to be widespread in the Swartland (Liebenberg *et al*., 2020). Shale derived parent materials generally have a higher pH compared to highly weathered soils (Fey, 2010). Burns *et al*. (2017) reported that in South East Australia the traditional pH measurements of 0-10 cm and 10-20 cm depths underestimated the pH stratification in the soil profile compared to tests from finer sampling increments.

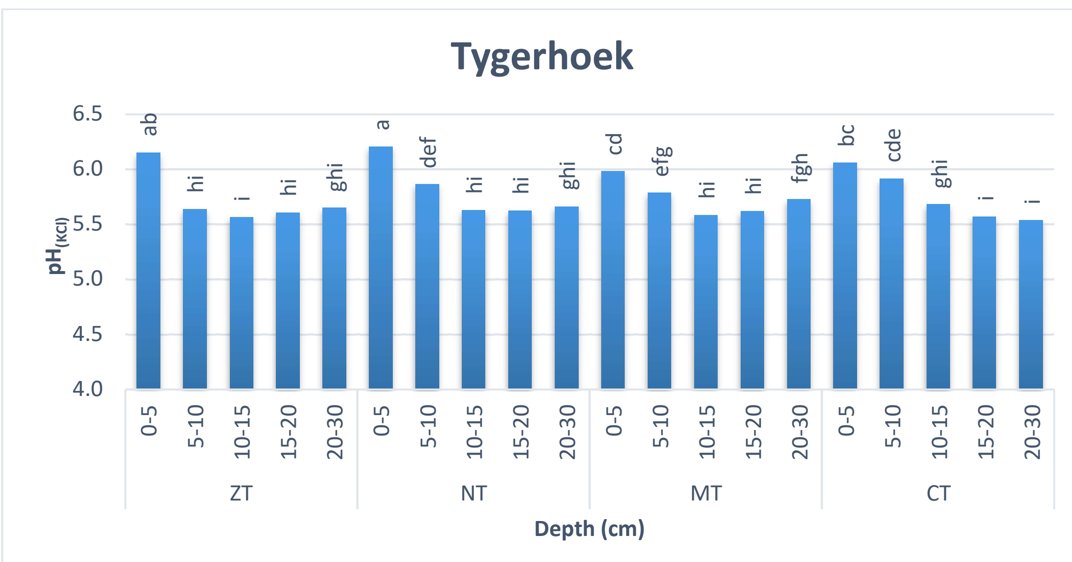

Figure 3.5 Depth distribution of soil pH $_{(KCl)}$ from 0-30 cm as influenced by tillage treatment and sampling depth at Tygerhoek long-term trial. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

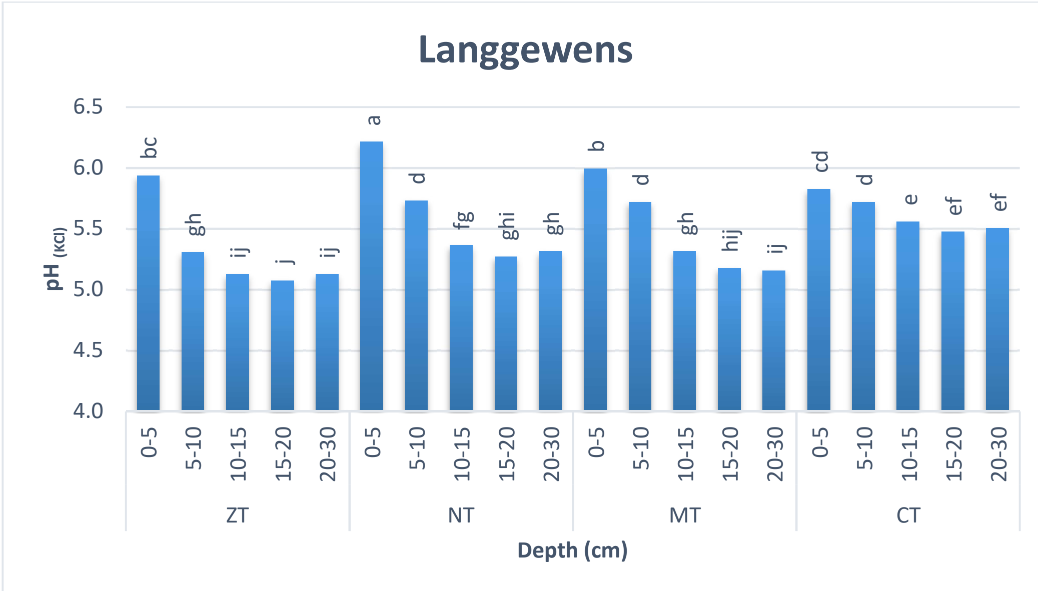

Figure 3.6 Depth distribution of soil pH (KCl) from 0-30 cm as influenced by tillage treatment and sampling depth at Langgewens long-term trial. Different letters on top of the bars denote a significant difference (P<0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

Figures 3.7 and 3.8 show soil exchangeable Ca distribution (0-30 cm) at Tygerhoek and Langgewens experimental sites, respectively. At both Tygerhoek and Langgewens the CA treatments had significantly higher Ca content at 0-5 cm compared to the 5-10 cm with ZT(49-51%) > NT (31-38%) > MT (16-18%), while CT did not result in a significant difference. The lower the extent of soil disturbance, the higher the % increase in Ca content in the 0-5 cm layer. All the tillage treatments showed a decline with depth in Ca levels. The soils at Tygerhoek and Langgewens were limed in 2012 at a rate of 1 ton ha^{-1} calcite and 1 ton ha^{-1} dolomite and in 2018 with 2 ton ha^{-1} calcite.

As previously discussed, lime is highly immobile in soil, thus it remains on the surface if not incorporated. In the CT treatments, the Ca content was more evenly distributed in the 0-10 cm layers. The lime was ploughed into the soil to a depth of 200mm with a disc plough.

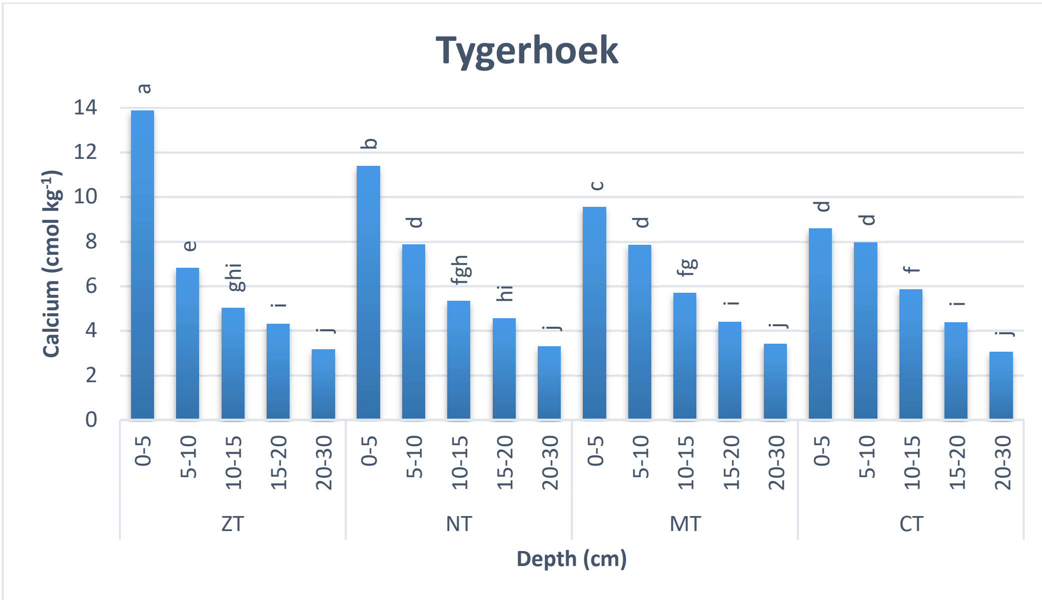

Figure 3.7 Depth distribution of soil exchangeable calcium from 0-30 cm as influenced by tillage treatment and sampling depth at Tygerhoek long-term trial. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

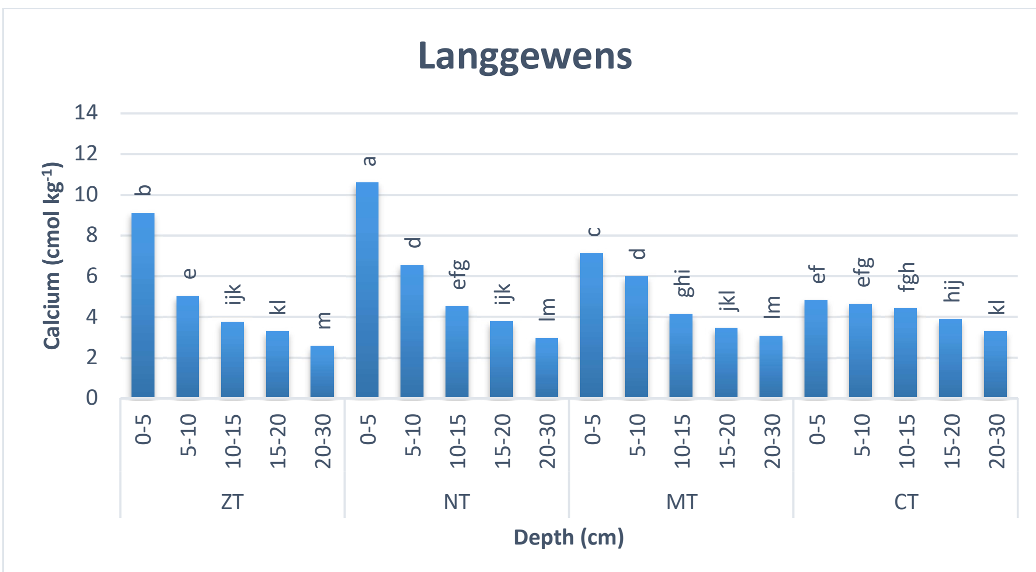

Figure 3.8 Depth distribution of exchangeable calcium from 0-30 cm as influenced by tillage treatment and sampling depth at Langgewens long-term trial. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

Figures 3.9 and 3.10 show exchangeable Mg distribution (0-30 cm) at Tygerhoek and Langgewens experimental sites, respectively. Magnesium (0-5 cm) stratification was more pronounced at Langgewens compared to Tygerhoek. This is likely due to the higher inherent Mg content for the subsoil (20-30 cm) at Tygerhoek (2.2-2.4 cmol.kg^{-1}) compared to Langgewens (07-0.9 cmol kg^{-1}). As previously discussed, this is related to differences in base saturation and parent material in the two regions. (Liebenberg *et al,* 2020). At Tygerhoek, all CA treatments had significantly higher Mg content at 0 - 5 cm compared to the 5 - 10 cm depths, with % differences ZT (20%) > NT (11%) > MT (2%).

Similarly, at Langgewens under CA was as follows: ZT (51%) > NT (38%) > MT (28%). No significant ($P<0.05$) difference occurred between the depth intervals under CT for Mg. There were no statistical differences in the 15-30 cm layers between the different tillage treatments. Magnesium does not get routinely supplemented at the sites, thus the stratification observed at CA sites is likely due to surface accumulation of organic residues, which provide basic cations and cation exchange capacity.

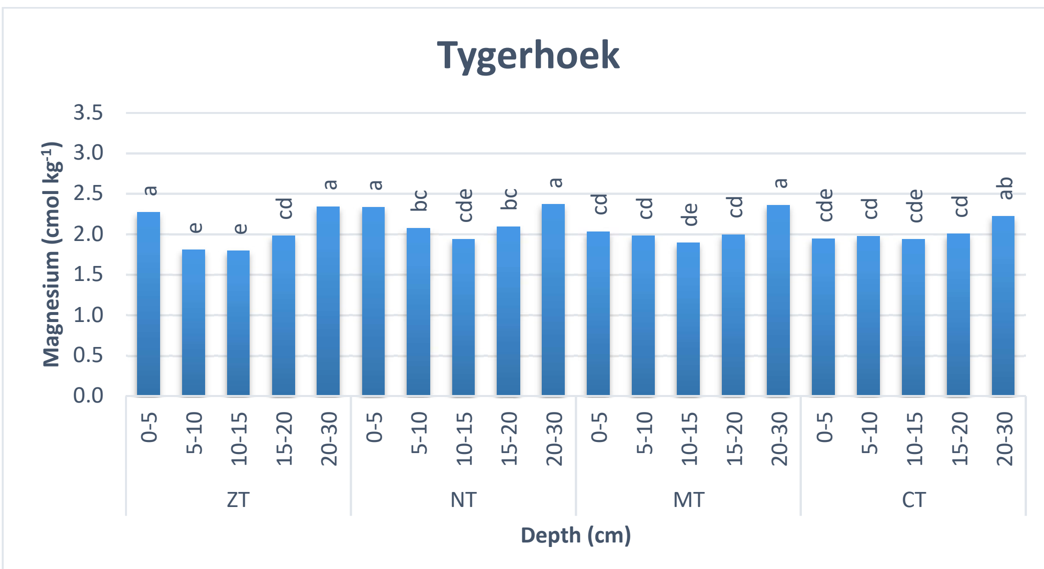

Figure 3.9 Depth distribution of soil exchangeable magnesium from 0-30 cm as influenced by tillage treatment and sampling depth at Tygerhoek long-term trial. Different letters on top of the bars denote a significant difference ($P < 0.05$). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

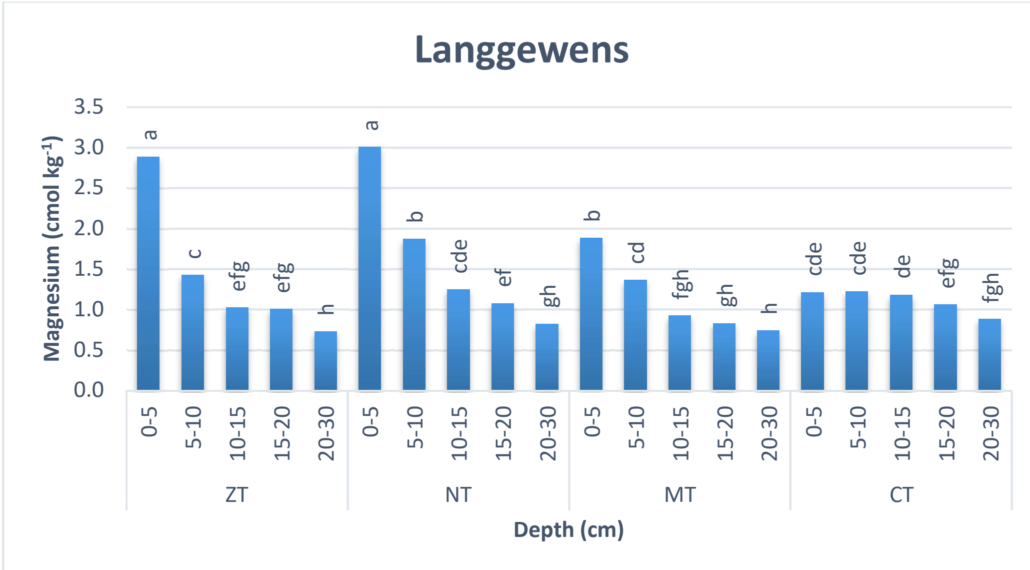

Figure 3.10 Depth distribution of soil exchangeable magnesium from 0-30 cm as influenced by tillage treatment and sampling depth at Langgewens long-term trial. Different letters on top of the bars denote a significant difference ($P < 0.05$). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

3.5.3 Phosphorus, potassium and sulphur

Figures 3.11 and 3.112 show soil extractable P distribution (0-30 cm) at Tygerhoek and Langgewens experimental sites, respectively. Phosphorus is a very immobile nutrient due to its reactive nature, which easily precipitates with cations such as Ca, Fe or Al, or adsorbs on edges of soil clays (Havlin *et al.,* 2013). At both sites, annually, the wheat and canola treatments received 12 kg ha^{-1} P in the form of 2:1:0 (29) + S and the lupine treatments received single superphosphate equivalent to 14 kg P ha^{-1}. Additionally, in 2017 all the treatments at Tygerhoek received 200 kg ha^{-1} superphosphate to increase the P and S in the soil.

Subsoil (20-30 cm) P levels were significantly higher at Langgewens (39 - 52 mg kg^{-1}) compared to Tygerhoek (6-7 mg kg^{-1}). As a result, P stratification was more evident at Tygerhoek than Langgewens, even in the CT treatments. The extent of P stratification of the 0-5 cm layer was substantially higher at Tygerhoek [ZT (48%) > NT (26%) > MT (19%) > CT (15%)] compared to Langgewens [ZT (21%) > NT (11%) > MT (8%)]. There was no significant P stratification under CT at Langgewens, except for the 20-30 cm layers being significantly lower. When the different depth increments were compared between the tillage treatments, only the 0-5 cm layers were significantly different between the treatments (ZT>NT>MT>CT). Higher P levels in surface soils compared to sub surface soils are attributed to the immobile nature of surface applied mineral P fertilizers, and the decomposition of soil organic residues (Wright *et al*., 2005).

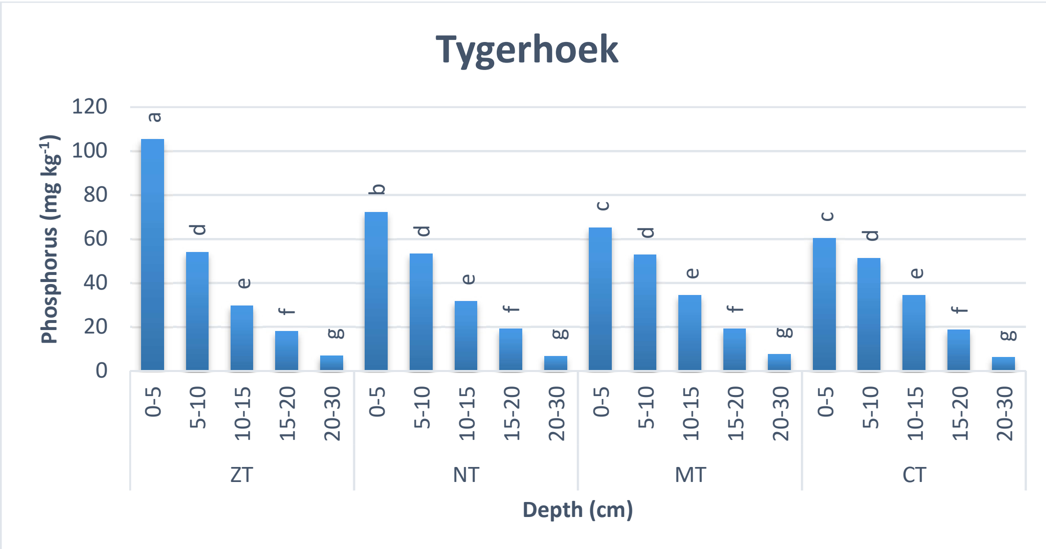

Figure 3.11 Depth distribution of soil extractable phosphorus 0-30 cm depth as influenced by tillage treatment and sampling depth at Tygerhoek long-term trial. Different letters on top of the bars denote a significant difference ($P < 0.05$). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

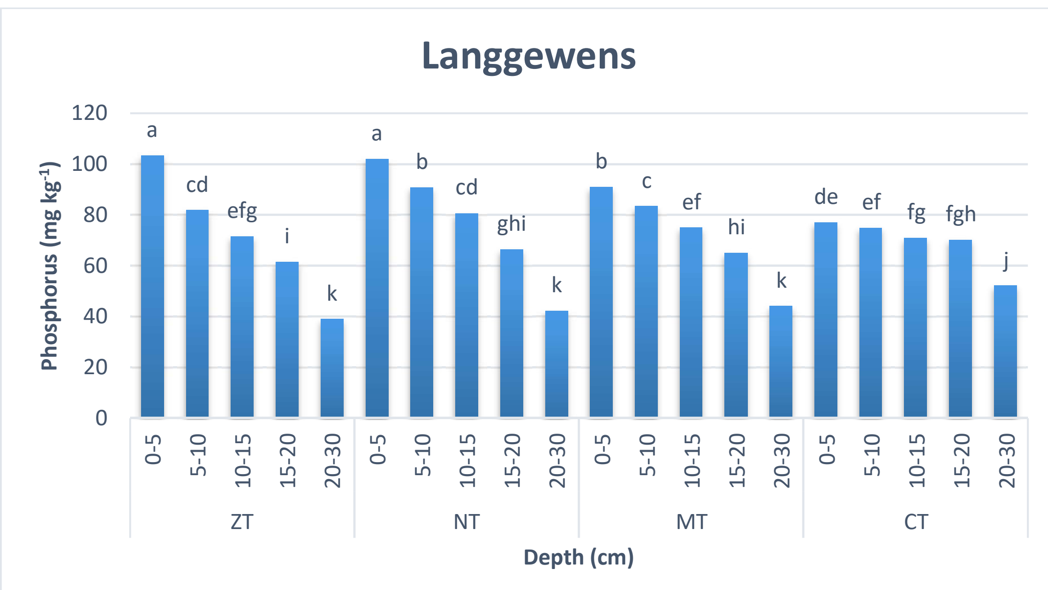

Figure 3.12 Depth distribution of soil extractable phosphorus from 0-30 cm as influenced by tillage treatment and sampling depth at Langgewens long-term trial. Different letters on top of the bars denote a significant difference ($P < 0.05$). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

Figures 3.13 and 3.14 show soil exchangeable K distribution (0-30 cm) at Tygerhoek and Langgewens experimental sites, respectively. Historically the soils were considered high in K and thus did not receive any K fertiliser. Western Cape cereal soils derived from K-rich Bokkeveld shale and Malmesbury shale, generally require little additional K fertilisation, except where high N applications are made (Laubscher, 1980). In all the tillage treatments, K accumulated at the surface and decreased with increasing depth in all the treatments. Similar to Mg, the subsoil (20–30 cm) exchangeable K at Tygerhoek (127-134 $mg.kg^{-1}$) was higher than at Langgewens (87-99 $mg.kg^{-1}$). Thus, stratification was more pronounced at Langgewens. At both sites, under all the tillage treatments, K was significantly higher at the surface and decreased with increasing depth.

At Tygerhoek, the increase in K stratification at 0-5 cm layers compared to the 5-10 cm layers was as follows: ZT (29%) > NT (23%) > CT (20%) and MT (16%), while at Langgewens it was: ZT (79%) > NT (37%) > MT (24%) and CT (21%). Crop residues are good sources of K because they contain more K than grain and most of the K is released from the residues, because it is in inorganic form in plants (Lupwayi *et al*., 2006). The changes in K levels between the 0-5 cm and 5-10 cm layers in ZT was the highest (29%) compared to the other treatments [20% (CT), 16% (MT) and 23% (NT)]. Asghar *et al*. (1996) reported an exchangeable K concentration 70% greater in the 0-5 cm layers than in the 5-10 cm layers at the end of 8 years of NT in Queensland.

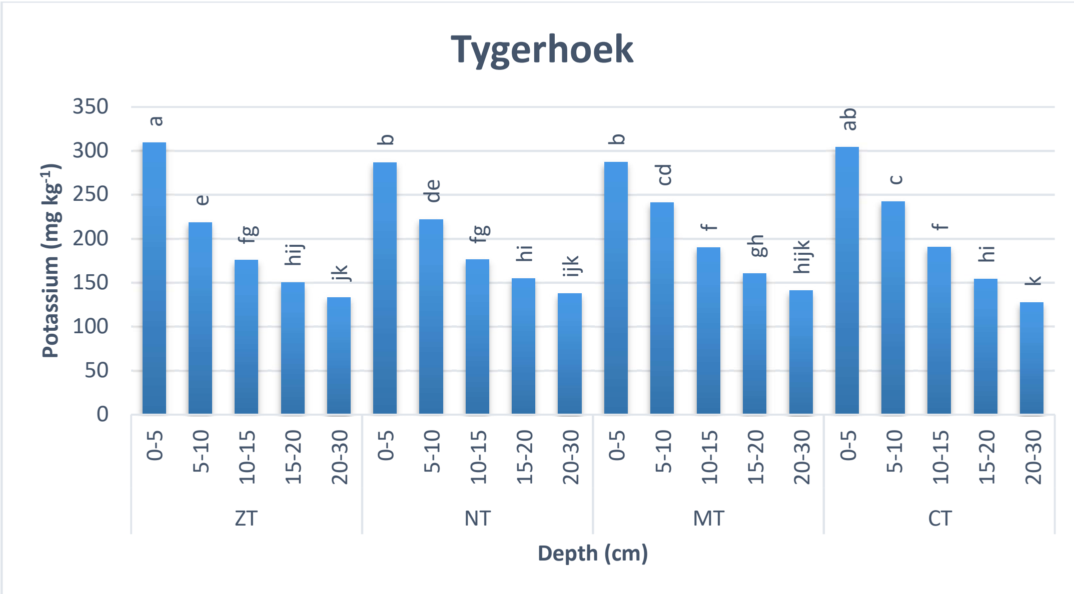

Figure 3.13 Depth distribution of soil exchangeable potassium from 0-30 cm as influenced by tillage treatment and sampling depth at Tygerhoek long-term trial. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

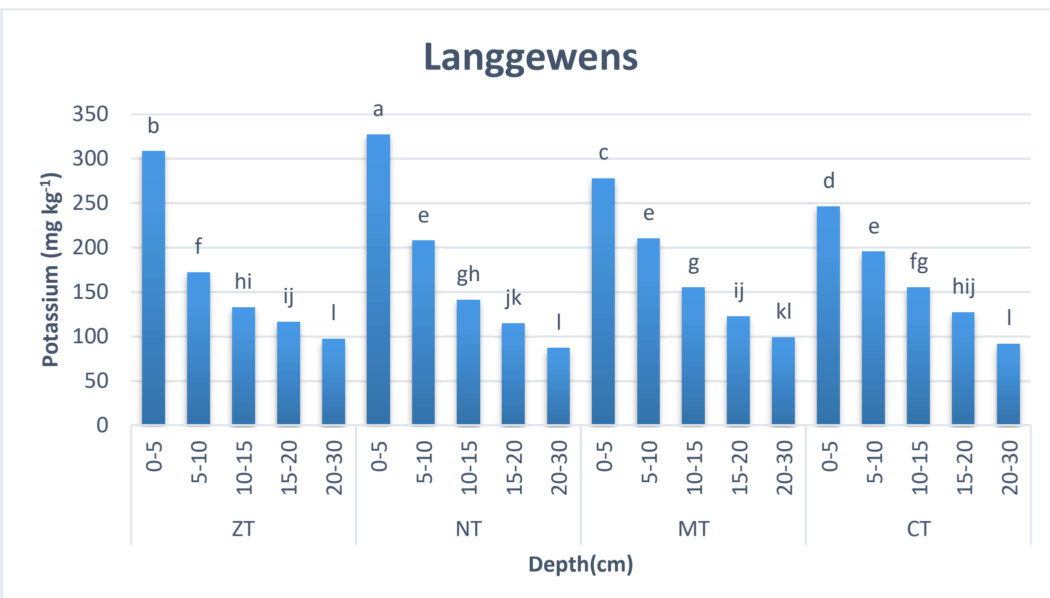

Figure 3.14 Depth distribution of soil exchangeable potassium from 0-30 cm as influenced by tillage treatment and sampling depth at Langgewens long-term trial. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

Figures 3.15 and 3.16 show soil exchangeable S distribution in the (0-30 cm) layers at Tygerhoek and Langgewens experimental sites, respectively. The average S content of the soil at Tygerhoek was much higher than Langgewens, ranging between 22.9 to 52.3

mg.kg^{-1} S and 9.5 to 16.1 mg.kg^{-1} S, respectively. This difference is likely due to the differences in parent material as previously discussed, and also all the plots at Tygerhoek received an additional 200 kg.ha^{-1} superphosphate in 2017 to increase the S and P in the soil. At both Tygerhoek and Langgewens, wheat and canola plots received 129 kg ha^{-1} 2:1:0 (29) +S at planting and lupines received 143 kg ha^{-1} single superphosphate annually. Topdressing was done ±40 days after emergence with LAN + S (27% N + 3% S) at a rate of 40 kg N for wheat and 50 kg N for canola. At Tygerhoek, the stratification in the 0 - 5 cm layer compared to the 5 -10 cm layers was as follows: ZT (15%), NT (22%), MT (1%) and CT (-24%).

The exchangeable S in the soil at Langgewens showed no significant stratification, likely due to the low inherent S levels and low annual S inputs. According to the Canola Production Guidelines (2016), a soil with S content between 7 mg kg^{-1} and 12 mg kg^{-1} S needs 15 kg ha^{-1} S for maintenance. The soil at Langgewens should thus have received more S at planting for optimum fertility for crop production.

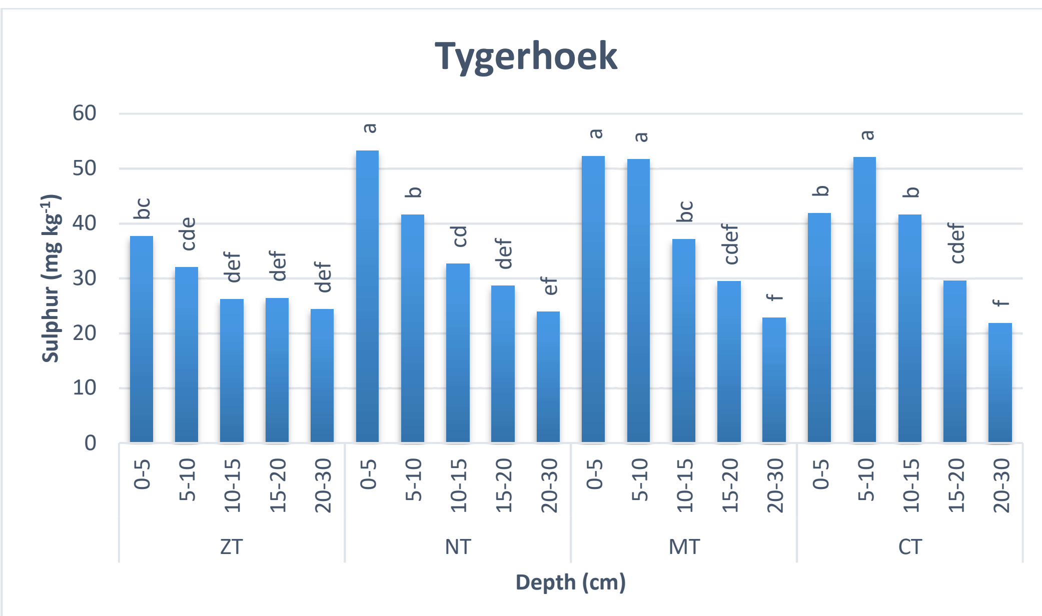

Fig 3.15 Depth distribution of soil exchangeable sulphur from 0-30 cm as influenced by tillage treatment and sampling depth at Tygerhoek long-term trial. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

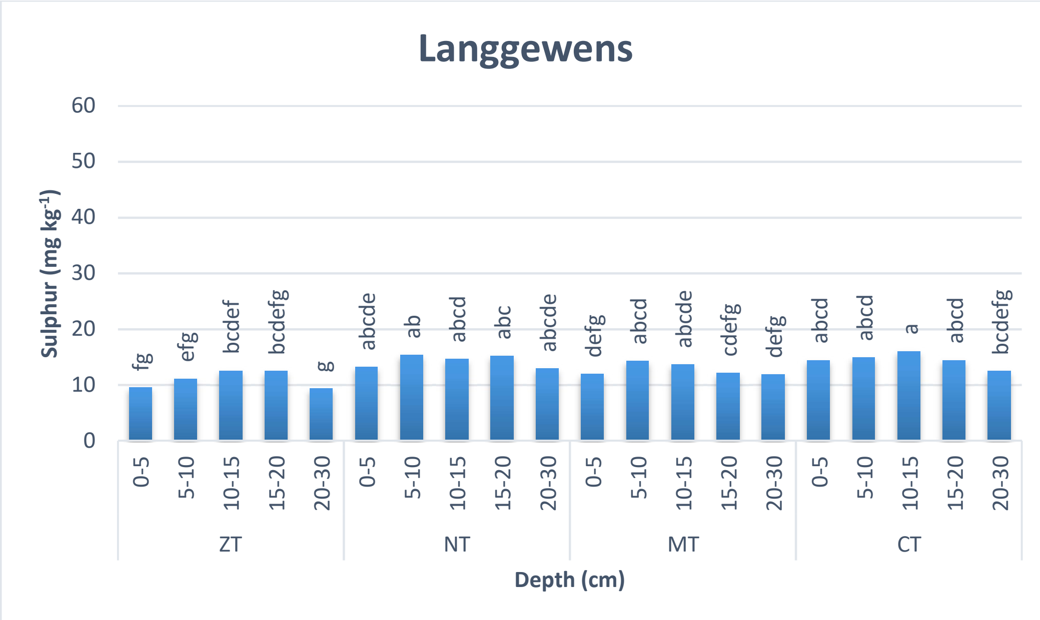

Fig 3.16 Depth distribution of soil exchangeable sulphur in the 0-30 cm layers as influenced by tillage treatments and sampling depth at Langgewens long-term trial. Different letters on top of the bars denote a significant difference ($P < 0.05$). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

3.5.4 Extractable trace elements

Figures 3.17 and 3.18 show soil extractable Zn distribution in the 0-30 cm layers at Tygerhoek and Langgewens experimental sites, respectively. At Tygerhoek, Zn showed significant stratification in the 0-5 cm layers for ZT, NT and MT respectively. The percentage of change between the 0-5 cm layer decreased with increase of soil disturbance [ZT (44%)> NT (28%)> MT (10%)]. The relative immobility of Zn in the soil could contribute to its stratification (Motta *et al.,* 2002; Shiwakoti *et al*., 2019). The mobility of zinc is low in soil mainly due to its strong adsorption to clay particles. Zinc becomes more soluble as soil pH decreases (Havlin *et al*., 2013).

Comparing the Zn content in the corresponding depth increments at Langgewens, the Zn in the 0-5 cm layers of ZT (6.74 mg kg^{-1}) and NT (6.15 mg kg^{-1}) were significantly higher than all other layers. The % change between 0-5 cm and 5-10 cm layers decreased with increasing soil disturbance [ZT (36%)>NT (29%)>NT (10%)].

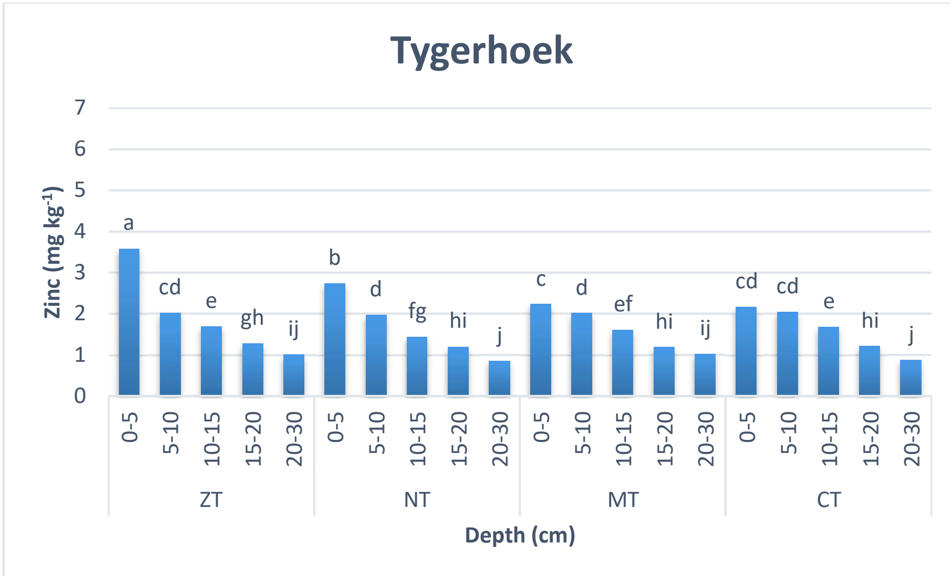

Figure 3.17 Depth distribution of soil extractable zinc from 0-30 cm as influenced by tillage treatments and sampling depth at Tygerhoek long-term trial. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

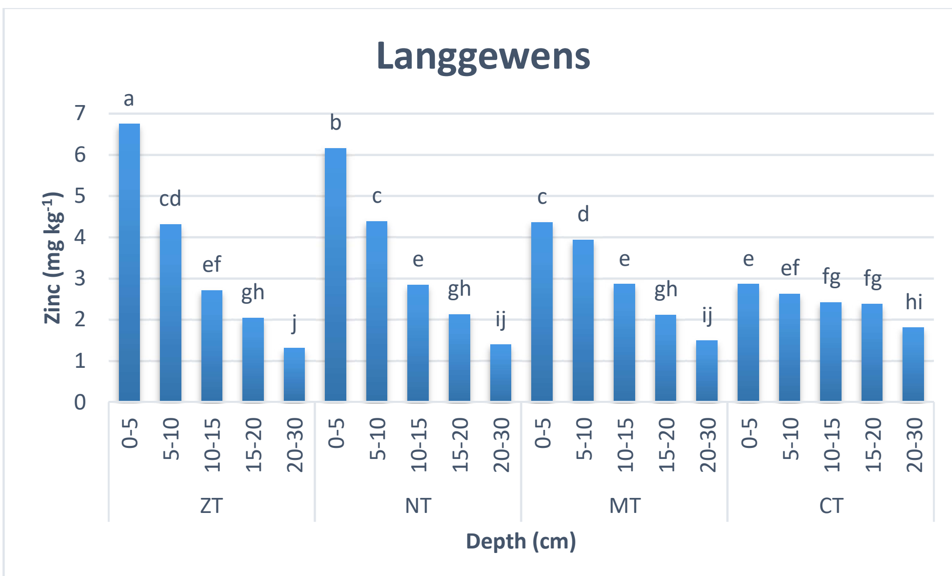

Figure 3.18 Depth distribution of soil extractable zinc from 0-30 cm as influenced by tillage treatment and sampling depth at Langgewens long-term trial. Different letters on top of the bars denote a significant difference (P < 0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

Figure 3.19 shows soil extractable B distribution (0-30 cm) at Langgewens experimental site. Boron data for Tygerhoek was not available. Boron showed the same tendency as Zn where only the 0-5 cm layers under ZT and NT were significantly higher than that of the other layers. The soil B under CT showed no significant differences at different depths.

When the increase in B stratification at 0-5 cm layer was compared to that of the 5-10 cm layer, the results at Langgewens were as follows: ZT (37%)>NT (22%)> MT (8%)>CT (6%). The boron was deemed deficient in the soil at Langgewens for the production of wheat and canola. According to Saha *et al*. (2018), the critical level for B in soil for wheat is 0.5 mg kg^{-1}. Soils of the canola-producing regions in the Western Cape often exhibit low boron contents. Boron is one of the eight essential micronutrients required for normal growth and development of most plants. Canola (*Brassica napus*) has a high demand for boron and may be a yield-limiting factor in these areas (Agenbag & Kempen, 2015). Lavado *et al*. (1999) found that the concentration of B showed no significant differences between tillage treatments in Argentina.

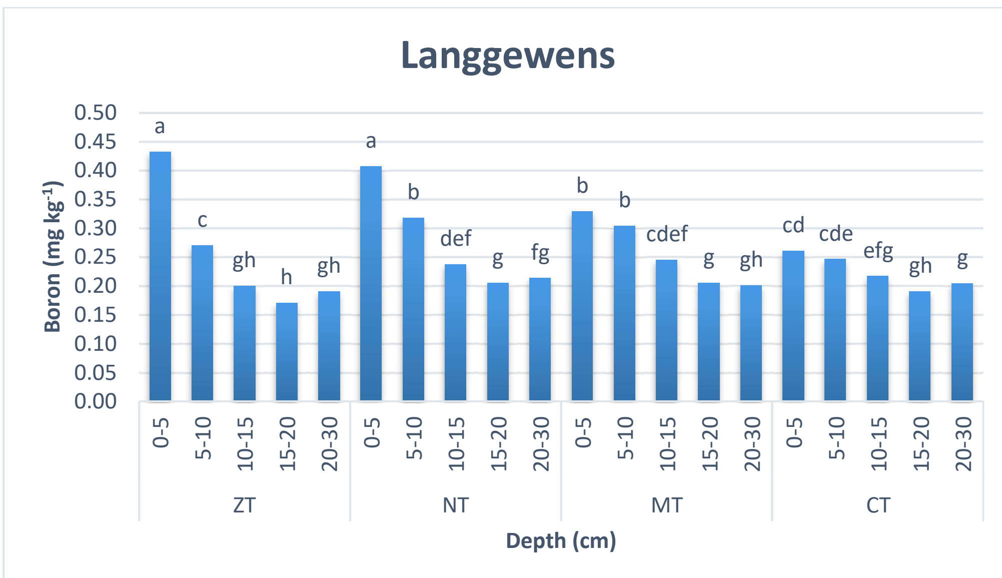

Figure 3.19 Depth distribution of soil extractable B from 0-30 cm as influenced by tillage treatments and sampling depth at Langgewens long-term trial. Different letters on top of the bars denote a significant difference (P<0.05). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

Figures 3.20 and 3.21 show soil extractable Mn distribution (0-30 cm) at Tygerhoek and Langgewens experimental sites, respectively. In the 0-15 cm layer at Tygerhoek (Fig 3.20), there was no significant stratification in any of the tillage treatments. From 10 cm and deeper, the soil Mn decreased with depth. At Langgewens, however, the Mn content tended to increase with depth, though this was not significant. The soil Mn levels is high throughout the soil and little stratification took place. Manganese availability is strongly affected by soil pH, becoming more soluble as soil pH decreases.

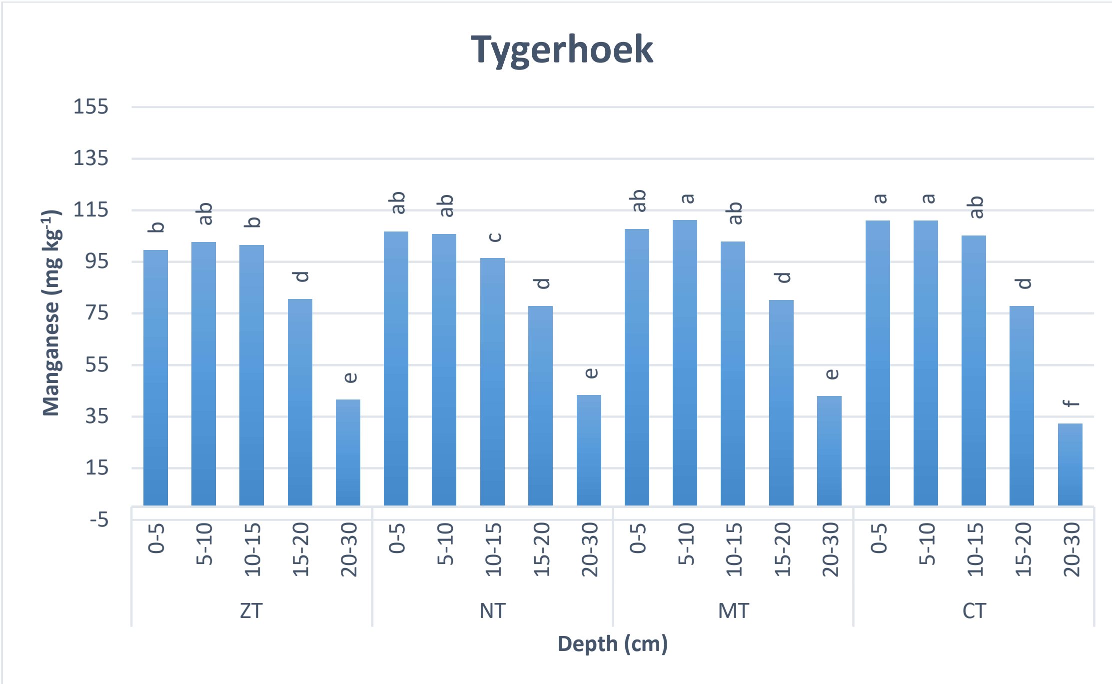

Figure 3.20 Depth distribution of soil extractable Mn from 0-30 cm as influenced by tillage treatment and sampling depth at Tygerhoek long-term trial. Different letters on top of the bars denote a significant difference ($P < 0.05$). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

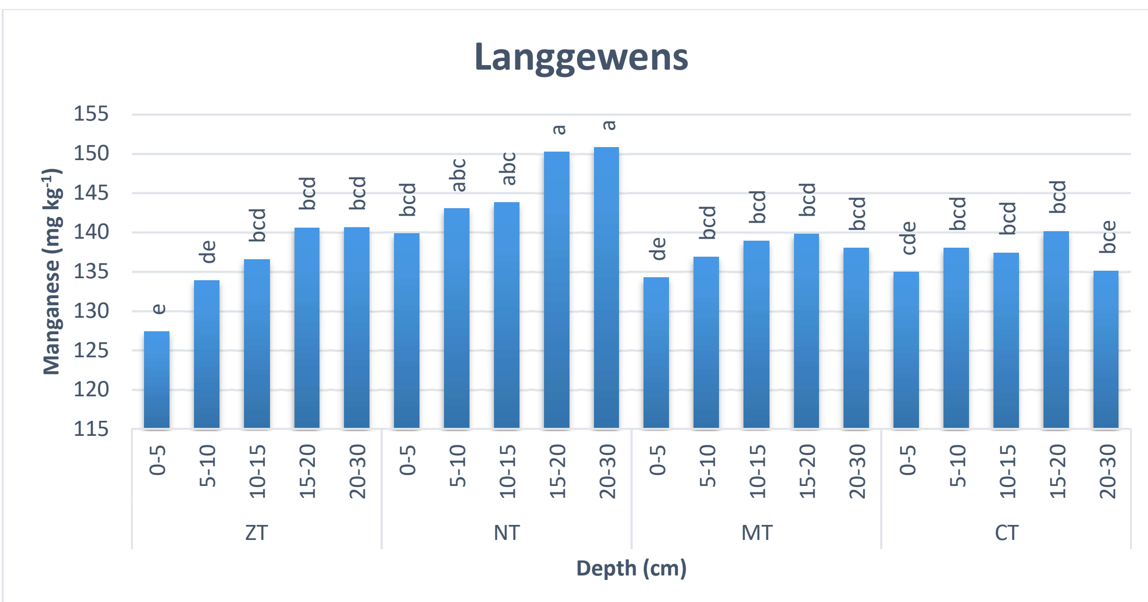

Figure 3.21 Depth distribution of soil available Mn from 0-30 cm as influenced by tillage treatments and sampling depth at Langgewens long-term trial. The different letters on top of the bars denote a significant difference ($P < 0.05$). ZT=zero tillage, NT=no-tillage, MT=minimum tillage and CT=conventional tillage.

3.5.5 Yield data and rainfall

Comparing average wheat yield for the past 5 years (2016-2020) for each tillage treatment at Tygerhoek Research Farm, significant difference between tillage treatments were only found in 2016. ZT was significantly (P<0.001) higher than NT, MT and CT. In the Swartland when the average wheat yield of the tillage treatments were compared for 2016 to 2020, ZT was either significantly lower (2016), higher (2019) or showed no difference from NT, MT and CT. This shows that nutrient stratification was not a limiting factor in production, but rather other production factor such as climatic conditions

Table 3.2 Average yield (ton ha^{-1}) at Tygerhoek for the different tillage treatments from 2016 to 2020. The different letters show the significant difference (P<0.05) in each year.

Tillage	2016	2017	2018	2019	2020
ZT	2557^{a}	2813^{a}	3829^{a}	2036^{a}	4307^{a}
NT	2076^{b}	3549^{a}	3485^{a}	2061^{a}	4337^{a}
MT	2035^{b}	3122^{a}	3699^{a}	2009^{a}	4776^{a}
CT	2085^{b}	3237^{a}	3605^{a}	1902^{a}	4674^{a}
P	<0.001	0.07	0.65	0.49	0.16

Table 3.3 Average yield (kg ha^{-1}) at Langgewens for the different tillage treatments from 2016 to 2020. The different letters show the significant differences (P<0.05) in each year.

Tillage	2016	2017	2018	2019	2020
ZT	2361^{b}	2468^{a}	3135^{b}	3095^{a}	3644^{a}
NT	2445^{a}	2615^{a}	4407^{a}	2820^{b}	4105^{a}
MT	2322^{a}	2381^{a}	4295^{a}	2649^{b}	4167^{a}
CT	2292^{a}	2263^{a}	4799^{a}	2624^{b}	4013^{a}
P	< 0.001	0.688	0.021	0.003	0.261

In Table 3.4 it is seen that 2017 and 2019 was very dry years in the southern Cape and Swartland. Nutrient that was placed on or near the soil surface would not have been washed into the soil as effectively as in a normal season. Nutrient stratification can also be influenced by different planters. The star-wheel planter, used for ZT, places the seed and fertiliser 3-4 cm deep. In contrast the no-tillage disc planter, used for NT, MT and CT, places the fertiliser 8-10 cm beneath the soil surface.

Table 3.4 Rainfall (mm) during the growing season (April to September) at the Research Farms from 2016 to 2020 (ARC-ISCW, 2021)

Research Farm	2016	2017	2018	2019	2020
Tygerhoek	269	217	245	129	258
Langgewens	304	170	309	187	299

3.6 CONCLUSIONS

The main objective of the study was to determine the long-term effects of different tillage and crop rotation practices on the stratification of soil nutrients at Tygerhoek and Langgewens Research Farms. Crop rotation was found to have no significant effect on nutrient distribution while tillage did have significant impact. Reduced tillage (ZT, NT and MT), which does not involve the inversion of soil, had a significant effect on the stratification of C, pH, Ca, P, K and Zn in the 0 - 5 cm layers compared to CT. Changes in nutrient availability under CA are attributed to the surface placement of soil amendments and surface accumulation of crop residues compared to conventional tillage.

CA leads to stratification of SOM and plant nutrients with higher concentrations in the 0-5 cm layer. Stratification occurred to the greatest extent for those nutrients that are relative immobile in the soil. The higher SOC in the topsoil under NT might be due to the minimum soil disturbance and retention of crop residue on soil surface leading to reduced mineralisation of SOM. In contrast, tillage (CT) can cause more soil disturbance and increase the exposure of SOC, thus accelerating mineralisation of SOM.

The amount of exchangeable Ca, Mg, P, K and soil organic C were all higher in the surface 5 cm of the soil under ZT and NT compared to CT. In environments where topsoil is prone to drying during the season, like the Swartland, nutrient uptake by crops are likely to be adversely affected despite the availability of water in the subsoil. This is likely due to impeded root growth in the dry topsoil or reduced diffusion of immobile nutrients to plant roots, or both. Stratification of soil nutrients did not seem to have a negative impact on crop growth and productivity.

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CHAPTER 4 SOIL STRATIFICATION ON COMMERCIAL FARMS

4.1 INTRODUCTION

The economy of the Western Cape (Swartland and southern Cape) has long been based on wheat production (Arckoll, 1998). The wheat industry is vital to ensure food security and rural development of the Western Cape Province. Winter cereals (predominantly wheat and barley) and oil and protein seeds, canola and lupines are produced in rain-fed farming systems in the -Mediterranean regions of the Western Cape. These crops may be grown in continuous cropping systems or in rotation with legume pastures (Hardy *et al*., 2011).

According to SAGIS (2021), 360 000 hectares of wheat were planted in the Western Cape in 2021 with an expected harvest of 1.134 million tons, 54% of the national annual production. Canola was produced on just over 100 000 ha with an expected average yield of 1.94 ton per hectare. Most of these crops are produced under conservation agriculture (CA) systems (Liebenberg *et al.,* 2020). CA combines the following basic principles: reduced tillage resulting in less than 20-25% soil surface disturbance, retention of adequate levels of crop residues to protect the soil surface and diversified crop rotation to help mitigate possible weed, disease and pest problems (Verhulst *et al,* 2010).

Conservation Agriculture (CA) is a dynamic system, offering farmers many combinations of practices to choose from and adapt according to their local production conditions and constraints (Pretty, 2008; Kassam *et al*., 2009; Godfray *et al*., 2010). Where livestock is part of the farming system, switching to CA from tillage agriculture, requires a different approach to managing the available biomass. This management implies that the needs of both soil health and livestock feed requirement should be met and that, over time, each year more residues should be allocated to cover the soil. This can be a challenge in certain dryland situations (Kassam *et al.,* 2012).

Tillage, residue management and crop rotation have a significant impact on nutrient distribution and transformation in soils (Etana *et al.* 1999; Galantini *et al*. 2000). In general, no-tillage results in increased nutrient concentrations near the surface soil, but these rapidly decrease with depth, while conventional tillage results in a more homogeneous distribution of nutrients with depth and depends on depth of cultivation (Tshuma *et al.*, 2021). Phosphorus, K, Ca, Mg, Zn and lime have limited mobility in the soil and when applied will remain in the top 5 cm (Anderson *et al*., 2010). In environments where the nutrient-rich topsoil is prone to drying, nutrient uptake by crops is likely to be adversely affected despite the availability of water in the subsoil. This is likely due to impeded root growth in the dry topsoil or reduced diffusion of immobile nutrients to plant roots or both (Sandral *et al*., 2019). Therefore, it is important to characterise nutrient stratification and enable producers to make appropriate fertiliser- and related management decisions (Lupwayi *et al*., 2006).

Nutrient stratification, especially C, N and P, is very common in undisturbed ecosystems (Prescott *et al.,* 1995). The majority of N, P, K and other nutrients will be moving from the roots to the leaves and stems, which will eventually die and fall onto the soil surface to decompose. This is how most stratification occurs under indigenous non-fertilised ecosystems (Grové *et al*., 2007).

Many farmers consider no-tillage as the new norm for crop production in Western Cape (Botha, 2013). Understanding the effects of tillage and rotation on plant available nutrients is critical to develop nutrient management strategies to optimise yield while maintaining cropping system sustainability (Houx *et al*., 2011).

Currently little is known regarding the extent to which the soils are stratified under CA in the southern Cape and Swartland wheat producing regions. Therefore, soil samples were collected with the objective to gain information on the extent of soil nutrient stratification. Stratification of nutrients can adversely affect the availability of soil nutrients, especially if the soil dries out during the season and roots are not able to absorb soil nutrients. The soil samples were taken at these depth increments with the purpose of identifying the change in soil nutrients with depth. This can provide producers with knowledge to make informed decisions on the available nutrients for fertiliser and lime recommendations.

4.2 MATERIAL AND METHODS

4.2.1. Localities

4.2.1.1 Commercial farms – southern Cape

Farm 1, Serjeantsrivier (-34.162242, 19.499757) is situated close to Caledon and receives an annual rainfall of 400-450 mm of rain. The soil is shallow and stony. Crop rotation was started 15 years ago with wheat and canola as cash crops and long-term (5 year) lucerne pasture. In the past 10 years bitter lupines and oats were added to the rotation, while in the past three years faba beans, radish, medics and vetch have been included, individually or in mixes. Fertiliser and seed are spread out on the soil surface and incorporated into with a single tine action with as little soil disturbance as possible. Nitrogen fertiliser management is adjusted according to the rainfall in the growing season. Topdressing of N is combined as foliar mix with fungicides. Grazing sheep is part of their system and recently cattle were added. A deeper tillage of 15 cm is done every four years after a grazing rotation due to hoof compaction. Fifty percent of the crop residue is baled and 50% is chopped and broadcast on the soil surface. The sheep graze the stubble after harvest.

Farm 2, De Vlei (-34.201372, 19.268714) is situated in the Caledon district with an average annual rainfall of 450 mm. The soil is shale-derived. Conservation farming has been practised for 12 years. Previously a long-term pasture cycle of lucerne for 5 years and cash crops for 4 years were followed. At the time of this study, the land was divided into continuous winter crop rotation on the best two-thirds and permanent mixed medics-lucerne pastures on the remainder. In order to diversify the grazing, black oats and other summer crops are include in the lucerne pastures at times. Wheat, barley or oats are planted with a planter equipped with knife point openers with 300 mm or 275 mm row spacing (Ausplow and Equaliser, repectively). The fertiliser is placed at various depths within the top 12 cm. Barley and wheat received 70 kg ha^{-1} N per annum. Minimum tillage is practised, but an occasional tillage is applied in order to address issues like drainage problems. Sheep graze the stubble after harvest. The conservation of the indigenous Renosterveld is a key focus on this farm.

Farm 3, Eerstekop (-34.184023 S, 20.779649 E) is situated in the Heidelberg area with an annual rainfall of 400 mm. The soil is shale-derived and predominantly Glenrosa soil form. In the nineteen seventies, lucerne was grown as pasture for merino sheep. In 1976 a switch was made to wheat under conventional till to alleviate compaction, converting to barley under no-till (Ausplow DBX) in 1981. The fertiliser is placed 2-3 cm below the soil surface. As a result of excessive crop residues and weed abundance, the cropping system was changed to 5 years of pasture followed by 5 years of barley and wheat in 1985. In 2000, pastures were replaced by cash crops only (wheat, barley and canola). The soil was holding more moisture and the plants were growing too tall and falling over from 40 kg ha^{-1} N and fertiliser rates were decreased to 25 kg ha^{-1}. Some years peas are planted for its N fixing properties, but every third year 2.5 ton ha^{-1} of chicken manure is spread on the field to compensate for the lack of other legumes in the system. The crop residue is chopped and spread out and left on the surface. There is no livestock on the farm. A combination of urea, MAP and ammonium sulphate is used for fertilisation.

4.2.1.2. Commercial farms - Swartland

Farm 1, Klipvlei (-33.284359 S, 18.350993 E) is situated near Darling with an annual rainfall of 350-450 mm. Most of the farm has sandy soil with patches of lime and clay. Wheat, lupines and canola were rotated and seeded with a tine planter for at least ten years prior to soil sampling. The fertiliser is placed 10cm deep. Initially lime was surface applied and left, but due to low subsoil pH, it was decided to incorporate lime using ploughs. To combat compaction (sandy soil) a ripping action is performed on average every 4th year at a depth of 40 cm. Planting is done with 10 kg N ha^{-1} and another 40 kg ha^{-1} N added later. During high potential seasons, an additional 20 kg N ha^{-1} is applied. Sheep is an important component of the farming system. The crop residue is spread out with the harvester and grazed by sheep.

Farm 2, Uitkyk (-33.192809 S, 18.651816 E) is near Moorrreesburg, receiving an annual rainfall of 390 mm. The soil is typical of the Swartland, i.e., sandy loam with a high stone content. Fertiliser is placed at 3 cm and 10 cm deep. Crop rotation has been practiced since 1995. Initially it was canola/wheat, but after 1997 lupines were added and since 2000 they switched to wheat/medics. In 2015 they also introduced cover crops like forage radish, Saia oats and rye. Since 2000, all lime is surface broadcast at variable rates to correct the $pH_{(KCl)}$ to 6. Lime is not worked into the soil and they don't do any deep tillage. Sheep is the primary livestock, but some cattle are kept to clean reeds and problem weeds. For the past 20 years, no wheat stubble has been baled, only the medics are baled. The sheep graze the wheat stubble and medic hay in the summer until the medic pastures are ready to graze in the new season.

Farm 3, NuHoop (-32.914031 S, 18.932759 E) is in the Porterville district and receives an annual rainfall of 300 mm. The soil was sandy loam with patches of clay loam. Crop rotation has been practiced since 1994 with canola, oats, lupines and more recently, medics. Since 2005 crops are planted with a DBX Ausplow and fertiliser is placed 5 cm deep in the soil. Lime is applied at a variable rate. Since the implementation of CA principles on the farm, less fertiliser is applied on the drier parts of the farm and the same amount as before CA was introduced on the wetter parts of the farm. Lately there is more focus on foliar application of nutrients and micronutrients. The sheep grazed the medics and heifers are kept on layover camps. Deep tillage is hardly ever used. Crop residue is baled for the dairy cows and graze the wheat stubble until middle April of the next year.

4.2.1.3. Natural veld

Renosterveld is the most abundant natural vegetation type in the southern Cape and Swartland. It is a shrub dominated plant community where Renosterbos (*Elytropappus Rhinocerotis)* is the most common specie (Vermeulen, 2010). Renosterveld has an extraordinary bulb diversity. Soil nutrients, in particular N and P, are very low under renosterveld (Kruger *et al*., 1983). Natural veld from each farm were included in the study to see the difference between natural stratification and stratification from cultivation practices.

4.2.1.4 Soil texture

The soil texture classes were determined by dispersing the soil by particle size diameter. The textural triangle was used to determine the textural classed based on the sand, silt and clay percentage. Unfortunately, only a 3 fraction test was done and not a 5 fraction test. The original soil analysis for the southern Cape is shown in Appendix A15, A17 and A19. All the soil sampled in the southern Cape were classified as sandy loam. The texture of Farm 1 in the Swartland was sandy and one camp was sandy loam (Appendix A21). On Farm 2 the soil was classified as sandy loam on all camps (Appendix A23). Farm 3 had one camp with clay loam soil, the remaining camps were all sandy loam (Appendix A25).

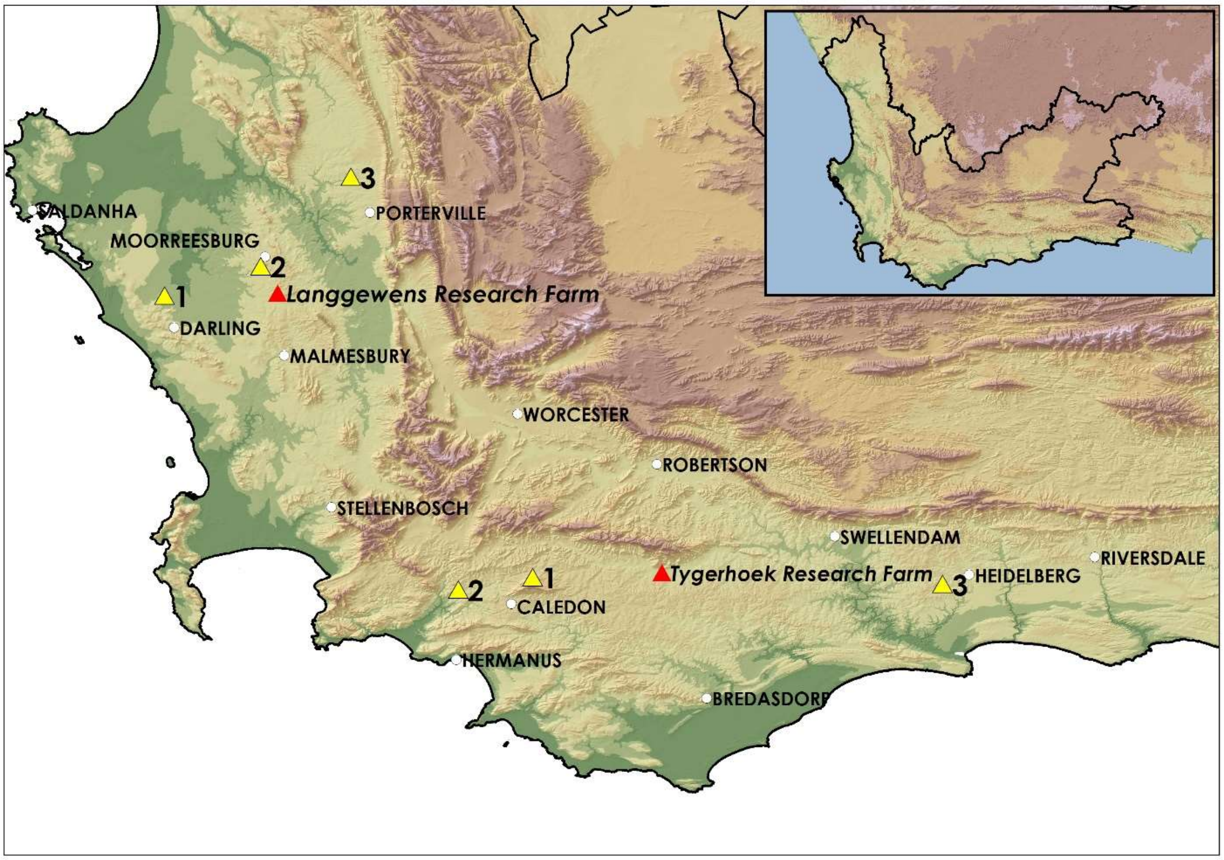

Figure 4.1 Map of the Western Cape showing the 3 commercial farms where soil samples were collected in the Swartland between Darling and Porterville and in the southern Cape between Caledon and Heidelberg.

4.2.2 Soil sampling

Samples were collected from six commercial farms with a history of practicing CA principles for at least 10 years, because that is how long it takes for stratification under CA to develop (Du Preez *et al.* 2001) Three farms, from each of the southern Cape and Swartland, were selected for this study. Soil samples were collected in four camps on each farm that had similar, but not identical, tillage and crop treatments histories. On each farm a composite soil sample was taken in the natural veld as close as practical possible to the sampled cultivated camps. These samples were used as an indication of the natural fertility status and stratification of the soil type and climatic condition in the particular area. Ten soil samples were collected with a 40 mm diameter steel cylinder at 0-5, 5-10, 10-15, and 15-20 and 20-30 cm depth increments respectively and bulked per depth.

The composite soil samples were air-dried and passed through a 2 mm sieve prior to chemical analysis at the Elsenburg Analytical Laboratory. All chemical analyses were done according to standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990: organic C (Walkley-Black method), pH (1:2.5 soil to water suspension), exchangeable Ca, Mg, K and P (citric acid), extractable Cu, Fe, Mn and Zn (DTPA method) and B (hot water method).

4.2.3 Climate

The Swartland has a typical semi-arid Mediterranean climate with a mean rainfall varies from 250 mm to 600 mm per annum of which about 80% occurs during the winter between April and September and mean annual temperature of 18.2 ˚C (Table 4.1). Summer months are warm and dry, while the winter is cool and wet. The average annual rainfall in the southern Cape is between 450 mm with 70% of the total rainfall occurring in April to October and the rest during the warm summer months.

Table 4.1: The typical climate in the 2 core wheat producing areas of the winter rainfall region, Western Cape (ARC, 2018)

Area	Mean Annual Rainfall	Mean annual Max temperature	Mean annual Min Temp
Swartland	364 mm	25.3 ° C	15.2 ° C
Southern Cape	334 mm	21.8 ° C	11.8 ° C

Lucerne pastures can be established in the southern Cape and will persist because a higher proportion of rain falls during the summer months and climate is milder and more temperate than in the Swartland (Hardy *et al.*, 2011). The Swartland has a typically

Mediterranean climate with 80% of annual rainfall occurring from April to September. Legume pastures are restricted to annual species of mostly medics (*Medicago* spp.).

4.3 STATISTICAL ANALYSIS

The experimental design was completely randomised. The treatment design was a split plot with the cultivation treatments as main plot factor and depth treatments as subplot factor. The data for each farm were analysed separately. The data were subjected to analysis of variance (ANOVA) using General Linear Models Procedure (PROC GLM) of SAS software (Version 9.4; SAS Institute Inc, Cary, USA). Shapiro-Wilk's test was performed to verify normality of standardised residuals (Shapiro and Wilk, 1965). Fisher's least significant difference (LSD) was calculated at the 5% level to compare treatment means (Ott and Longnecker, 2010). A probability level of 5% was considered significant for all significance tests. Levene's test verified homogeneity of farmer variances for the variables (Levene, 1960). There-after data for farmers were subjected to combined analysis of variances within a region, using General Linear Models Procedure (PROC GLM) of SAS software (Version 9.4; SAS Institute Inc, Cary, USA). Fisher's least significant difference (LSD) was calculated at the 5% level to compare treatment means (Ott and Longnecker, 2010). A probability level of 5% was considered significant for all tests.

4.4 RESULTS

In all the graphs (Figure 4.2 to Figure 4.20), the different letters on top of the bars denote a significant difference ($P < 0.05$).

4.4.1 Soil organic carbon (SOC)

Figures 4.2 and 4.3 show soil organic C distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. The soil organic C in the Swartland for all the layers (0.17 to 2.69 %) was much lower than in the southern Cape (between 0.65 and 6.08 %), possibly due to the harsher Mediterranean climate in the Swartland, compared to the more temperate climate of the southern Cape (ARC, 2018). Farm 3 in the southern Cape, had significantly higher soil carbon (3.9%) in the 0-5 cm layer, while Farm 1 and Farm 2 had values of 2.9 % and 2.65 % respectively. The percentage soil cover increased due to reduced soil disturbance a non-removal of crop residues in the no-till system by livestock on Farm3.

Soil carbon of natural veld in the southern Cape on Farm 1 and 3 was statistically higher ($P < 0.05$) than that of the cultivated fields (Figure 4.2) for the 0-5 cm layer. The soil C on Farm 2 of the cultivated field (2.62 %) was very similar to that of the natural veld in the 0-5 cm layer (2.52%). Soil organic C showed a significant ($P<0.001$) positive correlation with B (0.92), K (0.83) and Zn (0.82) in cultivated soil of the southern Cape for the 0-5 cm layer. In the 0-5 cm layer, soil organic C also showed a significant ($P<0.05$) positive correlation to S (0.76), Na (0.66) and Mg (0.58).This could be linked to the higher CEC caused by the higher SOC in the soil and increased nutrient cycling by microbes .

In the Swartland, the soil C in the 0-5 cm layers of the cultivated soil was either higher or almost the same as that of the natural veld (Figure 4.3). Farm 1 had the lowest C, because of the sandy soil (0.85 and 0.34%, for cultivated soil and natural crop, respectively), followed by Farm 3 (1.54 and 1.60%) that has been practicing CA principles for the past 20 years, but with a high removal rate of crop residue. Farm 2 (2.69 and 1.51%) has been practicing CA for the past 25 years and only lately planted one third wheat and the rest medics. Only the soil C of the 0-5 cm layer of Farm 2 was statistically higher than the other layers that was sampled on the three farms. This could be due to the harsh Mediterranean climate of the Swartland and sparse vegetation in the natural veld. In the cultivated land, crops are planted annually and the C input of wheat, medics and canola roots may exceed the natural veld. The cultivated soil (0.85%) on Farm 1 was higher in C than the natural veld (0.34%), but not statistically so. The soil is very sandy, but the stratification is more prominent in the cultivated soil than in the natural veld with a percentage change of 47% vs 8.8 % from the 0-5 cm to the 5-10 cm layer. The cultivated soil on the second farm had a soil C of 2.7 % in the 0-5 cm layer. This showed the possible potential for C build-up in the soil under CA practices in the semi-arid region of the Western Cape. In the Swartland (Appendix A14) the soil in the 0-5 cm layer had significant ($P<0.05$) positive correlation between soil organic carbon and B (0.76), K (0.75) and S0.61).

Du Preez *et al.* (2011) concluded that 58% of the soils in South Africa contained less than 0.5% organic carbon while 38% of the soils contained 0.5% – 2% organic carbon and only 4% contained more than 2% organic carbon. CA has been practiced for 25 years on Farm 2. The C in the cultivated soil for the top 0-5 cm was the highest at 2.7%. This soil layer also had the highest Ca, K and S (8.66 cmol.kg^{-1}, 354 and 23 mg.kg^{-1}, respectively). In recent years, wheat was planted only in rotation with medics. Medics are known to have very fibrous root systems, especially when compared to that of canola and lupines (Smith *et al.* 2020) and medics are self-regenerative (do not have to establish every time the field goes into the medic phase) and thus less soil disturbance by planters.

The SR of the soil C was calculated in the 0-5, 5-10, 10-15 and 15-20 cm soil layers by dividing it with that of the corresponding soil C in the 20-30 cm layer following the procedure described by Franzluebbers (2002). The lower depth is used to normalise the assessment and make valid comparisons among soils from different regions. Several studies have indicated that SR range for SOC is from 1.1 to 1.9 for conventional tillage and 2.1 to 4.1 for no-tillage (Díaz-Zorita & Grove, 2002). In Table 4.2 the SR for the 0-5 cm layer is all greater than 2. This shows an improvement of soil quality in the topsoil. In the southern Cape Farm 2 has the highest SR even if it did not have the highest soil org C (2.6%) it is greater than the undisturbed soil on the farm. Even if Farm 1 in the Swartland had the lowest soil C (0.85%), if the SR is calculated, it is shown that it is the highest for the Swartland and indeed an improvement in soil quality.

Table 4.2 Stratification ratios of the selected southern Cape and Swartland farms for the top 3 depth increments

	Soil depth ratio	Farm 1	Veld 1	Farm 2	Veld 2	Farm 3	Veld 3
Southern Cape	0-5: 20-30	3.46	5.31	4.07	3.71	2.30	2.39
	5-10: 20-30	2.30	2.67	2.76	3.16	1.76	1.92
	10-15: 20-30	1.41	1.86	1.81	2.53	1.54	1.74
Swartland	0-5: 20-30	4.71	2.00	4.25	4.87	2.68	4.32
	5-10: 20-30	2.49	1.82	2.41	3.06	2.34	2.57
	10-15: 20-30	1.36	1.76	1.61	1.42	1.19	1.95

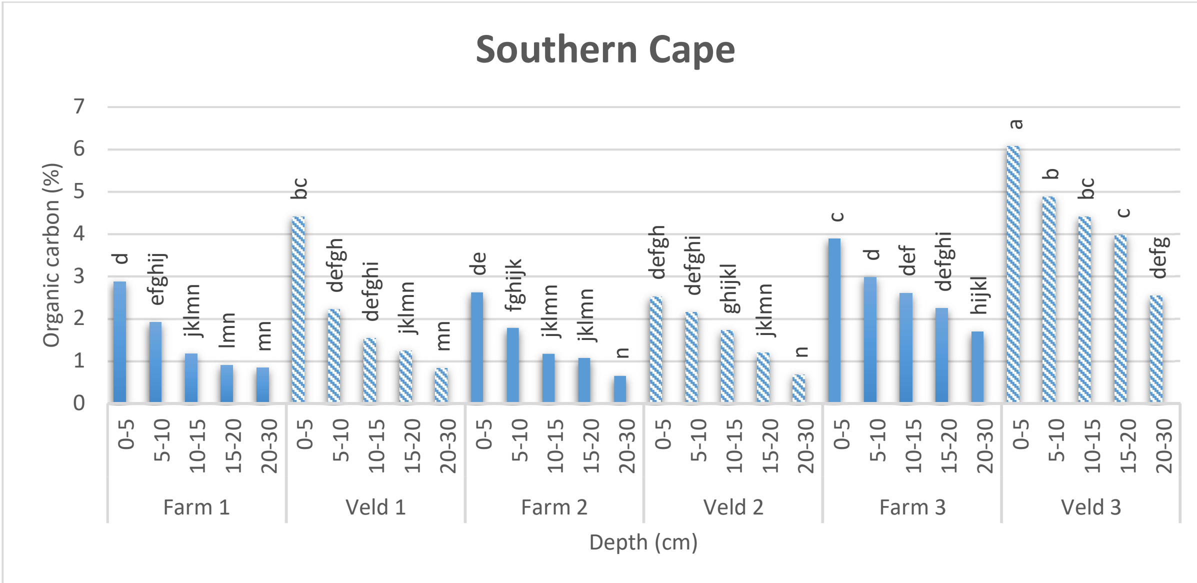

Figure 4.2 Depth distribution of soil organic C from 0-30 cm in the soil of three southern Cape commercial farms between cultivated soil and natural veld. The different letters on the bars denote a significant difference (P<0.05).

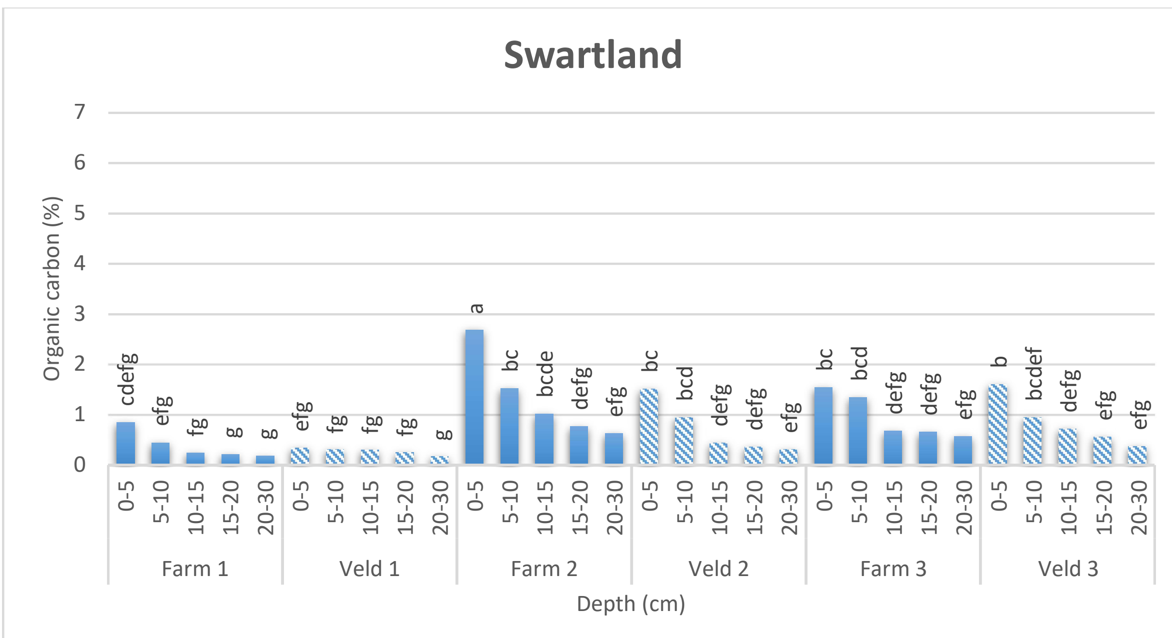

Figure 4.3 Depth distribution of soil organic carbon from 0-30 cm in three Swartland commercial farms between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

4.4.2 Soil pH, exchangeable calcium and magnesium

Figures 4.4 and 4.5 show soil pH distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. The pH of the cultivated soil of the 0-5 cm layer for both the southern Cape and Swartland were higher than that of the natural veld. In the southern Cape, mean soil $pH_{(KCl)}$ of the cultivated fields in the 0-5 cm layers (6.3, 6.4 and 6.2) were much higher than that of the natural veld (5.0, 5.1 and 4.7) for Farms 1, 2 and 3, respectively. The pH in the 20-30 cm layer (5.45) on the first farm was lower than what is usually recommended for wheat production. According to the South African fertiliser guidelines, the optimal $pH_{(KCl)}$ for wheat is 5.0 and for barley and canola it is 5.5 (FSSA, 2016).

The same tendency was seen in the Swartland with the pH of the 0-5 cm layers (6.3, 6.3 and 6.5) being higher than that of the natural veld (6.2, 4.7 and 6.0) for the three respective farms. Soil pH corrections are made by means of lime in the cultivated soil to create a pH suitable for commercial crops. Lime is highly immobile in soils due to its low solubility (Manson & Findlay, 2015). In the soil of the individual camps on Farm 1, subsoil acidity was noticed (Appendix A5).

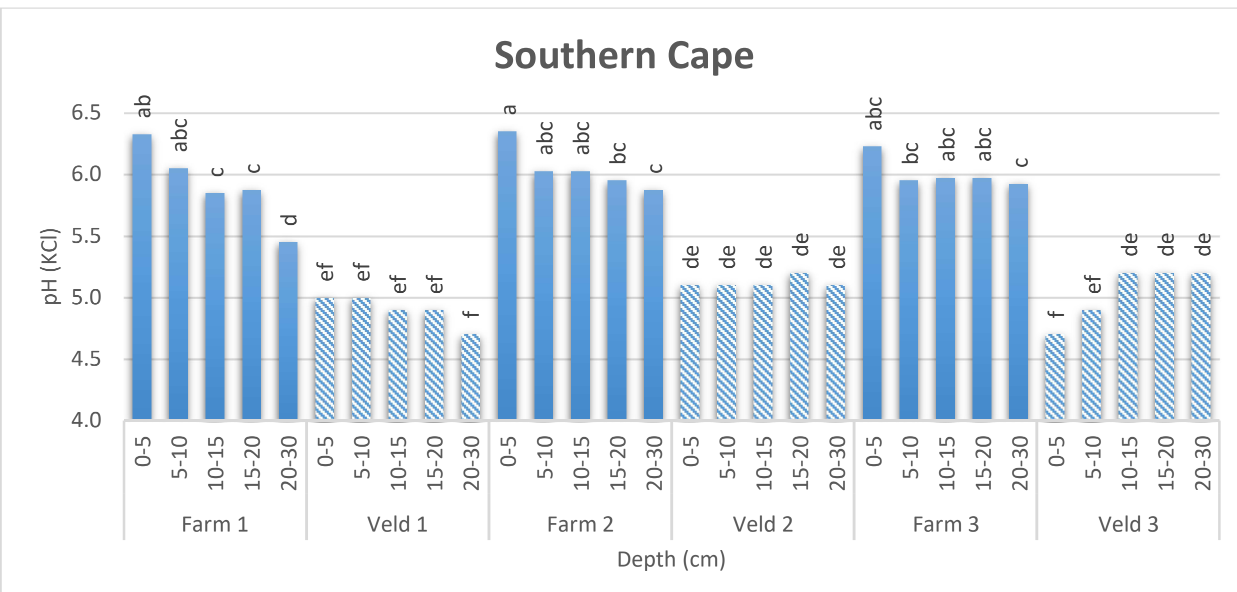

Figure 4.4 Depth distribution of $pH_{(KCl)}$ from 0-30 cm of three selected commercial farms southern Cape in cultivated soil and natural veld. Different letters on the bars denote a significant difference ($P<0.05$).

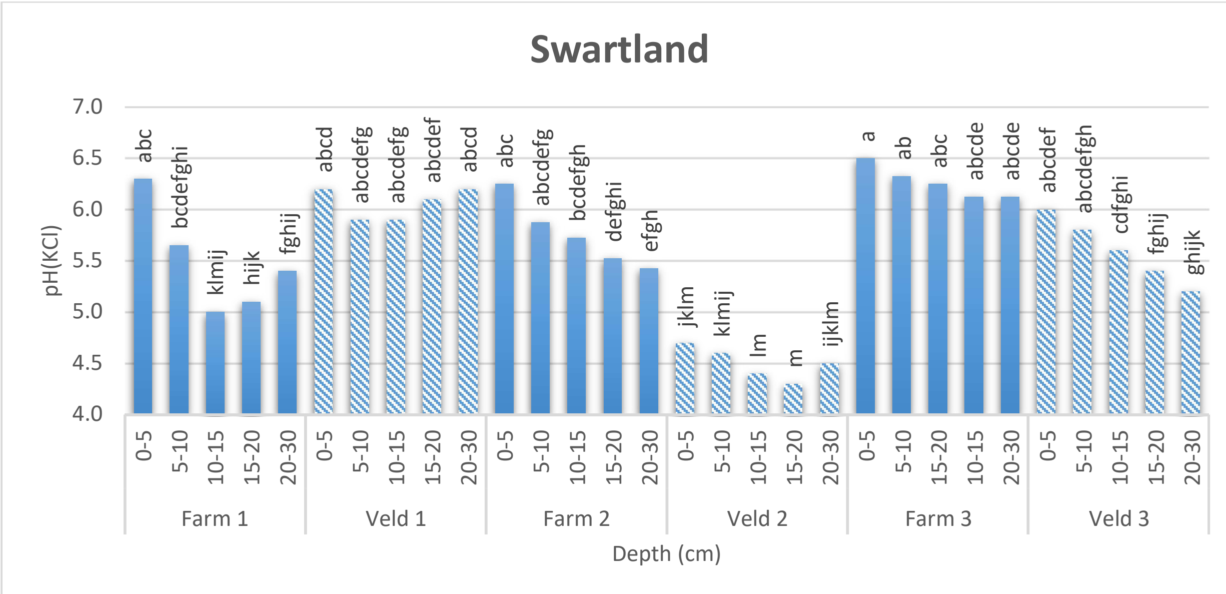

Figure 4.5 Depth distribution of pH from 0-30 cm in the Swartland of three selected commercial farms between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

Figures 4.6 and 4.7 show available Ca distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. The exchangeable Ca content showed the same tendency as did the soil pH, with higher values in the cultivated soil than in the natural veld. Except for 0-5 cm on Farm 3 that was significantly (P<0.05) higher than the other depths, the soil Ca decreased with depth in the cultivated soil. In the natural veld the Ca was different with depth, but this was not significant.

In the Swartland there was no significant difference between the soil exchangeable Ca in the different depths of Farm 1. The soil is very sandy and it is regularly ripped, to a depth of 40 cm, every 4 or 5 years. The 0-5 cm layer on Farm 2 had the highest Ca (8.7 $cmol.kg^{-1}$), followed by the 0-5 cm layer on Farm 3 (8.0 $cmol.kg^{-1}$).

Figures 4.8 and 4.9 show available Mg distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. In the southern Cape, soil Mg was higher in the 0-5 cm layers in the cultivated soil compared with natural veld. Only on Farm 3 in the southern Cape, the 0-5 cm layer was significantly higher in Mg than the deeper layers. None of the other layers were significantly different (P< 0.05).

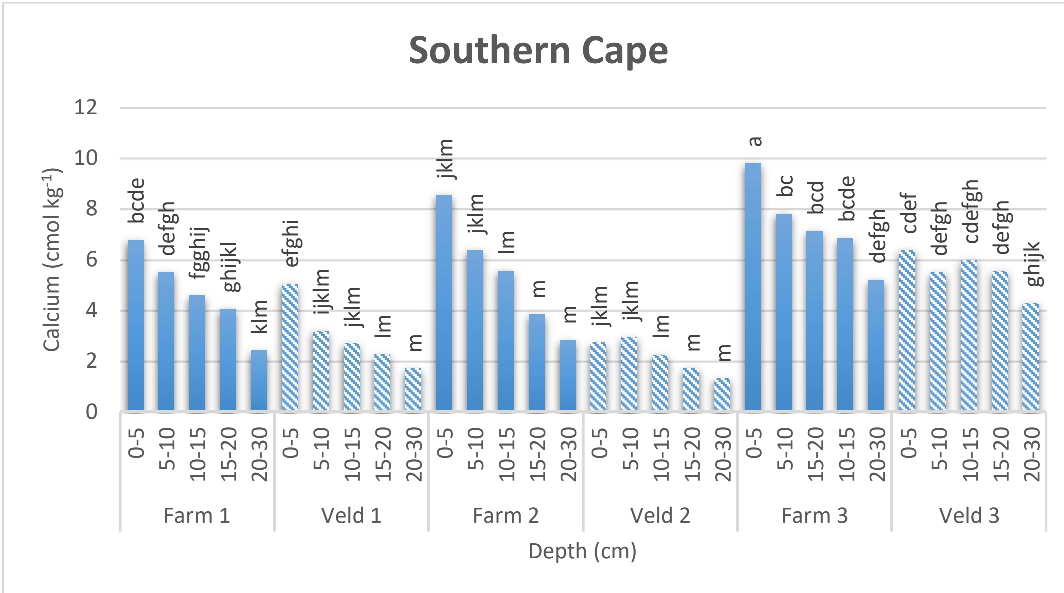

Figure 4.6 Depth distribution of soil exchangeable Ca from 0-30 cm of three selected commercial farms in the southern Cape between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

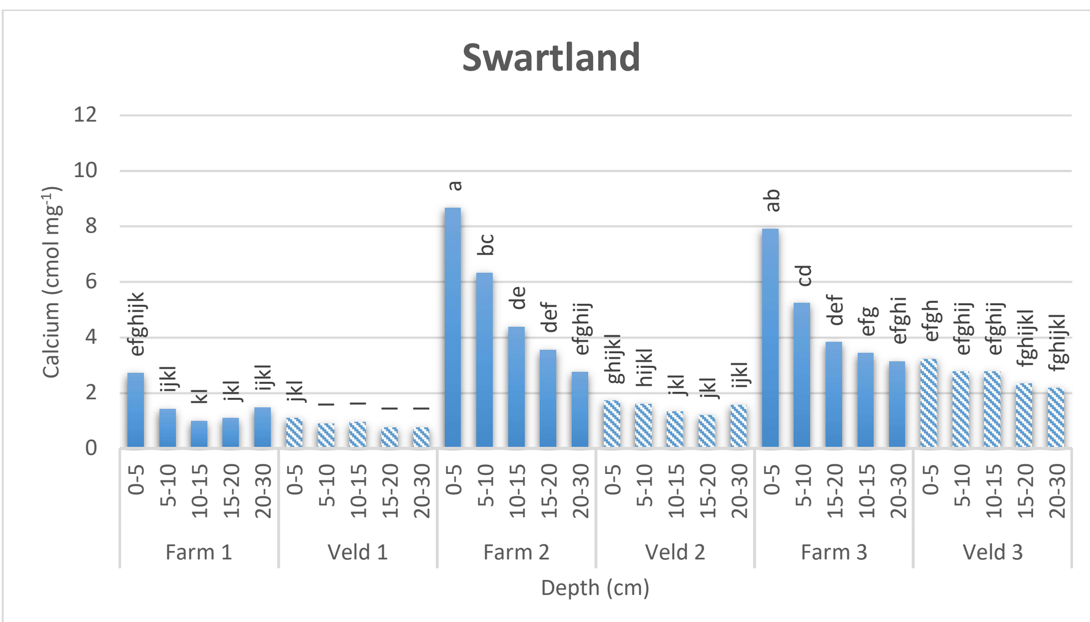

Figure 4.7 Depth distribution of soil exchangeable Ca from 0-30 cm of three selected commercial farms in the Swartland between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

The Mg in the Swartland was much lower than in the southern Cape on the selected farms. In the cultivated soils, the Mg was significantly higher in the 0-5 cm layers than in the deeper layers. In the Swartland, the natural veld of Farms 1 and 2 showed no significant difference between the layers, but in Farm 3 the soil Mg increased with depth.

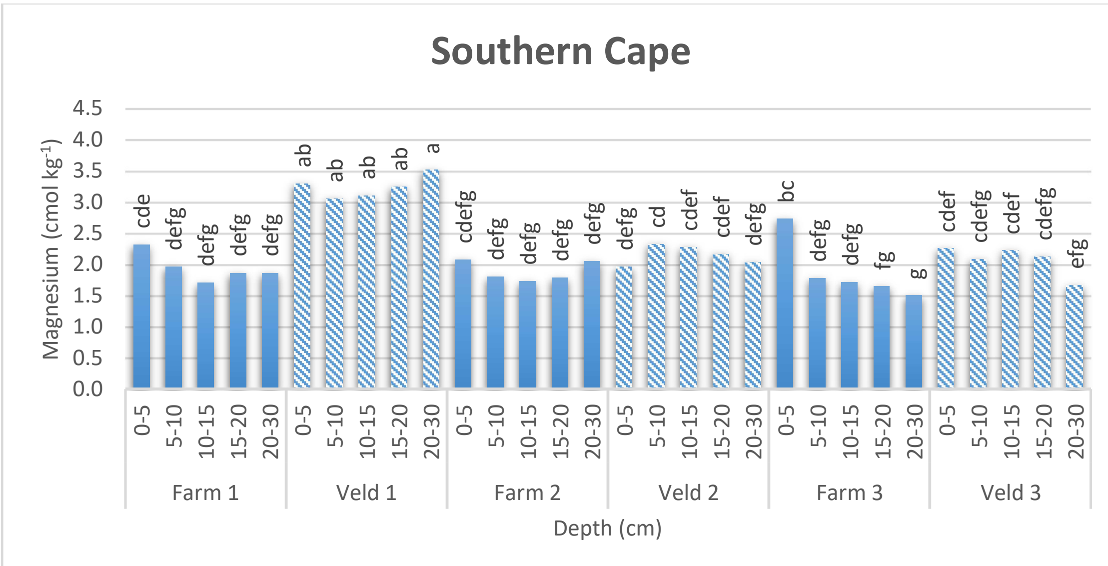

Figure 4.8 Depth distribution of soil exchangeable Mg from 0-30 cm of three selected commercial farms in the southern Cape between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

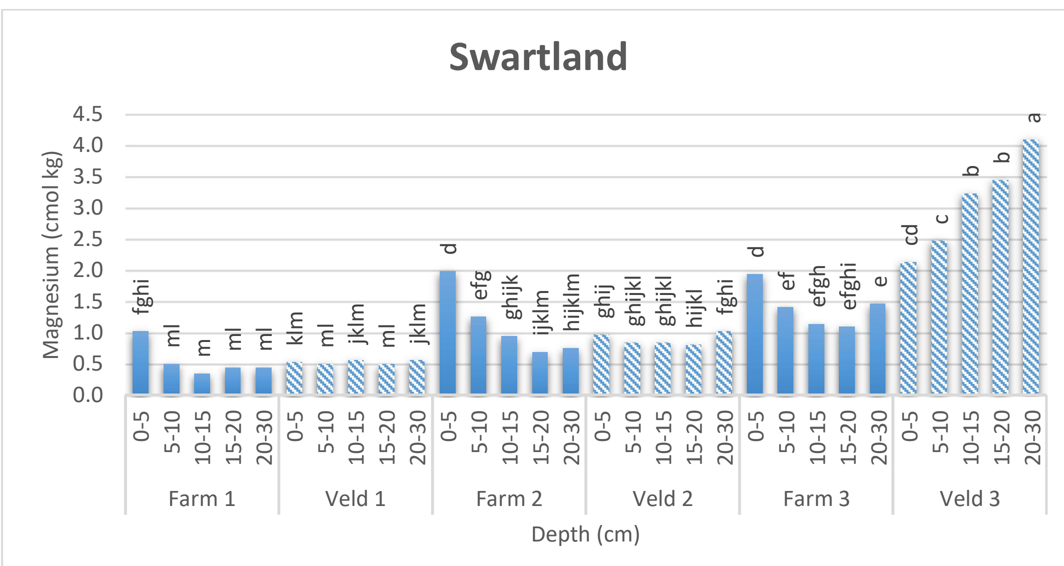

Figure 4.9 Depth distribution of soil exchangeable Mg from 0-30 cm of three selected commercial farms in the Swartland between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

4.4.3 Phosphorus, potassium and sulphur

Figures 4.10 and 4.11 show soil available P distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. The soil P in the 0-5 cm layers on Farm 2 and 3 in the southern Cape (Fig 4.10) were significantly higher in the cultivated sites (104 and 118 mg kg^{-1}) compared to that in natural veld (66 and 61 mg kg^{-1}). All the graphs show the same trend of P content decreasing with depth, but all at different gradients. After K, soil P (30, 37 and 33 %, Farm 1, 2 and 3, respectively) shows the highest percentage of change between the 0-5 cm and 5-10 cm layers in the cultivated soil. Phosphorus had a significant ($P<0.001$) positive correlation with sulphur (0.94). At Tygerhoek Research Farm (as seen in the previous chapter), P showed the most stratification (49, 26, 19 and 15 % for ZT, NT, MT and CT, respectively).

The same trend was found in the Swartland (Fig 4.11). Except for the sandy soil of Farm 1 in the Swartland, the 0-5 cm layer of cultivated soils were significantly higher in P than that of the deeper layers. This could be because the sandy soil is ripped occasionally to alleviate compaction. In the Swartland, the percentage of change in the P content (17, 44 and 25 % for the three farms, respectively) between the 0-5 cm and 5-10 cm layers, was the second highest. This trend was similar to what was found in the southern Cape. Farm 2 showed a significant decrease in P between 0-5 cm and 5-10 cm (44%). On Farm 3, a decrease was observed between depths 0-5 and 5-10 cm (25%), 5-10 and 10-15 cm (36%) and 10-15 and 15-20 cm (48%). The higher clay content in the soil on this farm could have had an influence. At Langgewens Research Farm, the P was much less stratified (ZT 21%, NT 11%, MT 8% and CT 3%) with percentage of change between 21 and 3% (as seen in the previous chapter). There are several reasons why P is often highly stratified near the soil surface in CA systems: (i) P is highly reactive in soils due to adsorption and precipitation reactions, thus surface broadcast P does not readily move, (ii) reduced soil mixing, and (iii) P in stubble retained at the soil surface (Sandral *et al*., 2019). The P present in the added residue plays an important role in regulating the mineralisation or immobilisation of P in soil, thus altering the P dynamics and affecting its availability (Singh *et al.,* 2009; Kumawat *et al*., 2018).

In both the southern Cape and Swartland, the 2 farms where the fertiliser is placed in the top 3-5 cm is more stratified for P and K.

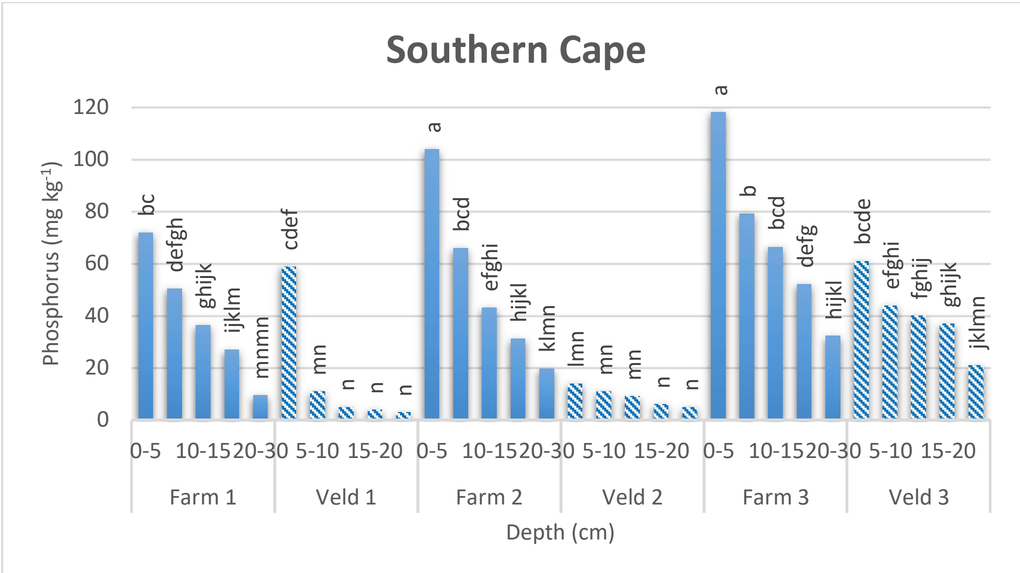

Figure 4.10 Depth distribution of soil available phosphorus from 0-30 cm of three selected commercial farms southern Cape sampled between cultivated soil and natural veld. The different letters on the bars denote a significant difference (P<0.05).

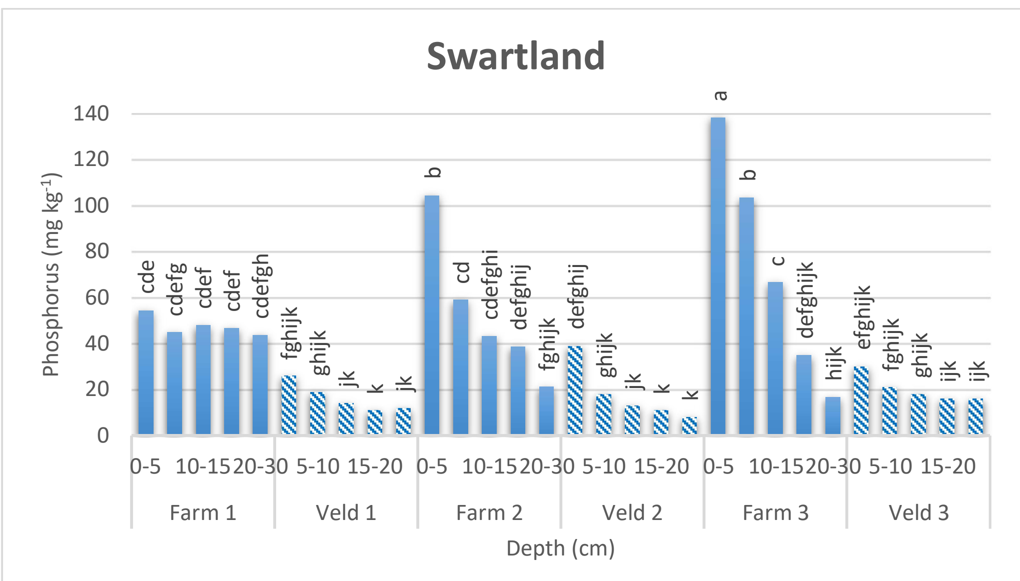

Figure 4.11 Depth distribution of soil available phosphorus from 0-30 cm of three selected commercial farms in the Swartland between cultivated soil and natural veld. The different letters on the bars denote a significant difference (P<0.05).

Figures 4.12 and 4.13 show soil exchangeable K distribution (0-30 cm) in the selected southern Cape and Swartland farms, respectively. Soil K had the highest percentage of change between the 0-5 cm and 5-10 cm layer in the southern Cape (44, 28 and 28%, Farm1, 2, and 3, respectively) (Fig 4.12). If the corresponding layers of cultivated soil and natural veld are compared, only the 5-10 and 10-15 cm depths of the natural veld were significantly higher in K than that of the cultivated soil. The other depth increments did not differ significantly between cultivated soil and natural veld. In both Farm 1 and Farm 2, the 10-30 cm layers was K deficient for the cultivation of wheat. At Tygerhoek Research Farm (as seen in the previous chapter), the soil K was the most stratified nutrient (ZT 79%, NT 37%, MT 24% and CT 21%). When comparing the K content of the different depth increments between the cultivated soil and natural veld in the Swartland (Fig 4.13), the only significant differences ($P > 0.05$) were found in the 0-10 cm layer of Farm 2 and Farm 3. At Tygerhoek Research Farm (as seen in the previous chapter), the soil K (Appendix A3) was the second most stratified nutrient (ZT 29%, NT 23%, MT 16% and CT 20%).

In the Swartland (Fig 4.13) in both the cultivated and natural veld, the soil K decreased with depth. No stratification ($p<0.05$) of K was found in the sandy soil of Farm 1, possibly because K is leached very quickly out of sandy soil (Goulding *et al*., 2021). The incremental sampling revealed the K deficiency in 10-30 cm of Farm 1. Western Cape soils derived from Bokkeveld shale and Malmesbury shale, both rich in K, generally requires little additional K fertilisation except where high N applications are made (Laubscher, 1980). Most of the K in cereals is returned to the soil surface in residues from which it is leached by rain into the topsoil (Rossolem *et al*., 2017). More K is extracted by the cultivated cereals and legumes than the natural veld. Crops grown for hay production, such as alfalfa (*Medicago sativa* L.), also remove large amounts of nutrients from the soil, especially K (Goulding *et al*., 2021). Addition of crop residues on the soil surface contributes to higher exchangeable K on the soil surface (Motta *et al*., 2002).

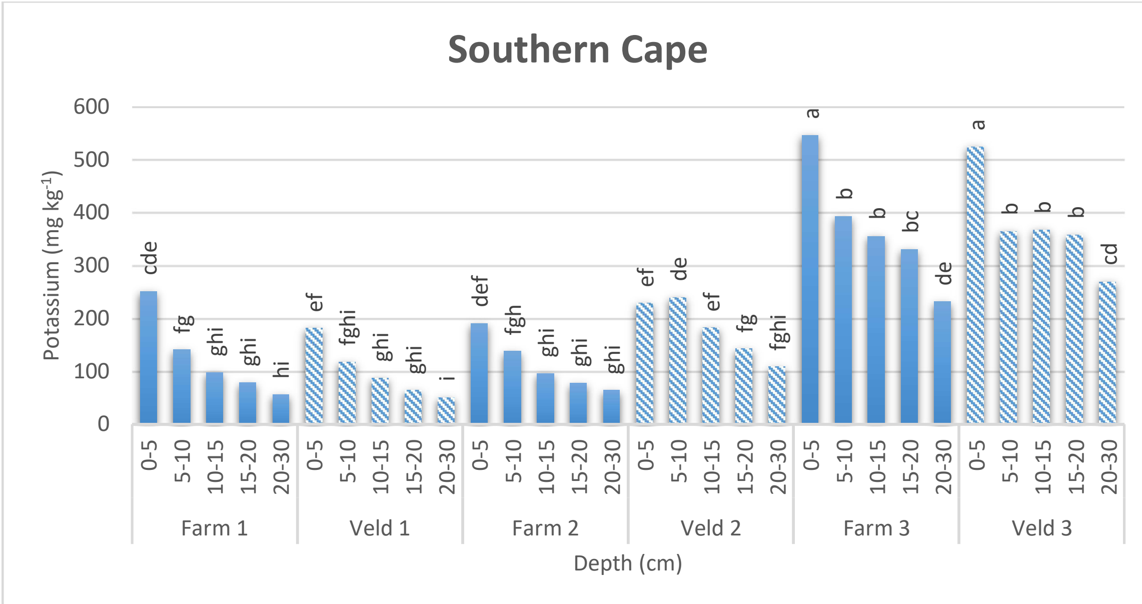

Figure 4.12 Depth distribution of soil exchangeable K from 0-30 cm of three selected commercial farms in the southern Cape between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

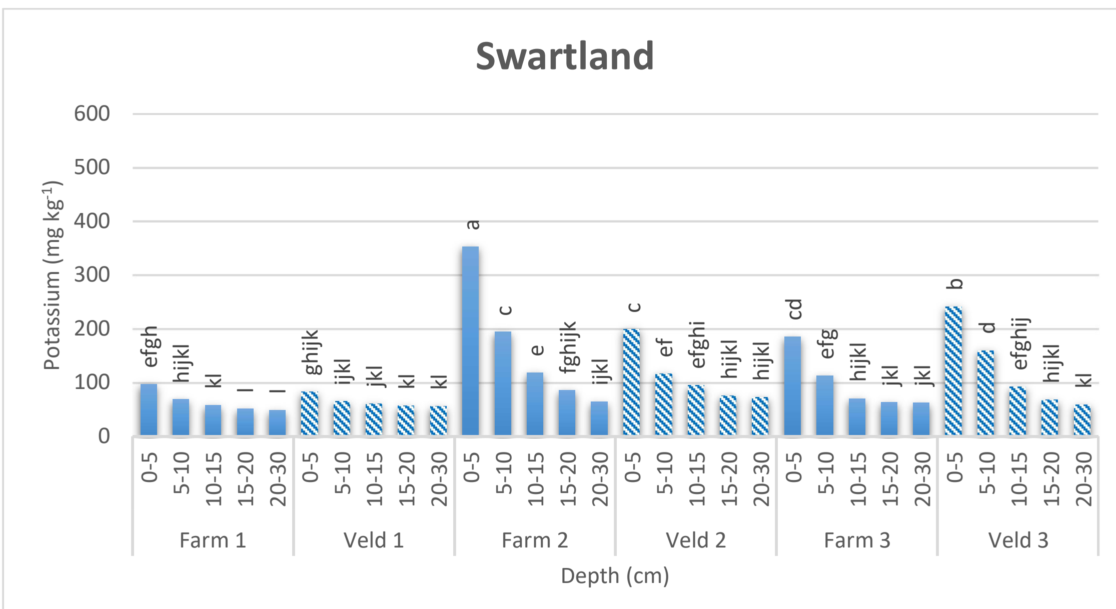

Figure 4.13 Depth distribution of soil exchangeable K from 0-30 cm of three selected farms in the Swartland between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

Figures 4.14 and 4.15 show soil exchangeable S distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. The data for Veld 2 was not available. In the southern Cape, the S on Farm 1 decreased with depth, but this was not significant. Sulphur less than 6.0 mg.kg^{-1} is the critical soil nutrient level at which this nutrient becomes deficient (Peverill *et al.*, 1999). The soils on Farm 2 was deficient in S from the 15-30 cm layer. The S in the 0-5 cm layer of Farm 3 was significantly higher than in the other layers. In a study between 2009 and 2011 Ngezimana & Agenbag (2014) found S values of between 2.1 and 8.7 mg kg^{-1} in the southern Cape and Swartland. In their study, the S content of the soil decreased with depth at all the localities. In this study soil exchangeable S was between 4.6 and 180 mg kg^{-1}, but most of the values were between 5 and 15 mg kg^{-1}.

In the Swartland (Figure 4.15), on Farm 1the soil was deficient (3.85-4.88 mg kg^{-1}), in S for wheat and canola production. The optimum level for S in the soil for canola is 7-12 mg kg^{-1} (Anonymous, 2008). Tsuji *et al*. (2005) reported that total sulphur in soil is primarily regulated by the amount of organic carbon, because 95% of total sulphur in arable soils is in organic form. Such a relationship between the amount of organic carbon in CA and total sulphur is also evident in the southern Cape. A significant (P<0.05) positive correlation (0.61) was observed between organic C and exchangeable S in the 0-5 cm layer of the cultivated soil in the Swartland.

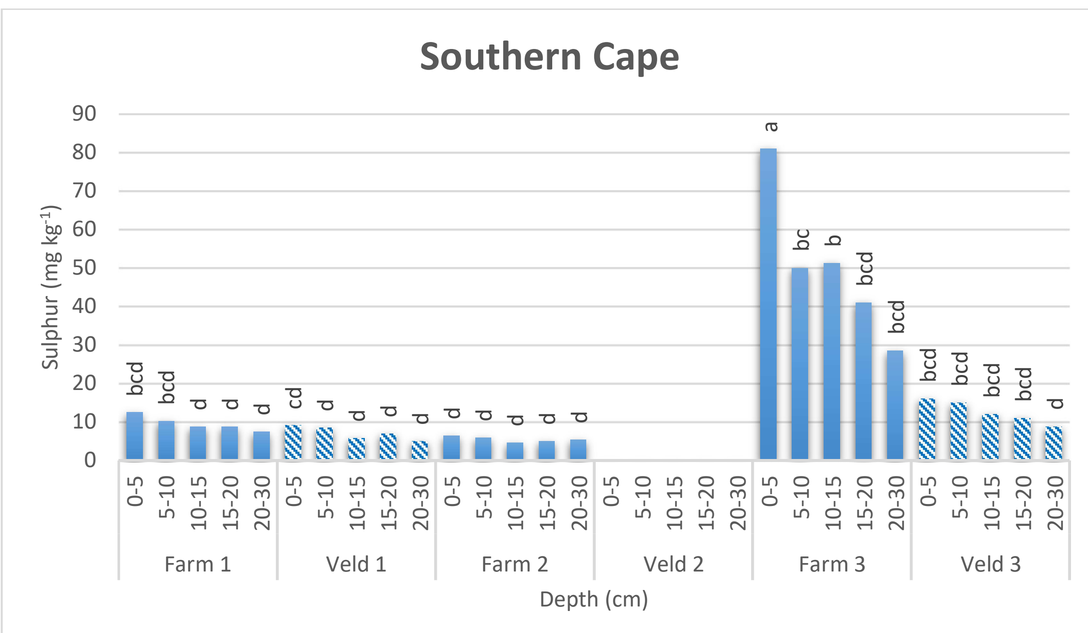

Figure 4.14 Depth distribution of soil exchangeable S from 0-30 cm of three selected farms in the southern Cape between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05). The data of Veld 2 was not available.

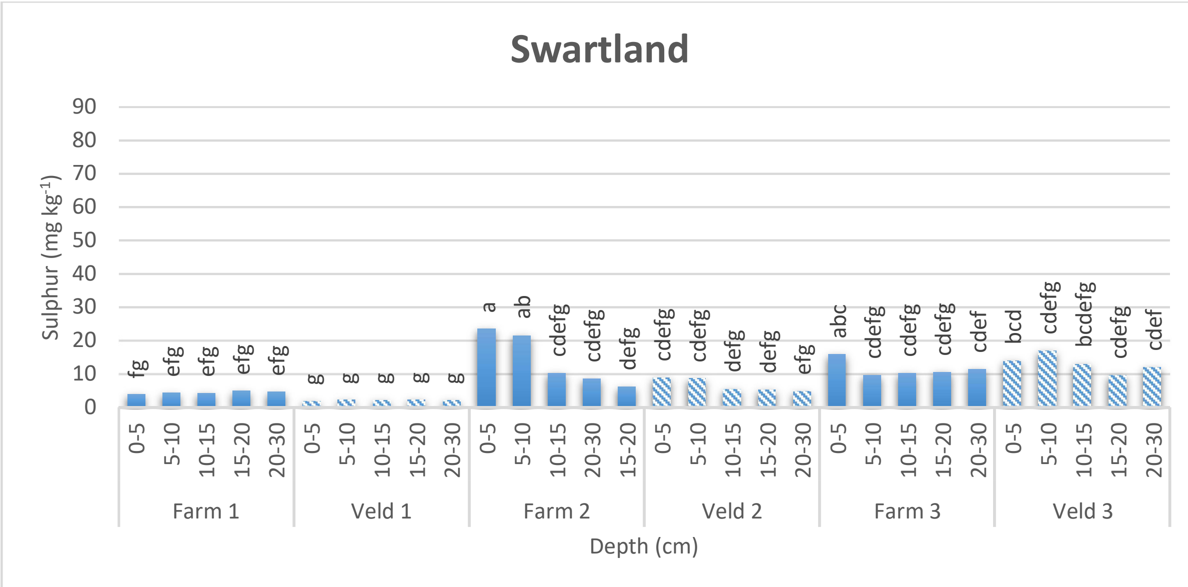

Figure 4.15 Depth distribution of soil exchangeable S from 0-30 cm of three selected farms in the Swartland between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

4.4.4 Extractable trace elements

Figures 4.16 and 4.17 show soil extractable Zn distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. Several factors influence the movement of micronutrients that comprise their naturally low total concentrations, such as soil organic matter, pH, soil-plant/soil-microbe interactions and plant genotype (Rengel, 2015, Agrawal *et al*., 2016). On the farms in the southern Cape (Fig 4.16 and Appendix A10), the Zn levels in the soil decreased with depth in the cultivated as well as in the natural veld. The 0-5 cm layer of Farm 3 farm was significantly higher in Zn than the 5-10 cm layer, with a change of 25 % and 52% between the 0-5 cm layer and the 5-10 cm layer in the cultivated and natural veld, respectively. The soils of Farm 3 also displayed the only significant differences in Zn between the veld and the cultivated land in the 5-15 cm depths where the Zn in the soil under cultivation was significantly higher than in the corresponding layers of the veld. Every third year, 2.5 ton ha^{-1} of chicken manure is spread on the cultivated soil. Animal manure products like poultry manure have been observed to contain potentially harmful trace elements like arsenic, copper and zinc (Bolan et al., 2010).

On the Swartland farms sampled (Fig 4.17), the extractable soil Zn decreased with depth, except for outliers like Farm 1 (15-20 cm) and Farm 3 (5-10 cm). The relative immobility of Zn in the soil could contribute to its stratification (Motta *et al.,* 2002; Shiwakoti *et al*., 2019). Some layers on Farm 1 and 2 (Appendix A12) were Zn deficient for the cultivation of wheat. An increase in soil pH value, lowers the availability of Fe, Mn, Cu and Zn. Edwards *et al.* (1992) found high linear relationships between OM and Mn and Zn concentrations. Higher SOM levels and the immobility of Zn in soil could be the reason for greater Zn near the soil surface than in the deeper layers (de Santiago *et al*. 2008). The planter used on Farm 3 place the fertiliser at 5 cm deep, this could explain the higher Zn in the 5-10cm layer.

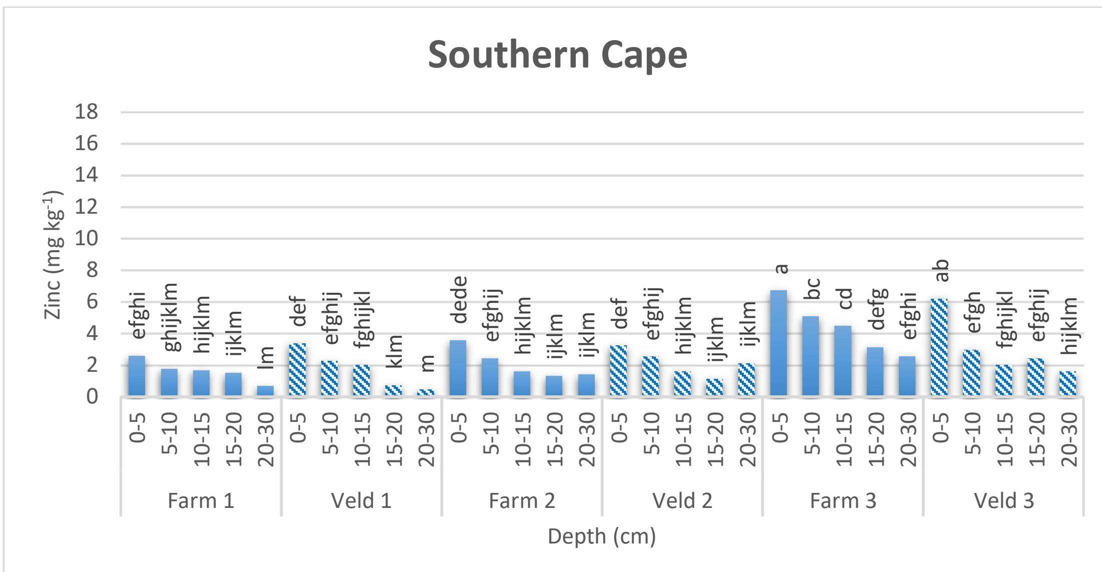

Figure 4.16 Distribution of extractable Zn from 0-30 cm of three selected farms in the southern Cape between cultivated soil and natural veld. The different letters on the bars denote a significant difference (P<0.05).

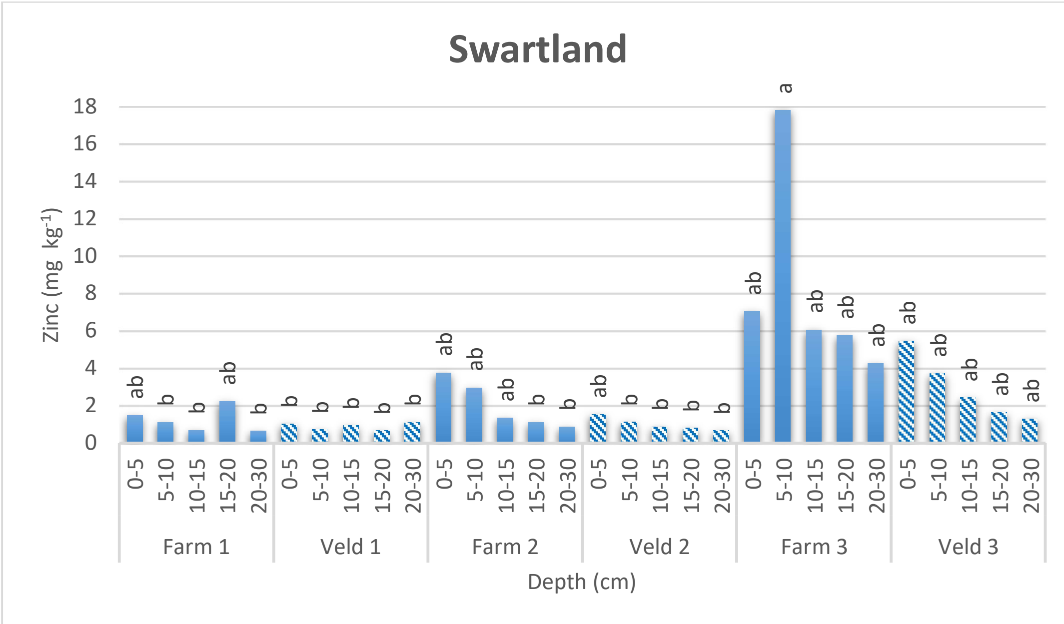

Figure 4.17 Distribution of soil available Zn from 0-30 cm of three selected farms in the Swartland between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

Figures 4.18 and 4.19 show soil exchangeable Mn distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. In the southern Cape on Farm 1 and 3 showed an accumulation of Mn in the soil in the 5-10 cm and 10-15 cm in the cultivated soil, although it was not significant. The Mn levels in the cultivated soil are lower than the natural veld. In the Swartland, the sandy soil of Farm 1 had the lowest Mn levels (40 mg kg^{-1}), but this was still adequate for crop production.

Results from Shiwakoti *et al.* (2019) suggested NT can play a vital role in sustaining micronutrient availability due to decreased soil pH and the greater amount of organic matter within the surface soil of NT compared to other tillage methods. Consequently, greater concentrations of some soil-extractable micronutrients, such as Mn and Zn, were reported under NT compared to conventional tillage (Follet & Peterson, 1988). On the other hand, Hickman (2002) reported that the tillage system did not affect extractable concentrations of soil Cu and Zn. Retention of crop residue and improved SOM in the topsoil under NT were shown to improve Mn availability (Moreira *et al.*, 2016).

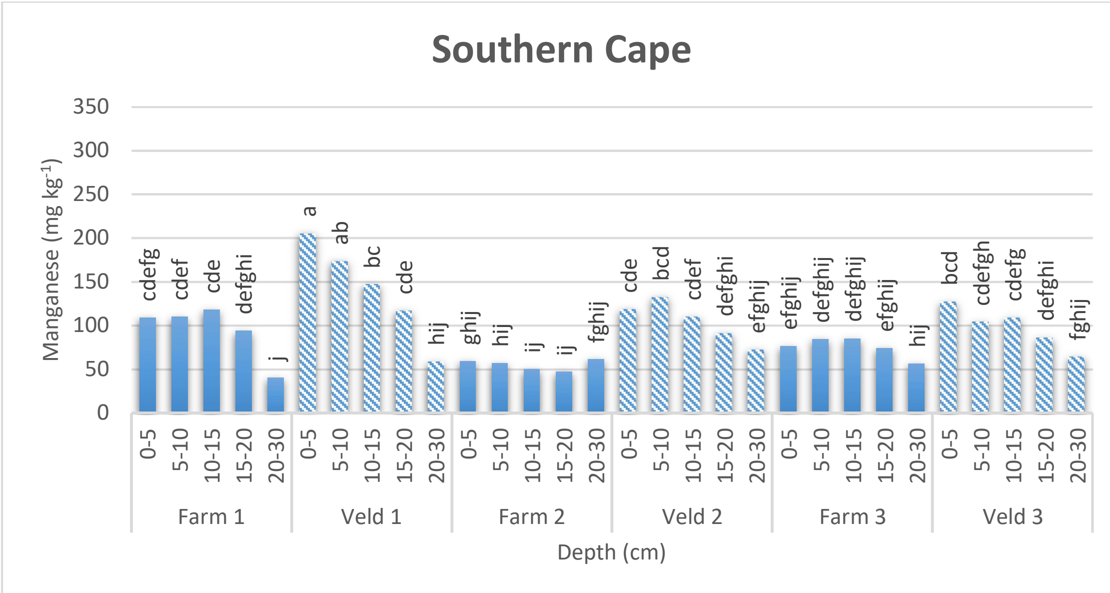

Figure 4.18 Distribution of soil available Mn from 0-30 cm of three selected farms in the southern Cape between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

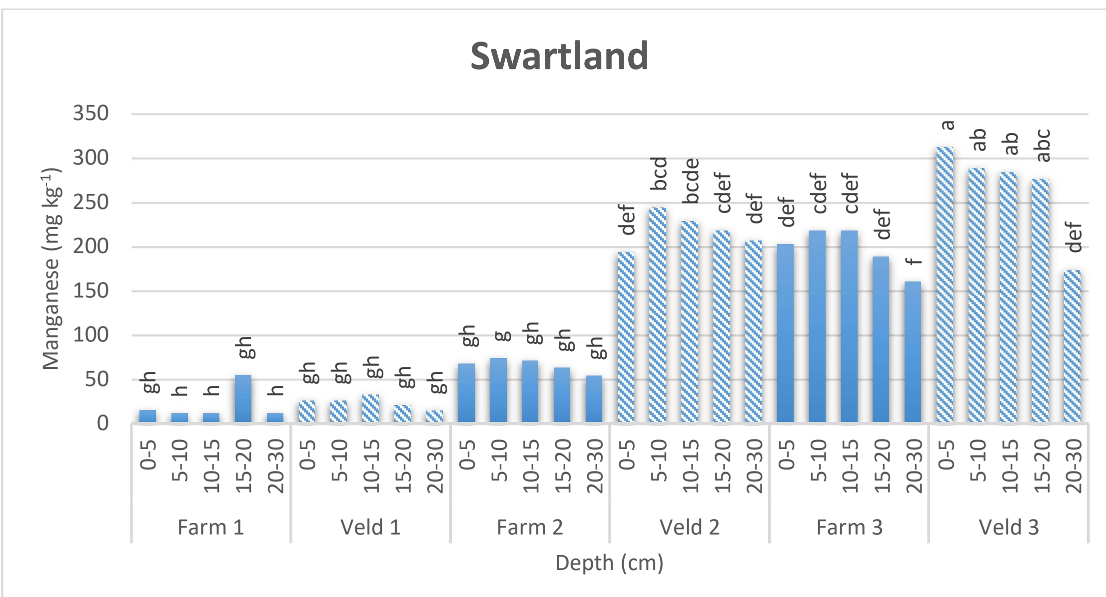

Figure 4.19 Distribution of soil available Mn from 0-30 cm of three selected commercial farms in the Swartland between cultivated soil and natural veld. Different letters on the bars denote a significant difference (P<0.05).

Figures 4.20 and 4.21 show soil exchangeable B distribution (0-30 cm) in the southern Cape and Swartland farms, respectively. In the southern Cape, only the 20-30 cm layer

(Appendix A10) of Farm 3 (0.43 mg kg^{-1}) was B deficient. According to Saha *et al*. (2018) the critical level for B in soil for wheat is 0.5 mg kg^{-1}.There were no significant differences between successive layers. In legume crops, boron is an essential requirement for nitrogen fixation for both *Rhizobium* and *Actinomycetes* species.

The soil boron was deficient in the Swartland (Appendix A12) for the production of wheat and canola in all the layers except for the topsoil (0-5 cm) of the Farm 2 (0.61 mg kg^{-1})). Soils of the canola-producing regions in the Western Cape often exhibit low boron contents less than 5 mg kg^{-1}, and since canola (*Brassica napus*) has a high demand for it, boron may be a yield-limiting factor in these areas (Agenbag & Kempen, 2015).

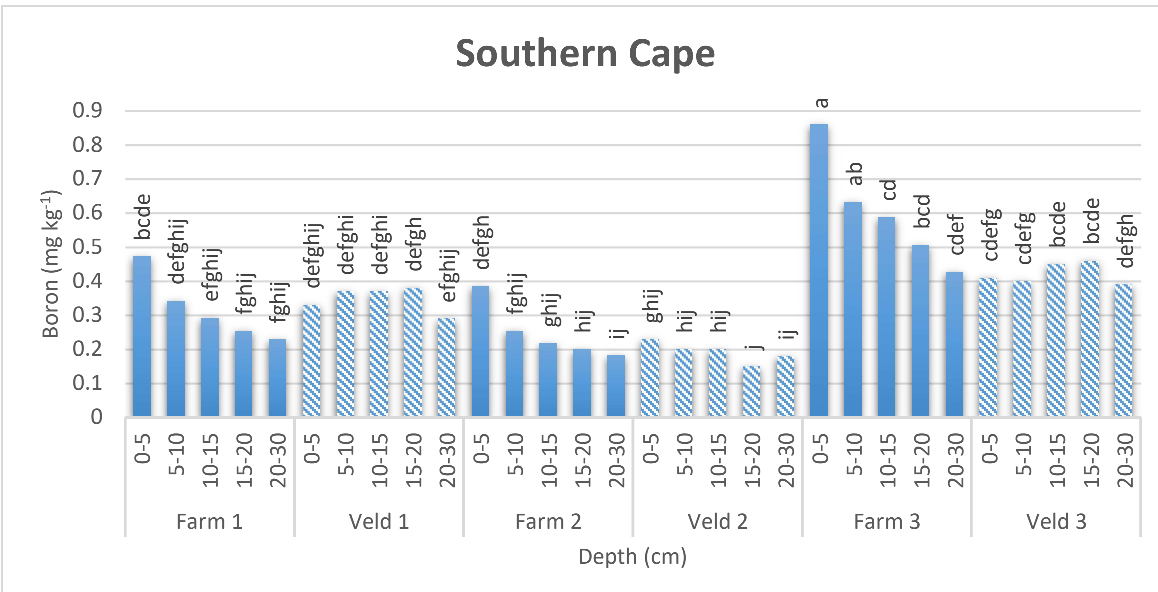

Figure 4.20 Depth distribution of soil available B from 0-30 cm of three selected southern Cape commercial farms between cultivated soil and natural veld. Different letters on the bars denote a significant difference of P<0.05.

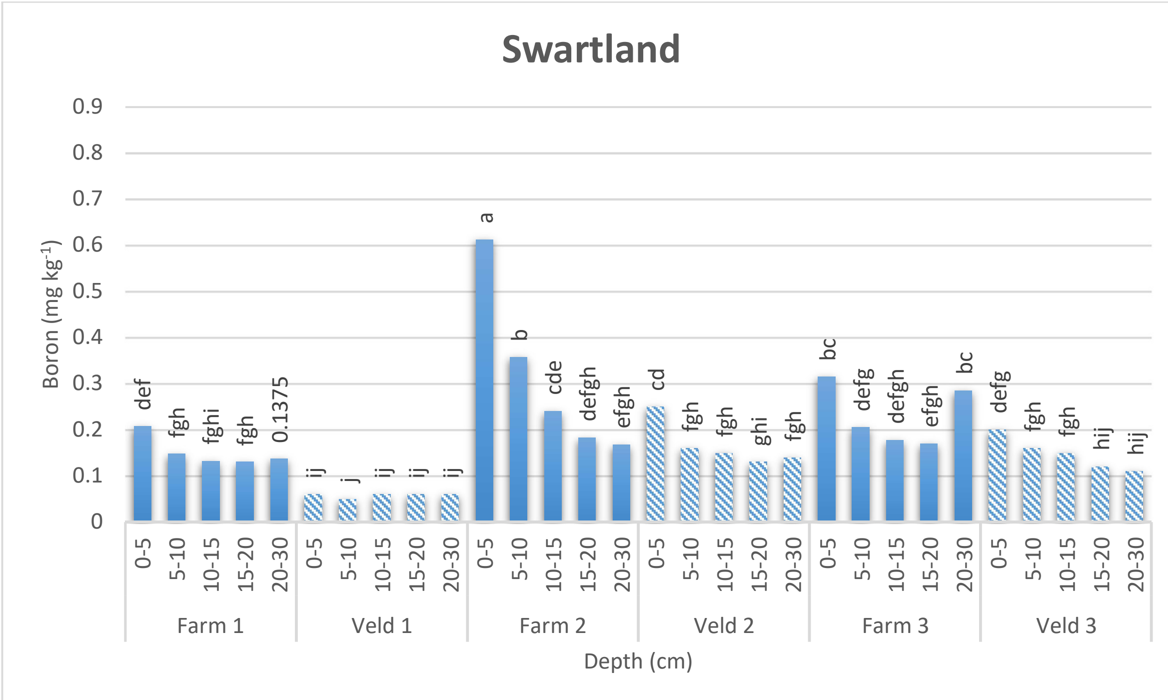

Figure 4.21 Depth distribution of soil available B from 0-30 cm of three selected commercial farms in the Swartland between cultivated soil and natural veld. Different letters on the bars denote a significant difference of P<0.05.

4.5 CONCLUSIONS

Stratification is seen in both the natural veld and the cultivated soil. This is a natural process as result of the environmental conditions and often the cultivated soil layers did not differ significantly from the cultivated soil. The cultivation and addition of ameliorates have accentuated the stratification of K, P, C and Zn, especially in the top 5 cm. In the southern Cape (Appendix A13), soil organic carbon was significantly (P<0.001) positively correlated with B (0.92), K (0.83) and Zn (0.82). Soil K, P, organic C and Zn was most stratified in the southern Cape.

In the Swartland, the nutrients that were most stratified were K, P, Ca, Mg, C and Zn. The soil organic C had a significant (P<0.01) positive relationship (Appendix A14) with B (0.76) and a significant (P<0.05) positive correlation with K (0.75) and S (0.61).

Doing incremental soil sampling, the presence of stratification was noticed and layers with deficient levels of K, S, Zn and subsoil acidity was detected. The knowledge of respective effects on soil macronutrients over time will provide insights into the sustainability of these management practices. Maintaining and building soil quality are essential for competitive, sustainable agriculture production.

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CHAPTER 5 FARM PRACTICES IN THE WESTERN CAPE

5.1 INTRODUCTION

The increase in population and high demand for food are putting pressure on agricultural sector to replace traditional practices with sustainable crop production methods. Soil degradation induced by persistent conventional farming with repeated tillage and removal or *in situ* burning of crop residue is a major limitation to food security and environmental sustainability (Chatterjee *et al*., 2020). Conservation Agriculture (CA) is increasingly promoted as an alternative to reduce soil degradation resulting from agricultural practices that deplete soil fertility (Kassam *et al*., 2009). CA is a solution to restore soil organic carbon and improve soil health. (Smith et al. 2016) CA is based on three basic principles per definition: minimum or no mechanical soil disturbance, where more than 30% of the soil surface is covered with crop residue, permanent soil cover (growing crop or mulch of crop residue) and diversified crop rotation, preferentially including legumes (FAO, 2008).

Wheat is by far the most important winter cereal crop in the Western Cape. Production in South Africa is not sufficient for domestic requirements and the country has to import wheat to meet its domestic demand. Wheat farmers of the Western Cape traditionally planted wheat in a monoculture system, but many of them have now adopted CA with crop rotation as one component (ARC, 2014). Other winter crops are malting barley, canola, oats and medics. On average, South Africa's CA adoption rate among grain producers is estimated between 20 and 30%, with the highest proportion of farmers (>70%) found in the Western Cape Province (Blignaut *et al*., 2015). Improved planters and more suitable herbicides led to the widespread adoption of CA in many parts of the world (ARC, 2014).

One outcome of NT practices is an increased frequency of nutrient stratification (Franzluebbers, 2002), whereby some nutrients become concentrated in the top few centimeters of soil (Kirkegaard et al., 2014; Moreno et al., 2006). This stratification can have beneficial effects. For example, stratification of SOC may enhance the soil surface characteristics, such as soil aggregation and improved soil aeration, leading to more effective water infiltration (Franzluebbers, 2002, Franzluebbers *et al*., 2007; Grove *et al*., 2007; Zhao *et al*., 2015). Nutrient stratification can, however, become a problem if the topsoil dries out.

5.2 STUDY BACKGROUND

Survey Monkey™ is an internet programme and hosting site that enables a person to develop a survey for use over the internet. The questionnaire can be set up with a variety of responses including yes/no responses, selecting one or more from a list and drop down menu responses.The purpose of the survey was to gain more insight into the grain farmers' practices and if these affect nutrient stratification on their farms in the Western Cape Province. The southern Cape and Swartland regions of the Western Cape Province produce a large portion of the country's wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), oats (*Avena sativa*) and canola (*Brassica napus*) under dryland conditions (Liebenberg *et al*., 2021).

The survey (Apppendix B) was conducted online and questions were asked to collect information about farmers' practices. The following topics were included in the survey: crop rotation systems, planting method, tillage practice, stubble management and fertiliser use. The questionnaire was developed in consultation with the ARC Economic and Biometrical services division and other professionals working in the field of wheat farming and CA technology. Most questions were designed as closed questions to assist with analysis of data. The questionnaire had been included as Appendix B.

The online survey link was disseminated in conjunction with agriculture companies, farmers' associations and co-operations in the Swartland and Overberg. The survey was open from May 2020 to November 2020. The survey was offered in Afrikaans and English.

The following limitations were experienced during data collection:

- There were no gatherings of Farmers' Associations during the Covid 19 restriction period. Face to face contact with farmers to motivate them to partake in the questionnaire was not possible.
- The Survey Monkey system that was used were not always reliable and some of the data were lost in the process.

Once the data was captured through the survey, a Microsoft Excel spreadsheet was used to capture the information from the questionnaires.

5.3 STATISTICAL ANALYSIS

The questionnaire used in the study was developed to gather information about the farming practices regarding CA and its characteristics. The total number of participants (32) was regarded as a poor statistical representation of the CA wheat farmers in Western Cape Province. Due to unforeseen circumstance with the programme, only 32 questionnaires were fully coded and analysed. The frequencies of the classes within the questions from the questionnaires were calculated by XLSTAT (Version 2020, Addinsoft, Paris).

The information was obtained by means of voluntary participation by producers and are therefore not statistical representative. Due to the small size of the case study sample it cannot be viewed as representative of the larger agriculture region, but gives a good indication of what is happening on farms. The Swartland is very poorly presented due to the data that was lost.

5.4 OVERVIEW OF SURVEY QUESTIONNAIRE RESULTS

Firstly, information on the farm environment e.g. location, soil type and annual rainfall was collected. This study represents the results of questionnaires completed by 32 wheat farmers with the aim to determine the farming practices on their farms. The geographical distribution of the participants are shown in Table 5.1. The most of the farmers (82%) were from the southern Cape.

Table 5.1 Geographical distribution of the participants.

Region	Number of respondents	Percentage
Southern Cape		
Albertinia, Riversdale, Heidelberg	1	3 %
Swellendam, Riviersonderend	7	22 %
Caledon, Villiersdorp	7	22 %
Bredasdorp, Napier	11	34 %
Swartland		
Moorreesburg, Koringberg	3	9 %
Porterville	3	9 %
Piketberg, Pools, Eendekuil	0	0 %
Philadelphia, Malmesbury	0	0 %
Hopefield, Vredenburg	0	0 %

The total area of the cultivated soil on the farms ranged from 300 ha to 5400 ha as grouped in Table 5.2. Farm sizes in the Swartland is relatively large and generally range from 300 to 2000 hectares, with some exceptions (Metelerkamp, 2011).

Table 5.2 Area of total cultivated land

Cultivated land	Amount of respondents	Percentage
>750 ha	8	25 %
751- 1500 ha	11	34.4 %
1501-2250 ha	4	12.5 %
2251-3000 ha	5	15.6 %
3001-5500 ha	4	12.5 %

The dominant age of the farmers were between 31 and 50 years. The age distribution of the farmers is indicated in Table 5.3. The average size of a farm in the Swartland in 2007 was about 1200 ha (Hardy *et al.,* 2011).

Table 5.3 Age distribution of the respondents taking part in the study

Age	Number of respondents	Percentage
Younger than 30	4	12.5 %
Between 31 and 45	12	37.5 %
Between 46 and 60	8	25 %
Between 61 and 70	8	25 %

Most of the respondents were in possession of a diploma or degree at 38% and 34%, respectively. The education level of the farmers is portrayed in Table 5.4. This follows the findings from the ARC study (ARC, 2015), where the highest level of education is an agricultural diploma or degree at 39.5% and 37.5% respectively.

Table 5.4 Education level of the respondents

Education level	Number	Percentage
Matric	3	9 %
Diploma	12	38 %
Bachelor's degree	11	34 %
Postgraduate	6	19 %

The respondents indicated that 88% of them belong to a study group or Farmer's Association.

The distribution of the annual rainfall on the farms are indicated in Table 5.5. The water requirement for wheat is about 600 mm per annum. In dry areas where cultivation practices such as zero tillage and minimum tillage are practised, stubble mulching is recommended for moisture conservation (DAFF, 2016. Rainfall in the winter rainfall regions of the southern Cape and Swartland varies between 250 and 400 mm per annum (Hardy *et al*., 2011).

Table 5.5 Distribution of rainfall on the farms of the respondents

Rainfall	Number of respondents	Percentage
151-250 mm	4	12.5 %
251-350 mm	9	28.1 %
351-400 mm	12	37.5 %
>400 mm	7	21.9 %

Farmers could describe their cropping systems by choosing from conservation agriculture, conventional, biological or precision farming (Table 5.6). The following definitions were given to the agricultural systems.

- Conservation - Practice promotes minimum soil disturbance, maximum soil cover and crop rotation.
- Conventional – Soil disturbance, Practice monoculture, use synthetic chemical fertiliser, spreading seed and incorporation, burning stubble
- Biological - Production without chemical fertiliser, herbicide or pesticide with organic fertiliser and pest control
- Precision - Use a GPS for soil taking samples, planting, fertiliser application, spraying and yield monitoring

Table 5.6 Distribution of agricultural system

Farming system	Number	Percentage
Conservation	20	62.5%
Conventional	0	0
Biological	0	0
Precision	12	37.5%

In the southern Cape crop-pasture rotation were more common than in the Swartland. Long rotations, where lucerne pastures are kept for 5-7 years followed by 5-7 years of cropping phase (Hardy *et al.,* 2011). Every farmer practiced their own combination of rotation crops. Most of the farmers had wheat, barley and canola in rotation. A third of the respondents had a long cycle of lucerne in the rotation. Farmers from the Swartland had medics and lupines in the rotation as a legume crop. Some farmers also planted oats in the rotation. In the Swartland, wheat monoculture was still practiced on some smaller production units, but crop rotation, either continuous cropping or crop-pasture, or both, was more typical (Hardy et al., 2011). Wheat was by far the winter cereal crop most planted in the Western Cape. The majority of farmers in the Swartland (98.8%) implemented crop rotation (Strauss *et al*., 2011).

Modiselle *et al*. (2015) determined in their study that 49% of the respondents were practising all three components of CA and that 76% of the producers interviewed used a crop rotations system. In this study the distribution of crops were wheat (28%), barley (25%), canola (20%), lucerne (11%), oats (7%) and lupine (2%).

Forty four percent of the respondents planted cover crops on a part of the farm. It was mostly legume mix (22%), then a multispecies mix (16%) and grain mix (6%). The results are summarised in Table 5.7.

Table 5.7 Utilisation of cover crops by respondents

Cover crops	Number	Percentage
Pulse mix	7	22 %
Multispecies mix	5	16 %
Grain mix	2	6 %
No cover crop	18	56 %

Most respondents had only sheep (47 %) and 41 % had cattle and sheep. A few had sheep and ostriches (6 %) and 3 % had sheep, cattle and game (Table 5.8). One respondent (3 %) had only game. Livestock plays an extremely important role in maintaining the stability of the farming operation in regions with low and variable crop production resulting from low and variable rainfall or shallow, infertile soils. Sheep graze mainly on legume pastures that are grown in rotation with winter cereal and oil and protein seed crops and on the crop residues during the dry summer months (Hardy *et al.,* 2011).

Table 5.8 Livestock distribution on the respondent's farms

Livestock	Number of respondents	Percentage
Sheep	15	47 %
Sheep and cattle	13	41 %
Sheep and ostriches	2	6 %
Sheep, cattle and game	1	3 %
Wild animal	1	3 %

As indicated in Figure 5.1, more than half the respondents (53 %) did not use primary tillage and planted directly into the stubble. A chisel plough was used by 35 % of the respondents to prepare the soil for planting, while the rest used either disc plough or other implements.

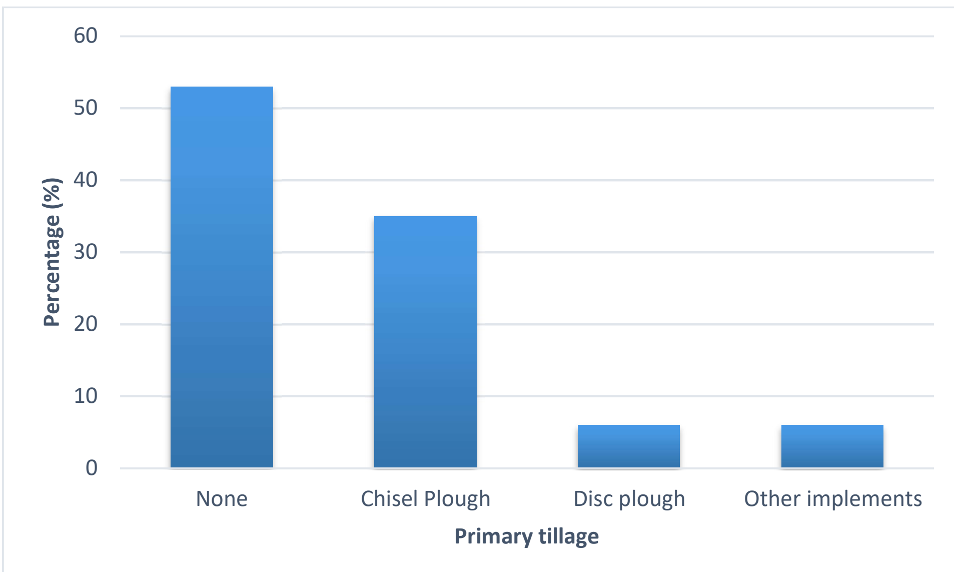

Figure 5.1 Primary tillage used by respondents.

Only 6% of the respondents used secondary tillage. Ten of the farmers (31%) never ripped their soil, whereas 19 (31%) would do it for strategic reasons, like breaking up restricted layers. The other respondents would rip every second, third or fourth year. Conventional cropping practices in South Africa have been based on aggressive tillage involving primary and secondary soil preparation for weeding and seedbed preparation before planting. A range of tractor-drawn implements, such as mouldboard ploughs, discs, chisels, rippers, rotary tillers, tine cultivators and disc harrows were used in these systems (Smith *et al*., 2017).

The majority of the farmers (88%) used no-till planters to place seed in the soil, while another 6% used no-till disc planters. The rest broadcast the seed and followed by a light harrow to cover the seed. Crop residue are left on the soil to protect it against erosion and compaction due to raindrop action by 44% of the respondents, while 41% baled the residue for feed (Table 5.9). Thirteen percent of the respondents let the livestock graze on the stubble while only one farmer (3%) flattened the residue with tyres pulled behind a tractor. Before the introduction of conservation tillage practices, the cropping system required the removal of crop residues by grazing, baling and burning (Tolmay, 2008).

Table 5.9 Residue practices as indicated by the respondents

Residue practices	Number	Percentage
Bale for feed	13	41 %
Drag tyres to flatten the residue	1	3 %
Let livestock graze	4	13 %
Leave stubble to protect soil surface	14	44 %

Only 28% of the respondents' soils were mapped. The mapping revealed a combination of Glenrosa, Mispah and Swartland soil forms.

Most of the respondents (44%) claimed to take soil samples each year on a section of the farm. The other respondents were divided between every third or fourth year (22%) or no set programme (3%) as indicated by Table 5.10.

Table 5.10 Frequency of soil samples for assessing soil fertility

Intervals of soil samples	Number of respondents	Percentage
Every year a section of the farm	14	44 %
Every second or third year	7	22 %
Every fourth or fifth year	10	31 %
No set program	1	3 %

The majority of the respondents (59%), used independent consulting companies to take soil samples, while 31% used fertiliser companies to take the soil samples. Half of the samples (50%) were taken at a 15 cm depth, 41% were taken to 30 cm depth and 9% to a depth of 10 cm as shown in Fig 5.2.

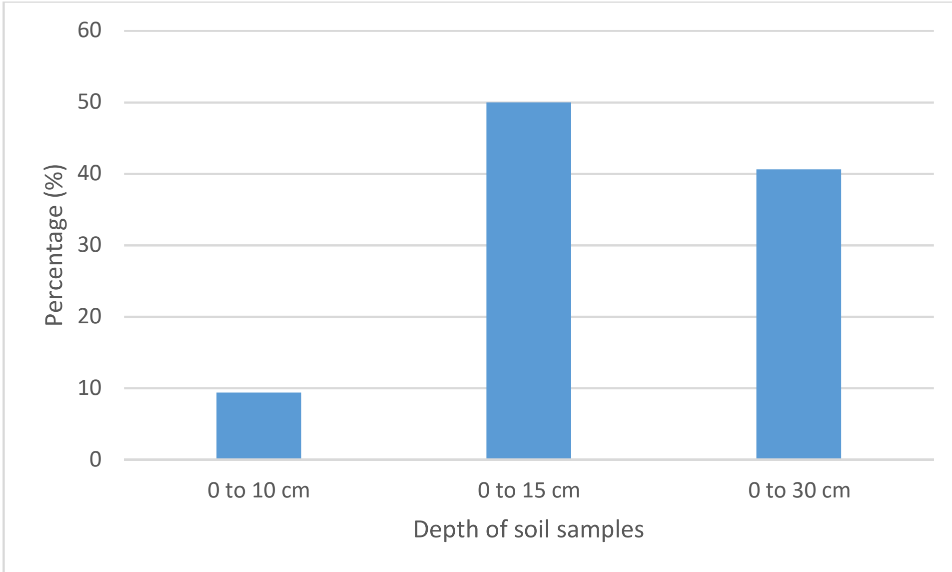

Figure 5.2 Depth of soil samples collected by producers as indicated by respondents

Most respondents (47%) used low calcium and magnesium to calculate their lime requirements. Only 3% of the respondents limed a set amount each year, while 30% used low pH and 20% use the Albrecht system to calculate the lime requirement. Seventy percent of the respondents did not have subsoil acidity, 10 % had subsoil acidity, while the rest (20%) did not know, as can be seen in Table 5.11.

Table 5.11 The presence of subsoil acidity as indicated by respondents

Subsoil acidity	Number of respondents	Percentage
No subsoil acidity	21	70 %
Presence of subsoil acidity	3	10 %
Unknown	6	20 %

The carbon content of the soil is presented in Table 5.12. Most of the respondents (54%) indicated a soil carbon content between 1.6 to 4%. Ten percent of the respondents did not know what the soil C content of their farm's soil was. South African soils have low organic matter levels (Du Preez *et al*., 2011). About 58% of soils contain less than 0.5% organic carbon and only 4% contain more than 2% organic carbon (Du Preez *et al*., 2011).

Table 5.12 Organic carbon content of the soil on producers farm as indicated by respondents

Carbon content	Number of respondents	Percentage
< 0.5%	1	3 %
0.5-1%	4	13 %
1.1-1.5%	6	20 %
1.6-2%	8	27 %
2.1-4%	8	27 %
Unknown	3	10 %

Respondents deemed the most important CA principles (Table 5.13) to be minimum soil disturbance (47%), followed by crop rotation (37%) and maximum stubble retention (10%). The ARC (2014) found in an interview of 51 wheat farmers that 49% of the respondents were practicing all three components of CA, followed by 29% who practiced only minimum tillage.

Table 5.13 The importance of CA principles according to the respondents

CA principles	Numbers of respondents	Percentage
Minimum soil disturbance	14	47 %
Crop rotation	11	37 %
Stubble retention	3	10 %
Animal factor	2	6 %

5.5 Conclusions

The responses to the online questionnaire were poor and more than 80% of the respondents were in the southern Cape. In the future, another mode of questioning should be employed. The experimental sample was too small to make any conclusions. The most respondents (63%) indicated that they use conservation agriculture. This is a significant uptake of CA in the winter rainfall area of the Western Cape. Minimum soil disturbance (47%) was indicated as the most important CA principle by the respondents, followed by crop rotation (37%) and stubble retention (10%). More than half of the respondents (54%), indicated that the carbon content in the soil were higher than 1.5 %. Seventy percent of the respondents did not have subsoil acidity, 10 % had subsoil acidity, while the rest (20%) did not know the status of their farm's subsoil acidity. The study showed that with the majority of the soil samples (50%) still collected at a depth of 0-15 cm, nutrient stratification can go undetected.

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CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

The Western Cape is the most important wheat and canola producing region in South Africa. The principles of CA have many benefits for production systems and rapid adoption took place in this Mediterranean climate. However, reduced tillage has challenges such as stratification of certain nutrients in the soil. The main aims of the study were to measure the extent of soil nutrient stratification on the experimental research farms after 12 years of production and on commercial farms with a diverse application of CA. Results obtained could be valuable in developing management strategies for wheat grown under different production systems. The research was undertaken to develop a better understanding of stratification and the extent of stratification in Western Cape soils in the grain producing areas. A survey, completed by 32 farmers, was part of the research. The soil of the long term trials at Langgewens and Tygerhoek Research Farms were sampled at different depth increments to assess the vertical distribution of nutrients. The study was concluded by investigating the soil from six commercial farmers practicing CA for at least 10 years.

6.2 GENERAL CONCLUSIONS

6.2.1 Research Farms

Zero tillage, NT and MT resulted in significant changes in soil organic C and exchangeable cations in the topsoil of Langgewens and Tygerhoek, compared to CT. At Tygerhoek, soil P, followed by K and Ca showed the highest percentage of change (stratification) between the 0-5 cm and 5-10 cm layers. At Langgewens, K, Mg, Ca and Zn showed the highest percentage of change between 0-5 and 5-10 cm layers. Except for Mg and K, MT showed no change greater than 20%. This could be due to the soil disturbance by tines in MT. Crop yields on the different treatment combinations showed that nutrient stratification did not influence crop performance, as long as the nutrient levels is sufficient for crop production. The profitability and sustainability of the system is more important.

6.2.2 Commercial farmers

Although the history of crop rotation, tillage and fertilizer applications were different for every field in the study, valuable information was gained with the incremental soil sampling. Nutrient stratification, subsoil acidification and layers with deficient levels of K, S and Zn for optimum crop production was detected.

The SOM of the southern Cape and Swartland can be maintained and even increased in the upper 0-10 cm by introducing reduced tillage, crop rotation and stubble retention, especially wheat/medics- system. In the southern Cape, soil K followed by P and organic C were the most stratified. In the Swartland, the nutrients that were most stratified were K, P, Ca, Mg, organic C and Zn. These are all immobile nutrients. The difference can be contributed to different parent material and liming that took place, rainfall difference between the two regions and depth of fertiliser placing.

The SR of SOC >2 show the improvement of soil quality on the farms under CA. It is clear that CA systems are well suited to adapt to semi-arid Mediterranean climate.

6.2.3 Survey

Most of the respondents (63%) indicated that they use CA as farming system. This is a significant uptake of CA in the winter rainfall area of the Western Cape. Minimum soil disturbance (47%) was indicated as the most important CA principle, followed by crop rotation (37%) and stubble retention (10%). More than half the respondents (54%) indicated that the carbon content in the soil were higher than 1.5 %, this could be considered as a build-up of soil carbon in the Mediterranean climate. Eighty two percent of the respondents were from the southern Cape and could explain the high carbon content.

6.3 RECOMMENDATIONS

The principle management issue from stratification is that the current soil test (0-30 cm) does not represent the nutrient availability accurately. Agronomic decisions like liming rate and fertilizer requirement are based on this information. With the greater adoption of CA, traditional fertilizer recommendations based on tilled soil may not accurately reflect the root available nutrients in the soil profile. Soil sampling methods for nutrient status should be re-evaluated for reduced tillage practices. Instead of the traditional 0-30 cm soil layer sample, the top 10 cm of soil may more accurately reflect changes in surface pH that affect both nutrient availability and also nutrient accumulation. The depth of soil samples is an important factor for correct interpretation of soil analyses. The management system should be taken into account when interpreting sail analysis results. Guidelines for the depths of soil samples should be recommended by laboratories to accommodate potential nutrient stratification in a CA farming system.

Producers should consider taking soil samples under conservation tillage at depth increments of 0-10 cm and 10-30 cm to monitor the change in the topsoil and subsoil. Nutrient stratification can be addressed by periodic strategic tillage to redistribute nutrients concentrated in the topsoil into deeper layers or by direct placement of nutrients into the depleted subsoil (Angus *et al*., 2019). Further research should be aimed at improving our understanding of crop accessible nutrients, root distribution in the soil profile and crop yield.

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APPENDIX A

Table A1 ANOVA from the soil analysis of Tygerhoek Research Farm for rotation (Rot), tillage (Till) and depth (D)

	pH	K	Ca	Mg	Na	P	Cu	Zn	Mn	S	C
Rotation	0.6934	0.5736	0.7056	0.6686	0.4483	0.9368	0.6441	0.4852	0.3351	0.467	0.24
Tillage	0.8149	0.806	0.5391	0.364	0.9751	0.02	0.9308	0.0339	0.9484	0.0822	0.5693
Rot x Till	0.1215	0.0516	0.6775	0.0023	0.1088	0.5752	0.97	0.7761	0.501	0.1012	0.1445
Depth	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Rot x D	0.009	0.2276	0.0499	0.1622	0.0319	0.5914	0.0139	0.0682	0.1803	< 0.0001	0.0791
Till x D	0.005	0.1438	< 0.0001	0.0032	0.7205	< 0.0001	0.4967	< 0.0001	0.0966	0.0007	< 0.0001
Rot x Till x D	0.9015	0.3659	0.9933	0.8286	0.999	0.8315	0.5102	0.6762	0.5451	0.7274	0.2129

Table A2 ANOVA from the soil analysis of Langgewens Research Farm for rotation (Rot), tillage (Till) and depth (D).

	pH	K	Ca	Mg	Na	P	Cu	Zn	Mn	B	S	C
Rotation	0.5558	0.0321	0.4045	0.3155	0.4582	0.7819	0.2758	0.9532	0.6529	0.3448	0.0336	0.2683
Tillage	0.0288	0.3346	0.027	0.0015	0.0332	0.4259	0.1628	< 0.0001	0.4672	0.0126	0.0181	0.0012
Rot x Till	0.5949	0.0106	0.4276	0.6871	< 0.0001	0.3393	0.3602	0.3183	0.1943	0.1509	0.0788	0.8005
Depth	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.1999	< 0.0001	< 0.0001	< 0.0001	0.0012	< 0.0001	0.0028	< 0.0001
Rot x D	0.0361	< 0.0001	0.029	0.0092	0.0135	< 0.0001	0.396	0.8913	0.0035	< 0.0001	0.4658	0.6035
Till x D	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.9402	< 0.0001	< 0.0001	< 0.0001	0.7119	< 0.0001	0.9714	< 0.0001
Rot x Till x D	0.0068	0.0007	< 0.0001	0.0025	0.9002	0.0529	0.3085	0.2707	0.9751	0.0476	0.9962	0.0529

Table A3 Soil nutrients per depth (cm) and percentage change at Tygerhoek Research Farm

Tillage	Depth	pH_{KCl}	%	Ca	%	Mg	%	Na	%	K	%	P	%	S	%
ZT	0-5	6.15		13.89		2.27		93.50		309.25		105.40		37.69	
	5-10	5.64	*8*	6.81	*51*	1.81	*20*	120.00	*-28*	218.63	*29*	53.94	*49*	32.00	*15*
	10-15	5.56	*1*	5.03	*26*	1.80	*1*	130.94	*-9*	175.81	*20*	29.75	*45*	26.19	*18*
	15-20	5.61	*-1*	4.30	*15*	1.98	*-10*	154.31	*-18*	150.06	*15*	17.88	*40*	26.40	*-1*
	20-30	5.65	*-1*	3.17	*26*	2.34	*-18*	215.19	*-39*	133.63	*11*	6.88	*62*	24.38	*8*
NT	0-5	6.21		11.38		2.34		118.94		286.75		72.31		53.33	
	5-10	5.86	*6*	7.87	*31*	2.07	*11*	132.13	*-11*	221.94	*23*	53.38	*26*	41.56	*22*
	10-15	5.63	*4*	5.34	*32*	1.94	*6*	130.06	*2*	176.38	*21*	31.75	*41*	32.69	*21*
	15-20	5.63	*0*	4.55	*15*	2.09	*-8*	151.81	*-17*	155.00	*12*	19.19	*40*	28.63	*12*
	20-30	5.66	*-1*	3.29	*28*	2.37	*-13*	200.31	*-32*	137.56	*11*	6.75	*65*	23.89	*17*
MT	0-5	5.98		9.55		2.03		93.81		287.21		65.14		52.33	
	5-10	5.79	*3*	7.86	*18*	1.98	*2*	112.31	*-20*	241.31	*16*	52.87	*19*	51.75	*1*
	10-15	5.58	*4*	5.69	*28*	1.89	*4*	127.75	*-14*	190.38	*21*	34.38	*35*	37.13	*28*
	15-20	5.62	*-1*	4.40	*23*	2.00	*-5*	152.25	*-19*	160.31	*16*	19.00	*45*	29.44	*21*
	20-30	5.73	*-2*	3.40	*23*	2.36	*-18*	203.50	*-34*	140.94	*12*	7.50	*61*	22.88	*22*
CT	0-5	6.06		8.59		1.94		108.56		303.94		60.50		41.87	
	5-10	5.91	*2*	7.97	*7*	1.98	*-2*	125.50	*-16*	242.63	*20*	51.31	*15*	52.07	*-24*
	10-15	5.68	*4*	5.87	*26*	1.94	*2*	132.75	*-6*	190.69	*21*	34.31	*33*	41.56	*20*
	15-20	5.57	*2*	4.38	*25*	2.00	*-4*	144.63	*-9*	154.25	*19*	18.75	*45*	29.62	*29*
	20-30	5.54	*1*	3.05	*30*	2.22	*-11*	174.75	*-21*	127.25	*18*	6.06	*68*	21.88	*26*

Table A4 Soil carbon and micronutrients and percentage change per depth (cm) at Tygerhoek Research Farm

Tillage	Depth	C	%	Cu	%	Zn	%	Mn	%
ZT	0-5	2.60		1.21		3.58		99.51	
	5-10	1.63	*37*	1.22	*-1*	2.02	*44*	*102.54*	*-3*
	10-15	1.21	*26*	1.23	*-1*	1.69	*17*	*101.44*	*1*
	15-20	0.98	*19*	1.10	*10*	1.28	*24*	*80.59*	*21*
	20-30	0.90	*8*	1.08	*2*	1.01	*21*	*41.47*	*49*
NT	0-5	2.23		1.22		2.73		*106.79*	
	5-10	1.89	*15*	1.21	*0*	1.97	*28*	*105.68*	*1*
	10-15	1.35	*28*	1.18	*2*	1.44	*27*	*96.27*	*9*
	15-20	1.13	*16*	1.14	*4*	1.20	*17*	*77.80*	*19*
	20-30	0.83	*27*	1.04	*8*	0.85	*29*	*43.16*	*45*
MT	0-5	2.15		1.21		2.23		*107.64*	
	5-10	1.74	*19*	1.24	*-3*	2.01	*10*	*111.09*	*-3*
	10-15	1.32	*25*	1.31	*-5*	1.61	*20*	*102.82*	*7*
	15-20	1.01	*23*	1.18	*10*	1.19	*26*	*80.20*	*22*
	20-30	0.83	*18*	1.06	*11*	1.02	*14*	*42.79*	*47*
CT	0-5	1.96		1.21		2.17		*110.94*	
	5-10	1.73	*11*	1.22	*-1*	2.04	*6*	*110.96*	*0*
	10-15	1.42	*18*	1.22	*0*	1.68	*18*	*105.14*	*5*
	15-20	1.06	*26*	1.09	*10*	1.21	*28*	*77.71*	*26*
	20-30	0.81	*24*	0.94	*14*	0.87	*28*	*32.36*	*58*

Table A5 Correlation table of soil parameters for the 0-5cm depth at Tygerhoek

	pH_{KCl}	Ca	Mg	Na	K	P	Cu	Zn	Mn	S	C
pH_{KCl}	1.00										
Ca	0.56 ***										
Mg	0.34 **	0.13									
Na	0.00	-0.36 **	0.44 ***								
K	0.45 **	0.40 **	-0.37 **	-0.33 **							
P	0.41 **	0.61 ***	0.23	0.04	0.27 *						
Cu	0.16	-0.09	-0.11	0.29 *	0.27 *	0.25					
Zn	0.28 *	0.32 *	0.22	0.38 **	0.15	0.72 ***	0.51 ***				
Mn	0.21 *	-0.05	-0.27 *	0.11	0.47 **	0.08	0.66 ***	0.32 *			
S	0.01	0.17	-0.20	-0.07	0.08	-0.19	-0.06	-0.14	0.12		
C	0.12	0.25	0.30 *	-0.01	-0.03	0.35 **	-0.21	0.13	-0.18	-0.19	1

***significant at the 0.001 level; ** significant at the 0.01 level; * significant at the 0.05 level

Table A6 Nutrients per depth (cm) and percentage change at Langgewens Research Farm

Tillage	Depth	pH KCl	%	Ca	%	Mg	%	Na	%	K	%	P	%	S	%
ZT	0-5	5.94		9.11		2.89		26.88		308.44		103.38		9.56	
	5-10	5.31	*11*	5.03	*45*	1.43	*51*	27.50	*-2*	171.88	*79*	81.88	*21*	11.14	*-17*
	10-15	5.13	*3*	3.76	*25*	1.03	*28*	31.00	*-13*	132.88	*29*	71.56	*13*	12.58	*-13*
	15-20	5.08	*1*	3.29	*13*	1.01	*2*	32.81	*-6*	116.44	*14*	61.50	*14*	12.48	*1*
	20-30	5.13	*-1*	2.58	*22*	0.73	*28*	29.25	*11*	97.31	*20*	39.00	*37*	9.41	*25*
NT	0-5	6.21		10.60		3.01		39.19		327.31		102.00		13.23	
	5-10	5.73	*8*	6.55	*38*	1.87	*38*	40.81	*-4*	207.75	*37*	90.81	*11*	15.42	*-17*
	10-15	5.36	*6*	4.52	*31*	1.25	*33*	34.13	*16*	141.25	*32*	80.67	*11*	14.68	*5*
	15-20	5.27	*2*	3.77	*17*	1.08	*14*	41.81	*-22*	114.69	*19*	66.38	*18*	15.24	*-4*
	20-30	5.31	*-1*	2.95	*22*	0.82	*24*	41.75	*0*	86.75	*24*	42.25	*36*	12.98	*15*
MT	0-5	5.99		7.14		1.88		28.50		278.06		90.88		11.99	
	5-10	5.72	*5*	5.99	*16*	1.36	*28*	30.56	*-7*	210.13	*24*	83.38	*8*	14.28	*-19*
	10-15	5.31	*7*	4.15	*31*	0.92	*32*	29.31	*4*	154.81	*26*	74.94	*10*	13.69	*4*
	15-20	5.18	*3*	3.46	*17*	0.83	*10*	29.19	*0*	122.50	*21*	65.06	*13*	12.15	*11*
	20-30	5.16	*0*	3.08	*11*	0.74	*11*	31.75	*-9*	99.13	*19*	44.13	*32*	11.85	*2*
CT	0-5	5.83		4.83		1.21		32.94		246.25		77.00		14.43	
	5-10	5.72	*2*	4.65	*4*	1.22	*-1*	35.31	*-7*	195.38	*21*	74.88	*3*	14.93	*-3*
	10-15	5.56	*3*	4.42	*5*	1.18	*3*	38.00	*-8*	155.31	*21*	70.88	*5*	16.07	*-8*
	15-20	5.48	*1*	3.90	*12*	1.06	*10*	36.69	*3*	127.00	*18*	70.06	*1*	14.48	*10*
	20-30	5.51	*-1*	3.29	*15*	0.88	*17*	40.19	*-10*	91.69	*28*	52.13	*26*	12.48	*14*

Table A7 Soil carbon and micronutrients per depth (cm) and percentage change of at Langgewens Research Farm

Tillage	Depth	C	%	Cu	%	Zn	%	Mn	%	B	%
ZT	0-5	2.16		1.35		6.74		127.40		0.43	
	5-10	1.41	*35*	1.41	*-5*	4.31	*36*	133.89	*-5*	0.27	*37*
	10-15	0.93	*34*	1.48	*-5*	2.72	*37*	136.58	*-2*	0.20	*26*
	15-20	0.71	*24*	1.47	*1*	2.04	*25*	140.61	*-3*	0.17	*15*
	20-30	0.62	*12*	1.56	*-7*	1.30	*36*	140.66	*0*	0.19	*-11*
NT	0-5	1.64		1.39		6.15		139.85		0.41	
	5-10	1.33	*19*	1.42	*-2*	4.39	*29*	143.02	*-2*	0.32	*22*
	10-15	0.97	*27*	1.50	*-6*	2.84	*35*	143.84	*-1*	0.24	*25*
	15-20	0.77	*21*	1.59	*-6*	2.13	*25*	150.31	*-4*	0.21	*13*
	20-30	0.69	*11*	1.73	*-9*	1.40	*34*	150.84	*0*	0.21	*-4*
MT	0-5	1.35		1.41		4.36		134.29		0.33	
	5-10	1.25	*7*	1.40	*1*	3.93	*10*	136.91	*-2*	0.30	*8*
	10-15	0.96	*23*	1.46	*-5*	2.87	*27*	138.91	*-1*	0.25	*20*
	15-20	0.74	*22*	1.50	*-3*	2.12	*26*	139.83	*-1*	0.21	*16*
	20-30	0.75	*0*	1.54	*-3*	1.49	*29*	138.07	*1*	0.20	*2*
CT	0-5	1.01		1.58		2.86		135.01		0.26	
	5-10	0.92	*10*	1.58	*0*	2.62	*8*	138.05	*-2*	0.25	*6*
	10-15	0.94	*-3*	1.58	*0*	2.42	*8*	137.44	*0*	0.22	*12*
	15-20	0.78	*17*	1.60	*-1*	2.38	*2*	140.16	*-2*	0.19	*12*
	20-30	0.64	*19*	1.62	*-1*	1.80	*24*	135.14	*4*	0.20	*-7*

Table A8 Correlation for 0-5 cm depth of soil nutrients for Langgewens Research Farm

	pH_KCl	Ca	Mg	Na	K	P	Cu	Zn	Mn	B	S	C
pH_KCl	1											
Ca	0.61 ***											
Mg	0.59 ***	0.88 ***										
Na	0.39 **	0.28 *	0.36 **									
K	0.44 ***	0.61 ***	0.62 ***	0.35 **								
P	0.50 ***	0.67 ***	0.62 ***	0.22	0.48 ***							
Cu	0.08	-0.19	-0.07	0.31 *	-0.15	0.08						
Zn	0.44 ***	0.69 ***	0.69 ***	0.14	0.44 ***	0.61 ***	0.04					
Mn	-0.09	-0.08	-0.09	-0.04	0.09	-0.09	0.13	0.07				
B	0.49 ***	0.66 ***	0.79 ***	0.34 **	0.64 ***	0.38 **	-0.07	0.57 ***	-0.05			
S	0.05	-0.10	-0.09	0.58 ***	0.13	-0.09	0.24	0.01	0.11	0.08		
C	0.32 **	0.65 ***	0.68 ***	-0.03	0.39 **	0.51 ***	-0.10	0.64 ***	0.03	0.49 ***	-0.35 **	1

***significant at the 0.001 level; ** significant at the 0.01 level; * significant at the 0.05 level

Table A9 Soil nutrient and percentage change between depth increments in the southern Cape.

Tillage	Depth	pH $_{KCl}$	%	Ca	%	Mg	%	K	%	P	%	S	%	C	%
Farm 1	0-5	6.33		6.8		2.32		252		72		12.43		2.88	
	5-10	6.05	*4*	5.5	*19*	1.97	*15*	141	*44*	51	*30*	10.18	*18*	1.91	*34*
	10-15	5.85	*3*	4.6	*17*	1.71	*13*	99	*30*	37	*28*	8.73	*14*	1.18	*38*
	15-20	5.88	*0*	4.1	*11*	1.87	*-10*	79	*20*	27	*26*	8.70	*0*	0.90	*23*
	20-30	5.45	*7*	2.4	*41*	1.87	*0*	56	*29*	10	*65*	7.40	*15*	0.83	*8*
Veld 1	0-5	5.00		5.0		3.30		182		59		9.10		4.41	
	5-10	5.00	*0*	3.2	*37*	3.06	*7*	118	*35*	11	*81*	8.50	*7*	2.22	*50*
	10-15	4.90	*2*	2.7	*15*	3.11	*-2*	88	*25*	5	*55*	6.90	*19*	1.54	*31*
	15-20	4.90	*0*	2.3	*16*	3.25	*-5*	64	*27*	4	*20*	5.80	*16*	1.24	*19*
	20-30	4.70	*4*	1.7	*24*	3.52	*-8*	51	*20*	3	*25*	5.00	*14*	0.83	*33*
Farm 2	0-5	6.35		8.5		2.08		191		104		6.40		2.62	
	5-10	6.03	*5*	6.4	*25*	1.81	*13*	138	*28*	66	*37*	5.90	*8*	1.78	*32*
	10-15	6.03	*0*	5.6	*13*	1.73	*4*	96	*30*	43	*34*	4.60	*22*	1.17	*35*
	15-20	5.95	*1*	3.8	*31*	1.79	*-3*	78	*19*	31	*28*	5.00	*-9*	1.07	*8*
	20-30	5.88	*1*	2.8	*26*	2.05	*-15*	64	*17*	20	*37*	5.30	*-6*	0.65	*40*
Veld 2	0-5	5.10		2.7		1.97		240		14		.		2.52	
	5-10	5.10	*0*	2.9	*-8*	2.33	*-18*	229	*5*	11	*21*	.	.	2.15	*15*
	10-15	5.10	*0*	2.3	*23*	2.28	*2*	183	*20*	9	*18*	.	.	1.72	*20*
	15-20	5.20	*-2*	1.7	*23*	2.17	*5*	143	*22*	6	*33*	.	.	1.19	*31*
	20-30	5.10	*2*	1.3	*24*	2.04	*6*	109	*24*	5	*17*	.	.	0.68	*43*
Farm 3	0-5	6.23		9.8		2.74		547		118		81.00		3.89	
	5-10	5.95	*4*	7.8	*20*	1.78	*35*	393	*28*	79	*33*	50.00	*38*	2.98	*23*
	10-15	5.98	*0*	6.8	*13*	1.72	*4*	356	*9*	67	*16*	51.25	*-3*	2.61	*13*
	15-20	5.98	*0*	7.1	*-4*	1.65	*4*	331	*7*	52	*21*	41.00	*20*	2.25	*14*
	20-30	5.93	*1*	5.2	*27*	1.51	*9*	232	*30*	32	*38*	28.50	*30*	1.69	*25*
Veld 3	0-5	4.70		6.4		2.26		525		61		16.00		6.08	
	5-10	4.90	*-4*	5.5	*14*	2.23	*1*	365	*30*	44	*28*	15.00	*6*	4.88	*20*
	10-15	5.20	*-6*	6.0	*-9*	2.13	*4*	368	*-1*	40	*9*	12.00	*20*	4.41	*10*
	15-20	5.20	*0*	5.5	*7*	2.09	*2*	358	*3*	37	*8*	11.00	*8*	3.98	*10*
	20-30	5.20	*0*	4.3	*23*	1.67	*20*	270	*25*	21	*43*	8.80	*20*	2.54	*36*

Table A10 Soil C and micronutrients and percentage change between depths increments in the southern Cape

Tillage	Depth	Cu	%	Zn	%	Mn	%	B	%
Camp 1	0-5	1.16		2.58		109.1		0.47	
	5-10	1.15	*1*	1.78	*31*	110.0	*-1*	0.34	*28*
	10-15	1.27	*-11*	1.67	*6*	117.8	*-7*	0.29	*15*
	15-20	1.26	*1*	1.49	*10*	94.0	*20*	0.26	*13*
	20-30	0.81	*35*	0.67	*55*	40.2	*57*	0.25	*1*
Veld 1	0-5	1.30		3.36		205.4		0.33	
	5-10	1.71	*-32*	2.25	*33*	173.6	*15*	0.37	*-12*
	10-15	1.73	*-1*	2.01	*11*	146.9	*15*	0.37	*0*
	15-20	1.44	*17*	0.71	*65*	116.8	*20*	0.38	*-3*
	20-30	1.03	*28*	0.46	*35*	58.7	*50*	0.29	*24*
Camp 2	0-5	1.45		3.55		59.2		0.39	
	5-10	1.40	*3*	2.42	*32*	56.7	*4*	0.26	*34*
	10-15	1.16	*17*	1.60	*34*	50.0	*12*	0.22	*15*
	15-20	1.23	*-6*	1.41	*12*	47.2	*6*	0.20	*8*
	20-30	1.08	*12*	1.31	*7*	61.5	*-30*	0.18	*9*
Veld 2	0-5	1.20		3.22		118.7		0.23	
	5-10	1.23	*-3*	2.53	*21*	132.5	*-12*	0.20	*13*
	10-15	1.08	*12*	2.09	*17*	110.1	*17*	0.20	*0*
	15-20	0.81	*25*	1.60	*23*	91.2	*17*	0.15	*25*
	20-30	0.72	*11*	1.12	*30*	72.4	*21*	0.18	*-20*
Camp 3	0-5	1.27		6.71		76.4		0.86	
	5-10	1.11	*13*	5.06	*25*	84.4	*-11*	0.63	*26*
	10-15	1.04	*6*	4.46	*12*	84.9	*-1*	0.59	*7*
	15-20	0.93	*11*	3.13	*30*	74.1	*13*	0.51	*14*
	20-30	0.85	*8*	2.55	*19*	56.3	*24*	0.43	*15*
Veld 3	0-5	0.73		6.19		126.9		0.41	
	5-10	0.70	*4*	2.96	*52*	104.1	*18*	0.40	*2*
	10-15	0.75	*-7*	2.42	*18*	108.8	*-5*	0.45	*-13*
	15-20	0.66	*12*	2.00	*17*	86.0	*21*	0.46	*-2*
	20-30	0.66	*0*	1.58	*21*	64.3	*25*	0.39	*15*

Table A11 Nutrients and percentage change between depth increments in the Swartland.

Tillage	Depth	pH_{KCl}	%	Ca	%	Mg	%	K	%	P	%	S	%	C	%
Farm 1	0-5	6.30		2.72		1.02		97		55		3.85		0.85	
	5-10	5.65	10	1.42	48	0.50	51	69	30	45	17	4.28	-11	0.45	47
	10-15	5.00	12	0.99	30	0.35	31	58	16	48	-7	4.23	1	0.25	45
	15-20	5.10	-2	1.10	-11	0.44	-28	51	11	47	3	4.88	-15	0.22	12
	20-30	5.40	-6	1.47	-34	0.44	0	49	5	44	6	4.58	6	0.18	16
Veld 1	0-5	6.20		1.09		0.53		83		26		1.80		0.34	
	5-10	5.90	5	0.89	18	0.50	6	65	22	19	27	2.20	-22	0.31	9
	10-15	5.90	0	0.94	-6	0.56	-12	61	6	14	26	2.10	5	0.30	3
	15-20	6.10	-3	0.75	20	0.49	13	57	7	11	21	2.30	-10	0.25	17
	20-30	6.20	-2	0.75	0	0.56	-14	56	2	12	-9	2.10	9	0.17	32
Farm 2	0-5	6.25		8.66		1.99		354		105		23.48		2.69	
	5-10	5.88	6	6.32	27	1.26	37	195	45	59	44	21.50	8	1.52	43
	10-15	5.73	3	4.38	31	0.94	25	119	39	43	27	10.28	52	1.02	33
	15-20	5.53	3	3.55	19	0.69	27	86	28	39	10	8.58	17	0.77	24
	20-30	5.43	2	2.74	23	0.75	-9	64	25	21	45	6.18	28	0.63	18
Veld 2	0-5	4.70		1.71		0.97		200		39		8.90		1.51	
	5-10	4.60	2	1.60	6	0.84	13	117	42	18	54	8.60	3	0.95	37
	10-15	4.40	4	1.32	18	0.84	0	95	19	13	28	5.50	36	0.44	54
	15-20	4.30	2	1.20	9	0.81	4	76	20	11	15	5.30	4	0.36	18
	20-30	4.50	-5	1.56	-30	1.02	-26	73	4	8	27	4.80	9	0.31	14
Farm 3	0-5	6.50		7.90		1.94		185		139		15.80		1.54	
	5-10	6.33	3	5.23	34	1.42	27	113	39	104	25	9.57	39	1.35	13
	10-15	6.13	3	3.43	34	1.14	19	71	38	67	36	10.20	-7	0.68	49
	15-20	6.25	-2	3.83	-12	1.10	4	63	11	35	48	10.57	-4	0.66	4
	20-30	6.13	2	3.13	18	1.47	-33	62	1	17	52	11.47	-9	0.58	12
Veld 3	0-5	6.00		3.22		2.13		241		30		14.00		1.60	
	5-10	5.80	3	2.76	14	2.48	-16	160	34	21	30	17.00	-21	0.95	41
	10-15	5.60	3	2.76	0	3.23	-30	92	43	18	14	13.00	24	0.72	24
	15-20	5.40	4	2.33	16	3.45	-7	68	26	16	11	9.60	26	0.56	22
	20-30	5.20	4	2.17	7	4.10	-19	59	13	16	0	12.00	-25	0.37	34

Table A12 Soil carbon and micronutrients per depth increments and percentage change of change in the Swartland

Tillage	Depth	Cu mg kg^{-1}	%	Zn mg kg^{-1}	%	Mn mg kg^{-1}	%	B mg kg^{-1}	%
Camp 1	0-5	0.52		1.47		109		0.21	
	5-10	0.59	-14	1.10	25	110	-1	0.15	29
	10-15	0.49	18	0.69	38	118	-7	0.13	10
	15-20	0.72	-47	2.23	-226	94	20	0.13	2
	20-30	0.45	38	0.64	71	40	57	0.14	-6
Veld 1	0-5	0.51		1.02		205		0.06	
	5-10	0.33	35	0.71	30	174	15	0.05	17
	10-15	0.87	-164	0.93	-31	147	15	0.06	-20
	15-20	0.32	63	0.66	29	117	20	0.06	0
	20-30	0.58	-81	1.10	-67	59	50	0.06	0
Camp 2	0-5	1.30		3.76		59		0.61	
	5-10	1.38	-6	2.96	21	57	4	0.36	42
	10-15	1.09	21	1.34	55	50	12	0.24	33
	15-20	1.08	1	1.10	18	47	6	0.18	24
	20-30	1.07	1	0.86	22	62	-30	0.17	8
Veld 2	0-5	1.30		1.53		119		0.25	
	5-10	1.77	-36	1.12	27	133	-12	0.16	36
	10-15	1.70	4	0.85	24	110	17	0.15	6
	15-20	1.72	-1	0.79	7	91	17	0.13	13
	20-30	2.10	-22	0.66	16	72	21	0.14	-8
Camp 3	0-5	2.14		7.05		76		0.32	
	5-10	2.31	-8	17.83	-153	84	-11	0.21	35
	10-15	2.55	-10	6.07	66	85	-1	0.18	13
	15-20	2.42	5	5.76	5	74	13	0.17	4
	20-30	2.51	-4	4.25	26	56	24	0.29	-68
Veld 3	0-5	2.01		5.45		127		0.20	
	5-10	2.07	-3	3.72	32	104	18	0.16	20
	10-15	1.99	4	2.42	35	109	-5	0.15	6
	15-20	1.37	31	1.64	32	86	21	0.12	20
	20-30	1.10	20	1.29	21	64	25	0.11	8

Table A13 Correlation table for soil nutrients of 0-5 cm depth for 3 selected commercial farms in the southern Cape

	pH	Ca	Mg	Na	K	P	Cu	Zn	Mn	B	S	C
pH	1											
Ca	0.79 **	1.00										
Mg	0.63 *	0.71 *	1.00									
Na	0.13	0.48	0.66 *	1.00								
K	-0.18	0.31	0.41	0.71 *	1.00							
P	0.19	0.54	0.24	0.59 *	0.62 *	1.00						
Cu	-0.24	-0.07	-0.26	0.08	0.17	0.38	1.00					
Zn	-0.30	0.12	0.26	0.74 *	0.91 ***	0.68 *	0.26	1.00				
Mn	-0.47	-0.28	-0.41	-0.31	0.11	-0.20	0.51 *	-0.04	1.00			
B	-0.26	0.05	0.40	0.64 *	0.88 ***	0.39	0.12	0.88 ***	0.08	1.00		
S	0.10	0.55	0.42	0.84 *	0.90 ***	0.94 ***	0.44	0.84 **	-0.01	0.72 *	1.00	
C	0.05 *	0.28	0.58 *	0.66 *	0.83 ***	0.46	0.04	0.82 ***	-0.09	0.92 ***	0.76 *	1

***significant at the 0.001 level; ** significant at the 0.01 level; * significant at the 0.05 level

Table A14 Correlation table of soil nutrients for 3 commercial farms in the Swartland sampled at 0-5 cm depth

	pH	Ca	Mg	Na	K	P	Cu	Zn	Mn	B	S	C
pH	1											
Ca	0.72 *	1.00										
Mg	0.37	0.80 **	1.00									
Na	0.69 *	0.73 *	0.56	1.00								
K	-0.22	0.23	0.58 *	0.05	1.00							
P	-0.08	0.29	0.56	0.51	0.42	1.00						
Cu	0.30	0.61 *	0.70 *	0.77 **	0.28	0.73 *	1.00					
Zn	0.25	0.60 *	0.61 *	0.72 *	0.21	0.73 *	0.96 ***	1.00				
Mn	0.13	0.41	0.57	0.59 *	0.12	0.86 ***	0.86 ***	0.84 ***	1.00			
B	-0.13	0.34	0.58 *	0.06	0.93 ***	0.26	0.24	0.22	0.01	1.00		
S	0.30	0.61 *	0.70 *	0.54	0.73 *	0.34	0.51	0.37	0.24	0.67 *	1.00	
C	0.00	0.22	0.57	0.18	0.75 *	0.33	0.29	0.14	0.10	0.76 **	0.61 *	1.00

***significant at the 0.001 level; ** significant at the 0.01 level; * significant at the 0.05 level

Table A15 Original soil sample of selected farmers in the southern Cape

Region	Farm	Camp	Depth	Texture	pH	Ca	Mg	Na	K	T-value	P	S	C
			cm		(KCl)	(cmol/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(%)
SC	Farm 1	Camp 1	0-5	Sandy loam	5.5	5.21	1.48	53	285	7.66	71	13	1.95
SC	Farm 1	Camp 1	05-10	Sandy loam	5.6	4.95	1.5	64	137	7.09	39	15	1.46
SC	Farm 1	Camp 1	10-15	Sandy loam	5.6	4.24	1.45	66	94	6.23	19	12	1.04
SC	Farm 1	Camp 1	15-20	Sandy loam	5.7	3.82	1.55	73	69	5.87	12	12	0.88
SC	Farm 1	Camp 1	20-30	Sandy loam	5.3	2.61	1.67	80	59	5.42	11	10	0.68
SC	Farm 1	Camp 2	0-5	Sandy loam	6.4	7.32	1.89	66	153	9.9	67	9	2.81
SC	Farm 1	Camp 2	05-10	Sandy loam	6	5.95	1.79	70	65	8.22	50	7.6	1.64
SC	Farm 1	Camp 2	10-15	Sandy loam	5.8	5.22	1.83	77	57	7.54	53	6.4	1.09
SC	Farm 1	Camp 2	15-20	Sandy loam	5.6	4.52	1.91	82	62	6.96	36	7.6	0.86
SC	Farm 1	Camp 2	20-30	Sandy loam	5.2	2.04	1.8	79	41	4.97	7	6.2	0.6
SC	Farm 1	Camp 3	0-5	Sandy loam	6.2	7.76	2.53	81	366	11.59	80	18	4.02
SC	Farm 1	Camp 3	05-10	Sandy loam	5.8	5.61	1.92	63	230	8.4	61	10	2.13
SC	Farm 1	Camp 3	10-15	Sandy loam	5.9	4.28	1.8	68	130	6.72	43	7.6	1.31
SC	Farm 1	Camp 3	15-20	Sandy loam	5.9	3.88	1.86	72	104	6.33	32	8.5	0.78
SC	Farm 1	Camp 3	20-30	Sandy loam	5.5	2.62	2.08	93	65	5.28	9	7.1	1.6
SC	Farm 1	Camp 4	0-5	Sandy loam	7.2	23.62	3.37	108	202	27.99	70	9.7	2.73
SC	Farm 1	Camp 4	05-10	Sandy loam	6.8	55.58	2.67	85	132	58.97	52	8.1	2.42
SC	Farm 1	Camp 4	10-15	Sandy loam	6.1	13.39	1.74	72	113	15.74	31	8.9	1.27
SC	Farm 1	Camp 4	15-20	Sandy loam	6.3	29.51	2.15	83	80	32.24	28	6.7	1.09
SC	Farm 1	Camp 4	20-30	Sandy loam	5.8	10.91	1.91	72	60	13.3	11	6.3	0.45
SC	Farm 1	Veld 1	0-5	Sandy loam	5	5.04	3.3	80	182	10.54	59	9.1	4.41
SC	Farm 1	Veld 1	05-10	Sandy loam	5	3.19	3.06	98	118	8.16	11	8.5	2.22
SC	Farm 1	Veld 1	10-15	Sandy loam	4.9	2.7	3.11	106	88	7.53	5	5.8	1.54
SC	Farm 1	Veld 1	15-20	Sandy loam	4.9	2.26	3.25	115	64	7.19	4	6.9	1.24
SC	Farm 1	Veld 1	20-30	Sandy loam	4.7	1.71	3.52	137	51	6.95	3	5	0.83

Table A16 Micronutrients analysis for Farm 1 in the southern Cape

Region	Farm	Camp	Depth	Cu	Zn	Mn	B
			cm	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
SC	Farm 1	Camp 1	0-5	1.58	2.61	195.4	0.33
SC	Farm 1	Camp 1	05-10	1.8	1.78	203.2	0.32
SC	Farm 1	Camp 1	10-15	1.79	1.55	201.9	0.27
SC	Farm 1	Camp 1	15-20	1.81	1.4	183.4	0.25
SC	Farm 1	Camp 1	20-30	1.36	0.7	78.71	0.31
SC	Farm 1	Camp 2	0-5	1.2	1.91	133.9	0.41
SC	Farm 1	Camp 2	05-10	1.08	1.31	122.5	0.28
SC	Farm 1	Camp 2	10-15	1.16	1	114.2	0.25
SC	Farm 1	Camp 2	15-20	1.3	1.55	85.85	0.21
SC	Farm 1	Camp 2	20-30	0.54	0.47	34.87	0.2
SC	Farm 1	Camp 3	0-5	1.16	4.73	70.83	0.79
SC	Farm 1	Camp 3	05-10	0.96	3.02	69.73	0.5
SC	Farm 1	Camp 3	10-15	0.96	1.8	66.1	0.36
SC	Farm 1	Camp 3	15-20	0.92	1.9	45.07	0.34
SC	Farm 1	Camp 3	20-30	0.65	0.84	21.97	0.29
SC	Farm 1	Camp 4	0-5	0.69	1.08	36.37	0.36
SC	Farm 1	Camp 4	05-10	0.74	1	44.7	0.27
SC	Farm 1	Camp 4	10-15	1.16	2.32	88.94	0.29
SC	Farm 1	Camp 4	15-20	0.99	1.12	61.62	0.22
SC	Farm 1	Camp 4	20-30	0.69	0.66	25.1	0.21
SC	Farm 1	Veld 1	0-5	1.3	3.36	205.4	0.33
SC	Farm 1	Veld 1	05-10	1.71	2.25	173.6	0.37
SC	Farm 1	Veld 1	10-15	1.73	2.01	146.9	0.37
SC	Farm 1	Veld 1	15-20	1.44	0.71	116.8	0.38
SC	Farm 1	Veld 1	20-30	1.03	0.46	58.66	0.29

Table A17 Soil analysis for Farm 2 of the southern Cape

Region	Farm	Camp	Depth	Texture	pH	Ca	Mg	Na	K	T-value	P	S	C
			cm		(KCl)	(cmol/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(%)
SC	Farm 2	Kamp 1	0-5	Sandy loam	6.4	9.36	2.7	138	141	13.03	93	6.4	2.59
SC	Farm 2	Kamp 1	05-10	Sandy loam	6.1	5.77	2.31	138	111	8.97	64	5.9	1.87
SC	Farm 2	Kamp 1	10-15	Sandy loam	6	4.47	2.36	161	81	7.75	40	4.6	1.01
SC	Farm 2	Kamp 1	15-20	Sandy loam	6	3.78	2.75	216	63	7.64	31	5	1.11
SC	Farm 2	Kamp 1	20-30	Sandy loam	6.1	2.92	2.98	238	60	7.1	30	5.3	0.7
SC	Farm 2	Kamp 2	0-5	Sandy loam	6.3	7.72	2.01	74	201	10.58	96	.	3.16
SC	Farm 2	Kamp 2	05-10	Sandy loam	6.2	5.94	1.67	67	154	8.31	62	.	1.72
SC	Farm 2	Kamp 2	10-15	Sandy loam	6	4.37	1.4	66	117	6.37	43	.	1.29
SC	Farm 2	Kamp 2	15-20	Sandy loam	5.9	3.83	1.42	70	104	5.83	33	.	0.76
SC	Farm 2	Kamp 2	20-30	Sandy loam	5.6	2.72	1.31	65	76	4.52	14	.	0.66
SC	Farm 2	Kamp 3	0-5	Sandy loam	6.3	10.22	1.85	122	111	12.89	90	.	2.24
SC	Farm 2	Kamp 3	05-10	Sandy loam	6	7.15	1.7	121	73	9.57	53	.	1.6
SC	Farm 2	Kamp 3	10-15	Sandy loam	6.1	5.37	1.55	123	56	7.61	26	.	0.86
SC	Farm 2	Kamp 3	15-20	Sandy loam	6	3.15	1.41	121	45	5.21	20	.	0.64
SC	Farm 2	Kamp 3	20-30	Sandy loam	5.9	2.32	2.26	245	40	5.76	20	.	0.42
SC	Farm 2	Kamp 4	0-5	Sandy loam	6.4	13.77	1.76	76	309	16.66	137	.	2.5
SC	Farm 2	Kamp 4	05-10	Sandy loam	5.8	6.63	1.54	70	214	9.03	85	.	1.93
SC	Farm 2	Kamp 4	10-15	Sandy loam	6	8.04	1.62	86	131	10.38	64	.	1.5
SC	Farm 2	Kamp 4	15-20	Sandy loam	5.9	4.61	1.58	101	98	6.89	41	.	1.76
SC	Farm 2	Kamp 4	20-30	Sandy loam	5.9	3.37	1.66	121	81	5.77	15	.	0.8
SC	Farm 2	Veld 3	0-5	Sandy loam	5.1	2.73	1.97	117	229	6.8	14	.	2.52
SC	Farm 2	Veld 3	05-10	Sandy loam	5.1	2.94	2.33	118	240	7.38	11	.	2.15
SC	Farm 2	Veld 3	10-15	Sandy loam	5.2	2.25	2.28	101	183	6.28	9	.	1.72
SC	Farm 2	Veld 3	15-20	Sandy loam	5.2	1.73	2.17	106	143	5.48	6	.	1.19
SC	Farm 2	Veld 3	20-30	Sandy loam	5.1	1.32	2.04	98	109	4.77	5	.	0.68

Table A18 Micronutrients for Farm 2 in the southern Cape

Region	Farm	Camp	Depth	Cu	Zn	Mn	B
			cm	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
SC	Farm 2	Kamp 1	0-5	1.56	2.72	66.42	0.41
SC	Farm 2	Kamp 1	05-10	1.49	2.01	63.26	0.25
SC	Farm 2	Kamp 1	10-15	1.47	1.23	56.35	0.25
SC	Farm 2	Kamp 1	15-20	1.95	1.55	55.5	0.3
SC	Farm 2	Kamp 1	20-30	1.48	1	50.1	0.3
SC	Farm 2	Kamp 2	0-5	1.53	4.09	95.35	0.55
SC	Farm 2	Kamp 2	05-10	1.95	2.81	98.68	0.33
SC	Farm 2	Kamp 2	10-15	1.19	1.62	87.32	0.22
SC	Farm 2	Kamp 2	15-20	1.24	1.18	84.91	0.19
SC	Farm 2	Kamp 2	20-30	0.8	0.75	44.7	0.15
SC	Farm 2	Kamp 3	0-5	1.45	3.22	31.86	0.23
SC	Farm 2	Kamp 3	05-10	1.12	1.86	29.37	0.16
SC	Farm 2	Kamp 3	10-15	0.99	2.07	28.67	0.15
SC	Farm 2	Kamp 3	15-20	0.78	0.95	26.34	0.15
SC	Farm 2	Kamp 3	20-30	0.62	0.71	18	0.11
SC	Farm 2	Kamp 4	0-5	1.24	4.18	43.28	0.35
SC	Farm 2	Kamp 4	05-10	1.04	3.01	35.48	0.28
SC	Farm 2	Kamp 4	10-15	0.99	1.48	27.59	0.25
SC	Farm 2	Kamp 4	15-20	0.94	1.56	21.89	0.16
SC	Farm 2	Kamp 4	20-30	1.4	3.19	133.3	0.17
SC	Farm 2	Veld 3	0-5	1.2	3.22	118.7	0.23
SC	Farm 2	Veld 3	05-10	1.23	2.53	132.5	0.2
SC	Farm 2	Veld 3	10-15	1.08	1.6	110.1	0.2
SC	Farm 2	Veld 3	15-20	0.81	1.12	91.16	0.15
SC	Farm 2	Veld 3	20-30	0.72	2.09	72.43	0.18

Table A19 Farm 3 Soil analysis for Farm 3 in the southern Cape

Region	Farm	Camp	Depth	Texture	pH	Ca	Mg	Na	K	T-value	P	S	C
			cm		(KCl)	(cmol/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(%)
SC	Farm 3	Kamp 1	0-5	Sandy loam	6	12.79	2.91	216	790	18.67	126	170	4.64
SC	Farm 3	Kamp 1	05-10	Sandy loam	5.7	10.43	1.89	108	510	14.1	92	82	3.24
SC	Farm 3	Kamp 1	10-15	Sandy loam	5.9	10.99	2.05	109	532	14.88	89	97	3.98
SC	Farm 3	Kamp 1	15-20	Sandy loam	5.9	9.35	1.82	104	496	12.9	68	78	3.04
SC	Farm 3	Kamp 1	20-30	Sandy loam	5.8	7.01	1.38	66	372	9.64	43	52	1.99
SC	Farm 3	Kamp 2	0-5	Sandy loam	7	30.53	3.17	198	553	35.99	151	180	3.98
SC	Farm 3	Kamp 2	05-10	Sandy loam	6.6	15.98	1.66	84	420	19.09	97	47	3.71
SC	Farm 3	Kamp 2	10-15	Sandy loam	6.4	12.09	1.4	65	363	14.71	72	48	2.03
SC	Farm 3	Kamp 2	15-20	Sandy loam	6.4	11.24	1.33	62	374	13.81	61	34	2.05
SC	Farm 3	Kamp 2	20-30	Sandy loam	6.5	10.06	1.14	58	287	12.2	50	32	2.07
SC	Farm 3	Kamp 3	0-5	Sandy loam	5.8	10.03	2.24	157	463	14.15	102	81	3.63
SC	Farm 3	Kamp 3	05-10	Sandy loam	5.6	7.46	1.46	87	358	10.22	65	42	2.63
SC	Farm 3	Kamp 3	10-15	Sandy loam	5.7	7.07	1.3	76	275	9.41	63	29	2.34
SC	Farm 3	Kamp 3	15-20	Sandy loam	5.7	6.84	1.33	75	232	9.1	45	29	2.15
SC	Farm 3	Kamp 3	20-30	Sandy loam	5.7	5.71	1.16	59	118	7.44	25	15	1.62
SC	Farm 3	Kamp 4	0-5	Sandy loam	6.1	9.8	2.62	169	380	14.14	94	46	3.32
SC	Farm 3	Kamp 4	05-10	Sandy loam	5.9	8.17	2.11	111	285	11.5	63	29	2.34
SC	Farm 3	Kamp 4	10-15	Sandy loam	5.9	6.59	2.12	103	254	9.82	42	31	2.07
SC	Farm 3	Kamp 4	15-20	Sandy loam	5.9	5.19	2.13	99	221	8.33	35	23	1.76
SC	Farm 3	Kamp 4	20-30	Sandy loam	5.7	2.89	2.34	106	152	6.09	11	15	1.08
SC	Farm 3	Veld 4	0-5	Sandy loam	4.7	6.37	2.26	118	525	12.69	61	16	6.08
SC	Farm 3	Veld 4	05-10	Sandy loam	4.9	5.49	2.09	92	365	10.65	44	15	4.88
SC	Farm 3	Veld 4	10-15	Sandy loam	5.1	5.98	2.23	83	368	10.82	40	12	4.41
SC	Farm 3	Veld 4	15-20	Sandy loam	5.2	5.54	2.13	79	358	10.04	37	11	3.98
SC	Farm 3	Veld 4	20-30	Sandy loam	5.2	4.28	1.67	61	270	8.1	21	0.66	1.58

Table A20 Micronutrients for Farm 3 in the southern Cape

Region	Farm	Camp	Depth	Cu	Zn	Mn	B
			cm	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
SC	Farm 3	Kamp 1	0-5	1.58	9.04	93.27	1.3
SC	Farm 3	Kamp 1	05-10	1.39	7.14	95.7	0.86
SC	Farm 3	Kamp 1	10-15	1.2	7.89	92.84	0.85
SC	Farm 3	Kamp 1	15-20	1.06	5.83	72.98	0.64
SC	Farm 3	Kamp 1	20-30	1.36	5.62	53.72	0.57
SC	Farm 3	Kamp 2	0-5	1.64	6.13	96.44	0.66
SC	Farm 3	Kamp 2	05-10	1.39	4.33	108	0.46
SC	Farm 3	Kamp 2	10-15	1.22	3.92	103.6	0.45
SC	Farm 3	Kamp 2	15-20	1.08	1.96	82.63	0.46
SC	Farm 3	Kamp 2	20-30	0.9	1.72	65.91	0.41
SC	Farm 3	Kamp 3	0-5	1.13	6.3	95.47	0.9
SC	Farm 3	Kamp 3	05-10	1.06	4.55	116.6	0.7
SC	Farm 3	Kamp 3	10-15	1.19	3.23	127.3	0.57
SC	Farm 3	Kamp 3	15-20	1.06	1.97	128.9	0.46
SC	Farm 3	Kamp 3	20-30	0.87	1.55	98.8	0.35
SC	Farm 3	Kamp 4	0-5	0.72	5.37	20.42	0.58
SC	Farm 3	Kamp 4	05-10	0.59	4.23	17.41	0.51
SC	Farm 3	Kamp 4	10-15	0.55	2.79	15.82	0.48
SC	Farm 3	Kamp 4	15-20	0.5	2.77	11.89	0.46
SC	Farm 3	Kamp 4	20-30	0.28	1.32	6.63	0.38
SC	Farm 3	Veld 4	0-5	0.73	6.19	126.9	0.41
SC	Farm 3	Veld 4	05-10	0.7	2.96	104.1	0.4
SC	Farm 3	Veld 4	10-15	0.75	2	108.8	0.45
SC	Farm 3	Veld 4	15-20	0.66	2.42	85.99	0.46
SC	Farm 3	Veld 4	20-30	64.26	0.39	8.8	2.54

Table A21 Original soil analysis for selected Swartland Farm 1

Region	Farm	Camp	Depth	Texture	pH	Ca	Mg	Na	K	T-value	P	S	C
			cm		(KCl)	(cmol/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(%)
SW	Farm 1	Camp 1	0-5	Sandy loam	6.6	3.62	1.22	17	48	5.05	46	0.5	0.81
SW	Farm 1	Camp 1	05-10	Sandy loam	5.9	1.47	0.69	17	26	2.31	41	0.48	0.81
SW	Farm 1	Camp 1	10-15	Sandy loam	4.9	0.88	0.33	17	25	1.74	46	0.45	0.79
SW	Farm 1	Camp 1	15-20	Sandy loam	5.4	1.01	0.38	15	31	1.84	40	1.15	6.58
SW	Farm 1	Camp 2	20-30	Sandy loam	5.3	1.12	0.46	16	29	2.06	35	0.41	0.88
SW	Farm 1	Camp 2	0-5	Sandy loam	5.9	2.04	0.73	14	100	3.1	59	0.58	1.96
SW	Farm 1	Camp 2	05-10	Sandy loam	5.5	1.45	0.48	15	73	2.19	39	0.52	0.94
SW	Farm 1	Camp 2	10-15	Sandy loam	5.5	1.1	0.34	16	53	1.66	34	0.43	0.76
SW	Farm 1	Camp 2	15-20	Sandy loam	5.6	1.65	0.75	20	48	2.62	34	0.65	0.98
SW	Farm 1	Camp 3	20-30	Sandy loam	6.5	1.94	0.45	23	48	2.62	30	0.48	0.48
SW	Farm 1	Camp 3	0-5	Sand	6.4	2.55	0.88	22	96	3.78	60	0.51	1.87
SW	Farm 1	Camp 3	05-10	Sand	5.6	1.32	0.46	28	65	2.08	54	0.43	1.11
SW	Farm 1	Camp 3	10-15	Sand	4.8	0.88	0.39	25	53	1.93	61	0.45	0.74
SW	Farm 1	Camp 3	15-20	Sand	4.6	0.74	0.31	25	42	1.69	62	0.51	0.88
SW	Farm 1	Camp 4	20-30	Sand	4.7	0.8	0.4	23	47	1.81	66	0.49	0.75
SW	Farm 1	Camp 4	0-5	Sand	6.3	2.65	1.26	14	145	4.35	53	0.49	1.23
SW	Farm 1	Camp 4	05-10	Sand	5.6	1.42	0.36	15	110	2.14	46	0.94	1.55
SW	Farm 1	Camp 4	10-15	Sand	4.8	1.1	0.32	19	100	2.18	51	0.62	0.45
SW	Farm 1	Camp 4	15-20	Sand	4.8	0.98	0.32	18	84	1.98	51	0.55	0.48
SW	Farm 1	Camp 4	20-30	Sand	5.1	2	0.45	26	70	3.06	44	0.4	0.44
SW	Farm 1	Veld 1	0-5	Sand	6.2	1.09	0.53	18	83	1.92	26	0.51	1.02
SW	Farm 1	Veld 1	05-10	Sand	5.9	0.89	0.5	16	65	1.64	19	0.33	0.71
SW	Farm 1	Veld 1	10-15	Sand	5.9	0.94	0.56	19	61	1.75	14	0.87	0.93
SW	Farm 1	Veld 1	15-20	Sand	6.1	0.75	0.49	15	57	1.46	11	0.32	0.66
SW	Farm 1	Veld 1	20-30	Sand	6.2	0.75	0.56	19	56	1.55	12	0.58	1.1

Table A22 Original micronutrients analysis for Farm 1 in the Swartland

Region	Farm	Camp	Depth	Cu	Zn	Mn	B
			cm	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
SW	Farm 1	Camp 1	0-5	10.17	0.16	3.6	1.99
SW	Farm 1	Camp 1	05-10	5.38	0.11	4.1	0.88
SW	Farm 1	Camp 1	10-15	9.31	0.09	4.3	0.21
SW	Farm 1	Camp 1	15-20	173.8	0.09	4.7	0.21
SW	Farm 1	Camp 2	20-30	9.1	0.11	4	0.26
SW	Farm 1	Camp 2	0-5	28.53	0.27	3.8	0.65
SW	Farm 1	Camp 2	05-10	21.91	0.18	4.3	0.27
SW	Farm 1	Camp 2	10-15	17.86	0.18	4.5	0.26
SW	Farm 1	Camp 2	15-20	24.17	0.2	4.3	0.26
SW	Farm 1	Camp 3	20-30	18.25	0.18	5.2	0.19
SW	Farm 1	Camp 3	0-5	8.85	0.19	5.7	0.47
SW	Farm 1	Camp 3	05-10	5.42	0.15	5.4	0.37
SW	Farm 1	Camp 3	10-15	2.48	0.11	5	0.28
SW	Farm 1	Camp 3	15-20	2.33	0.1	6.3	0.21
SW	Farm 1	Camp 4	20-30	3.32	0.1	5	0.13
SW	Farm 1	Camp 4	0-5	12.38	0.21	2.3	0.28
SW	Farm 1	Camp 4	05-10	13.17	0.15	3.3	0.27
SW	Farm 1	Camp 4	10-15	17.22	0.15	3.1	0.23
SW	Farm 1	Camp 4	15-20	17.64	0.13	4.2	0.18
SW	Farm 1	Camp 4	20-30	16.36	0.16	4.1	0.14
SW	Farm 1	Veld 1	0-5	25.91	0.06	1.8	0.34
SW	Farm 1	Veld 1	05-10	25.75	0.05	2.2	0.31
SW	Farm 1	Veld 1	10-15	32.44	0.06	2.1	0.3
SW	Farm 1	Veld 1	15-20	20.8	0.06	2.3	0.25
SW	Farm 1	Veld 1	20-30	14.88	0.06	2.1	0.17

Table A23 Farm 2 Swartland original soil samples

Region	Farm	Camp	Depth	Texture	pH	Ca	Mg	Na	K	T-value	P	S	C
			cm		(KCl)	(cmol/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(%)
SW	Farm 2	Kamp 1	0-5	Sandy loam	6.1	10.98	2.07	70	325	14.2	140	1.04	3.48
SW	Farm 2	Kamp 1	05-10	Sandy loam	5.7	5.84	1.19	91	175	7.88	72	1.23	3.08
SW	Farm 2	Kamp 1	10-15	Sandy loam	5.6	4.05	0.91	65	103	5.52	42	0.93	1.32
SW	Farm 2	Kamp 1	15-20	Sandy loam	5.6	3.67	0.71	43	81	4.78	42	1.02	1.68
SW	Farm 2	Kamp 1	20-30	Sandy loam	5.7	3.15	0.84	42	63	4.34	23	0.95	0.6
SW	Farm 2	Kamp 2	0-5	Sandy loam	6	7.83	1.84	63	350	10.85	100	1.41	3.97
SW	Farm 2	Kamp 2	05-10	Sandy loam	5.6	5.92	1.16	95	203	8.02	50	1.2	4.05
SW	Farm 2	Kamp 2	10-15	Sandy loam	5.6	4.76	0.95	42	129	6.23	41	0.83	1.49
SW	Farm 2	Kamp 2	15-20	Sandy loam	5.3	3.51	0.62	44	91	6.85	34	0.78	0.96
SW	Farm 2	Kamp 2	20-30	Sandy loam	5.1	2.94	0.97	34	69	6.14	17	0.76	1.61
SW	Farm 2	Kamp 3	0-5	Sandy loam	6.3	9.49	1.63	50	364	12.28	75	1.47	4.97
SW	Farm 2	Kamp 3	05-10	Sandy loam	6.1	5.13	1.04	69	209	7.01	50	1.63	2.3
SW	Farm 2	Kamp 3	10-15	Sandy loam	5.9	3.85	0.9	47	121	5.27	37	1.18	0.99
SW	Farm 2	Kamp 3	15-20	Sandy loam	5.7	2.89	0.59	34	80	3.84	29	1.15	0.64
SW	Farm 2	Kamp 3	20-30	Sandy loam	5.6	2.15	0.48	32	55	2.92	16	1.26	0.48
SW	Farm 2	Kamp 4	0-5	Sandy loam	6.6	20.43	2.41	81	375	24.16	103	1.29	2.63
SW	Farm 2	Kamp 4	05-10	Sandy loam	6.1	8.38	1.64	71	191	10.83	64	1.46	2.4
SW	Farm 2	Kamp 4	10-15	Sandy loam	5.8	4.87	1.01	39	121	6.37	53	1.43	1.56
SW	Farm 2	Kamp 4	15-20	Sandy loam	5.5	4.14	0.83	38	91	5.38	50	1.38	1.11
SW	Farm 2	Kamp 4	20-30	Sandy loam	5.3	2.73	0.72	37	70	4.33	29	1.31	0.74
SW	Farm 2	Veld 2	0-5	Sandy loam	4.7	1.71	0.97	36	200	4.44	39	1.3	1.53
SW	Farm 2	Veld 2	05-10	Sandy loam	4.6	1.6	0.84	40	117	3.88	18	1.77	1.12
SW	Farm 2	Veld 2	10-15	Sandy loam	4.4	1.32	0.84	28	95	3.43	13	1.7	0.85
SW	Farm 2	Veld 2	15-20	Sandy loam	4.3	1.2	0.81	23	76	3.32	11	1.72	0.79
SW	Farm 2	Veld 2	20-30	Sandy loam	4.5	1.56	1.02	22	73	3.72	8	2.1	0.66

Table A24 Original micronutrients of Farm 2

Region	Farm	Camp	Depth	Cu	Zn	Mn	B
			cm	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
SW	Farm 2	Kamp 1	0-5	91.24	0.61	8.9	2.77
SW	Farm 2	Kamp 1	05-10	100.6	0.34	11	1.58
SW	Farm 2	Kamp 1	10-15	95.08	0.22	7.1	1.05
SW	Farm 2	Kamp 1	15-20	84.61	0.15	4.6	0.75
SW	Farm 2	Kamp 1	20-30	68.81	0.15	4.3	0.39
SW	Farm 2	Kamp 2	0-5	31.74	0.55	30	2.63
SW	Farm 2	Kamp 2	05-10	29.49	0.42	26	1.95
SW	Farm 2	Kamp 2	10-15	24.75	0.28	9	1.27
SW	Farm 2	Kamp 2	15-20	19.61	0.22	6.6	0.94
SW	Farm 2	Kamp 2	20-30	13.48	0.19	6.9	1.17
SW	Farm 2	Kamp 3	0-5	39.39	0.71	19	2.61
SW	Farm 2	Kamp 3	05-10	40.59	0.33	25	1.25
SW	Farm 2	Kamp 3	10-15	33.92	0.21	13	0.72
SW	Farm 2	Kamp 3	15-20	31.03	0.17	6.2	0.62
SW	Farm 2	Kamp 3	20-30	34.57	0.15	18	0.39
SW	Farm 2	Kamp 4	0-5	107.9	0.58	36	2.73
SW	Farm 2	Kamp 4	05-10	125.6	0.34	24	1.31
SW	Farm 2	Kamp 4	10-15	130.2	0.25	12	1.03
SW	Farm 2	Kamp 4	15-20	116.4	0.19	7.3	0.77
SW	Farm 2	Kamp 4	20-30	98.67	0.18	5.1	0.58
SW	Farm 2	Veld 2	0-5	193.7	0.25	8.9	1.51
SW	Farm 2	Veld 2	05-10	244.3	0.16	8.6	0.95
SW	Farm 2	Veld 2	10-15	228.8	0.15	5.5	0.44
SW	Farm 2	Veld 2	15-20	218.2	0.13	5.3	0.36
SW	Farm 2	Veld 2	20-30	206.5	0.14	4.8	0.31

Table A 25 Original soil analysis of Farm 3

Region	Farm	Camp	Depth	Texture	pH	Ca	Mg	Na	K	T-value	P	S	C
			cm		(KCl)	(cmol/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(cmol/kg)	(mg/kg)	(mg/kg)	(%)
SW	Farm 3	Kamp 1	0-5	Sandy loam	7.2	38.1	2.53	233	144	42.02	108	2.41	8.58
SW	Farm 3	Kamp 1	05-10	Sandy loam	7.2	38.07	2.2	167	82	41.22	77	2.54	2.59
SW	Farm 3	Kamp 1	10-15	Sandy loam	7	14.96	1.44	152	57	17.22	56	3.13	5.68
SW	Farm 3	Kamp 1	15-20	Sandy loam	6.5	6.31	1.24	181	56	8.49	34	2.82	8.29
SW	Farm 3	Kamp 1	20-30	Sandy loam	6.3	5.18	1.58	246	60	7.99	15	3.04	3.56
SW	Farm 3	Kamp 2	0-5	Sandy loam	6.7	8.9	1.59	225	161	11.89	130	2.11	5.85
SW	Farm 3	Kamp 2	05-10	Sandy loam	6.4	6.53	1.35	167	99	8.87	110	2.16	6.11
SW	Farm 3	Kamp 2	10-15	Sandy loam	5.7	3.16	1.08	195	51	5.23	89	1.78	6.81
SW	Farm 3	Kamp 2	15-20	Sandy loam	6.3	2.9	1.11	270	50	5.32	45	1.96	8.06
SW	Farm 3	Kamp 2	20-30	Sandy loam	6.3	1.7	1.58	410	42	5.18	16	2	7.22
SW	Farm 3	Kamp 3	0-5	Sandy loam	6.2	8.84	1.63	101	250	11.56	180	1.86	6.8
SW	Farm 3	Kamp 3	05-10	Sandy loam	5.8	4.81	1.03	65	142	6.5	114	2.11	4.9
SW	Farm 3	Kamp 3	10-15	Sandy loam	5.7	3.21	1	74	84	4.76	50	2.22	5.6
SW	Farm 3	Kamp 3	15-20	Sandy loam	5.9	2.8	1.13	98	72	4.55	31	2.41	3.68
SW	Farm 3	Kamp 3	20-30	Sandy loam	5.9	2.59	1.43	120	59	4.7	15	2.44	2.75
SW	Farm 3	Kamp 4	0-5	Sandy loam	5.9	5.96	2.01	41	186	8.63	136	2.19	6.96
SW	Farm 3	Kamp 4	05-10	Sandy loam	5.9	4.35	1.08	41	129	5.95	113	2.42	2.74
SW	Farm 3	Kamp 4	10-15	Sandy loam	6.1	3.92	1.04	58	90	5.45	72	3.06	6.17
SW	Farm 3	Kamp 4	15-20	Sandy loam	6.3	3.29	0.92	72	74	4.72	30	2.47	2.99
SW	Farm 3	Kamp 4	20-30	Sandy loam	6	3.06	1.28	130	88	5.14	21	2.54	3.47
SW	Farm 3	Veld 3	0-5	Clay loam	6	3.22	2.13	97	241	6.4	30	2.01	5.45
SW	Farm 3	Veld 3	05-10	Clay loam	5.8	2.76	2.48	107	160	6.12	21	2.07	3.72
SW	Farm 3	Veld 3	10-15	Clay loam	5.6	2.76	3.23	149	92	6.88	18	1.99	2.42
SW	Farm 3	Veld 3	15-20	Clay loam	5.4	2.33	3.45	132	68	6.54	16	1.37	1.64
SW	Farm 3	Veld 3	20-30	Clay loam	5.2	2.17	4.1	165	59	7.15	16	1.1	1.29

Table A 26 Original soil analysis of Farm 3 micronutrients

Region	Farm	Camp	Depth	Cu	Zn	Mn	B
			cm	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
SW	Farm 3	Kamp 1	0-5	173.3	0.38	23	1.21
SW	Farm 3	Kamp 1	05-10	194.3	0.24	13	0.77
SW	Farm 3	Kamp 1	10-15	249.6	0.24	11	0.65
SW	Farm 3	Kamp 1	15-20	186.5	0.16	11	0.6
SW	Farm 3	Kamp 1	20-30	113.3	0.27	13	0.62
SW	Farm 3	Kamp 2	0-5	169.7	0.24	.	2.07
SW	Farm 3	Kamp 2	05-10	163.5	0.19	.	2.61
SW	Farm 3	Kamp 2	10-15	104.5	0.14	.	0.7
SW	Farm 3	Kamp 2	15-20	110.7	0.16	.	0.74
SW	Farm 3	Kamp 2	20-30	92.55	0.28	.	0.42
SW	Farm 3	Kamp 3	0-5	228.2	0.32	17	1.35
SW	Farm 3	Kamp 3	05-10	270.6	0.16	9.5	0.99
SW	Farm 3	Kamp 3	10-15	265.3	0.13	11	0.62
SW	Farm 3	Kamp 3	15-20	219.6	0.16	12	0.62
SW	Farm 3	Kamp 3	20-30	218.5	0.23	9.4	0.64
SW	Farm 3	Kamp 4	0-5	238.5	0.32	7.4	1.54
SW	Farm 3	Kamp 4	05-10	243.1	0.23	6.2	1.01
SW	Farm 3	Kamp 4	10-15	253	0.2	8.6	0.76
SW	Farm 3	Kamp 4	15-20	238.1	0.2	8.7	0.66
SW	Farm 3	Kamp 4	20-30	218.3	0.36	12	0.62
SW	Farm 3	Veld 3	0-5	312.4	0.2	14	1.6
SW	Farm 3	Veld 3	05-10	288.6	0.16	17	0.95
SW	Farm 3	Veld 3	10-15	284.2	0.15	13	0.72
SW	Farm 3	Veld 3	15-20	276.1	0.12	9.6	0.56
SW	Farm 3	Veld 3	20-30	173.7	0.11	12	0.37

APPENDIX B-QUESTIONNAIRE

1. In which municipal district do you farm?

- ☐ Albertinia, Riversdale, Heidelberg
- ☐ Swellendam, Riviersonderend
- ☐ Caledon, Villiersdorp, Bredasdorp, Napie
- ☐ Philadelphia, Malmesbury
- ☐ Hopefield, Vredenburg
- ☐ Moorreesburg, Koringberg
- ☐ Porterville, Piketberg, Pools, Eendekuil
- ☐ Somewhere else

2. **What is the total area of cultivated soil on the farm you manage?** _________ ha

3. How old are you?

- ☐ Younger than 30
- ☐ Between 31 and 45
- ☐ Between 46 and 60
- ☐ Between 61 and 70
- ☐ Older than 70

4. What is your highest qualification?

- ☐ Grade 8
- ☐ Matric
- ☐ Diploma
- ☐ Degree
- ☐ Postgraduate

5. Do you belong to a study or farmers group?

- ☐ Yes
- ☐ No

6. What is the annual rainfall on the farm?

- ☐ Less than 150 mm
- ☐ 151 to 250 mm
- ☐ 251 to 350 mm
- ☐ 351 to 400 mm
- ☐ More than 400 mm

7. What term describes your farming operation the best?

- ☐ Conservation- minimum tillage, maximum soil cover and crops rotation
- ☐ Conventional- practice monoculture, spreading and cover, burn stubble
- ☐ Organic/Biologic- production without chemical fertilizer, herbicide or pesticides
- ☐ Precision- Use a GPS for soil samples, planting, fertilize application, spraying and yield monitor

8. How long have farmed this way?

- ☐ Less than 5 years
- ☐ Between 5 and 10 years
- ☐ Between 10 and 20 years
- ☐ Between 20 and 30 years
- ☐ Longer than 30 years

9. Which of the following crop did you plant the previous year?

- ☐ Wheat
- ☐ Canola
- ☐ Barley
- ☐ Oats
- ☐ Lupine
- ☐ Medics
- ☐ Lucerne
- ☐ Other______________________

10. Give an example of your crop rotation for example wheat/medics/wheat/canola.

____

11. What cover crop mix do you use?

- ☐ No cover crop
- ☐ Pulse mix
- ☐ Grain mix
- ☐ Multi specie mix
- ☐ Another mix ____________________

12. Which of the following livestock grazed on the farm in the last year?

- ☐ Cattle
- ☐ Sheep
- ☐ Goats
- ☐ Ostriches
- ☐ Game

13. What implement do you use for primary tillage?

- ☐ No primary tillage
- ☐ Disc implement (Disc plough, mold board plough)
- ☐ Tine implement (Chisel Plough)
- ☐ Offset disc
- ☐ Scarifier
- ☐ Another___________________

14. What implement do you use for secondary tillage?

- ☐ No secondary tillage
- ☐ Rotary tiller
- ☐ Tined cultivar
- ☐ Scarifier
- ☐ Ander _____________________________

15. Do you rip on a regular basis?

- ☐ Never
- ☐ Every year or second year
- ☐ Every third or fourth year
- ☐ Just as strategic operation like get rid of compaction layer or work in lime

16. How do you plant your grains?

- ☐ Spread out and scratch in
- ☐ With a drill
- ☐ No-till tine planter
- ☐ No-till planter disc planter
- ☐ Another ________________________________

17. What happens to the crop residue after harvest?

- ☐ I keep it to protect the soil
- ☐ Bale for feed
- ☐ Let livestock graze
- ☐ Burn
- ☐ Drag tyres to flatten the residue

18. Is the soil on your farm mapped (classified)?

- ☐ Yes
- ☐ No

19. What is the dominant soil form on your farm?

- ☐ Swartland
- ☐ Glenrosa
- ☐ Mispah
- ☐ Clovelly
- ☐ Another ___________________
- ☐ Do not know

20. How often do you take soil samples?

- ☐ Each year a section of the farm
- ☐ Every second or third year
- ☐ Every fourth or fifth year
- ☐ Only when there is a problem
- ☐ No set program, for example when I have money
- ☐ Never

21. Who takes your soil samples?

- ☐ I do it
- ☐ Fertilizer company
- ☐ Independent company
- ☐ Agronomist at the co-op
- ☐ Other ________________________

22. How deep do you take soil samples?

- ☐ 0 to 10 cm
- ☐ 0 to 15 cm
- ☐ 0 to 30 cm
- ☐ 30 to 60 cm

23. How do you calculate your lime requirement?

- ☐ Soil samples- calcium and magnesium levels too low
- ☐ Soil samples- low pH
- ☐ Set amount each year
- ☐ Albrecht system

24. Is subsoil acidity a problem on your farm?

- ☐ Yes
- ☐ No
- ☐ I don’t know

25. What is the carbon content of your soil?

- ☐ I don't know
- ☐ Less than 0.5 %
- ☐ Between 0.5 and 1.0 %
- ☐ Between 1.1 and 1.5 %
- ☐ Between 1.6 and 2 %
- ☐ Between 2.1 % and 4 %
- ☐ Greater than 4 %

26. What is the clay percentage (including silt) of your soil?

- ☐ 0-5 %
- ☐ 6-10 %
- ☐ 11-15 %
- ☐ 16-20 %
- ☐ 21-25 %
- ☐ More than 25% clay

27. Have you ever checked the nematode status of your soil?

- ☐ Yes
- ☐ No

28. Is there certain year you don't sow some camps? Except lucerne.

- ☐ Yes
- ☐ No

29. Which of the following Conservation Agriculture principles do you apply?

- ☐ Minimum soil disturbance
- ☐ Maximum ground cover
- ☐ Crop rotation
- ☐ Animal factor
- ☐ Plant cover crops

30. Which product do you use as fertilizer?

- ☐ Chemical
- ☐ Organic
- ☐ Combination of chemical and organic
- ☐ Manure
- ☐ Compos