Effect of soil carbon on yield and quality of wheat in crop rotational system under conservation agriculture

by

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Declaration

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Summary

Conservation agriculture (CA), which includes no-till (NT) and crop rotation, can be implemented for a positive effect on soil organic matter (SOM) accumulation and carbon sequestration. This can lead to greater soil health and resilience, with subsequently increased yields. Previous research has shown soil organic carbon (SOC) accumulation is site-specific, with the climate, crops, and the soil properties to be considered. Studies about the role that SOC plays in wheat yield are lacking in the Western Cape. In this study, soil (0-15 cm) and yield data from long-term field trials under CA conducted at Langgewens Research Farm (24th year) and Tygerhoek Experimental Farm (20th year) in the Western Cape were analyzed. The rotational systems implemented during the trials included wheat monoculture, 100% crop, 50% crop/50% pasture, and 33% crop/67% pasture.

The objectives of this research project were i) to look at the long-term effect of the no-till crop rotations systems on SOC and wheat yield, ii) explore the relationship between the SOC content and the yield and protein content of wheat, and iii) obtaining optimum values and sufficiency ranges for the factors affecting wheat yield, protein content, and SOC content using boundary Line Analysis (BLA).

Over the entire trial period, a significant increase in SOC content was only found at Langgewens (0.4%) attributed to it its substantially lower starting SOC (0.91%). The average SOC content being higher at Tygerhoek (1.68%) compared to Langgewens (1.17%) attributed to differences in soil properties and climate. It was observed that the SOC had likely reached a 'saturation point' at both sites. At both sites, the wheat monoculture had a significantly lower yield, and the incorporation of natural vegetation (pastures and saltbush) had a benefit on the SOC content, wheat yield, and protein content. The rainfall showed a significant linear correlation with wheat yields. While soil pH, lime, gypsum, N fertilizer, soil nutrients, and the clay:C ratio did not show a significant correlation. No linear correlation was found between wheat yield and the SOC content, while some seasons showed a significant partial correlation. A panel regression showed significant correlations of some variables to wheat yield. Wheat monoculture and 100% crops had a significantly lower protein content at Langgewens and Tygerhoek respectively. The BLA for wheat yield showed that above and below a certain SOC point wheat yield will decrease at each site. Protein content decreased above 20 mg kg^{-1} soil Sulphur. The BLA showed a decreased protein content above and below a certain SOC point. A significant negative correlation between average minimum temperatures and SOC content was found.

The focus of this study was the long-term dynamics of SOC and yields, and their relationship. There was SOC accumulation with the implementation of CA but is dependent on the soil and climate, along with a 'saturation point'. The SOC did not directly correlate with yield as it is likely not directly addressing the main yield limiting factors in this production area, which are mainly climate and soil related.

Opsomming

Bewaringslandbou (BL), wat geenbewerking (GB) en wisselbou insluit, kan geïmplementeer word vir 'n positiewe effek op grondorganiese materiaal (GOM) akkumulasie en koolstofsekwestrasie. Dit kan lei tot groter grondgesondheid en veerkragtigheid, met gevolglik verhoogde opbrengste. Vorige navorsing het getoon dat grond-organiese koolstof (GOK) akkumulasie terrain spesifiek is, met die klimaat, gewasse en die grondeienskappe wat in ag geneem moet word. Studies oor die rol wat GOK in koringopbrengs speel, ontbreek in die Wes-Kaap. In hierdie studie is grond (0-15 cm) en opbrengsdata van langtermyn veldproewe onder BL wat by Langgewens Navorsingsplaas (24ste jaar) en Tygerhoek Proefplaas (20ste jaar) in die Wes-Kaap uitgevoer is, ontleed. Die wisselboustelsels wat tydens die proewe geïmplementeer is, het koringmonokultuur, 100% gewas, 50% gewas/50% weiding en 33% gewas/67% weiding ingesluit.

Die doelwitte van hierdie navorsingsprojek was i) om te kyk na die langtermyn effek van die GB wisselboustelsels op GOK en opbrengs, ii) die verband tussen die GOK-inhoud en die opbrengs en proteïeninhoud van koring te ondersoek, en iii) die verkryging van optimum waardes en voldoende reekse vir die faktore wat koringopbrengs, proteïeninhoud en GOK-inhoud beïnvloed deur grenslynanalise (GLA) te gebruik.

Oor die hele proeftydperk is 'n beduidende toename in GOK-inhoud slegs by Langgewens gevind (0.4%), aangesien die begin GOK (0.91%) aansienlik laer was. Die gemiddelde GOK-inhoud is hoër by Tygerhoek (1.68%) in vergelyking met Langgewens (1.17%) wat toegeskryf word aan verskille in grondeienskappe en klimaat. Daar is waargeneem dat die GOK waarskynlik 'n 'versadigingspunt' by beide terreine bereik het. By beide terreine het die koringmonokultuur 'n aansienlik laer opbrengs gehad, en die inkorporering van natuurlike plantegroei (weidings en soutbos) het 'n voordeel op die GOK-inhoud, koringopbrengs en proteïeninhoud gehad. Die reënval het 'n beduidende lineêre korrelasie met koringopbrengste getoon. Terwyl grond pH, kalk, gips, N kunsmis, grondvoedingstowwe en die klei:K verhouding nie 'n beduidende korrelasie getoon het nie. Geen lineêre korrelasie is gevind tussen koringopbrengs en die GOK-inhoud nie, terwyl sommige seisoene 'n beduidende gedeeltelike korrelasie getoon het. 'n Paneelregressie het beduidende korrelasies van sommige veranderlikes tot koringopbrengs getoon. Koringmonokultuur en 100% gewasse het 'n aansienlik laer proteïeninhoud by onderskeidelik Langgewens en Tygerhoek gehad. Die GLA vir koringopbrengs het getoon dat bo en onder 'n sekere GOK-inhoud koringopbrengs by elke proef sal afneem. Proteïeninhoud het tot bo 20 mg kg^{-1} grond Swael afgeneem. Die GLA het 'n verlaagde proteïeninhoud bo en onder 'n sekere GOK-punt getoon. 'n Beduidende negatiewe korrelasie tussen gemiddelde minimum temperature en GOK-inhoud is gevind.

Die fokus van hierdie studie was die langtermyndinamika van GOK en opbrengste, en hul verhouding. Daar was GOK-akkumulasie met die implementering van BL, maar was afhanklik van die grond en klimaat, tesame met 'n 'versadigingspunt'. Die GOK het nie direk met opbrengs

gekorreleer nie, aangesien dit waarskynlik nie die belangrikste opbrengsbeperkende faktore in hierdie produksiegebied direk aanspreek het nie, wat eerder die klimaat en grond was.

This thesis is dedicated to

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who passed during the writing of this thesis

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Preface

This thesis is presented as a compilation of 6 chapters. Each chapter is introduced separately and is written according to the style of the journal South African Journal of Plant and Soil to which Chapters 3 and 4 is submitted for publication.

Chapter 1	**General introduction and project aim**
Chapter 2	**Literature review** Factors affecting soil carbon content and its role in grain yields and quality
Chapter 3	**Research unit 1** Long-term effect of no-till crop rotation systems on soil carbon content and wheat yield
Chapter 4	**Research unit 2** Effect of soil organic carbon content on yield and quality of wheat
Chapter 5	**Research unit 3** Boundary line analysis of relationships between wheat yields and quality, soil organic C content and environmental factors
Chapter 6	**General discussion and conclusions**

Table of Contents

List of Figures

List of Tables

List of Equations

List of Abbreviations

BD	Bulk density
BLA	Boundary line analysis
C	Carbon
CA	Conservation agriculture
Ca	Calcium
CCC	Pure Cash crop thus 100% crop
Cf	Cartref
CO_2	Carbon dioxide
CT	Conservation tillage
Gs	Glenrosa
H	Hydrogen
HI	Humidity index
HLM	Hectolitre mass
HMP	Sodium Hexametaphosphate
ICP	Inductively Coupled Plasma
K	Potassium
KCl	Potassium chloride
Km	Klapmuts
Mg	Magnesium
MT	Minimum tillage
N	Nitrogen
Na	Sodium
NT	No-till
O	Oxygen
Oa	Oakleaf
OC	Organic carbon
P	Phosphorus
PCPC	Pasture-pasture-crop-crop thus 50% cash crop and 50% pasture
POC	Particulate organic carbon
POM	Particulate organic matter
PPC	Pasture-pasture-crop thus 33% crop and 67% pasture
PPCC	Pasture-pasture-crop-crop thus 50% cash crop and 50% pasture
S	Sulphur
Se	Sepane
SOC	Soil organic carbon

SOM	Soil organic matter
Ss	Sterkspruit
Sw	Swartland
TOC	Total organic carbon
Tu	Tukulu
Vf	Vilafontes
VIF	Variance inflation factor
WCWL	Wheat, canola, and lupin rotation
WMCM	Wheat, canola, and medic rotation
WMcWMc	Wheat and medic or clover rotation
WMcWMc+saltbush	Wheat and medic or clover rotation
WMWM	Wheat and medic rotation
WWCL	Wheat, canola, and lupin rotation
WWWC	Wheat and canola rotation
WWWW	Wheat monoculture

Chapter 1: General introduction and research aim

This research project investigates the long-term dynamics of soil organic C and yields in no-till grain production systems of the Western Cape, South Africa. There is a lack of published literature on the role and the relationship between soil organic carbon (SOC) and wheat yield. This is especially the case in semi-arid regions, particularly in the Western Cape production area of South Africa. This research project will attempt to answer this question and explore what management practices producers could implement to maximize the SOC content and increase the wheat yield produced.

Long-term field trials were conducted at Langgewens Research Farm, located close to Moorreesburg in the Swartland region, and Tygerhoek Experimental Farm, close to Riviersonderend in the Overberg region of the Western Cape, over an extended period to examine crop and crop/pasture rotation systems under Conservation agriculture (CA). These trials were conducted by Directorate Plant Sciences of the Western Cape Department of Agriculture. The study conducted on Langgewens Research farm is in its 24th year, while the study at Tygerhoek Experimental farm is in its 20th year. The crops were grown under dryland conditions, as is the case for most farms in these regions. The climate at Langgewens is classified as semi-arid Mediterranean with warm and dry summers and cold wet winters with an average rainfall per year of 375 mm. Eighty percent of the annual rainfall occurs in the period between April and October. At Tygerhoek the climate is more temperate, with an average annual rainfall of 490 mm per year, while only fifty-two percent of the annual rainfall occurs in the production season.

The crops grown at both trials included wheat, canola, lupines, oats, and pastures (medic or clover). Barley was only produced in the Tygerhoek trial. The lupines and pastures were implemented as legumes in the crop rotations. The rotational systems implemented during the trials included wheat monoculture, 100% crop, 50% crop/50% pasture, and 33% crop and 67% pasture. Conservation agriculture is starting to grow in popularity, even if conventional tillage techniques are still commonly used in these regions. Both trials were under CA. The switch to CA, that includes no-till (NT) was aimed at reducing soil organic matter (SOM) loss, and the subsequent restoration of SOC stocks in the soil (Alvaro-Fuentes & Lopez, 2008). This will, in turn, affect the health of the soil (Six, et al., 2000), and subsequently, the yield produced.

The factors that will affect the SOM content of the soil have been extensively researched (Ros, 2012; Culman, et al., 2013; de Moraes Sa, et al., 2014; Osborne, et al., 2017; Sun, et al., 2020). These findings correlate with each other but highlight that there are site-specific differences that need to be considered, especially the climate, crops, and the soil's chemical and physical properties. Some studies looked at the effect that tillage and crop rotation have on the SOM and SOC in the Swartland and Overberg (Labuschagne, et al., 2013; Strauss, 2015; Cooper, et al., 2016; Smith, et al., 2020). Only a minor part of the study done by Smith, et al., (2020) included the effect of SOC fractions on yield. Some studies looked at the role that SOC plays in wheat yield, such as Hillier et al. (2009) who looked at this role in England and Wales, while Feng et al. (2018) studied a semi-arid region in Australia, and Oldfield et al. (2019) did a meta-analysis on this on a global scale, but no studies could be found which were undertaken in the Western Cape. There are also limited studies done on the factors which affect the quality of wheat, especially winter wheat in semi-arid climates. The wheat protein level is an excellent general indicator of the quality of the wheat. Depending on the wheat class, region, type, and quality of the soil and fertilizer, the protein content will vary significantly. Another aspect that has not been looked at for wheat is Boundary line analysis (BLA). This method will give critical concentrations and sufficiency ranges for the factors which influence yield, protein content, and SOC content. This method has been used for mangoes, bananas, grapevines, and soybeans among other crops (Myburgh & Howell, 2014; Maia & de Morais, 2015; Ali, 2018; de Souza, et al., 2020).

Therefore, the main objective of this research project was to explore whether there is an effect of and relationship between the SOC content in the soil and the yield and protein content of wheat in a crop rotational system under NT in the Swartland and Overberg regions. To understand the factors that will influence the SOC content, the effect that different crop rotational systems have on SOC was also studied, along with the rate of SOC accumulation. Finally, BLA was used to obtain optimum values and sufficiency ranges for the factors which effect wheat yield, protein content, and SOC content.

Chapter 2: Literature review – Factors affecting soil carbon content and its role in grain yield and quality

2.1 Introduction

Carbon (C) is one of the building blocks from which the earth consists of (Drake & Righter, 2002) and all life on earth depends on C. Animals release it as part of respiration, plants use it during photosynthesis and all rocks and sediment are made up of C. Each day human activities release tonnes of C into the atmosphere, in the form of carbon dioxide (CO_2), such as fossil fuel combustion, land-use change, and industrial processes. The highest amount of CO_2 released was recorded in 2019 at 43.1 billion tonnes (The World Counts, 2022). It is possible to offset this by increasing the C sinks. A C sink is anything that can absorb more carbon than it releases, e.g. plants, the soil, or the ocean. It is however considered easier to adapt the soil than the ocean or plants (Smith, 2004). Lal (2011) estimated that between 1200 and 2200 Gt of C is stored in the soil as organic matter. One of the ways to increase this stored carbon is to implement regenerative agricultural practices. This will limit the amount of carbon lost from the soil and increase productivity. Carbon loss from the soil can occur because of land-use change and deforestation, which in most cases is because of lower soil organic matter (SOM) inputs (Smith, 2004). Tillage intensity can also influence the SOM (Alvaro-Fuentes & Lopez, 2008), along with the crops which are grown.

SOM is of great importance in soil health (Six, et al., 2000). Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (Lehmann, et al., 2020). Various factors affect the health and quality of the soil. These include management practices, soil physical, chemical, and biological properties, and the climate. The factors which are affected are among other things cation exchange capacity, buffering capacity, resistance to compaction, aggregate formation and stability, water retention and infiltration, microorganism population, and the release of nutrients such as N, P, and S (Murphy, 2015). If these factors are favourable it could result in a crop with optimal yield.

Critical concentrations and sufficiency ranges are key in attempting to ascertain the necessary nutrient levels that is needed to obtain an optimal yield. Walworth et al. (1986) proposed a method to obtain these values and is referred to as Boundary line analysis (BLA). This method proposes that values beneath the critical level must be a result of measurement errors, biological data variability, and general variation brought on by other interacting or controlling factors. (Hernández-Vidal, et al., 2020). This approach has been used to attain sufficiency ranges for mangoes (Ali, 2018), banana (Maia & de Morais, 2015), grapevines (Myburgh & Howell, 2014), and soybeans (de Souza, et al., 2020) among other crops.

Various studies tested the factors that affect the SOM content of the soil (Jagadamma & Lal, 2010; Sombrero & De Benito, 2010; Deiss, et al., 2021). These studies consistently found that crop rotation, tillage, soil texture, and rainfall have significant influence on the SOM and subsequently the soil organic carbon (SOC) content of the soil. Along with this the effect that certain factors such as the nutrients in the soil, carbon, soil physical properties, biological influences, and the climate has on yield has been published (Ros, 2012; Culman, et al., 2013; de Moraes Sa, et al., 2014; Osborne, et al., 2017; Sun, et al., 2020). Each paper presents a differing view of the certain effect, but very few are opposed to the findings.

Although there are extensive studies on these topics, insufficient attention has been paid to climate specific results pertaining to the role that SOC plays on yield of specifically wheat production in a semi-arid winter rainfall region in South Africa. Hillier et al. (2009) looked at this role in England and Wales, which is a high rainfall area, while Feng et al. (2018) studied a semi-arid region in Australia, and Oldfield et al. (2019) did a meta-analysis on this on a global scale.

2.2 Carbon sequestration

Carbon sequestration according to Britannica (2022) is the long-term storage of C in plants, soil, and the ocean. It can occur naturally or through anthropogenic activities. A C is the result when C is stored and kept from entering the earth's atmosphere. We can classify deforestation as a C source, while forest regrowth is a form of C sequestration, which makes the forest a C sink. Since the industrial revolution, the amount of CO_2 released has increased which has raised concerns about climate change (The World Counts, 2022). This has resulted in considerable interest in ways to combat the change. Proposed ways include changes in land use and forestry to increase carbon sequestration, as well as carbon capture and storage.

The way that C sequestration works is that the CO_2 from the atmosphere is taken up by the plants through photosynthesis and is then stored in the aboveground biomass or the roots, in the form of carbohydrates. The implementation of replacement vegetation on cleared land and management practices, such as cover crops, leaving harvest residues on the field, or using manure as fertiliser, will result in reversal. It is important to note that the sequestered carbon has the potential for release if land-use practices, climate change, burning of stubble or even decomposition continues. The consequences of severe depletion of SOC in the soil are low yield, weak soil structure, and reduced use efficiency of mineral inputs (Lal, 2011). This shows that soil quality is of great importance. The C level of the soil will also determine the microorganism population which is necessary for sustainable crop production systems.

Cropland soils are low in SOC when it is compared to soils with natural vegetation. Conversion of soils from forests, grasslands, woodlands, and savannahs to croplands, Poeplau & Don (2015) indicated a possible 30-40% reduction in SOC content. This is the result of the removal of plant biomass by management practices and even harvesting. They further stated that the change in SOC content will continue until it reaches a new equilibrium. There are certain critiques about these statements. Chan (1997) reported that when converting from pastures to cropping 70% of the organic carbon (OC) loss was in the form of particulate organic carbon (POC). This is further supported by Bowman et al. (1999) who observed that a continuously cropped soil had 20% more total organic carbon (TOC) than a wheat-fallow soil, while the POC was double that of the wheat-fallow. Even when comparing no-till (NT) to conventional tillage (CT) Needelman et al. (1999) found that the POC was twice that of the corresponding difference in TOC. This shows that the carbon pools need consideration when assessing at the amount of carbon of a soil.

2.3 Factors affecting SOM content

2.3.1 Effect of crop rotation on soil organic matter

Crop rotation is the planting of different crops in a certain sequence in consecutive years on the same plot of land. This improves soil health through the different root systems, plant biomass, microbial diversity, and optimal nutrients in the soil by implementing legumes, combatting disease, and weed pressures by not having crops of the same family in consecutive seasons (Grant, et al., 2002). These all have positive effects on the soil and if correctly implemented on the yield of the crop.

Crop rotation plays a major role in the accumulation and stratification of soil organic matter (Deiss, et al., 2021). Soil organic matter stratification tends to favour plant roots (Qin, et al., 2004) and soil organisms (Schenk, 2008). This is because of the increase of resources made readily available closer to the surface where most of the roots occur. However, the management decisions and environmental factors greatly influence this (Isbell, et al., 2017), which in turn influence the biomass input, root architecture, organism habitat, and soil organic matter (SOM) stabilization.

The type of crop and planting sequence will have a huge effect on the quality and quantity of biomass produced. Each species will have a different effect depending on its characteristics of residue, root system, and the microbial community it influences (Tivet, et al., 2013). Chan (2001) found that a rotational system that included pastures had greater TOC content compared to the corresponding cropped soils, which can be attributed to the greater root biomass compared to grain crops (Syswerda, et al., 2011). In a study done by Smith et al. (2020) in the Overberg region of South Africa they found that the total C and N content of the soil was higher in crop/pasture rotations if it contained medics/clover. Annual medics are temperate legumes found in Mediterranean regions (Queensland Government, 2013). Hardy (2007) found that in the Western Cape the use of medic pastures is restricted to only a few producers as it is not as economically viable because the land will remain unproductive for a season, medics are not adapted to all soil types, and an animal factor needs to be included. The paper also stated that this practice increases N availability and retain moisture for the subsequent crop, as well as the control of weeds and diseases.

The input of nitrogen (N) to the soil also plays a role in higher SOM as it leads to higher production of biomass and plant residue in the system. It is wise to include legumes in the rotational system as these species will fix nitrogen in the soil (Raphaela, et al., 2016). The availability of N is also related to the soil physical factors such as the texture, as higher clay content can decrease N and carbon losses from the soil which will lead to further stabilization of SOM (Wattel-Koekkoek, et al., 2001).

It is not only the N in the soil that is important, but also the C:N ratio. High quality organic matter has a low C:N ratio which means that it has a higher mineralization rate and essential nutrients, such as N, P, and K, are more readily available. Thus, a higher ratio will lead to higher sequestration of C and N in the soil (Wright & Hons, 2005). According to Abberton (2010) if there are more legumes included (lucerne, medics, and lupines) this will result in a higher C:N ratio of the organic matter which will increase the soil carbon sequestration.

The tillage system affects the SOM accumulation and stratification. Deiss et al. (2021) found that intensive tillage reduces the effect crop rotation compared to NT. The system also affects the total organic carbon (TOC) in the soil as higher levels can be found in more conservative management (e.g. No-till and stubble retention) rather than conventional systems (e.g. Stubble burning) (Chan, 2001).

2.3.2 Effect of tillage on soil organic matter

Tillage is the manipulation of the soil for crop production. Tillage practices consist of three classes, namely conventional, conservation, and no-tillage (NT). Conventional tillage uses tillage as seedbed preparation and weed control by inversion, loosening, mixing, and/or breaking down soil and occurs more than once in a growing season (Deiss, et al., 2021). Conservation tillage, which includes minimum and NT, creates a suitable soil environment by reduced intensity of tillage and retention of 30% or more plant residue. Deiss et al. (2021) found that soil organic matter distribution in the soil profile is affected by tillage.

Some of the benefits of implementing a NT system is the reduced risk of soil erosion, leaching of nutrients, and compaction (Logan, et al., 1991). It will also positively alter the soil structure with a greater amount of macropores (Martino & Shaykewich, 1994), which in turn will influence the root growth (Lampurlane´s, et al., 2001) (Martino & Shaykewich, 1994). Ghimire et al. (2017) found that soil pH in the 0-10cm layer is influenced by tillage, N, and climate of that particular year. They found that the pH was higher under CT compared to NT. However, there are downsides to implementing a NT system. It can result in a higher bulk density (BD) which will result in greater soil strength (Martino & Shaykewich, 1994), but over time a deep compaction layer can occur from the implements used, which makes it harder for roots to penetrate deep in the soil, which can result in root branching and slow the growth of the proximodistal axis of the roots (Lampurlane´s, et al., 2001) which will then affect the plant growth by limiting the nutrient uptake (Peterson, et al., 1984).

Tillage intensity influences the patterns of root distribution. In a NT system the roots accumulate from 0 – 5 cm more so than in a CT system (Chan & Mead, 1992; Wulfsohn, et al., 1996). Qin et al. (2004) found that in a NT system about 65% of the roots were found in the 0 – 30 cm layer and the largest mean diameter of the roots was found at 0 – 5 cm and decreased when going further down. This fits in with what Chen et al. (2009) found in a 11-year study. The OM was much higher in the surface layer of the soil and the same trend was then observed for the soil organic carbon (SOC) where different tillage practices only showed a difference in the 0 – 15 cm layer, with

SOC being higher in the NT system. Alvaro-Fuentes & Lopez (2008) found that in a NT system there was an increase of SOC in the 0 – 10 cm layer, but in a CT system there was accumulation of SOC in the subsoil due to the ploughing in of the crop residues in a CT system while crop residues are left on the surface in NT.

Time also plays a big role when looking at the SOM and especially SOC content of the soil. It is conveyed that the positive effect of conservation practices will only be visible after several years. Sombrero & De Benito (2010) compared the SOC in a NT and CT system and found that after 6 years, the NT was 7% higher but after 10 years, there was a 25% difference. This study was done in Spain, which is a semi-arid region, and shows that the NT and minimum tillage (MT) raised the SOC content of the soil (Figure 1) and the maximum rate of the sequestration was after 5 years (Figure 2a) but the total carbon sequestered plateaued at about 11 years after NT was implemented (Figure 2b). A possible reason for the slow carbon sequestration is that the crop residues are incorporated into the soil at a much slower rate than in a CT system, initially. The carbon sequestered rate depends on the physical properties of the soil, climate, land-use history, and management practices (West & Post, 2002).

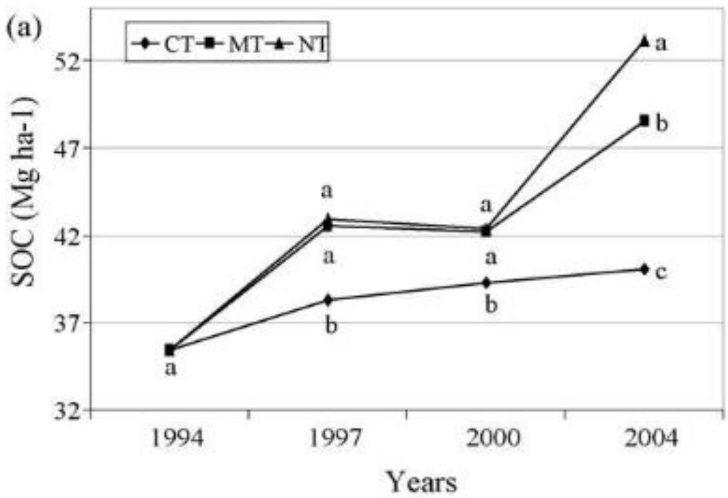

Figure 1: SOC levels in 0-30cm layer with CT, MT and NT between 1994 and 2004 (Sombrero & de Benito, 2010)

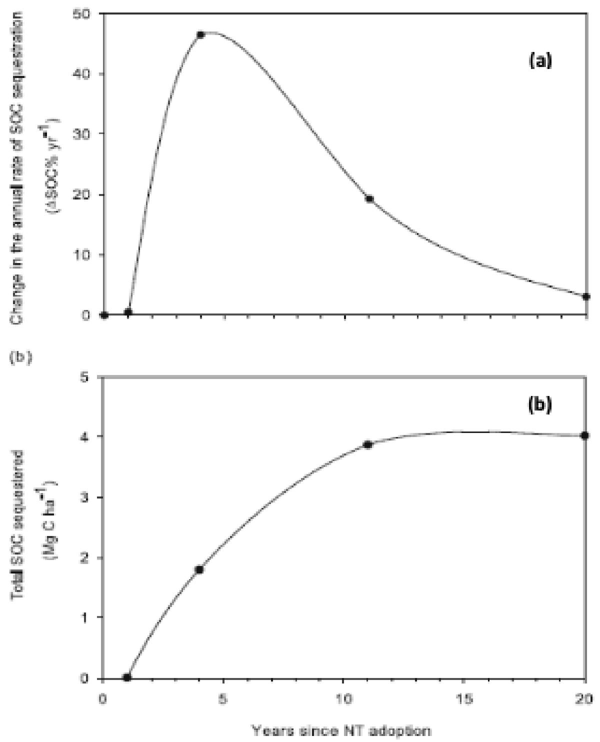

Figure 2: (a) rate of change of SOC sequestration for 20 years after adoption of NT in the 0-30cm layer; (b) Total SOC sequestered over the 20 years (Alvaro-Fuentes et al., 2012)

2.3.3 Effect of mineralogy, texture, and climate on soil organic matter

SOM has a portion that readily decomposed by soil organisms known as the labile SOM. There are also more stable fractions that take longer to decompose and consist of finer-sized organic matter which is physically protected (clay or aggregates) or chemically persistent (Chan, 2001). Stabilization of SOM has been often related to soil texture and clay mineralogy (Christensen, 1992), while the composition is influenced by the nature of the OM input, soil biological activity, environmental factors such as climate, and the stage of decomposition. According to Keber et al. (2005) soil clay minerals are also important parameters which have an influence on the storage of SOM, in particular SOC, by mineral association.

Studies have shown that an increase in clay content is associated with an increase in aggregate stability. As mentioned before, the clay will physically protect the SOM and thereby rendering it inaccessible to degradation by soil microbes. This complex process is occlusion. Kolbl & Kogel-Knabner (2004) found a 72% correlation between occluded particulate organic matter (POM) and the clay content of the soil. This shows that more C occluded in aggregates if there is an increase in the clay content. The paper further stated that at a clay content of between 5 and 30% this effect is most prominent and if the clay content further increase there would be a decline in the occluded POM.

Christensen (1992) demonstrated the evidence of the importance of clay particles in the stabilization of OM and the degree of decomposition. The paper states that stabilization generally increases with particle size fractions in the order of — sand < silt < clay. The protection of the OM also causes the clay-rich soils to contain higher OC and total N than the clay poor soils, shown by Krull et al. (2003) who added similar rates of OM to all the soils. Management practices that have a high input of OM and minimum soil disturbance would also assist in protecting and building SOM in these clay-rich soils (Jindaluang, et al., 2013). According to Chivenge et al. (2007) the elevated turnover rate of SOM through the disruption of aggregates through CT practises can be seen in both fine and coarse-textured soils.

The amount of OC that is associated with arable land is similar between clay and silt, which both have a particle size smaller than 20 µm. This can be attributed to particles being small enough for the C to associate to it and this is supported by Chan (2001) who found a positive relationship between the amount of particles <20 µm in the soil and the amount of C associated in the top 10 cm of the soil in both temperate and tropical soils. The effect of the climate and clay content on the SOC is further complexed because in heavy rainfall areas the clay minerals heavily regulate the SOC, whereas in semi-arid regions with more sandy soils the SOC is weakly related to clay particles (Saiz, et al., 2012; Zhong, et al., 2018). Sandy soil does not hold OM as it has a lower surface area compared to clayey soils. Water holding capacity of the sandy soils is low, which, paired with the low OM, can result in lower yields (Vitosh, 1998).

To state that all clay particles are equal in the association of OC is an overstatement. Different clay minerals have differing sizes. Layer silicates, hematite, sesquioxides, short-range ordered Fe-oxides and amorphous Al- oxides have a much larger surface area for the OC to adsorb, Mikutta et al. (2005) compared to quarts which have a very low specific surface area. Torn et al. (1997) proposed that it is better to look at the mineral activity than just the texture, as the activity is a better predictor of residence time and turnover rate of stable SOC.

Carbon stabilization is also dependent on the environment which includes the pH, wetness, OM chemistry, and cation availability. Chan (1997) found a correlation between the level of OC and aggregate stability and mineralizable N, while Chan (2001) showed there is even a strong correlation between SOM and N mineralization in different farming systems. Hassink (1997) proposed that soil mineralogy and climate have a major influence on the soil's ability to stabilize C. He found that Australian soils are highly weathered, dominated by kandites and illites, which have a lower cation exchange capacity and surface area. Added to this the area had low precipitation and high temperatures.

The effect of weather on soil functions is well known. The soil water content will affect vegetative growth (Porporato, et al., 2003), growth cycles (Nielsen & Ball, 2015), soil respiration (Curiel Yuste, et al., 2007), biogeochemical and greenhouse gas emissions (e.g. CO_2, CH_4, NO_x) (Kim, et al., 2012)). High soil water content with lower temperatures will cause retardation in decomposition (Wagai, et al., 2008), but is it not always as straightforward to predict and has been the target of many research efforts. When the amount of rainfall is decreased SOM mineralization can be suppressed due to stronger microbial water stress (Schimel, et al., 2007) and reduced nutrient mobility, but rainfall extremes can also reduce the SOC through leaching of dissolved organic and inorganic carbon (Liu, et al., 2018).

The amount of rainfall is not the only factor that needs consideration, but the timing is also of great importance. Both these components will affect the soil water storage, evapotranspiration, infiltration, and runoff from the soil. Overly wet conditions during the production season, which results is in a lower availability of oxygen available to microorganisms. A decrease will lead to lower redox conditions, which will retard OM breakdown. Supplementary rainfall during late spring or early summer, during a time when plant growth and evaporative demand is high, will lead to higher biomass from the plants and perfect conditions for the microorganisms. After a 6-year experiment where the rainy season was extended, Berhe et al. (2012) found a higher concentration and C:N ratio in the soil with spring treatments compared to the control.

2.4 Factors that affect yield and quality of wheat

In agriculture, the main purpose is to obtain a yield, which is a measurement of crop harvested per land area. Various factors will affect the yield of the crop. The most important factors are the soil's fertility, water available for the crop, the climate in which the crop is grown, and diseases or pests. The producer can influence some of these factors with management practices.

2.4.1 Nutrient availability

To be able to grow, develop and produce a yield, plants must have an adequate amount of certain nutrients. If any one of the nutrients are lacking or an external stress factor is applied the plant cannot produce a maximum yield or under extreme conditions be able to complete its life cycle; namely germination, developing roots, stems, leaves, and flowers, and produce seeds. The same is true for the oversupply of nutrients, which will lead to toxicity. Liebig's law state yield is limited by the nutrient present in the least quantity relative to its demand and represented by Figure 3. There are 16 essential nutrients and are grouped according to how much the pant needs. Primary macronutrients are those that require the highest amount and include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), and potassium (K). The secondary nutrients needed in moderate amounts include calcium (Ca), magnesium (Mg), and sulphur (S). The micronutrients that include boron, chlorine, copper, iron, manganese, molybdenum, and zinc require only trace amounts. Each of these nutrients affects certain functions of plant growth and development.

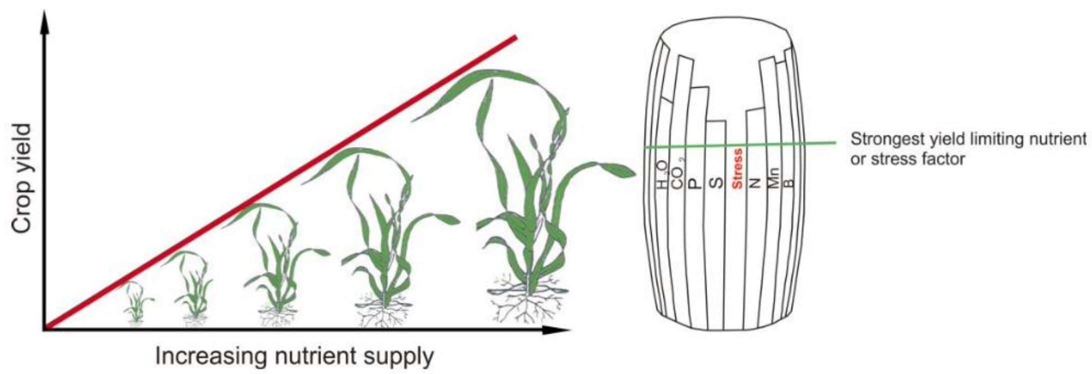

Figure 3: Liebig's law of minimum (Haneklaus, et al., 2018)

2.4.1.1 Macronutrients

The most important but limiting nutrient in wheat production is usually nitrogen. In the past few decades, the additional N fertilizers have helped substantially increase the yields of crops. Inadequate amounts on N can result in reduced yields and an oversupply in lodging, eutrophication, acidification, decreased yields, and reduced profit (Vitosh, 1998). For most producers, additional mineral N fertilizers are standard practice. Using targeted N application is important to avoid any of these negative impacts. This can also prove vital when building SOM in the soil because of the effect that the C:N ratio of the soil can have on the yield (Schjønning, et al., 2018). This is due to the higher mineralization in the soil. Ros (2012) found that soils with a higher SOC content have higher N mineralization rates. Soinne et al. (2020) found a 16kg yield increase for every 1kg N fertilizer applied. On top of this, they also found that the additional N used by the crop becomes smaller and smaller as it approaches its maximum level and fields that have previously been low yielding had a varying response to N application. The protein content of the wheat is also directly affected by the amount and timing of nitrogen availability during the growing season. The protein content will vary widely depending on the wheat class, region, type, and quality of the soil and the fertilizer (Xue, et al., 2019). The target grain protein level is 11.5% and a hectolitre mass higher than 76 kg in the South African context. The protein content gives a good overall indication of the quality of the wheat and ultimately the bread.

Phosphorus plays a role in cell division and development of new cell tissue. Other functions include complex energy transformations, root growth and winter hardiness, stimulating tillering in wheat, and the hastening of maturity (Wang & Shengxiu, 2004). Tillering is the production of side shoots which will result in multiple ears. Phosphorus deficiency will result in stunted growth and a reduced yield and quality (von Wandruszka, 2006). The roots absorb P through diffusion in the form of orthophosphate or certain forms of organic phosphorus. Potassium is also a regulator for plant growth and plays a pivotal role in the activation of various enzymes, such as protein synthesis, sugar transport, N and C metabolism, and photosynthesis (Oosterhuis, et al., 2014). It also plays an important role in cell growth and elongation, and the movement of water, nutrients and carbohydrates in plant tissue. There is evidence that the level of K in the soil can affect the absorption and utilization of other nutrients. All of these affects will ultimately determine the yield of the crops. Hydrogen in the form of H^+ will affect the pH of the soil – acidification; which can be advantageous in calcareous soils. H_2 will affect the plant itself with better seed germination, seedling growth, and root elongation. The least limiting nutrient is oxygen. A water saturated root zone is saturated with water which will lead to reduced respiration, mineral uptake and water movement, and ultimately reduce the plant growth and productivity.

Only moderate amounts of the following nutrients are required, while deficiency and toxicity can reduce the growth of the crop. Calcium affects the absorption of ammonium, potassium and phosphorus, and makes N use more efficient, but too high levels can raise the soil pH. Calcium also plays a role in cell elongation in both shoots and roots (Burstrom, 1968). Magnesium plays an important role in photosynthesis and its deficiency can hamper nutrient uptake and decrease the growth rate and thus the yield. Sulphur also plays a role in photosynthesis, the accumulation of dry matter, and it increases the 1000 seed weight and yield (Burkitbayev, et al., 2021). The main effect it has is on protein biosynthesis in crops. Both sulphur and nitrogen are essential macronutrients and building blocks of protein biosynthesis (Yu, et al., 2018). The average N to S ratio in protein is 12:1 and is constant in production. This shows that S plays a major role in the efficient uptake and use of N.

2.4.1.2 Micronutrients

Micronutrients are often neglected in plant production. In many ways micronutrients holds the key to how the other nutrients are used and subsequently plant performance. The biggest effect that micronutrients have on plants are on root development, fruit setting and grain filling, seed viability, and plant vigour and health (Siddika, et al., 2016). Micronutrients are present in most soil because of the gradual breakdown of rock minerals, but are not always present in plant available forms, thus the environment plays a big role in the absorption of these minerals.

2.4.2 Soil pH

Soil fertility correlates to the pH of the soil. Low pH levels can have a negative effect, as this will cause the conversion of nutrients to forms that the plant is unable to absorb. The solubility of plant toxic metals is also increased which can result in stunted growth or lack of plant vigour. A pH for wheat that has optimal micronutrient availability and growth is between 6.0 and 7.0, with a target of 6.4 (Monsanto, 2015).

2.4.3 Climate

It is much more complex than assuming that higher rainfall will result in higher yields. Too much rainfall (heavy rain, hail, floods) can lead to injuries to plants, compaction of the soil, erosion, or leaching of nutrients, while too little rain can retard the growth or even kill the crops. Good rainfall infiltration, water holding capacity, and reduced soil evaporation are all benefits of conservation agriculture by providing soil cover by mulch residue (Kahlon, et al., 2013). This can be a major benefit for dry areas which will result in soil moisture conservation before the planting (Page, et al., 2019). Giller et al. (2015) found that some individual sites had a decrease in crop yield with an increase in rainfall during the season. The intensity and distribution of the rainfall also has a big influence on the yield. If rainfall falls at a great intensity it can result in higher runoff. The main importance of rainfall is to replenish the water stored in the soil, which the crop will use when the growing season starts. The findings of Wakjira et al. (2021) that the onset of the rainy season strongly determines the total cereal production supports the previous statement. Quicker and stronger emergence with higher soil moisture resulting in better root growth enabling the crop being to reach soil moisture deeper in the soil.

The average global temperature has increased over the past few decades and predictions point to a rise in the short to medium term. High temperatures affect wheat yield in two ways: chronic stress caused by sustained, moderately high temperatures up to 32°C, or heat-shock caused by a sudden, but relatively brief exposure to 33°C and higher (Paulsen, 1994). An increase in temperature from emergence to anthesis can cause accelerated phenological development and result in a shorter growing period (Asseng, et al., 2011). This can result in a reduced yield. High temperature stress makes the double-ridge stage (period prior to anthesis) extremely vulnerable. The development of spikelet primordia on the apex is sensitive to high temperatures. Temperature stress during reproductive development is a significant obstacle. The direct effect of high temperature on grain number and grain weight has a direct effect on the yield. The interval between the onset of meiosis in pollen or embryo sac mother cells and the early development of micro or megaspores is the most heat sensitive stage of wheat reproductive development (Saini & Aspinall, 1982). During the period between flower initiation and anthesis, wheat plants are extremely susceptible to severe temperature stress, indicated by a decrease in kernel number. In wheat, T_{min}, T_{opt}, and T_{max} for effective anthesis are 9, 18–24, and 31°C, respectively (Russell & Wilson, 1994).

In an experiment by Ferris et al. (1998) the yield showed a reduction by 50% when grown in conditions of 40^{o}C 12 days before and after anthesis. Although the grain-filling rate is higher, when higher temperatures occur, while reducing the kernel weight. Along with this, there is also a reduction in the number of spikelets and grains per spike. During the period before anthesis a 4% reduction in number of wheat grains per unit area for each degree increase above the mean (Wheeler, et al., 1996) and 10°C increase in T_{max} cause 40% reduction in grain number per spike. High temperature from anthesis to maturity can caused 20% reduction in average grain weight of wheat (Stone & Nicolas, 1998). Lobell et al. (2005) reported that grain yield in wheat is more sensitive to increases in daily T_{min} than T_{max}.

Most of these experiments done in glass houses, with influences not anticipated as in the field. An example is the soil temperature, which will be higher in the greenhouse than in the field under the same temperature. Thus, it is good to acknowledge the effect that temperature has on growing wheat, but keep in mind that the yield has also increased significantly in the past two decades, attributed to rainfall, radiation, improved cultivars, increased nutrition, and new technologies. This causes difficulty quantifying the effect of temperature the yield in the field.

2.4.4 Soil physical properties

Soil physical characteristics may not have a direct impact but are of utmost importance to crop yield. The soil texture will influence the water holding capacity, infiltration, permeability, aeration, aggregate stability, and organic matter- and nutrient availability (He, et al., 2014).

Sun et al. (2020) also found that soil texture explains some of the variations in yield. Soinne et al. (2020) looked at the yield of crops and found that in both fertilized and unfertilized fields there was a negative correlation between the clay to C ratio and grain yield. This was found especially in areas with a clay to C ratio higher than 15. This indicates a low N utilisation because of the clay minerals protecting the N molecules. Another reason for this is that together with the SOC the texture will also influence the soil physical properties (Kay, 1998). This relationship is expressed by the clay to C ratio. The biggest is aggregate stability. To maintain the same level of aggregate stability when clay content increased, a higher SOC content was required (Johannes, et al., 2017). Johannes, et al., (2017) found that a reasonable goal is 1:10 and the optimal value for soil structure quality is 1:8. The other properties that are also yield limiting are slope and very fine sand content (Jiang & Thelen, 2004). Other soil properties such as base saturation, CEC, elevation, and pH also explain yield variation. The amount of coarse fragments in the soil also has a significant effect on the yield. Various papers have found a decrease in crop yield when comparing soils with higher coarse fragments to those with lower (Grewal, et al., 1984; Chow, et al., 2007). The higher coarse fragments resulted in a higher bulk density, decline in water content, higher soil temperature, and lower nutrient holding capacity. The soil depth has a positive correlation to the yield. This is because of the greater space for the roots to grow and higher water content and amounts of nutrients available to the plants. Hirzel & Matus (2013) found a greater yield, plant height, and number of stems in wheat when there is an increase in soil depth.

The environment is of utmost importance for the growth of a crop. For corn yield, Cox et al. (2006) found that field elevation plays a significant role in the yield, while Yang et al. (1998) determined that elevation, slope, and aspect can potentially explain up to 35% of variabilities found in wheat yield. Lower yields were evident at higher elevations and higher at lower convex locations. Work done by Jowkin & Schoenau (1998) support this finding, with higher yields at bottom slopes. Prevailing weather conditions often accompany these topographic indices.

Rainfall is a major limiting factor; some might even suggest the most important factor, especially when the crop is grown under dryland conditions (Osborne, et al., 2017). Feng et al. (2018) found that not only rainfall but also temperature and solar radiation, leading to fluctuating crop yields. The direct effect of high daytime temperatures during anthesis is that it will result in decreased seed set and grain number. Musa et al. (2021) found that an increase in both day and night temperatures negatively affects yield.

2.4.5 Biological properties

Pests and diseases could reduce the yield potential and the quality of a crop. This is caused by a continuous disturbance by a causal agent that alters a plant's normal structure, growth, function, or other functions by causing an abnormal physiological process. Crop productivity declines by various ways. Examples include assimilate sappers (nematodes, pathogens), light stealers (weeds, some pathogens), stand reducers (damping-off pathogens), photosynthetic rate reducers (fungi, bacteria, viruses), leaf senescence accelerators (pathogens), tissue consumers (chewing animals, necrotrophic pathogens), and sucking arthropods (Bockus, et al., 2010).

2.4.5.1 Pests

Insects can have differing effects on plants. Some are beneficial for plants such as bees for pollination, while other such as ladybugs and parasitoids will predate on the pests. Others are harmful to the crops. These can attack different parts of the plants, above and below the soil. Therefore, it is important to implement a series of pest management evaluations, decisions, and controls. There is a four-tiered approach, which include setting an action threshold, monitoring, and identifying the pests, prevention such as crop rotation and resistant varieties, and control once the threshold is surpassed (Stenberg, 2017). These management practices need to be implemented to reduce or prevent pests to interfere with the growth and cause damage to crops, which will result in the failure for the crops to reach their genetic potential. The Agricultural Research council (2014) compiled a list of pests on wheat in South Africa, which including insects that damage the seed and stems such as Black maize beetle (*Heteronychus arator Fabricius*), false wireworm (*Gonocephalum macleayi*), and the larvae of the Western Province grain worm (*Eremnus cerealis*) and Sandveld grain worm (*Pseudopophylia smaragdipennis*). Seed treatment and cultural practices can reduce incidence. Russian wheat aphids (*Diuraphis noxia*) attack both the leaves and stems. Resistant cultivars is the best control option. Bollworm (*Helicoverpa armigera*), brown ear aphid (*Sitobion avenae*) and oat aphid (*Rhopalosiphum padi*) primarily attack the ears of the wheat. This will cause direct yield loss and requires chemical intervention is needed.

2.4.5.2 Diseases

Plant diseases classifies into either infectious or non-infectious. Infectious plant diseases are caused by a pathogenic organism such as a bacterium, fungus, mycoplasma, nematode, virus, viroid, or parasitic flowering plant (Singh, et al., 2016). Infectious diseases are capable of reproducing and spreading within or on the host plant and from one to another. Unfavourable growing conditions cause non-infectious plant diseases are caused by unfavourable growing conditions, which can include temperature, moisture, toxic substances, and excess or deficient essential minerals. A plant under these unfavourable conditions are often more susceptible to infectious diseases. To reduce the risk of a disease outbreak, integrated disease management practices need implementation. This includes a range of measures to prevent and reduce the risk of disease in plants. The fundamental principles include exclusion, eradication, protection, resistance, and avoidance of insect vectors and weed hosts. Pest management of wheat would require scouting the fields to identify the disease problem before it gets out of control. The treatment can be either curative or preventative, but chemical treatment should not be the only measure implemented. Disease epidemics can only occur when there is a combination of inoculum, favourable environment, and the host is susceptible.

In a study done by Jalli et al. (2021) they looked at the effect of crop rotation on disease control and found that leaf blotch disease, and other stem and root diseases were lower after a diverse crop rotation or if wheat is only grown every four years. On the other hand, Duveiller et al. (2007) found that necrotrophic pathogens such as those responsible for tan spot or Septoria are likely to emerge, and Fusarium head blight may increase when implementing conservation agricultural practices. In South Africa various diseases needs control to reduce yield loss and quality impairment. According to the Agricultural Research council (2014) the diseases of small grain of South Africa that affect wheat include stem rust (black rust), stripe rust (yellow rust), and leaf rust (brown rust), powdery mildew, Septoria leaf blotch, which affect leaves and stems, Loose smut affects the ear, Karnal bunt infects the kernels, take-all affects the roots, crown and basal stem, and eyespot affects the base of the plant.

2.4.5.3 Management practices

Angus et al. (2015) found that crops generally produce greater yields when grown after certain unrelated species. This paper had extensive research about the effect that crops have on wheat yield in a rotational system. There is no significant difference when using barley as a rotation crop, due to similar biology, root diseases, and nutrition of barley and wheat. Implementing oats in the system resulted in a significant higher yield for the wheat. The increase in yield was consistent over a wide range of yields. Canola also showed a positive response which was significant and uniform, but mustard, which is another brassica showed even better results. It is widely known that implementing a legume will result in N fixation in the soil and a break in the life cycle of soilborne pathogens, which will positively influence the wheat yield of the following season. Angus et al (2015) concurs with this statement and found that the yield of the wheat did increase after each of field peas, lupines, faba beans, chickpeas, and lentils was grown.

In the case of implementing a fallow season into a rotational system Connor et al. (2011) found that there is also an effect on the yield. Leaving the field fallow allows the farmer to control weeds as well as allowing for a disease break. Both fallow (to a lesser extent) and implementing legumes will supplement the N needs of the wheat (Sims, 1977). Unlike the other crops mentioned, fallow can conserve soil water by reducing the runoff and assisting with infiltration and this is one of the most important benefits, especially in semi-arid regions, soils with low infiltration and with the implementation of pastures in the system. Smith et al. (2020) found that implementing medics increase the yield and protein content of wheat when implementing a MMWW rotational system. Some farmers will implement the rotational crop twice before returning to the main crop again. Although advantageous, these fields historically deliver lower yields than on high-yielding fields (Angus, et al., 2015). We can conclude that not all rotational crops have the same effect and we can rank them on the influence it has on wheat yield: oats < canola, mustard < field peas, faba beans, chickpeas, lentils, lupins.

Grazing during the fallow season is widely implemented. This has economic advantage as the producer does not need to invest in feed for the animals during this time. There is also the management of the residue and weeds if implemented. Lessen et al. (2013) looked at the effect that grazing has on yield and soil properties when comparing fallow, grazed and tillage during the fallow season. The paper found that the fallow had greater crop residue and soil water, while grazing resulted in higher bulk density, lower EC, NO_3-N, Ca, and SO_4-S, but a higher Na concentration. No effect on yield, between the three treatments was observed. Unkovich et al. (1998) found that the availability and uptake of N by the following crop was higher when implementing intensive grazing compared to light grazing.

2.4.6 Soil carbon

There are various effects that the SOC has on the soil chemical- and physical environment. These will have major effects on crop production. Looking at SOC as an avenue to ensure stable and long-lasting crop productivity and by decreasing the over-reliance on external inputs such as mineral fertilizer can lead to a much more sustainable way of farming. In different areas and climates, the building of SOC in the soil might have differing effects. In higher rainfall areas, this can reduce the need for fertilizer and irrigation; while in regions that are more arid it can lead to drought protection and mineral release. All of these factors will indirectly influence the yield of the crop. In a global meta-analysis which Oldfield et al. (2019) did, they found a positive relationship between SOC and yield which started to level off at ~ 2% SOC (Culman, et al., 2013; de Moraes Sa, et al., 2014). To reach this level of SOC it can take between ~ 9 and ~ 47 years when starting at 0.5% SOC. This shows that various factors that influence the build-up of SOC. The meta-analysis also found that the SOC in dryland climates has an average of 0.9% while in temperate climates the SOC was 1.4%. This links to the lack of OM returning back to the soil. A positive takeaway is that when the SOC is increased from 0.5 to 0.8% it can result in a 10% increase in the yield in dryland climates (Oldfield, et al., 2019), which might be due to the increased water retention and nutrient supply.

When looking at the relationship between SOC and crop yield under conservation agriculture in a meta-analysis Sun et al. (2020) used a humidity index (HI) which is the MAP/MAT to divide all regions into HI <40, 40<HI<100, and HI>100 (Figure 4). For the HI<40 they found that there was a SOC gain as well as an increase in yield. In areas with HI between 40 and 100 there was an increase in SOC but no change in yield, while regions with HI>100 had no change in the SOC but risked yield loss when adopting conservation agriculture. The HI along with the conservation agriculture can be linked to soil moisture, temperature and infiltration, and erosion (Fischer, 2019), which can all affect the SOM turnover rate. Another observation indicated that gains in crop yield is achievable, when the SOC sequestration rate is higher than 0.4 Mg C $ha^{-1}year^{-1}$ (Sun, et al., 2020). This can give a good account when looking at the SOC and yield of a certain area.

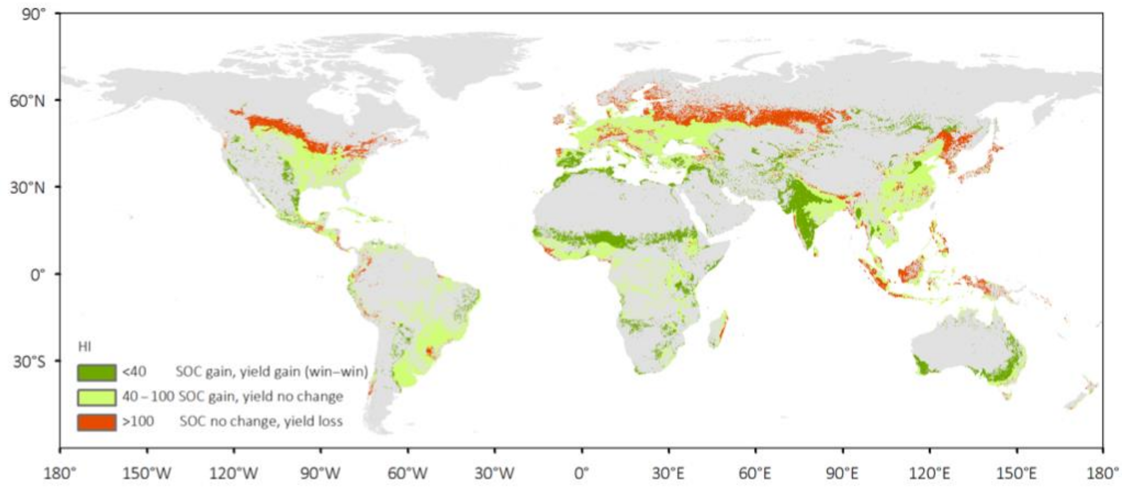

Figure 4: Three different humidity index (HI) levels and corresponding outcomes after adopting conservation agriculture (Sun, et al., 2020)

2.5 Boundary line analysis

Since the beginning of agriculture, farmers have tried to identify and quantify factors relating to plant performance. Researchers reason that optimising a quantifying factor between a growth factor and yield leads to the highest yield. Observation of these relationships indicated that the specific factor is varied and the conditions unique to each experiment. This means that critical values cannot be applicable to all regions, while sufficiency ranges attempt to alleviate this problem. Using a regression relationship might explain the results of a certain season but other factors become more important and the regression might be different for the following season. Using percentage yield can help but this ignores the complexity of the factors. Walworth et al. (1986) proposed solving this with enough data that include variability and creating a scatter plot with yield as the dependent variable against the growth factor as independent variable, showing the optimum for the factor at the peak. A line can then be fitted which separate real from unreal situations, where this boundary line would represent the limiting cases. This “boundary line” would give the maximum yield for any value of the growth factor. The chances of the yield to be on this line are very small. All other growth factors except the one in question would need to be optimal.

Schnug et al. (1996) proposed a 5-step algorithm to determine the path of the upper boundary line. Step 1 is to identify the outliers. The inclusion of outliers in the boundary line determination process would invalidate the results. There are two criteria for detection of outliers. Both criteria identify data points that are separated from the rest of the data by a certain distance in terms of nutrient status and yield. The rectangular criteria impose rectangular cells on the scattered data with each cell the same size. The size is determined by the standard variation of each parameter, with the yield determining the vertical size and the nutrient parameter the horizontal. Circular criterion uses a single radius like parameter on the data, applied in the lack of standard variation. Another method to exclude outliers, used more recently, by using box-and-whiskers diagram on the nutrient status data (Ali, 2018; Iheshiulo, et al., 2019).

The next step is to divide the scatter plot into 10-15 intervals and only the highest point in each interval is selected. The intervals cannot contain more than 25% of the data (de Souza, et al., 2020). Next a second-degree polynomial function is generated from the new range of data points.

The function would be:

Equation 1: $Y = ax^2 + bx + c$

where Y is the relative fruit yield; X is the nutrient concentration; and a, b, and c are regression coefficients. The function is at a significant level of α = 0,1. According to Schnug et al. (1996) a significant effect appears with the introduction of a third variable. This will result in two or more distinct clouds of data points, each with its own boundary line; this will result in a fourth order polynomial (Figure 5b). The last step is to determine the optimum values and range for the independent variable. The optimum concentration can be obtained by solving the first derivation of the regression equation:

Equation 2: $Maximum\ yield = \frac{-b}{2a}$

where a and b are the second-degree regression coefficients. To obtain the minimum and maximum range which will be at 90% of the maximum yield. This is done by using the following equation:

Equation 3: $Confidence\ interval = \bar{X} \pm z \frac{s}{\sqrt{n}}$

where $\bar{X}$ is the sample mean, z the confidence level value, s the sample standard deviation and n the sample size.

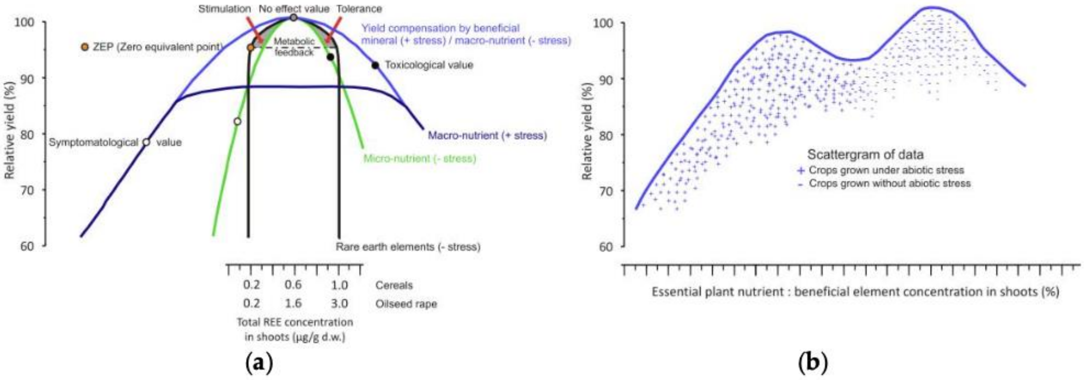

Figure 5: (a) Mitscherlich growth curve showing the relationship between nutrient status and the yield of the crop (b) a third growth variable is introduced which creates two distinct clouds of data points (Haneklaus, et al., 2018)

The nutrient status of a plant follows the Mitscherlich growth functions as shown in Figure 5a. Evaluation of the nutrient status of a crop focus on the critical values. The symptomatic value is where deficiency symptoms become visible; the no-effect values between which the plant has sufficient nutrient supply to achieve maximum yield, also known as the sufficiency range; values 5, 10, and 20% lower than maximum yield; and toxicological value where the nutrient concentration causes toxicity symptoms. None of the abovementioned values and range has one specific value for a specific crop. The value will be dependent on the growing conditions, developmental stage of the plant, plant part, the specific nutrient, the targeted yield and the mathematical approach to calculate the values (Haneklaus, et al., 2018). Numerous critical values exist in literature for almost any crop. Many of the published critical values originate from a single experiment where not all confounding factors were accounted or the climate not taken into account. Smith & Loneragan (1997) stressed that producers should consider ranges opposed to specific values. Various things result from the growth function. The shape of the 2nd degree polynomial will show the concentration of the element in the growth function of the plant tissue. If the slope increases steeply this will show a decrease in the need for the critical element’s concentration.

2.6 Conclusions

Soil organic matter plays a vital role in the health of the soil and consequently the yield of the crop. It controls certain soil chemical, biological and physical characteristics which have great impacts on the crop produced. There are certain factors that the producer can control such as the tillage can crop rotation, which if implemented incorrectly can cause SOM loss. No agricultural system can be sustainable and continuously productive when there is a net loss of SOM. The implementation of conservation tillage, crop rotation, and the correct application of nutrients can go a long way in the prevention of SOM loss. Certain other factors play a role, including the texture of the soil, the physical environment of the field, and the climate of the region. These can lead the producer when choosing the crops and the land management practices. Ultimately, these will affect the yield, along with the control of pests and diseases.

There are certain values obtained through boundary line analysis that a producer uses to determine the amount of nutrients needed. The problem is that these values may not be accurate for every area; thus, there is an opportunity to use this method to look at the nutrients against the yield or the role of carbon against the yield of the crops.

Various studies relate the effect that tillage and crop rotation have on the SOM content of the soil. The effects of soil mineralogy, texture, and climate as well as their effect on SOC are plentiful. Where there is a relative lack is when looking at the role that carbon plays in the yield of wheat. A possible solution is studying yield data on a field where the management practices are such that it will positively influence the SOM content and subsequently the SOC content of the soil. By looking at the role that the carbon plays it is also important to look at the factors that affect the carbon content itself, how these affects the yield potential as well as the quality of the wheat. The best crop rotational system for obtaining the highest yield as well as improving SOC in the soil is harder to find. This is especially the case when you are looking for the effects it the local area of the Western Cape. Rainfall is of great importance, especially in rain-fed agriculture but looking at when is the best timing of the rainfall to obtain better yields in semi-arid regions is lacking. Various areas in the literature are lacking but this gives an opportunity to explore these avenues.

Chapter 3: Long-term effect of no-till crop rotation systems on soil carbon content and wheat yield

3.1 Introduction

Arid and semi-arid regions are characterized by unfavorable environmental conditions such as little and unpredictable rainfall, intense solar radiation, and high evapotranspiration (Neenu, et al., 2013). In South Africa, about 47% of the land is classified as arid and 39% as semi-arid. In the Western Cape, these figures are 64% and 24% (Hoffman & Todd, 1999). This results in various challenges in crop production.

The Western Cape produces roughly 60% of South Africa's dryland wheat with the two biggest production areas being the Swartland and the Southern Cape (Grain SA, 2015). Thus, the improvement in wheat yield, in these production areas, is of great importance. This is possible through landscape restoration and soil and water conservation. These practices can include changing cropping patterns, exploring different rotational systems, reduction of tillage intensity, and integration of livestock (Golla, 2021).

The climate is one of the main factors that will determine the amount of soil organic matter (SOM) present in the soil. High soil water content with low temperatures retards organic matter decomposition (Wagai, et al., 2008) which will result in higher SOM contents. Both locations in the long-term crop rotation and tillage trials are in Mediterranean, semi-arid regions which means that building soil organic matter is challenging. Many soil characteristics, such as nutrient availability and exchange, water infiltration and retention, physical resistance, and biotic activity, benefit from a higher SOM (Lal, 2011). SOM depletion can result in nutrient depletion and soil degradation, a decline in agronomic activity and biomass production, food insecurity, and environmental degradation due to CO_2 emissions (Lal, 2004). This underlines the need that management practices that limit SOM loss, increase C sequestration and OM input needs to be implemented. Almost all of literature suggests the best way is to combine NT with a diverse and high biomass input cropping system (Logan et al., 1991; Lampurlanés et al., 2001; Qin et al., 2004; Deiss et al., 2021). This is because NT practices will increase aggregate stability which will in turn enhances SOM concentration within aggregates (Chivenge, et al., 2007). This will lead to a higher residence time for the OM which will result in a higher C sequestration. As mentioned, this process is time-dependent and significant results may only appear after 10 years (Sombrero & De Benito, 2010), which can be attributed to slow incorporation of SOM into the soil because of NT. This may lead to a lack of C sequestration in the first few years, especially in water-limited regions (Six, et al., 2000). Another trend that can be observed is a decline in yields during the first few years which will also result in lower biomass returned to the soil.

Plant roots are an important but somewhat poorly understood source of carbon (van Vleck & King, 2011). The biomass produced by the roots is retained more efficiently than the aboveground inputs. In arid regions with annual cropping systems, the rate of decomposition is slower which makes the belowground input more important. This shows that the incorporation of crops in the rotational system which produces a higher root mass, especially in the topsoil is important. These crops can include canola and wheat (Gan, et al., 2009), lucerne and pasture (Dodd, et al., 2011), and barley and oats (Hoad, et al., 2001). Once the OM has been decomposed C accumulation through C sequestration will take place, which will store C in the soil and help to improve the quality of the soil.

The effect that crop rotation and especially the types of crops and pastures have on the soil C content is of great importance, especially in semi-arid regions under dryland production. Therefore, this study was conducted in the Swartland and Overberg to explore which of the systems under no-till, – monoculture, continuous cropping, or rotation with pastures/medics – will have a positive effect on soil C.

The main aim of this chapter is to examine the effect of long-term (18 years) no-till and crop rotation, varying in crop/pasture contribution to each system from a 33/66 crop/pasture combination to a 100/0 crop/pasture rotation, on soil organic C content. This also will involve exploring which soil, crop, and climatic characteristics will have a significant influence on the C content of the soil.

3.2 Materials and methods

3.2.1 Study area

This study was conducted on two trial sites: Langgewens and Tygerhoek. Langgewens Research farm is situated near Moorreesburg in the Swartland region of the Western Cape, South Africa (33°16’34.41” S, 18°45’51.28” E). The farm is shown in Figure 6. This is an important winter grain region in the country with grain crops grown under dryland conditions. The soils are predominantly derived from Malmesbury shale and tend to be shallow and stony.

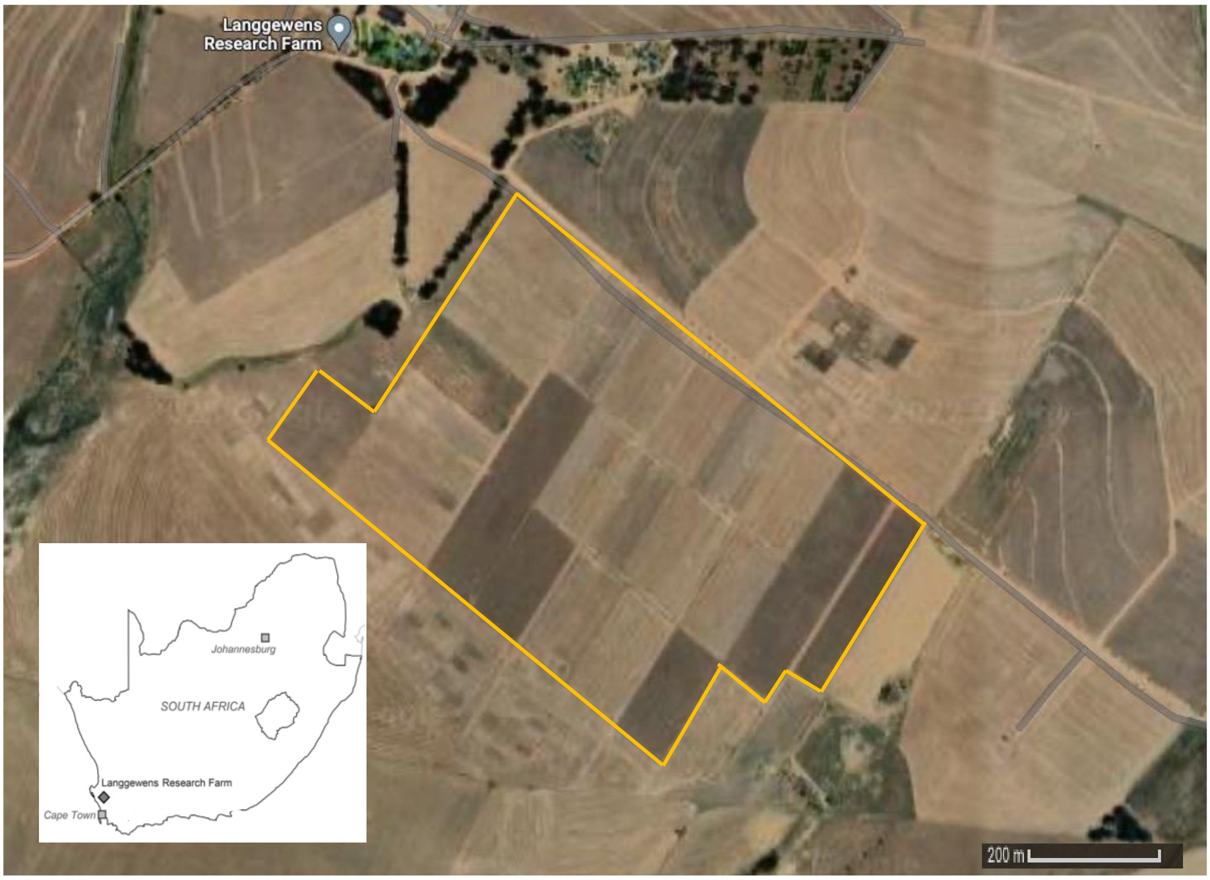

Figure 6: The location of the study site at Langgewens Research farm, Swartland, Western Cape, South Africa (33°16'34.41" S, 18°45'51.28" E)

Tygerhoek Experimental farm is situated just outside Riviersonderend, in the Overberg region, Western Cape, South Africa (34° 09' 32" S, 19° 54' 30" E). The farm is shown in Figure 7. This is also a well-known dryland grain production area. The soils are shallow with a high coarse content with the parent material being Bokkeveld shale.

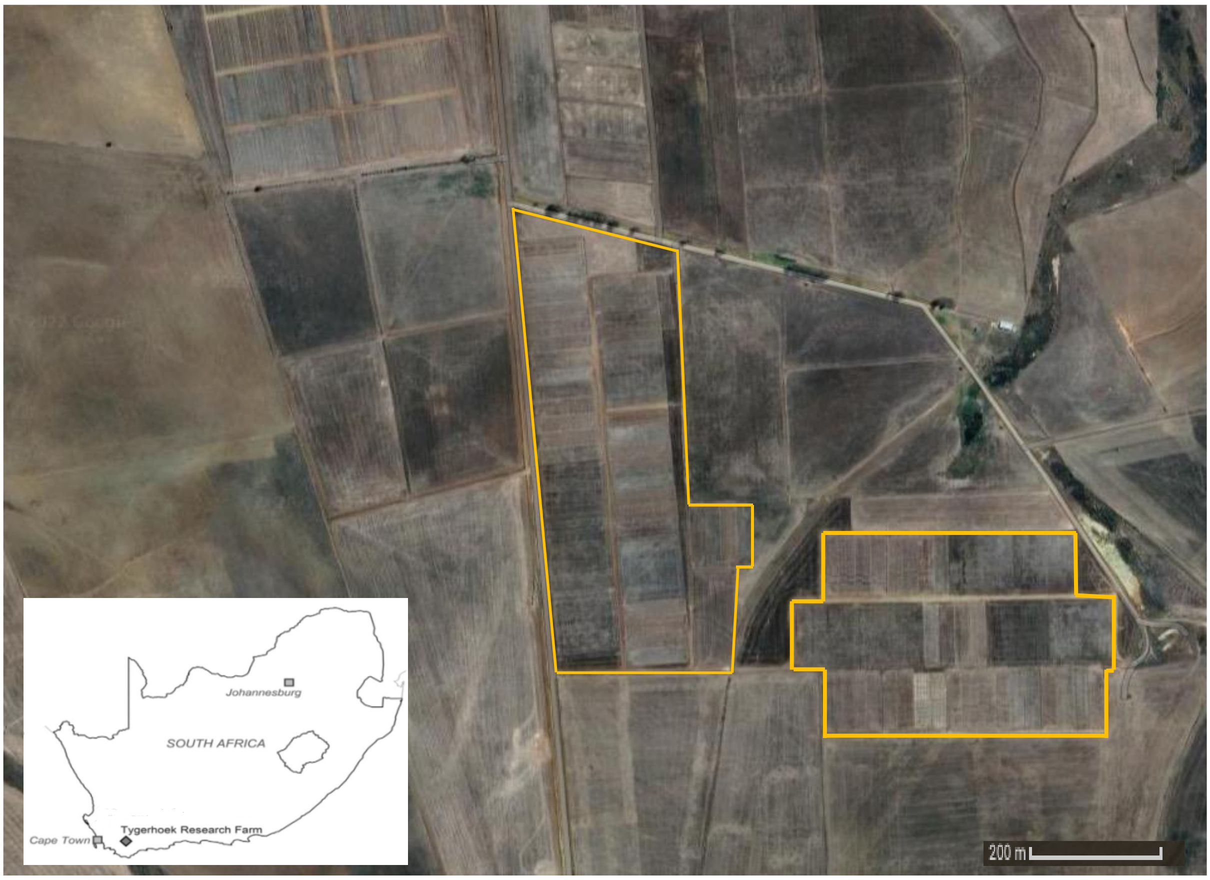

Figure 7: The location of the study site at Tygerhoek Experimental farm, Riviersonderend, Western Cape, South Africa (34° 09' 32" S, 19° 54' 30" E)

3.2.2 Climate

The climate at Langgewens Research farm is semi-arid Mediterranean with warm and dry summers and cold wet winters with an average of between 350-450 mm of rainfall per year (Figure 8). Eighty percent of the annual rainfall occurs in the period between April and October. The average annual rainfall was between 280-380 mm, with the lowest being 232 mm in 2017, and 238 mm in 2015.

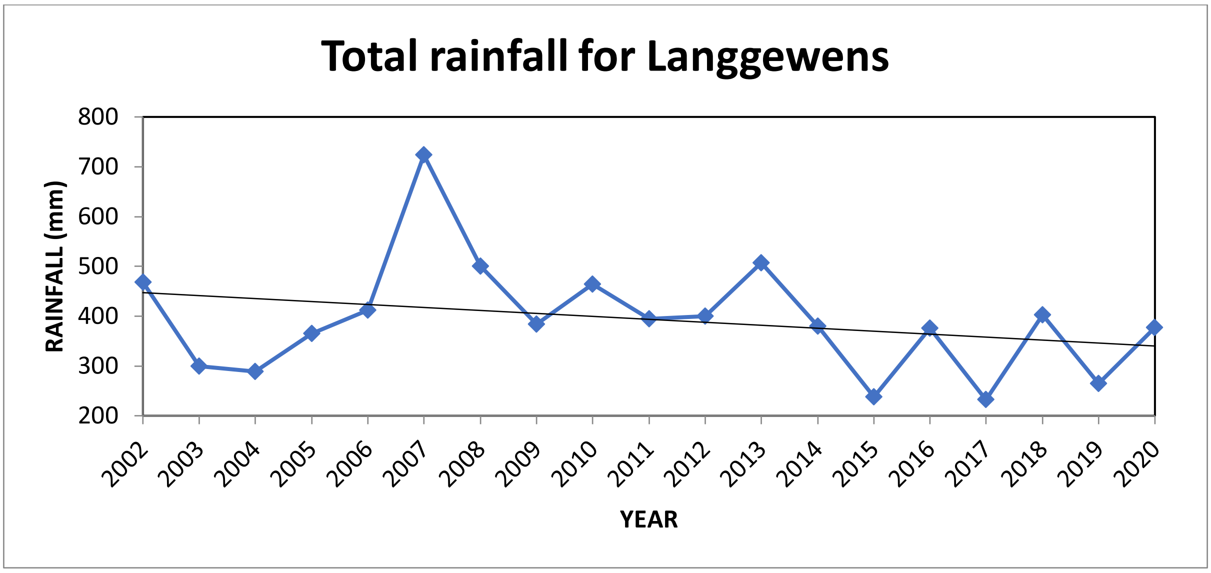

Figure 8: Total rainfall for Langgewens Research farm from 2002 to 2020

The climate at Tygerhoek Experimental farm is more temperate, with an average annual rainfall between 450- and 550 mm per year (Figure 9). Fifty-two percent of the annual rainfall occurs in the production season between April and October, with the average being between 200-300 mm.

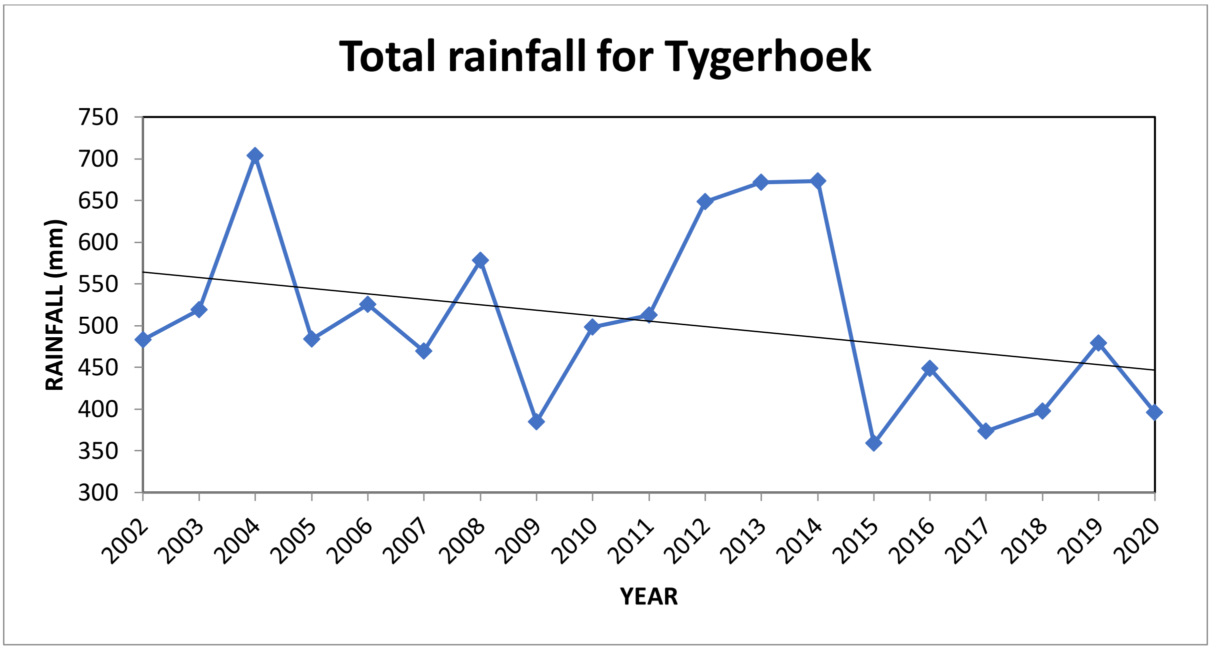

Figure 9: Total rainfall for Tygerhoek Experimental farm from 2002 to 2020

3.2.3 Experimental design

The study conducted on Langgewens Research farm is in its 24th year where the effect of crop rotation in different systems under conservation agriculture. The fields are situated on a lower slope with a gradient of between 5 and 10%. The working depth was 40-60 cm and consisted of sandy loam textured soil.

The trial was done on 48 different fields consisting of eight different 4-year crop rotation systems. Each of the rotational systems was replicated twice. The rotational systems studied were:

100% crop rotation consisting of:

- Wheat monoculture (WWWW)
- Wheat and canola rotation (WWWC)
- Wheat, canola, and lupin rotation (WCWL)
- Wheat, canola, and lupin rotation (WWCL)

50% crop 50% pasture rotation consisting of:

- Wheat and medic rotation (WMWM)
- Wheat and medic or clover rotation (WMcWMc)
- Wheat, canola, and medic rotation (WMCM)
- Wheat and medic or clover rotation (WMcWMc + saltbush)

The study conducted on Tygerhoek Experimental farm is in its 20th year where the effect of crop rotation in different systems under conservation agriculture. There is a greater focus on pastures in this system. The fields are situated on a middle to lower foot slope with a gradient of about 5%. The soils are very shallow with the working depth being 30-40 cm and consisting of sandy loam textured soil with a high coarse fraction.

The trial consists of 112 camps divided into 4 main rotation systems, replicated twice. The main systems included were as follows:

- Pasture-pasture-crop thus 33% crop and 67% pasture (PPC)
- Pasture-pasture-crop-crop thus 50% cash crop and 50% pasture (PPCC)
- Pasture-crop-pasture-crop thus 50% cash crop and 50% pasture (PCPC)
- Pure Cash crop thus 100% crop (CCC)

Within each of these main systems, there were sub-systems that varied in the cash crop components. In the PPC system, two consecutive years of pasture were followed by a single crop and included 4 sub-systems (PPWheat, PPBarley, PPOats, PPVariable). In the PPCC there were 4 sub-systems where two consecutive years of pasture were followed by two consecutive years of cash crops in different combinations (PPWheatWheat, PPOatsWheat, PPWheatBarley, PPCanolaWheat). The 5 PCPC sub-systems consist of alternating pasture and cash crops (PWheatPWheat, POatsPWheat, PBarleyPWheat, PCanolaPWheat, PvariablePVariable). The two sub-systems with the “variable” component did not follow a set choice of cash crop and included mostly wheat, some years of canola, and two years of triticale. The pure cash crop rotation system consisted of two sub-systems, namely a 4-year and a 6-year rotation sequence (WheatCanolaWheatLupine, WheatBarleyLupine-WheatBarleyCanola).

3.2.4 Classification of the soil

A total of 66 soil profile pits were excavated and classified according to the Taxonomic system for South Africa (Soil classification working group, 1991) on Langgewens Research farm and a map was made shown in Figure 10. The most dominant soil form on the farm is the Swartland soil form

(Sw)(Orthic A on a Pedocutanic B on Saprolite), followed by a Klapmuts soil form (Km)(Orthic A on an E-Horizon on a Pedocutanic B Horizon). The other soil forms also present are Cartref (Cf)(Orthic A on an E-horizon on a Lithocutanic B), Glenrosa (Gs)(Orthic A on a Lithocutanic B), Oakleaf (Oa)(Orthic A on a Neocutanic B), Sepane (Se)(Orthic A on a Pedocutanic B Horizon on Unconsolidated Material showing signs of wetness), Sterkspruit (Ss)(Orthic A on a Prismacutanic B Horizon), Tukulu (Tu)(Orthic A on a Neocutanic B on Unspecified material with signs of wetness), and Vilafontes (Vf)(Orthic A on an E-Horizon on a Neocutanic B horizon).

Figure 10: A soil map of the study site at Langgewens Research farm, Western Cape, South Africa. The soil form are Swartland (Sw), Klapmuts (Km), Cartref (Cf), Glenrosa (Gs), Oakleaf (Oa), Sepane (Se), Sterkspruit (Ss), Tukulu (Tu), and Vilafontes (Vf) (Ellis, 2010)

At Tygerhoek Experimental farm, 112 profile pits were excavated for soil classification. The soil map is shown in Figure 11. The most dominant soil form is Glenrosa, with Oakleaf and Vilafontes also present. During the classification of both farms, the quantification of the coarse fragments was also done.

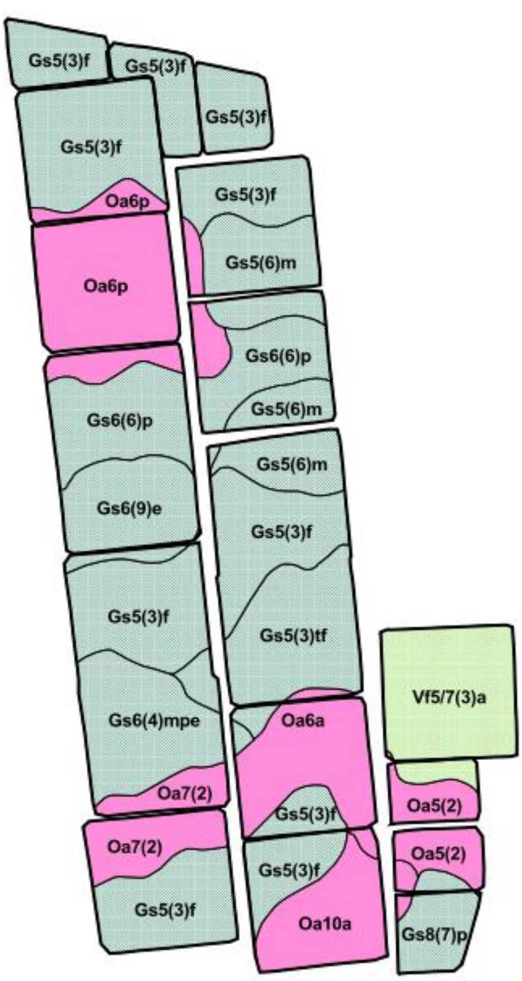

Figure 11: A soil map of the study site at Tygerhoek Experimental farm, Western Cape, South Africa. The soil form is Glenrosa (Gs), Oakleaf (Oa), and Vilafontes (Vf) (Ellis, 2010)

3.2.5 Tillage/planter

The type of tillage that was implemented at Langgewens was minimum tillage with loosening of soil with tine implement then planting with adapted seed drill from 1997 to 2001, from 2002 to 2015 no-till with Ausplow tine seeder, and from 2016 onwards zero-till with Piket double disc seeder. At Tygerhoek no-till was implemented and from 2002 to 2016 an Ausplow tine seeder, while from 2017 onwards a Xfarm double disc seeder was used.

3.2.6 Fertilizer, lime, and gypsum

Nitrogen fertilizer was applied to each of the fields with planting and then a topdressing, while at Langgewens there was a second topdressing in some years. The amount which was applied varied between each system and for each year. Sufficient N fertilizer was applied when either wheat or canola was planted, while lupine received significantly smaller amounts. The amount of N fertilizer that was added to the wheat and canola varied between 20 and 120 kg N ha^{-1}. All the fertilizer amounts applied are in Table A 5 and Table A 6 in the Appendix.

Calcitic and dolomitic lime along with gypsum was added to the soil at Langgewens. The application of lime varied between 0.3 and 1.7, and gypsum between 0.25 and 2.5 tonnes per hectare. The additions took place in the following years: 2002-2007, 2009-2014, and 2017-2018. At Tygerhoek calcitic lime and gypsum were also added to the soil when needed. It was either applied at a rate of 0.5 or 1 tonne per hectare. This only occurred in the seasons of 2007, 2009, 2010, and 2011. All the lime and gypsum applications are in Table A 7 and Table A 8 in the Appendix.

3.2.7 Grazing

At both farm sites, sheep grazing was implemented. At Langgewens systems e to h were grazed with sheep on the medics in winter, and in summer on both medics and crop residues. Sheep grazed the medic pastures at Tygerhoek during Winter, and medic and crop residues grazed in the summer.

3.2.8 Soil sampling and preparation

Soil samples at both Langgewens and Tygerhoek were collected in late December to mid-January of each year. The sampling depth was in the top 15 cm of the soil. This is due to the shallow depth of the soil (Tang, et al., 2011). At Langgewens two composite samples were taken per plot initially (one in the top half and one in the bottom half), but later in the timeline, only a single composite sample was taken. Thus, resulting in 96 samples initially and then reduced to 48. At Tygerhoek one composite sample was taken at each of the 112 camps. After the samples were taken, it was transferred to the Soil, plant, and water laboratory, Western Cape Department of Agriculture, Elsenburg. The samples were then air dried and sieved through a 2 mm sieve and then analyzed by the lab.

3.2.9 General soil characterization

3.2.9.1 Organic carbon

Soil organic carbon is determined by the Walkley-Black method (Allison, 1965).

3.2.9.2 pH

Soil pH was measured in 1M potassium chloride (KCl) at a 1:2.5 soil-to-solution ratio. Samples were shaken for 30 min on a horizontal shaker and then allowed to stand for 30 min before the pH was measured (Thomas, 1996).

3.2.9.3 Resistance

Soil resistance was determined on a saturated paste extract using a resistance meter (UC Davis Analytical Lab, 2017).

3.2.9.4 Nutrient content

ICP (Inductively Coupled Plasma) spectroscopy is an analytical method used to detect and measure elements to analyse chemical samples (Zivanovic, 2017). The nutrients which were measured are Ca, Mg, Na, K, S, and P, determined by ICP in 1% citric acid (Soil Analysis Work Committee, 1990).

3.2.9.5 Particle size distribution

Soil particle size distribution was determined using sieving and the hydrometer method as described by Gavlack et al. (2005). The air-dried soil is sieved (<2mm) and placed in Sodium Hexametaphosphate (HMP) solution and then put on a horizontal shaker. It is then placed in a sedimentary cylinder with deionised water. A plunger is used to thoroughly mix the content and place a hydrometer in. Record the reading and after 6 hours record the temperature and the reading. This will determine the (dispersed) clay content. The % sand, silt, and clay are then determined by the sieving method.

3.2.10 Yield and protein content

The yield of the crops was determined after harvesting the whole plot and determining its mass. A seed sample from each plot went to the local silo for quality assessment.

3.2.11 Statistical analysis

Statistical analysis was done using Statistica Version 14.0.0.15. A mixed model ANOVA was used to determine if the difference between the carbon and yield of each system and year are statistically different at both locations.

3.3 Results and discussion

3.3.1 Soil characteristics

3.3.1.1 Soil chemical properties

The topsoil (0-15 cm) for Langgewens research farm was mildly acidic, with a pH range of 4.8 – 6.8, with minimal variation and a slight increase over time. The increase can be due to no-till, crop rotation, limited N fertilizer applied, and the application of lime. This is within the optimal range for crop production. The resistance has a range of 115 – 2425 Ohms and an average of 752.89 Ohms. The higher values may be explained by the low rainfall in these areas. Soluble salts are more likely to be accumulated than to be washed below the root zone in arid and semi-arid regions (USDA, 2022). Shallow soils also have higher values because the salts cannot be leached from the root zone. The T-value of the soils varies between 2.8 and 23.3 cmol kg^{-1} with the average being 6.9 cmol kg^{-1}. This correlates with the soil texture being predominantly sandy loam. The soil characteristics is shown in Table A 1 in the Appendix.

At Tygerhoek experimental farm, the range for the pH of the topsoil (0-15 cm) is between 5 and 8. The soil is slightly more alkaline than Langgewens, with a slight increase during the trial period, and has a low variation between the different fields. The resistance of the soil ranges between 60 and 1760 Ohms, with an average of 596.52 Ohms. The T-value ranges between 5.03 and 35.72 with an average of 9.83 cmol kg^{-1}. The soil characteristics is shown in Table A 2 in the Appendix.

3.3.1.2 Soil texture

The soil texture for most of the sites was classified as a sandy loam at both Langgewens and Tygerhoek. The texture along with the amount of clay present will influence the SOM stabilization (He, et al., 2014). The clay content of all the soils at Langgewens was generally similar with a range of 9-16%. With the clay being lower, this will influence the C content of the soil as clay can act as a stabilizing mechanism by forming a protective barrier around the SOM in the soil (Wattel-Koekkoek, et al., 2001; Kolbl & Kogel-Knabner, 2004; Jindaluang, et al., 2013). At Tygerhoek the range for the clay content was between 13 and 29%. The soil texture is shown in Table A 3 and Table A 4 in the Appendix.

3.3.1.3 Coarse fragments

Soil coarse fragment content is linked to the location of the site with the landscape position and the parent material having a significant influence. The tillage practices that are implemented also have a significant impact not only on the amount but also on the distribution of the coarse fragments in the soil profile. Deep tillage can break saprolitic soils and bring these fragments to the surface layers. A higher coarse fragment content in the soil will result in the dilution of soil C stocks by reducing the volume of the fine fraction where the C is usually stored. The soils in both locations are relatively shallow and shale-derived, it can be expected for the soil to have a higher coarse fraction. The range at Langgewens is between 10 and 65 % and at Tygerhoek it is between 37 and 83%. The coarse fragments are shown in Table A 3 and Table A 4 in the Appendix.

3.3.2 Soil organic carbon (SOC) content across the trial period

One of the main objectives of this study is to determine whether there is a significant increase in topsoil C (0-15 cm) over the trial period. At Langgewens there is a significant increase in SOC content over the first seven years of the trial, after which it decreases slightly and then a rapid significant increase, decrease, and increase again over the next five years (Figure 12). The C content then plateaus off between 2014 and 2020. The C content shows an average increase of 0.02% per year across the trial period, with a total average increase of 0.4% over the 19-year period. When looking at soil C from 2002 to 2020 of all the crop rotational systems, there are statistical differences between years. There is a significant decrease in C between 2011-2012 and 2013-2014, and an increase between 2008-2009, 2012-2013, and 2018-2019.

According to Deiss et al. (2021) crop rotation plays a role in the accumulation of SOM which is then sequestered as soil C. This could explain the increase in SOC which was observed over the trial period. Chen et al. (2011) concluded that soil C was much higher in the surface layer, along with NT having a higher SOC content after the trial. In the research by Sombrero & De Benito (2010), they found that 11 years after NT was implemented the C sequestered started to plateau off. Franzluebbers, et al., (2012) also found that the rate of C accumulation drops by half after 10 years, a quarter after 20, and almost zero after 50. The term which was used to describe this is sink saturation. It was also described by Six et al., (2002) as 'saturation potential'. This can be seen happening at Langgewens from 2013 as well. It was found that when using a second degree polynomial that the 'saturation point' at Langgewens is 1.33% for SOC, as shown in Figure 13. According to Berthelin, et al., (2022) at least 90% of plant residue which is added to the soils, for the goal of increasing SOC content, is mineralized relatively rapidly and released as CO^2 to the atmosphere. To have the increase in SOC that farmers expect from their fields, 10 times the amount of organic matter needs to be added.

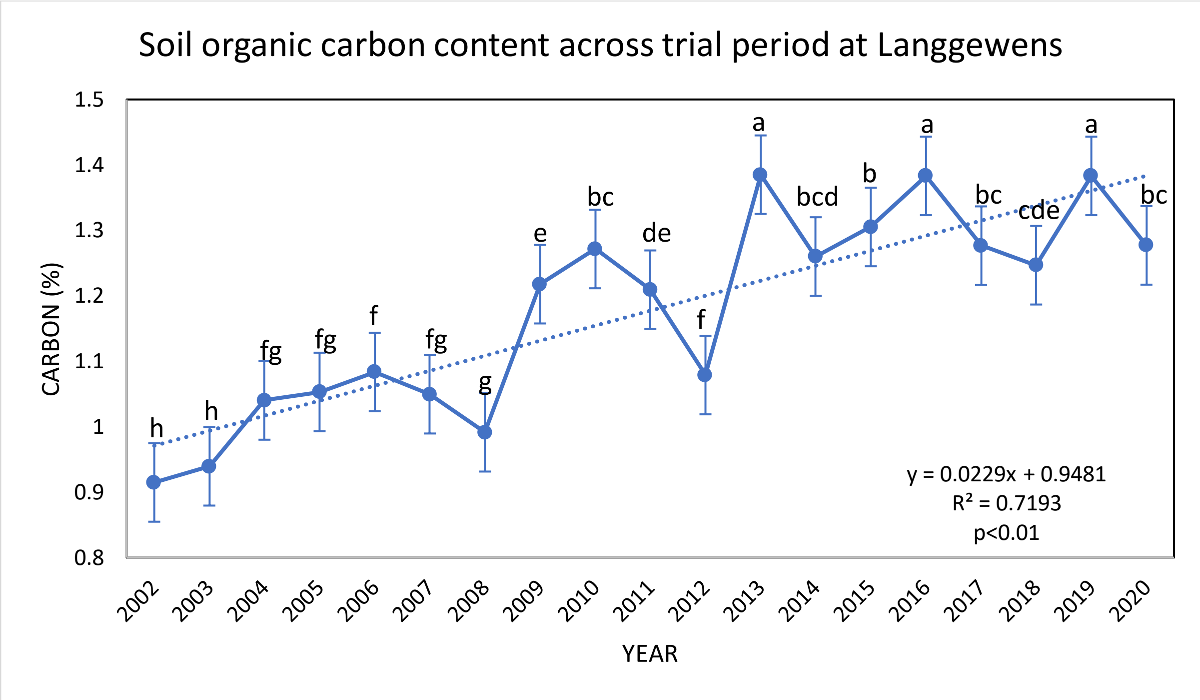

Figure 12: The soil organic carbon content (%) in the topsoil (0-15 cm) for each year at Langgewens from 2002 to 2020

The 'saturation point' can only be reached when there is a saturation deficit where new C inputs can be stored as physicochemically stabilized SOC (Castellano, et al., 2015). According to Castellano, et al., (2015) this 'saturation point' is best observed at lower levels of SOC, with the greatest limitations to SOC stabilization being the management and climate. This is seen at Langgewens (Figure 13) where the increase in SOC accumulation decreases after 2013, although the amount of C returned to the soil through NT remains constant.

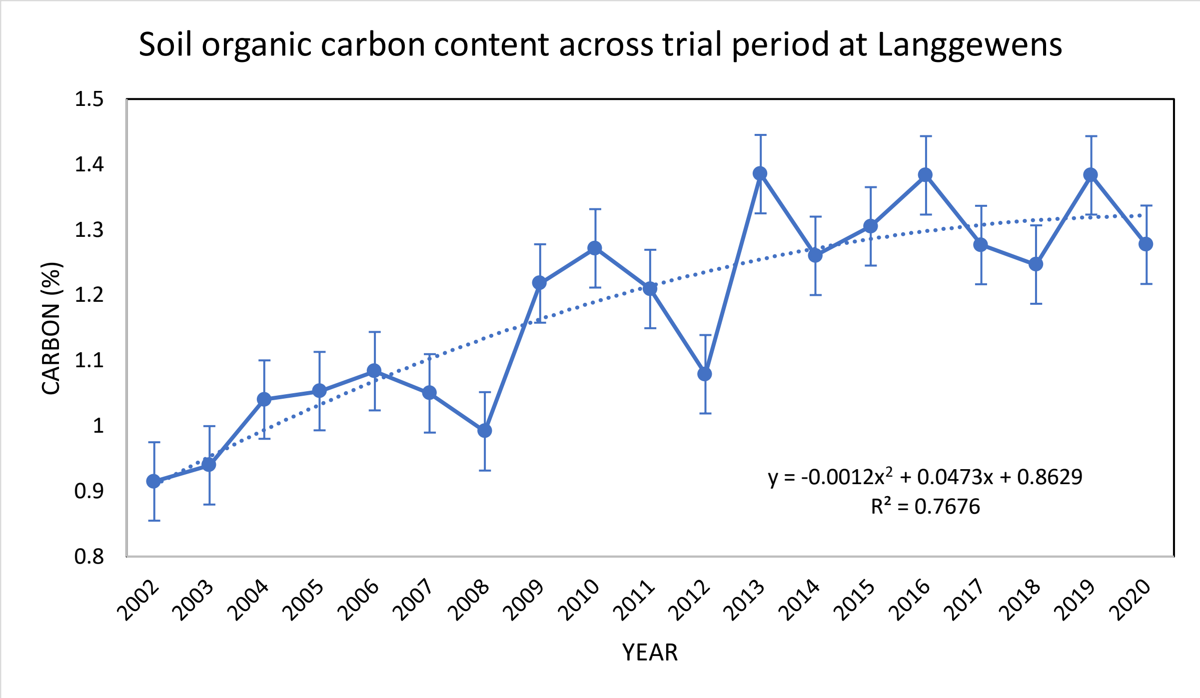

Figure 13: The soil organic carbon content (%) in the topsoil (0-15 cm) for each year at Langgewens from 2002 to 2020 with a second degree polynomial function for the trendline.

When looking at the change in C between the different years (Figure 14), some years differ significantly from each other. Those that are significantly higher are 2008-2009 compared to 2007-2008, 2012-2013 compared to 2011-2012, 2014-2015 compared to 2013-2014, and 2017-2018 compared to 2016-2017. Those that were significantly lower are 2009-2010 compared to 2008-2009, 2013-2014 compared to 2012-2013, 2016-2017 compared to 2015-2016, and 2019-2020 compared to 2018-2019. These results show that some years had much higher increase in SOC, while some of the changes in years were negative, such as 2006-2007, 2007-2008, 2010-2011, 2011-2012, 2013-2014, 2016-2017, 2017-2018, and 2019-2020. The biggest increase in % C was between 2012-2013 with 0.306 and 2008-2009 with 0.226.

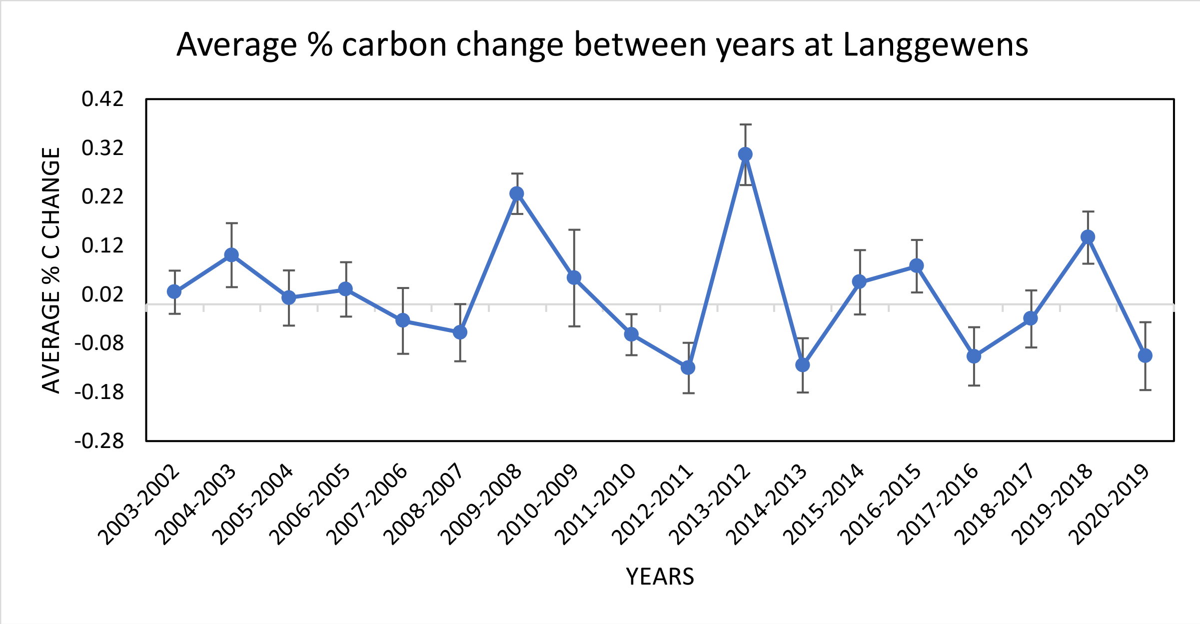

Figure 14: Average increase in soil organic carbon between the different years at Langgewens. The system with WWWW is wheat monoculture, WWWC is wheat and canola rotation, WCWL and WWCL is wheat, canola, and lupin rotation, WMWM is wheat and medic rotation, WMcWMc is wheat and medic/clover rotation, WMWC is wheat, medic, and canola rotation, and WMcWMc+saltbush is wheat and medic/clover rotation with saltbush

At Tygerhoek the change in C content between the years differs significantly, but there is only a slight average increase of 0.0035 % per year, with a total average increase of 0.06% over the 18-year period (Figure 15). Various years were significantly lower than the previous year: 2003-2005, 2008-2009, 2014-2015, and 2017-2018. The significantly higher years were: 2005-2006, 2012-2013, 2016-2017, and 2018-2019. Various factors could cause soil C to increase/decrease. When comparing Langgewens and Tygerhoek it is obvious that Langgewens has a much higher rate of accumulation in soil C. The main reason is the C content at the start of the trial; at Langgewens the starting C content was 0.91% while that of Tygerhoek was 1.72%. It could also be that the soil has reached its ‘saturation point’ at Tygerhoek, which could explain why very little of the years have significant differences, along with the low rate of change. This point is proposed to be reached after 2006. A linear trendline was added between 2006 and 2019 and this proposed ‘saturation point’ was seen to be 1.70%, shown in Figure 16.

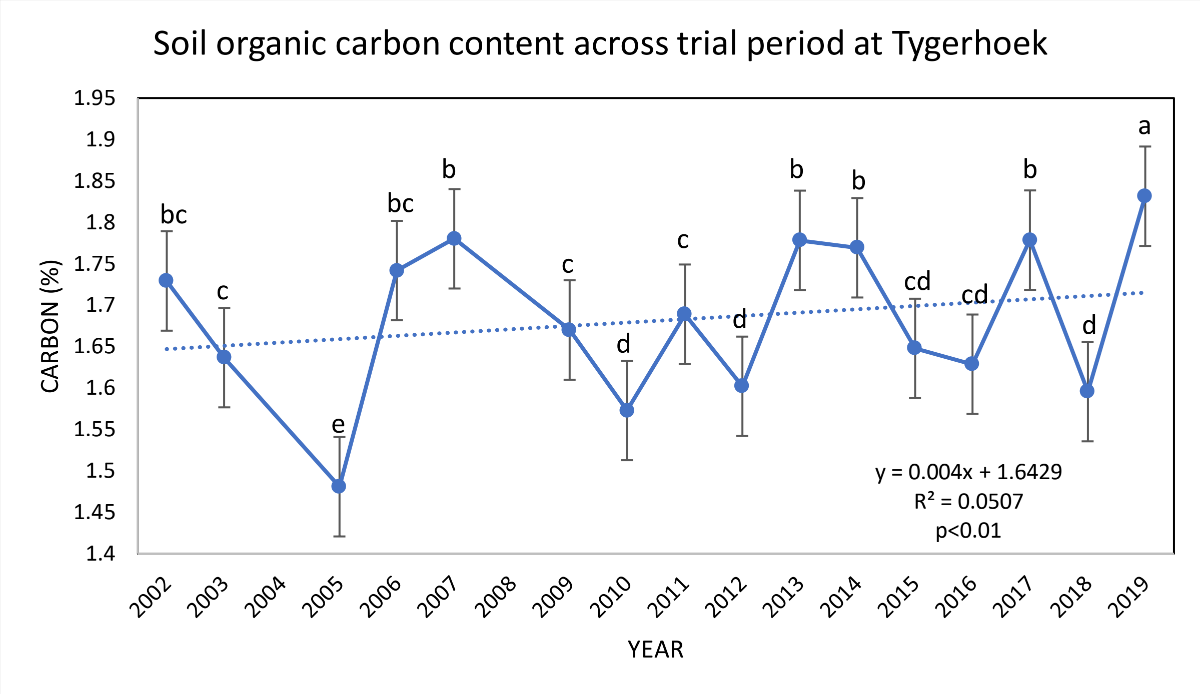

Figure 15: The soil organic carbon content (%) in the topsoil (0-15 cm) for each year at Tygerhoek from 2002 to 2019

The 'saturation point' will differ between locations as researchers found due to silt + clay protection, soil structure (physical protection within aggregates), and the biochemical complexity of the organic compounds (Stewart, et al., 2007), as well as the climate and management practices. The theory is that the further a soil is from saturation the greater its capacity and efficiency to sequester C, whereas a soil approaching its 'saturation point' will accumulate a smaller amount of SOC at a slower rate and efficiency (Hassink, 1997). This is evident when comparing the proposed saturation points of Langgewens and Tygerhoek (Figure 16) to the overall SOC content across the trial periods.

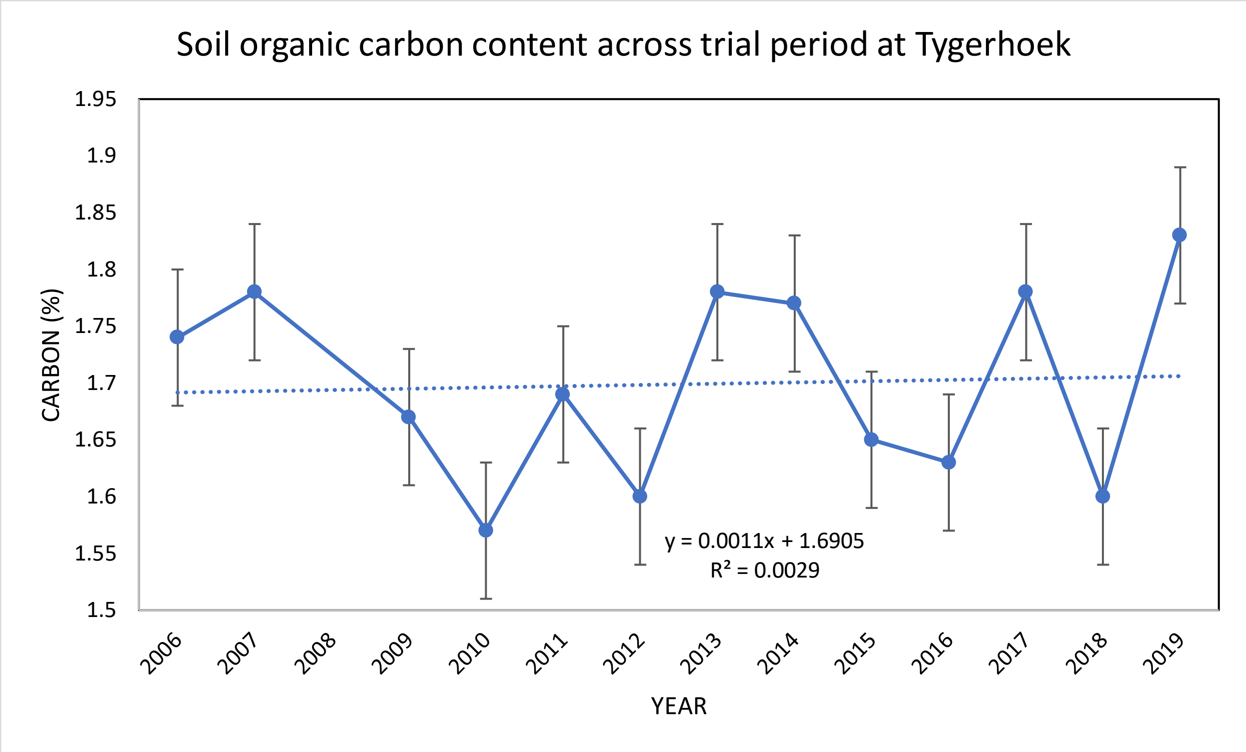

Figure 16: The soil organic carbon content (%) in the topsoil (0-15 cm) for each year at Tygerhoek from 2006 to 2019 with a linear function for the trendline.

When looking at the change in SOC content between consecutive years, there are significant differences between the years (Figure 17). The significantly higher years are 2005-2006 compared to 2004-2005, 2010-2011 compared to 2009-2010, 2012-2013 compared to 2011-2012, 2016-2017 compared to 2015-2016, and 2018-2019 compared to 2017-2018. Those that were significantly lower are 2004-2005 compared to 2003-2004, 2006-2007 compared to 2005-2006, 2008-2009 compared to 2006-2007, 2011-2012 compared to 2010-2011, 2013-2014 compared to 2012-2013, 2014-2015 compared to 2013-2014, and 2017-2018 compared to 2016-2017. These results show that some years had much higher increase in SOC, while some of the changes in years were negative, such as 2002-2003, 2004-2005, 2008-2009, 2009-2010, 2011-2012, 2013-2014, 2014-2015, 2015-2016, and 2017-2018. The biggest increase was between 2005-2006 with 0.265 and 2018-2019 with 0.237.

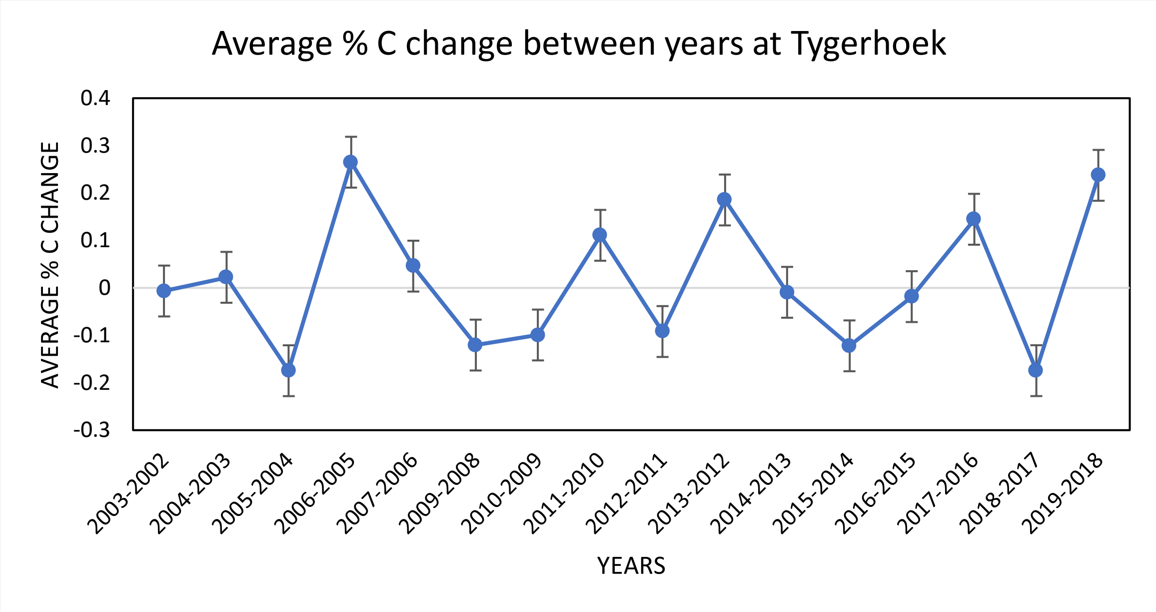

Figure 17: Average increase in soil organic carbon between the different years at Tygerhoek. The system with PPC is 33% crop and 67% pasture rotation, PCPC and PCCP is 50% crop and 50% pasture rotation, and CCC is 100% cash crop rotation. The crops included wheat, barley

3.3.3 Factors affecting soil organic carbon content

The factors that affect the SOC content can include climate, crop productivity, and soil pH. Rainfall and temperature have a significant effect on the SOM content, with higher rainfall and cooler temperature resulting in higher SOM (Deiss, et al., 2021). Warmer soils cause the SOM to decompose more rapidly (Wagai, et al., 2008). This is also true for moist soils where temperature is not limiting. Plant productivity will also influence the amount of SOM in the soil. The greater the plant growth, the more organic matter is made available to the soil. This statement assumes that not all the plant biomass is removed. The pH of the soil plays a role in the amount of C found in the soil. According to Zhou et al. (2019), there is a negative correlation between C and pH, demonstrating that relatively low pH values will positively influence the accumulation of SOM. This was found by Shaofei & Wang (2018) as well where decreasing soil pH will decrease the SIC but increase the SOC. These studies were done in Thailand and China. If pH plays a role, subsequently the addition of lime also plays a role. Lime will increase the pH of the soil. In a long-term trial done by Wang et al. (2016), they found that SOC decreased or remained unchanged after liming. Liming can enhance soil C loss by increasing C solubility, microbial activity, and consequently C breakdown rates (Fuentes, et al., 2006). Other studies have found that liming improved SOC stability through redistribution of C from being labile to more humified, and complexation of SOC with Ca^{2+}, thereby increasing its resistance to breakdown (Manna et al. 2007; Morris et al. 2007). The addition of lime will also influence the root and shoot growth, thus increasing the SOM added to the soil. Grover et al. (2017) observed greater SOC solubility during the first three days after liming, but the occurrence did not last long. It was seen that SOC mineralization was lower in limed than non-limed soils and they attributed this to increased microbial C-use efficiency due to a more suitable pH.

3.3.3.1. Rainfall

Knowing all the factors that could potentially have affected the change in C between years, it can be presented as graphs against C. These factors could be looked at to explain the significant differences between years. When looking at the soil C at Langgewens, there is a significant decrease in C between 2011-2012 and 2013-2014. When comparing the rainfall during these periods (Figure 18), the rainfall decreased between 2010-2011, while 2013 had a slight increase from 2012. This can point to a different factor having an influence. The increase in C between 2008-2009 could be due to the very wet season in 2007 and 2008 having a higher-than-average rainfall thus resulting in higher biomass production. However, the rainfall is not able to explain the increase in soil C from 2012-2013. The rainfall in 2018 was higher than in 2017, while the C also increased between 2018 and 2019. From this, we can conclude that the rainfall of the previous year has a bigger influence than the current rainfall, and it is better to look at the rainfall during the growing season than the yearly rainfall. According to the statistics, neither yearly nor seasonal rainfall has a significant influence on C (p= 0.9639 and 0.9077), and C has a low negative correlation with rainfall. The R^2 values are -0.305 and -0.297 for yearly and seasonal rainfall.

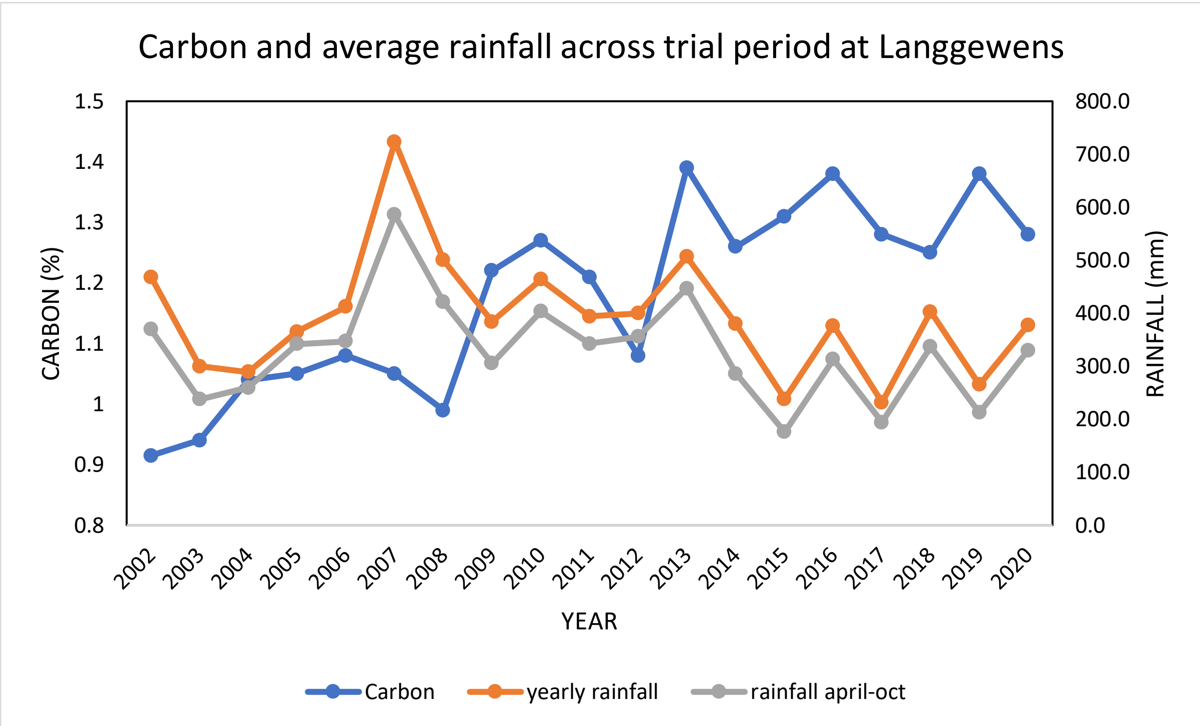

Figure 18: The soil organic carbon content (%) and yearly and seasonal rainfall (mm) at Langgewens from 2002 to 2020

The soil C at Tygerhoek shows a significant increase between 2005-2006, 2012-2013, 2016-2017, and 2018-2019, and a significant decrease during 2003-2005, 2008-2009, 2014-2015, and 2017-2018. When looking at C against rainfall (Figure 19), the rainfall could explain the increase in 2013 as 2012 had the highest rainfall season. The soil C and rainfall are very variable during the trial, and it is thus difficult to attribute all the variation of soil C to rainfall. There is once again no significant influence between rainfall and C (p= 0.121 and 0.133). The correlation coefficient is negligible.

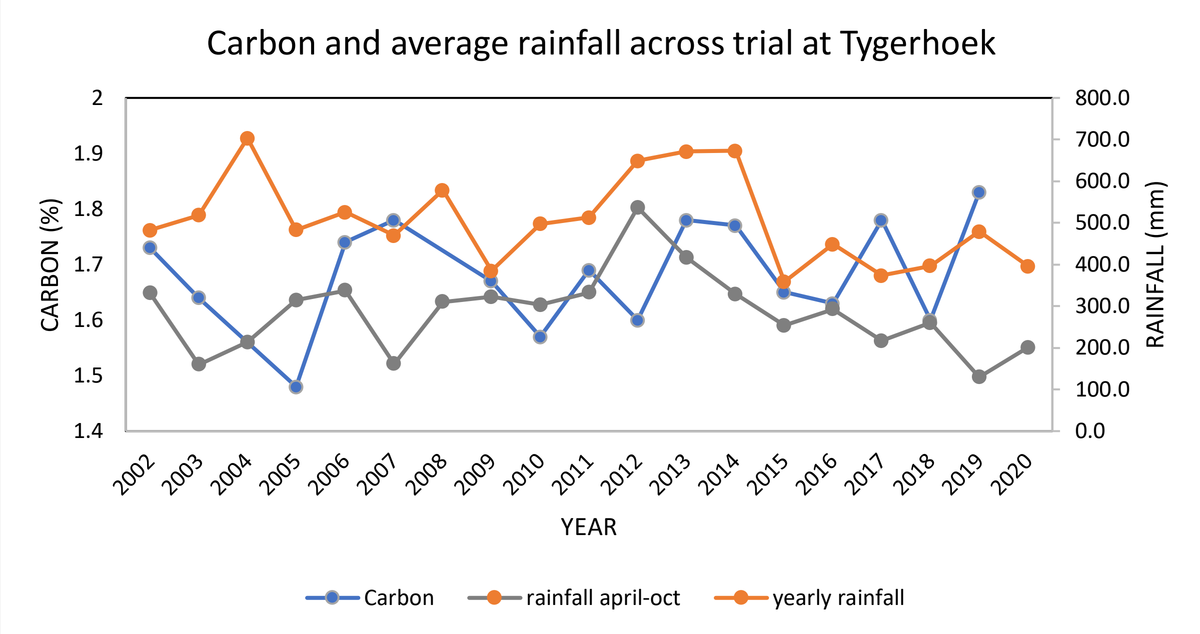

Figure 19: The soil organic carbon content (%) against yearly and seasonal rainfall (mm) at Tygerhoek from 2002 to 2020

The effect that rainfall has on the soil organic C content is not simple. It will depend on the moisture stored in the soil which will, in turn, affect the decomposition rate (Schimel, et al., 2007) and leaching of SOC (Liu, et al., 2018). Yost & Hartemink (2019) found that the SOC concentrations were highest when mean annual precipitation was between 700 and 1300 mm. This is also found in this study where Tygerhoek, which had a higher mean annual rainfall had a higher SOC content compared to Langgewens.

3.3.3.2. Temperature

A higher temperature will result in warmer soils and thus an increase in the rate of decomposition. The average monthly temperature data (Figure 21) shows that 2011 and 2016 had the highest average summer temperatures at Langgewens. The soil C was significantly lower in 2012. The same significant decrease cannot be seen after 2016. This is not the case when there was an increase in soil C in 2009, 2013, and 2019. When looking at the average yearly temperatures (Figure 20) the highest temperature was observed in 2004, which saw no significant change in soil C in the years following 2004. There is no significant effect of temperature on C, with p-values of 0.9686 and 0.9388 for the maximum and minimum temperatures. There is a moderate negative correlation (R^2= -0.523) between the minimum temperature and C.

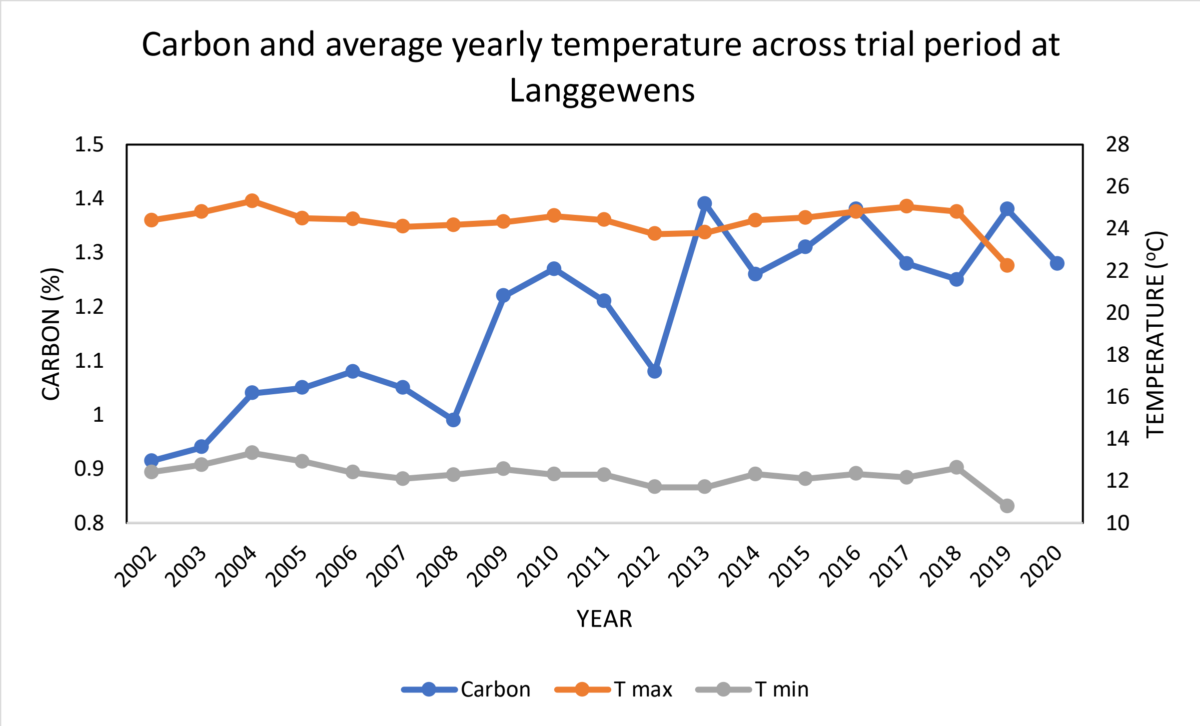

Figure 20: The soil organic carbon content (%) against the average yearly minimum and maximum temperature (°C) at Langgewens from 2002 to 2019

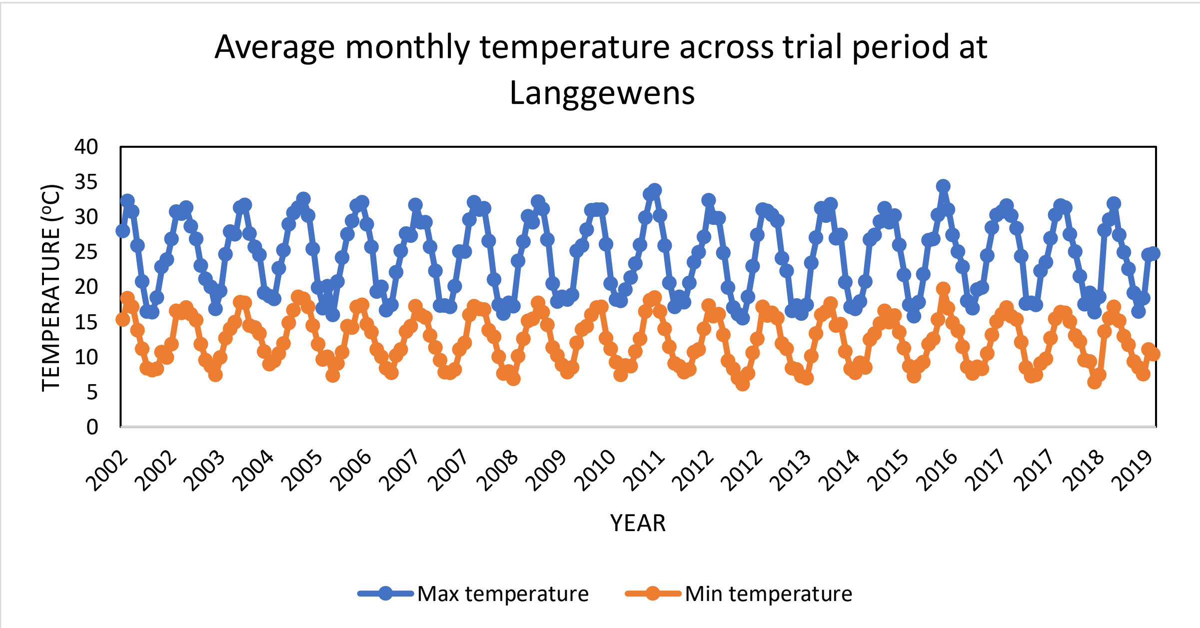

Figure 21: Average monthly minimum and maximum temperature (°C) at Langgewens from 2002 to 2019

According to the average minimum and maximum temperatures at Tygerhoek, it can be roughly seen that when the C increased significantly the year had lower temperatures and the opposite as well (Figure 23). There was a significant C increase in 2006 and the maximum average monthly temperature was 29°C compared to 2007 which had no significant change in C and an average monthly temperature of 31°C. On the average yearly temperatures when it was the lowest average temperature observed in 2006 there was a significant increase in soil C (Figure 22). There is no significant effect of temperature on C, with p-values of 0.1881 and 0.5353 for the maximum and minimum average monthly temperatures. The correlation between temperature and C is negligible.

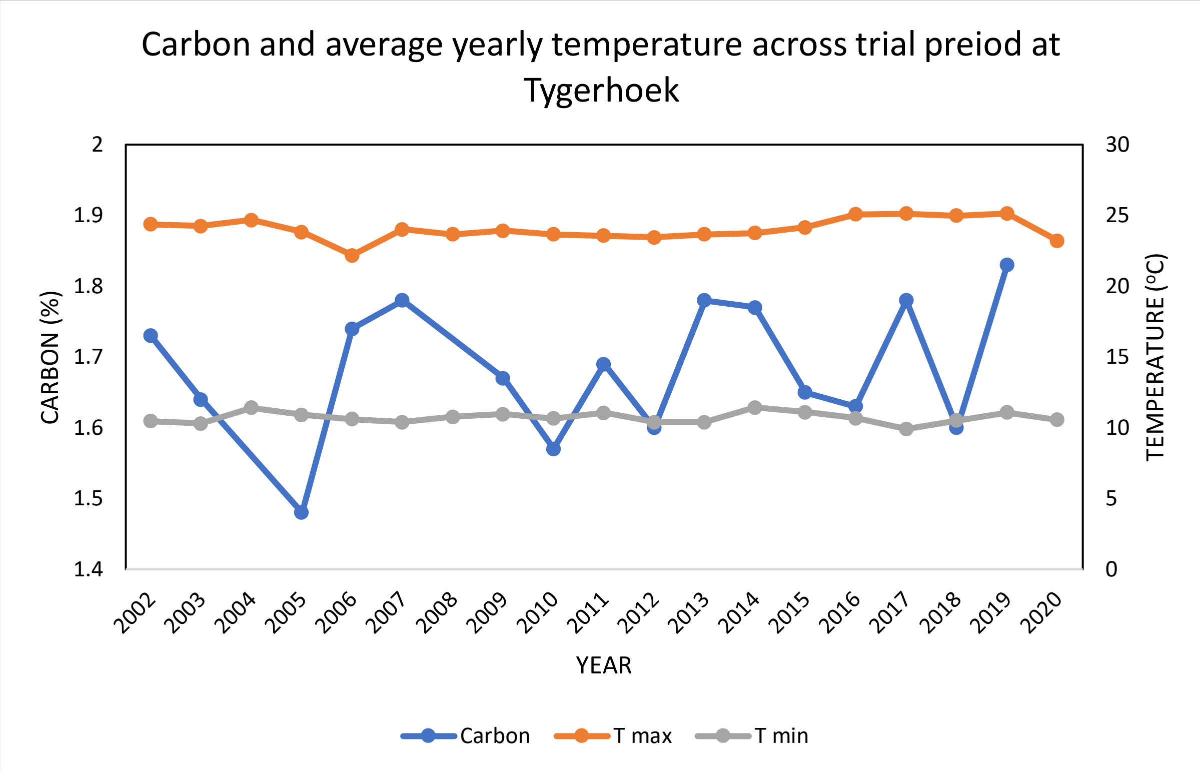

Figure 22: The soil organic carbon content (%) against the average yearly minimum and maximum temperature (ºC) at Tygerhoek from 2002 to 2019

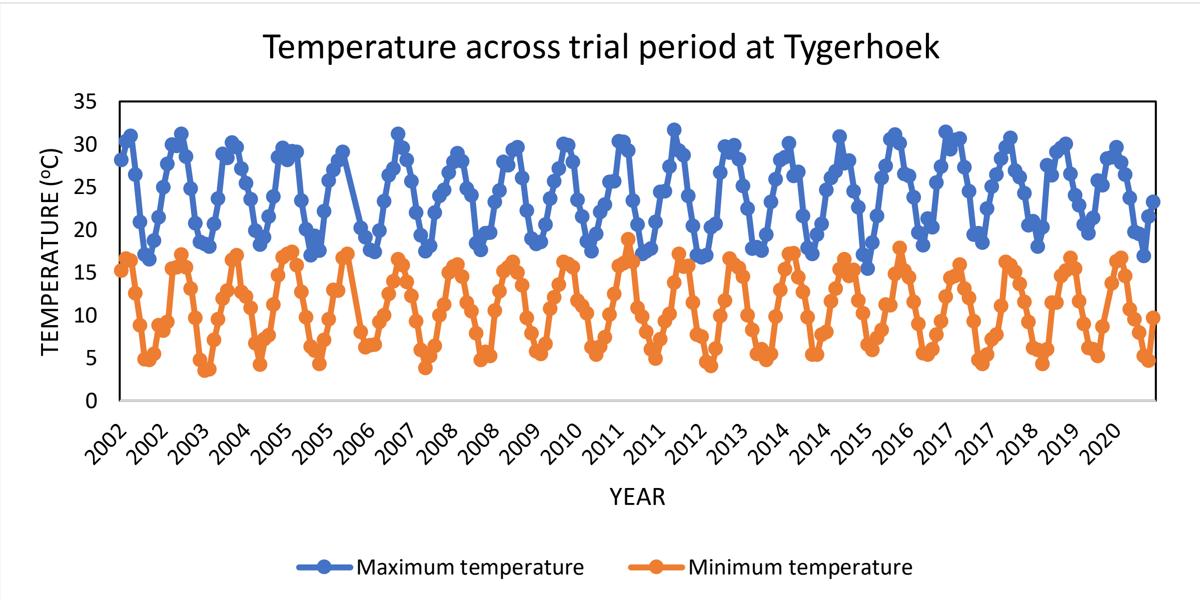

Figure 23: Average minimum and maximum temperature (ºC) at Tygerhoek from 2002 to 2020

3.3.3.3. Crop yields

The yield that is produced during the growing season will have a direct influence on the OM which is returned to the soil. The quantity and quality of OM will then influence the C content of the soil (Zhou, et al., 2019). Because the plant reallocates several metabolites and mineral components during senescence (especially sugars and nitrogen compounds), while mostly leaving structural compounds, the dead tissue left after harvest does not have the same composition as living tissue (Guiboileau, et al., 2010). In this way, green manure is distinct from other plant inputs since it is made from freshly cut living tissue. In sandy soils, there is a higher dependence on seasonal OM inputs and residue management because of the lack of physical and structural protection (Swanepoel, et al., 2018). At Langgewens the yield of wheat, canola, and lupins showed a decrease during the first three years, where after it increased until 2008 (Figure 24). The highest wheat yields were observed during 2006-2008 while the C had a significant increase during 2008-2009. The yields decreased again until 2011 when the C also had a significant decrease during 2011-2012. Wheat yield increased from 2011-2012 and C from 2012-2013. Wheat and lupin yields decreased between 2012-2013 and C 2013-2014. The same cannot be seen for the 2018-2019 increase in C. These results point to a correlation between the previous one or two seasons' yield and the C content of the soil. It also points to wheat and lupins having a greater influence on the soil C content than canola. This correlation between yield and C content was also observed by Culman, et al., (2013) and de Moraes Sa et al., (2014). It was also found that cereal crops produce a higher crop residue (Lal, 2005).

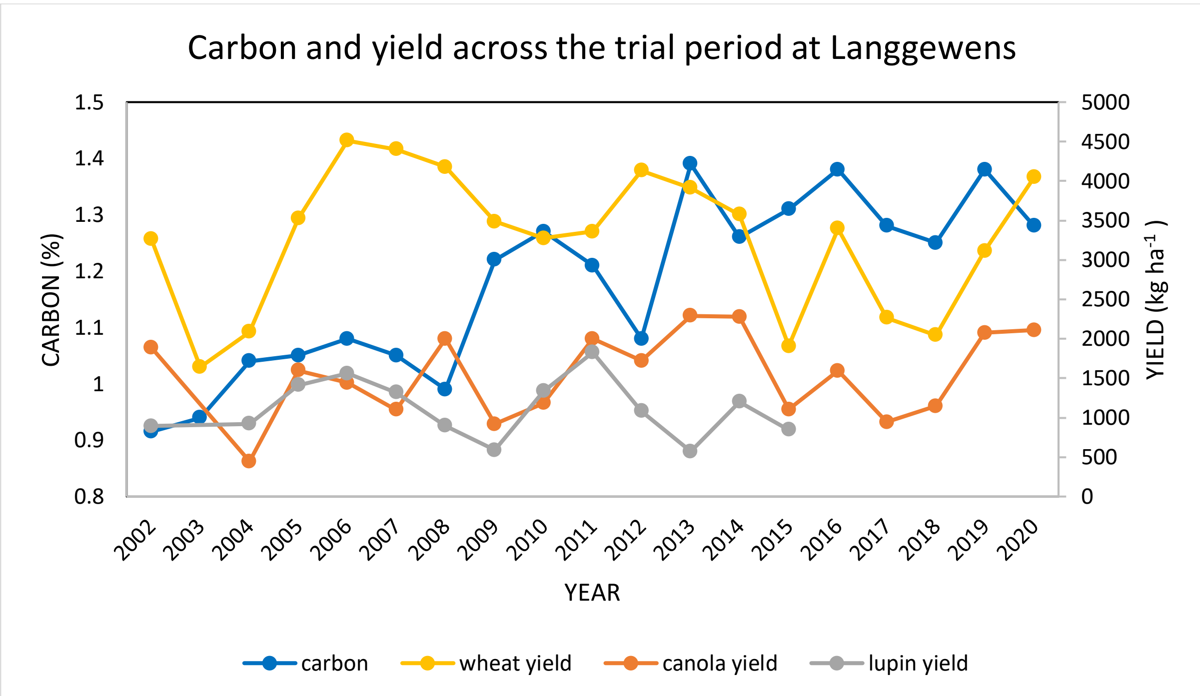

Figure 24: Average topsoil organic carbon (%) and wheat, canola, and lupin yield at Langgewens from 2002 to 2020

At Tygerhoek the wheat, canola, barley, oats, and lupin show a similar trend in their yields for each of the seasons across the trial period (Figure 25). All yields show an increase from 2002-2003 and a decrease from 2003-2004, and then an increase from 2004-2006. The soil C content shows a significant decrease between 2003 and 2005, and then increased between 2005 and 2006. These two trends show a correlation between the previous season's yield and the current C content. The wheat, canola, and barley yield then decrease between 2005-2008, while the C decreases between 2008-2009. The wheat, canola, barley, and oats yield increased between 2008-2012, and C between 2012-2013. The rest of the seasons are more variable and thus no correlation can be seen. These results show once again the importance of OM input for the C content. It is also important to look at the previous season's yield rather than the current season's as there is it takes time for the residues to decompose. For wheat, canola, and barley there is a better correlation between the previous seasons' yield and for oats and lupin the previous one to two seasons' when looking at the effect on the SOC content.

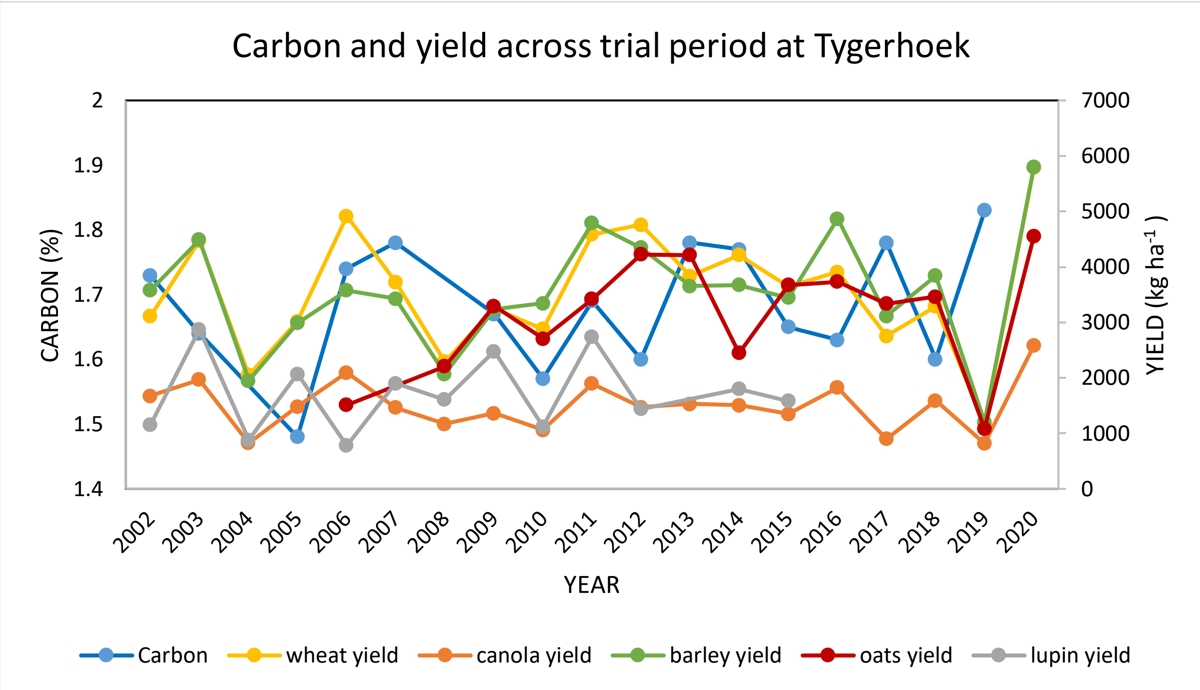

Figure 25: Average topsoil organic carbon (%) and wheat, canola, barley, oats, and lupin yield at Tygerhoek from 2002 to 2020

3.3.3.4. Soil pH

The pH of the soil will determine the activity of the microorganisms and thus the rate at which OM is broken down. It will also affect the growth of the crop through nutrient availability, thus affecting OM input. At Langgewens the pH and soil C content over the trial period follow a similar trend. There is a sudden increase at the start of the trial after which it starts to stabilize at about 5.8-5.9. The pH increased by an average of 0.0227 per year throughout the trial. The significant changes in soil C (Figure 26) it is clear that when C increases (2009, 2013, 2019) there was an increase in soil pH between 2007-2009, 2013-2014, and 2018-2020, and a decrease in 2009-2010 and 2012-2013. When soil C decreased (2012, 2014) there was a decrease between 2011-2013 and 2014-2015 and a decrease between 2013-2014. From this finding, we can conclude that some years had an increase in pH followed by an increase in C while others had an increase in C followed by an increase in pH, with a decrease in C showing the same trend. The statistics show no significant interaction between C and pH with p= 0.2268. There is a moderate positive correlation with R^2= 0.656 between pH and C for the current season, but also for the previous and next season's pH (R^2= 0.649 and 0.606).

The stabilization of pH towards the end of the trial is in line with what Zhou et al. (2019) said; a higher OM content, thus soil C, will have a buffering effect on the soil pH and be more resistant to change. OM is usually considered to lower the pH of the soil by releasing hydrogen ions that were associated with organic ions. Possible mechanisms to explain the increase of pH with soil C are the mineralization of organic anions to CO_2 and water (removing the H^+) (Ritchie & Dolling, 1985) or the 'alkaline' nature of the plant material. Heylar (1976) described the 'alkaline' nature of plants as the dissociation of organic acids (metabolized within the plant) in reaction to a cation/anion imbalance generated by NH^{4+} absorption or N_2 fixation. By excreting H^+ ions, the plant corrects the imbalance, and the anion concentration within the plant rises (Israel & Jackson, 1978).

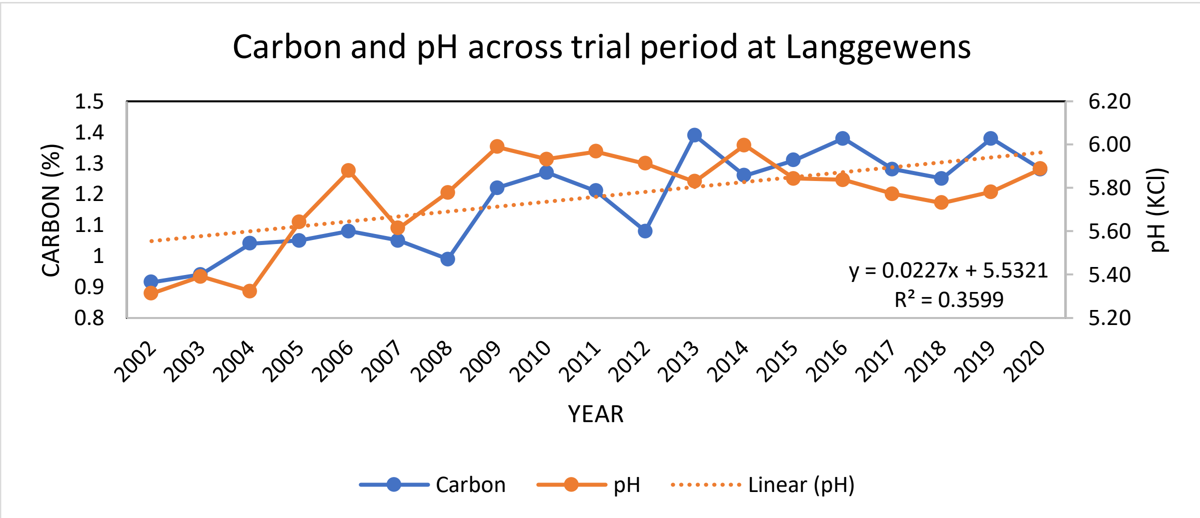

Figure 26: The topsoil organic carbon content (%) versus topsoil pH (KCl) at Langgewens from 2002 to 2020.

At Tygerhoek a trend between the soil C and pH can also be observed (Figure 27). Both decreased for the first 4 years and then increased. The pH showed an average increase of 0.0422 per year across the trial period. The significant increase in C (2006, 2013, 2017, 2019) showed an increase during 2006-2007, 2012-2014, 2016-2017, and 2018-2019, and a decrease during 2005-2006 and 2017-2018 in pH. When C significantly decreased (2005, 2009, 2015, 2018) there was an increase during 2014-2016 and 2018-2019, and a decrease during 2002-2006, 2008-2010, and 2017-2018 in pH. There is also no significant interaction between C and pH with p= 0.729. The correlation is negligible (R^2=0.275).

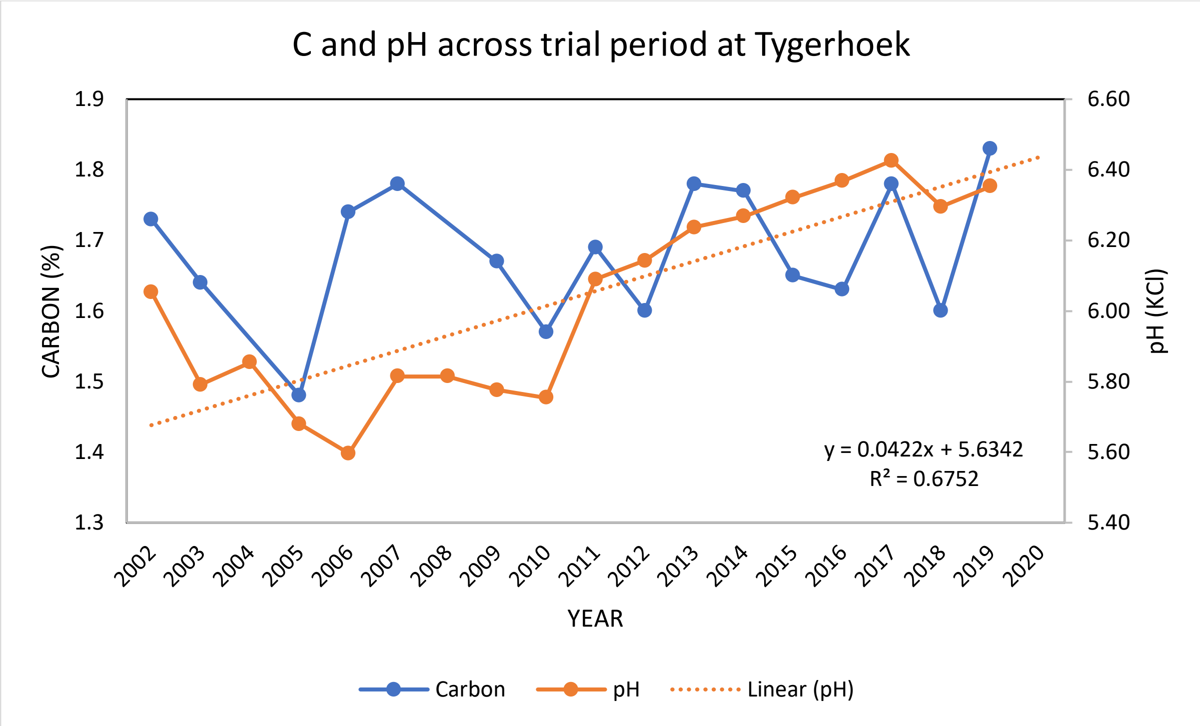

Figure 27: The topsoil organic carbon content (%) versus topsoil pH (KCl) at Tygerhoek from 2002 to 2019

3.3.3.5. Lime and gypsum

According to literature, addition of lime can either have a positive or negative impact on soil C. In the Langgewens trial the results are variable (Figure 28). In the first three seasons an average of 1.5 tones of calcitic and dolomitic lime was added, followed by 1 and 0.5 tones. During this time the soil C increased yearly, as well as the soil pH. The following two seasons saw 2.0 and 2.5 tons of gypsum added which saw a decrease in both the SOC and pH. The pH started to stabilize after this with additions of both lime and gypsum (Figure 29). During the seasons where there was a significant change in the C content, no direct effect can be found with the addition of lime or gypsum. This is backed up by the p-values of 0.7428, 0.5961, and 0.9485 for calcitic and dolomitic lime, and gypsum. There was a moderate negative correlation for calcitic lime (R^2= -0.534) with the current seasons C and gypsum (R^2= -0.588) for the next seasons C. There is also no significant correlation between pH and the addition of lime and gypsum, with p-values of 0.167, 0.329, and 0.731. There was a moderate negative correlation (R^2= -0.603 and -0.582) between lime addition and pH of the following season.

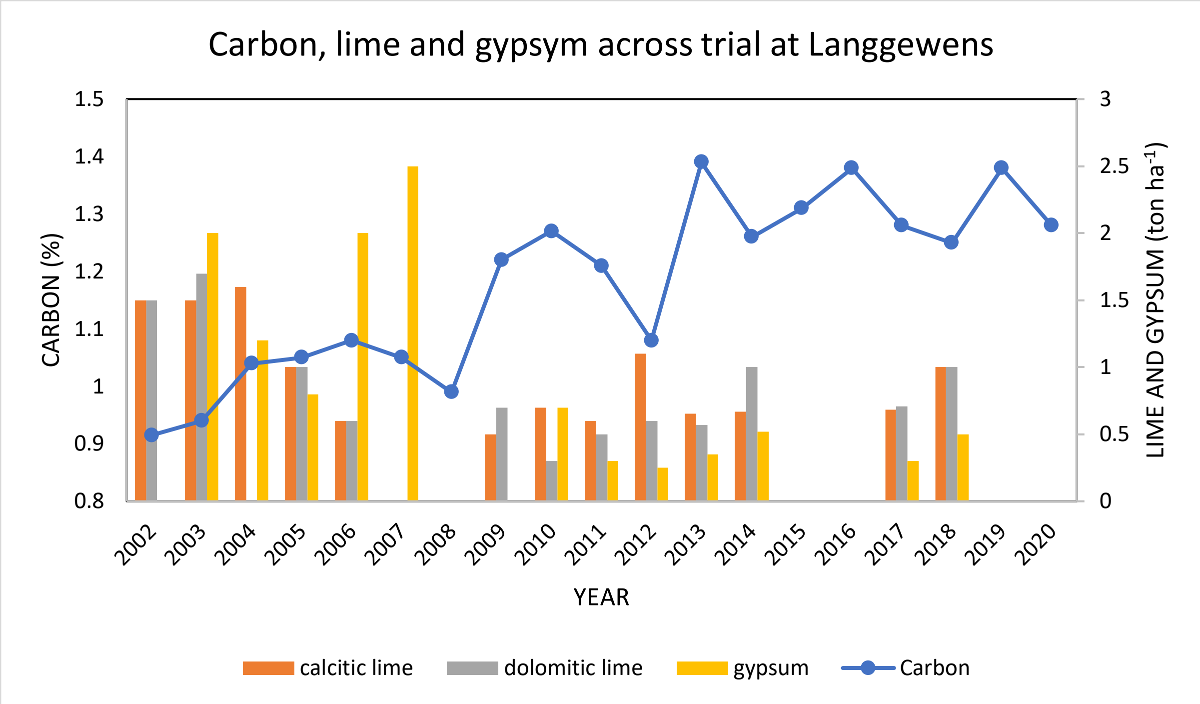

Figure 28: The topsoil organic carbon content (%) against calcitic and dolomitic lime and gypsum (tonnes ha^{-1}) at Langgewens from 2002 to 2020

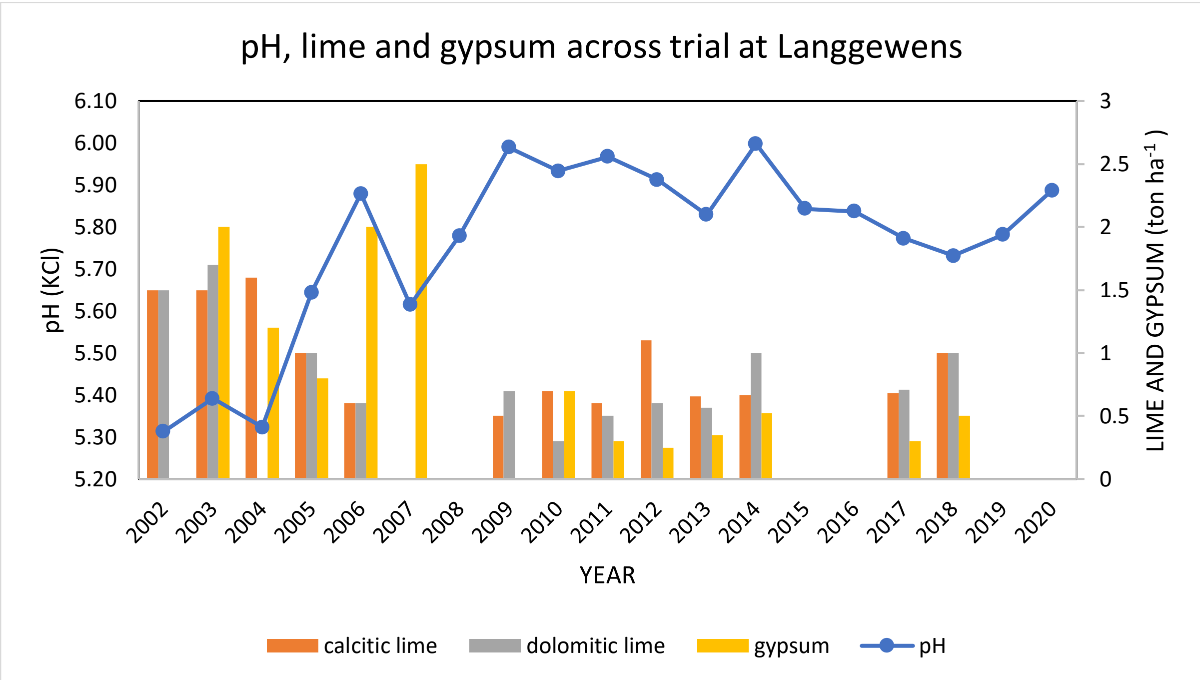

Figure 29: The topsoil pH against calcitic and dolomitic lime and gypsum (tonnes ha^{-1}) at Tygerhoek from 2002 to 2020

Tygerhoek had a higher average soil pH value (Figure 30), thus the addition of lime and gypsum was much less during the trial period. Calcitic lime was added in 2007, 2009, and 2011 (1.5, 1.5, 2 tones) and 2-ton gypsum in 2010. After the first lime was added the pH started to increase, while every year after the lime was added the C decreased and increased after gypsum was added (Figure 31). Neither the addition of lime nor gypsum had a significant effect on soil C with a p-value of 0.990 and 0.416. There was a very high positive correlation between calcitic lime and C with R^2 value of 0.994.

There was also no significant correlation between pH and the addition of lime and gypsum, with p-values of 0.301, and 0.830. The direct correlation between lime addition and soil pH is negligible. These findings are for the current season and do not show the correlation between lime addition and future soil pH values.

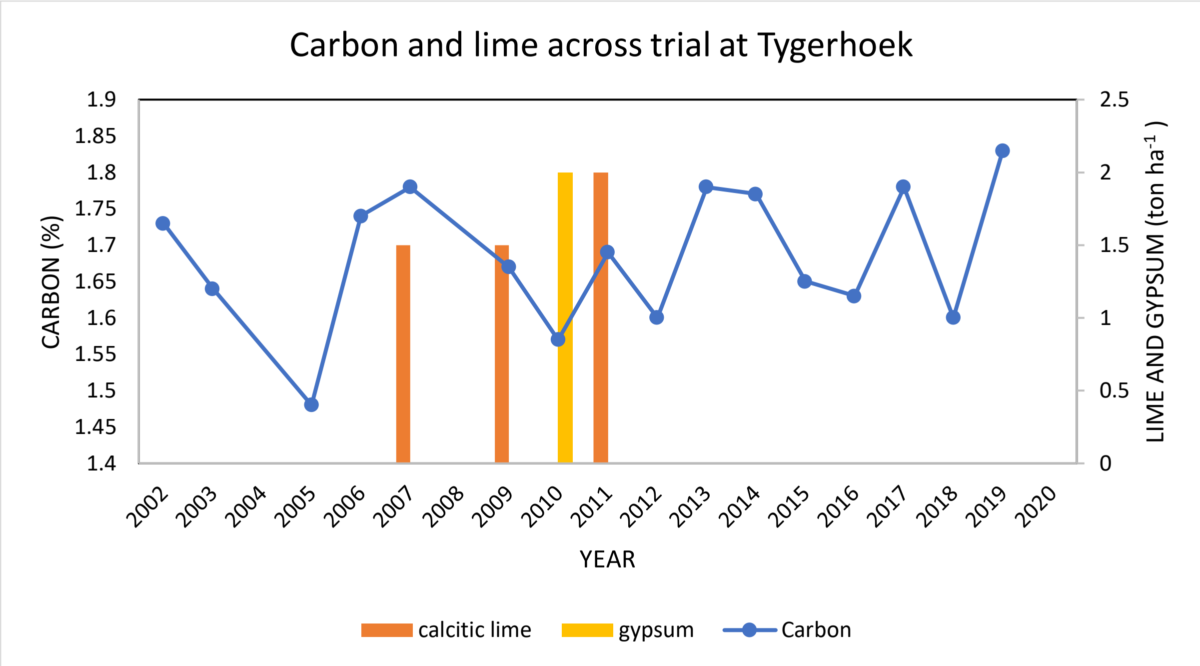

Figure 30: The topsoil organic carbon content (%) against calcitic and dolomitic lime and gypsum (tonnes ha^{-1}) at Tygerhoek from 2002 to 2020

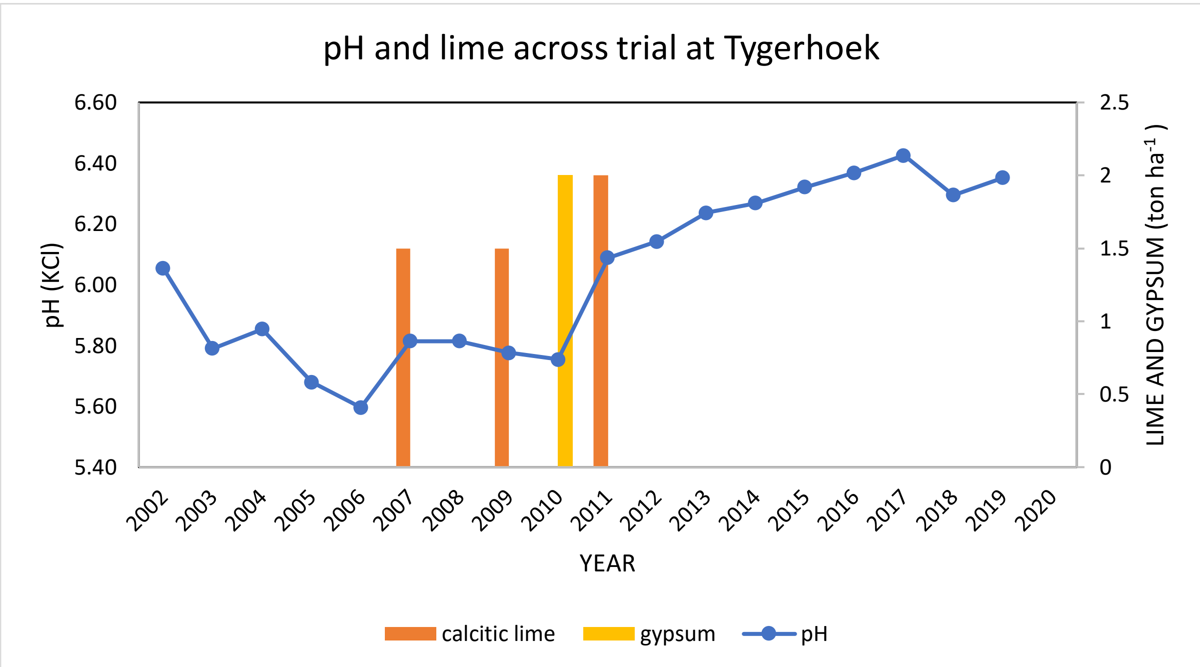

Figure 31: The topsoil pH against calcitic and dolomitic lime and gypsum (tonnes ha^{-1}) at Tygerhoek from 2002 to 2020

3.3.3.6. Nitrogen application

At Langgewens the application of N varied between 30 and 120 kg ha^{-1}. There is a slight trend of an increase in SOC one to two years after a higher amount of N was applied (Figure 32). When the nitrogen application is compared to the significant changes in SOC there was a decrease in 2011-2012 in SOC while the N applied was 46 and 63 kg ha^{-1} in 2009 and 2010 respectively, which is lower than the average of 75 kg ha^{-1}. The increase in SOC was seen during 2008-2009, with the highest N application of 118 kg ha^{-1} in 2007, and 2012 had the second highest N application, with a significant increase in SOC during 2012-2013. This. Shows that there is a positive correlation between SOC and the amount of N applied to the soil.

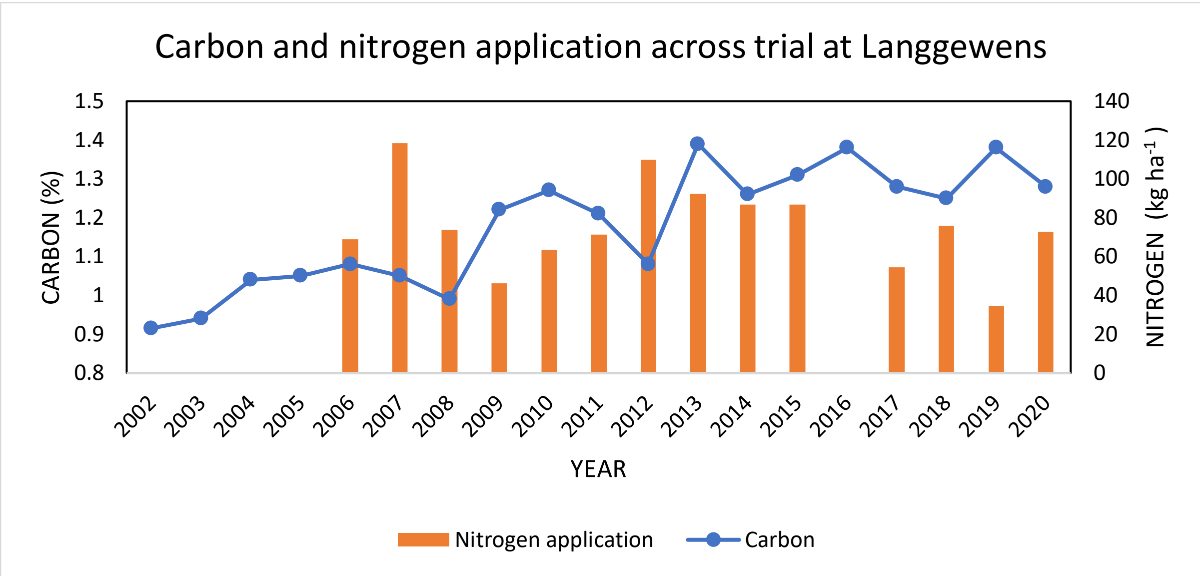

Figure 32: The topsoil organic carbon content (%) against nitrogen applied (kg ha^{-1}) at Langgewens from 2002 to 2020

At Tygerhoek the average N application was 49 kg ha^{-1} (Figure 33). When the SOC was significantly lower in 2017-2018 it could be explained by 2015 having no N applied. The years which show a significant increase in SOC were 2012-2013 and 2018-2019, which can be explained by the 61 and 58 kg ha^{-1} N applied to the soil, while the highest N application of 62 kg ha^{-1} showed an increase in SOC during 2010-2011. These results correlate to what was found in Langgewens where the effect of the N application on SOC content is seen one to two years after the application.

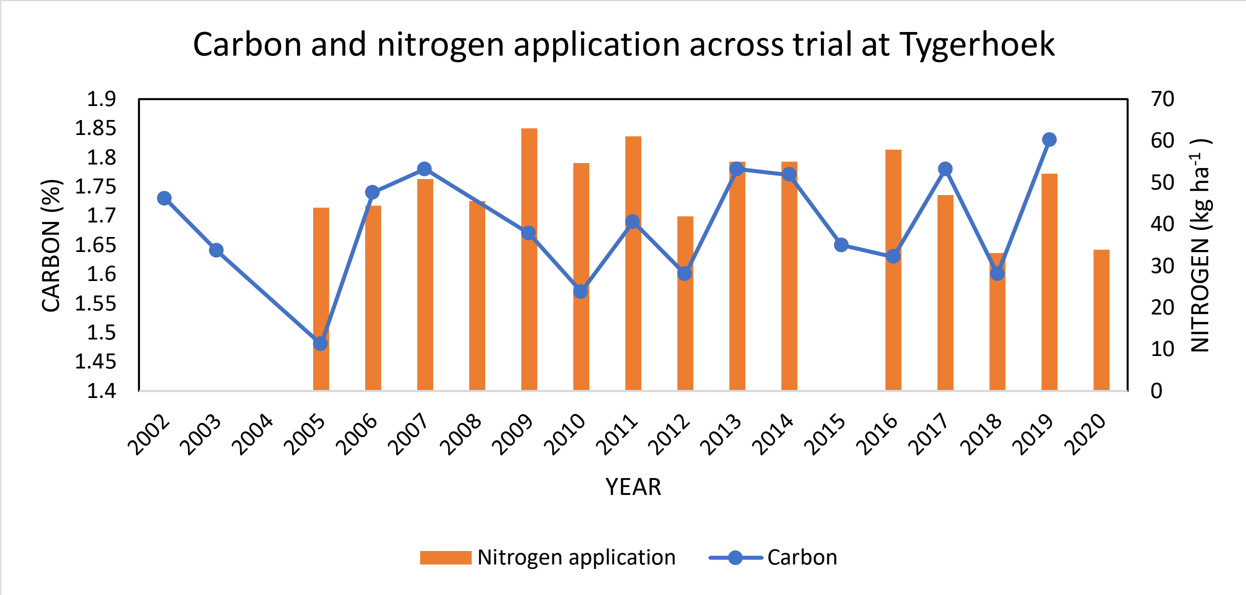

Figure 33: The topsoil organic carbon content (%) against nitrogen applied (kg ha^{-1}) at Tygerhoek from 2002 to 2020

This positive correlation is expected as N will increase the plant growth, thus the amount of SOM returned to the soil, while it will also influence the soil microbial populations and their respiratory and enzymatic activities (de Forest, et al., 2004). The type of N fertilizer will also affect the pH of the soil. In a study by Begum, et al., (2021) they found that N fertilization at rates of 120 and 140% of the recommended rates of wheat, there was a significant increase in TOC compared to the control. This is in line with our findings. According to Kirkby, et al., (2016) when there is an adequate supply of N, P, and S, in the form of fertilizers, this will increase the proportion of crop residue-C which is sequestered as SOC. This is in contrast to only applying enough nutrients for crop uptake.

3.3.4 Effect of crop rotational system on soil organic C content

3.3.4.1. Difference between soil C content of rotational systems

On examining the soil C content of all the rotational systems at Langgewens there is no significant difference between the systems. This can be seen in Figure 34. The system which included medics or clover with the wheat, and wheat, canola, and lupins had the highest average soil C, with wheat monoculture having the lowest. The average % C of the systems are 1.07, 1.16, 1.21, 1.24, 1.15, 1.09, 1.15, and 1.23 for WWWW, WWWC, WCWL, WWCL, WMWM, WMcWMc, WMWC, and WMcWMc+saltbush respectively.

One of the main reasons to expect there to be a significant difference when comparing the rotational systems is the root architecture and subsequently, the root biomass left in the soil by different crops. It has been discovered that a significant portion of the C in soils comes from belowground sources (plant roots and the rhizosphere), as it is maintained in soils considerably more effectively (Rasse, et al., 2005). Smith, et al., (2020) found that lucerne and medic/clover had the highest root density at 5-10 cm depth, and barley the lowest. Medic/clover also have complete dieback and reestablishment in winter which results in new roots forming. Cooper et al. (2017) looked at the C distribution with depth under no-till on Langgewens and found WMWM was significantly different only at 0-5 cm, with no significance at 5-10, 10-20, or 20-40 cm. Wheat above and belowground residue has a wider C:N ratio, which means that the decomposition is slower and the residue remains in the soil for longer compared to the medic/clover residues, but the medic/clover SOM could be lost rather quickly (Brady & Weil, 2014). The higher N in the lucerne and medic/clover is due to legume residue having higher N compared to other crops. These C averages are for the whole 18-year trial which means that soil C could have reached its maximum for the soil and climate. This maximum point is known as the saturation point (Six, et al., 2002; Franzluebbers, 2012). Sombrero & De Benito (2010) found in their study that the soil C started to plateau after 11 years. If these factors are considered, along with the fact that the C of the top 15 cm is considered, the results may be better explained.

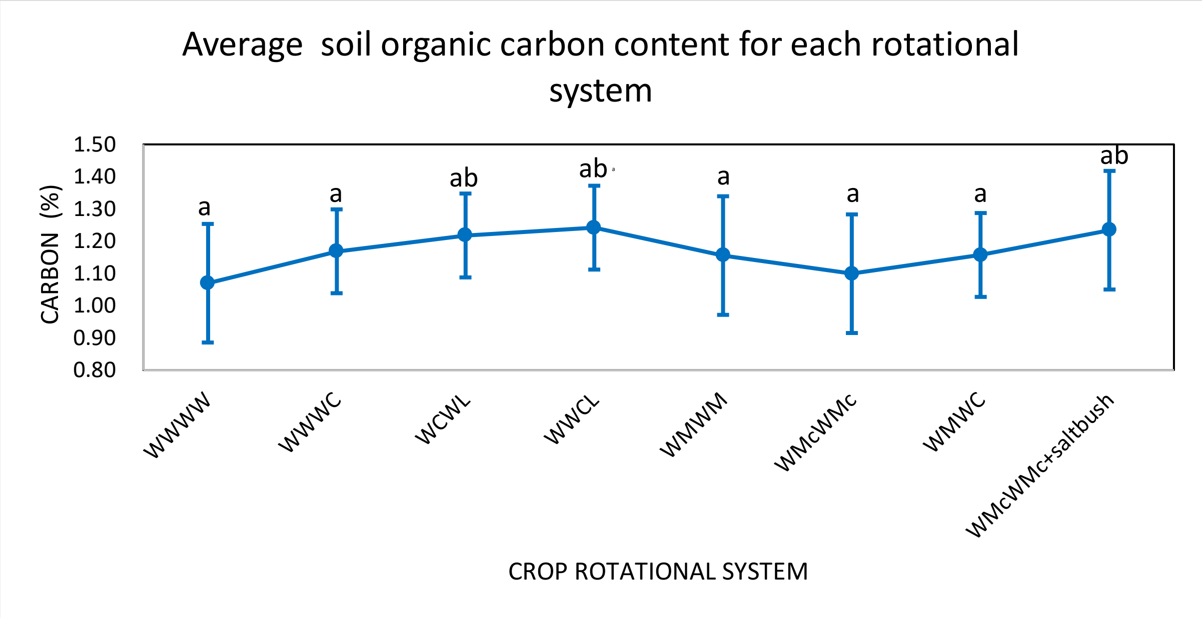

Figure 34: The average soil organic carbon content (%) in the top 15 cm for each crop rotational system at Langgewens from 2002 to 2020. The system with WWWW is wheat monoculture, WWWC is wheat and canola rotation, WCWL and WWCL is wheat, canola, and lupin rotation, WMWM is wheat and medic rotation, WMcWMc is wheat and medic/clover rotation, WMWC is wheat, medic, and canola rotation, and WMcWMc+saltbush is wheat and medic/clover rotation with saltbush

At Tygerhoek there was a significant difference between the C content of the different rotational systems (Figure 35). The rotational system with PPC had significantly higher C (1.83%) than PCCP (1.69%), CCC (1.65%), and PCPC (1.61%). This can be seen in Figure 35. This finding is supported by Chan (2001) who observed a higher C content when pastures are implemented into the rotational system.

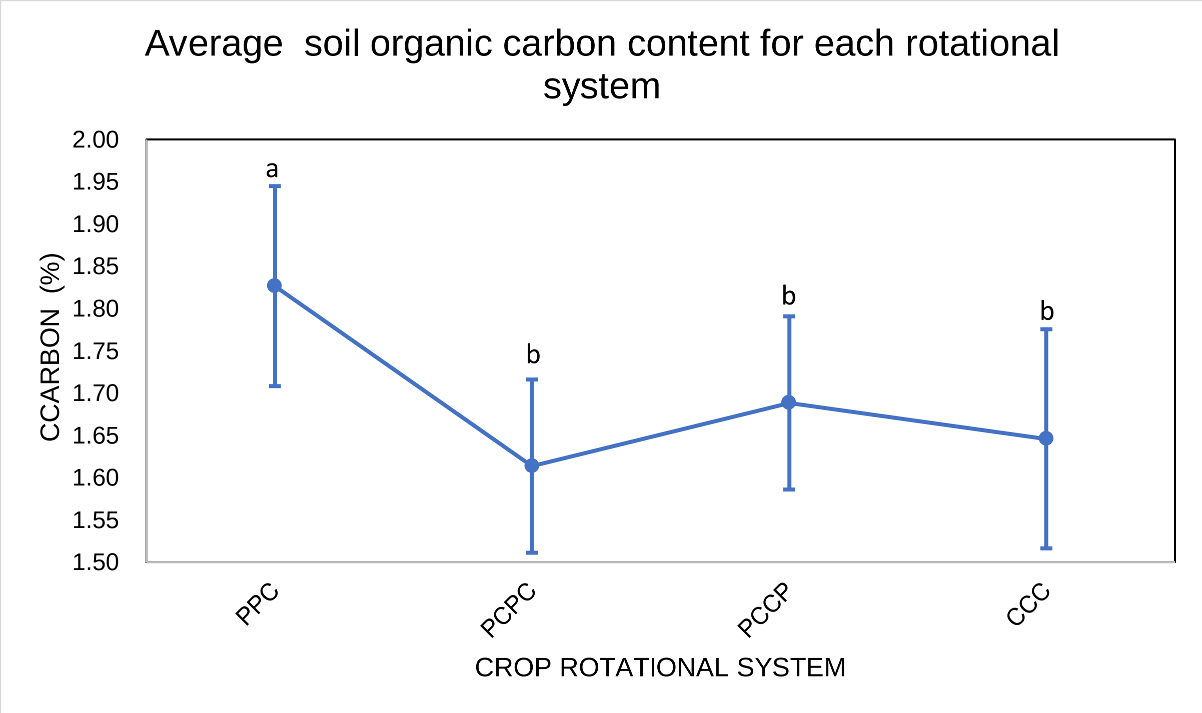

Figure 35: The average soil organic carbon content (%) in the top 15 cm of the soil for each crop rotational system at Tygerhoek from 2002 to 2019. The system with PPC is 33% crop and 67% pasture rotation, PCPC and PCCP is 50% crop and 50% pasture rotation, and CCC is 100% cash crop rotation. The crops included wheat, barley, canola, and oats.

3.3.4.2. Difference in soil organic C change between rotational systems

Looking at the average for the entire 18-year trial for C between the rotational systems can result in misleading results. One of the systems might have increased by 0.8% while another only by 0.1%, but the latter could result in a higher average for the period. For this reason, it is important to look at the rate of change and total average change for each of the rotational systems.

3.3.4.2.1. Rate of SOC change (%C per year)

At Langgewens, the SOC content over time in each rotation showed significant differences and was fitted with a linear trendline (Figure 36), from which the rate of change in soil organic C per year could be estimated from the gradient. The rate of C accumulation (%C per year) was highest in WWWC (0.0280) was the highest, closely followed by WMWM (0.0269), WMcWMc (0.0258), WMCM (0.0257), WWWW (0.0247), and WMcWMc+saltbush (0.0229). The rest of the rotational systems had much lower rates of accumulation per year with 0.0182 for WWCL and 0.0154 for WCWL. The R^2 values show that all systems but WCWL show a moderate positive correlation for the trendline. This shows that the trendline is a good explanation for the accumulation of soil C through the trial, and thus the rate of change is a good way to explain the difference between the systems.

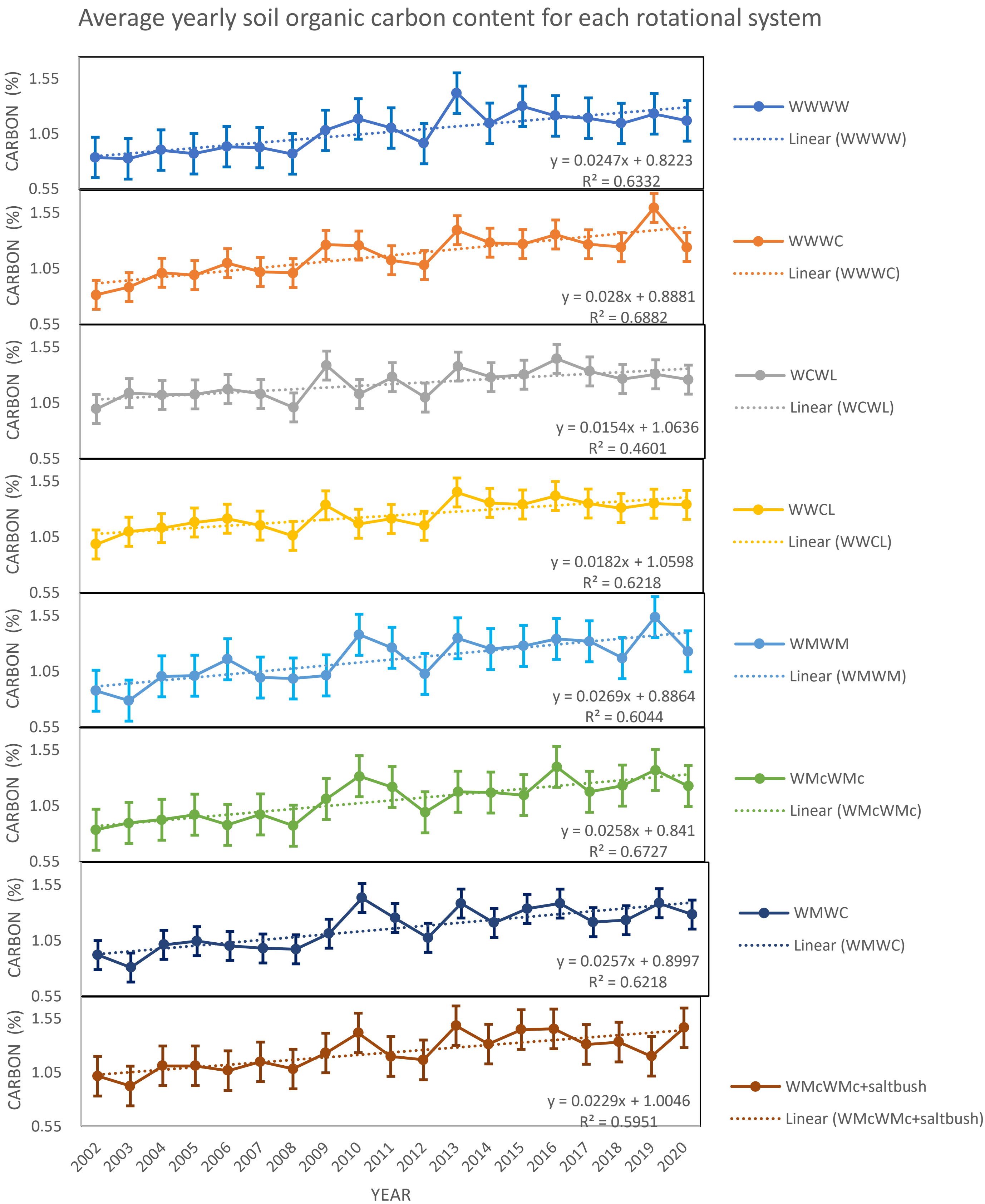

Figure 36: The average soil organic carbon content (%) in the top 15 cm of the soil for each crop rotational system per year at Langgewens from 2002 to 2020. The system with WWWW is wheat monoculture, WWWC is wheat and canola rotation, WCWL and WWCL is wheat, canola, and lupin rotation, WMWM is wheat and medic rotation, WMcWMc is wheat and medic/clover rotation, WMWC is wheat, medic, and canola rotation, and WMcWMc+saltbush is wheat and medic/clover rotation with saltbush

At Tygerhoek each of the systems showed significant differences and was given a trendline (Figure 37) which gave the rate of change in soil organic C per year. The system with PCPC (0.0087) was the highest, followed by CCC (0.0045) and PCCP (0.002). The system with PPC had a negative rate of change with -0.00003 per year. This could be due to the PPC system having the highest C content in all years and a significantly higher C content at the beginning. The R^2 values obtained for the trendlines are 0.000001, 0.1819, 0.0179, and 0.0515 for PPC, PCPC, PCCP, and CCC respectively. This shows that the linear trendlines do not explain enough of the variation in the data to be considered a good correlation with the change in soil organic C throughout the trial.

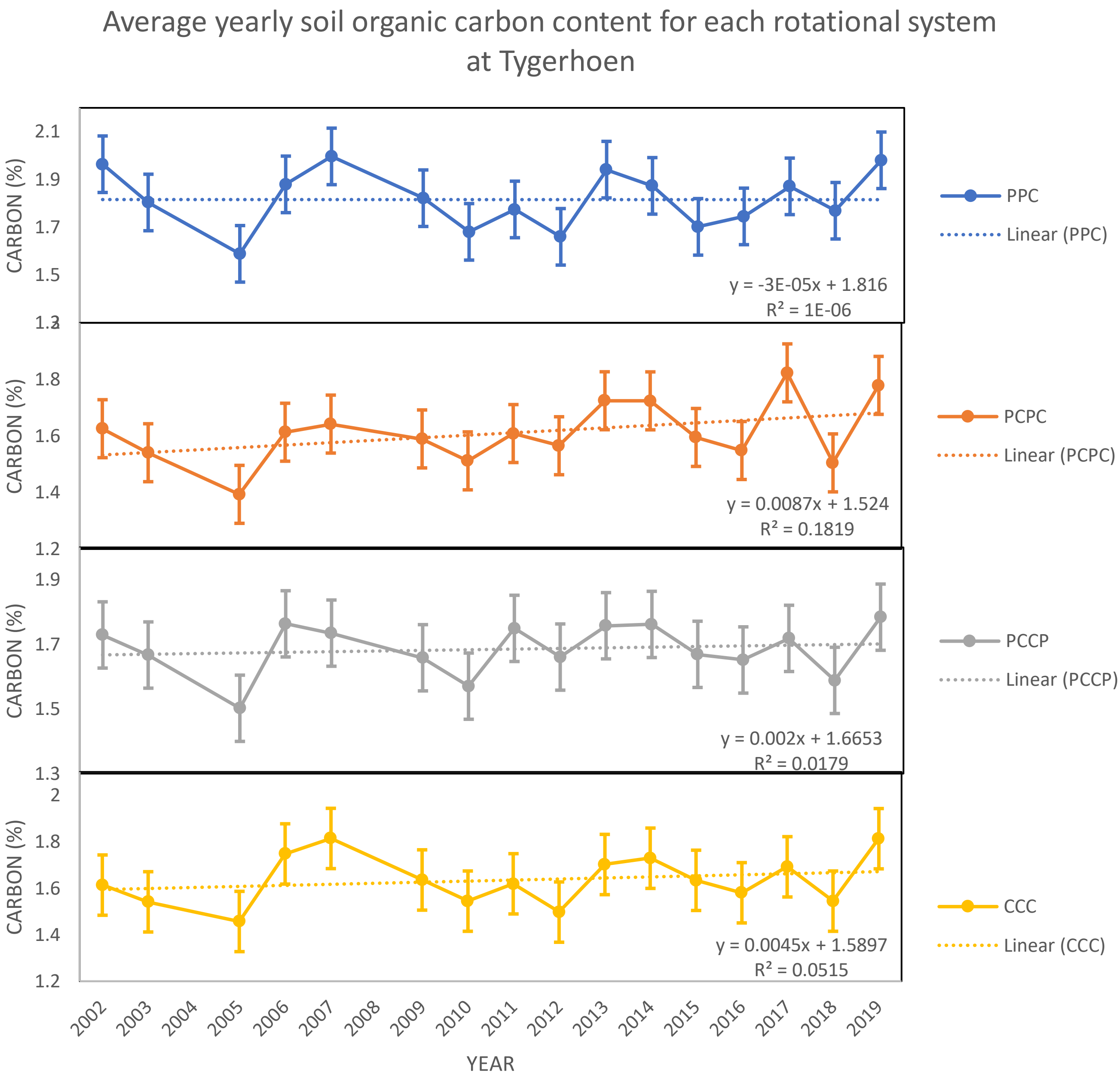

Figure 37: The average soil organic carbon content (%) in the top 15 cm of the soil for each crop rotational system for each year at Tygerhoek from 2002 to 2019. The system with PPC is 33% crop and 67% pasture rotation, PCPC and PCCP is 50% crop and 50% pasture

3.3.4.2.2. Average % C increase from 2002-2020

The average change in soil C for each of the rotational treatments of the trial from 2002-2020 was calculated. There were no significant differences between the crop rotational systems (Figure 38). The system with WMcWMc+saltbush had the highest % change with 0.0249, followed by WWWC with 0.0237 per year. The other systems had an increase of 0.0218 for WMcWMc, 0.0202 for WMCM, both WMWM and WWCL had 0.0197, 0.0185 for WWWW, and WCWL had the lowest with 0.0147. The average change in soil C considers any fluctuations which might have occurred throughout the trial.

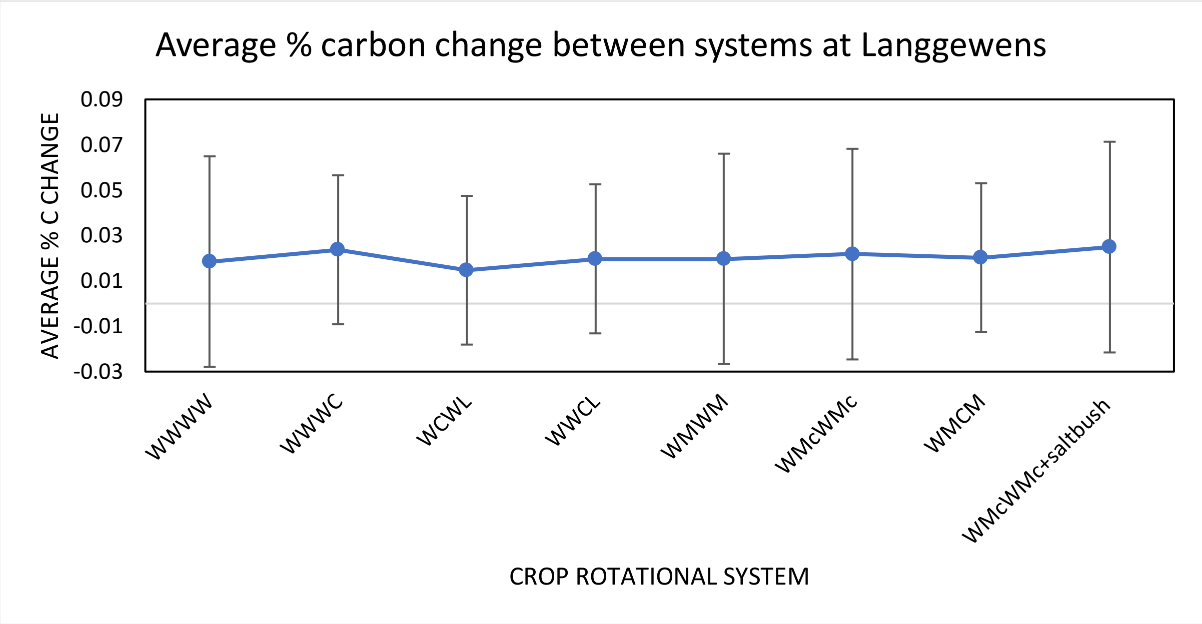

Figure 38: Average increase in soil organic carbon between the different crop rotational systems at Langgewens from 2002 to 2020. The system with WWWW is wheat monoculture, WWWC is wheat and canola rotation, WCWL and WWCL is wheat, canola, and lupin rotation, WMWM is wheat and medic rotation, WMcWMc is wheat and medic/clover rotation, WMWC is wheat, medic, and canola rotation, and WMcWMc+saltbush is wheat and medic/clover rotation with saltbush

At Tygerhoek none of the systems showed a significant difference in % C change. The system with PCPC had the highest average % C increase per year with 0.017, followed by CCC with 0.012 and PPC with 0.011. The systems with PCCP showed the lowest increase with 0.009 per year. This gives a clearer view of the change in soil C along with the differences which can be observed between the systems.

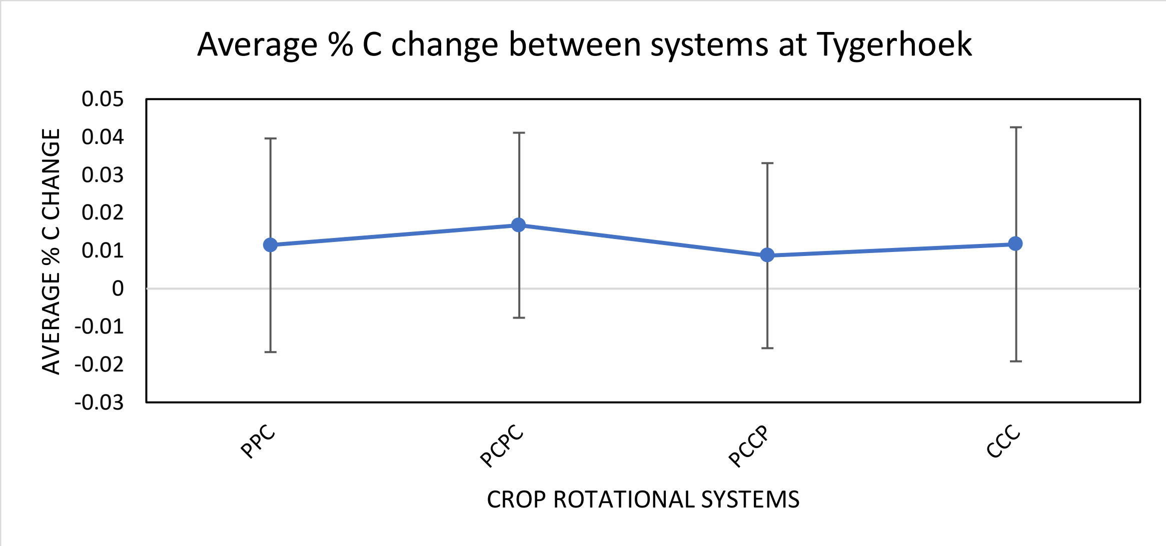

Figure 39: Average increase in % C for each crop rotational system at Tygerhoek from 2002 to 2020. The system with PPC is 33% crop and 67% pasture rotation, PCPC and PCCP is 50% crop and 50% pasture rotation, and CCC is 100% cash crop rotation. The crops included wheat, barley

3.3.4.2.3. Comparing methods

When comparing the two methods in Table 1 at Langgewens WWWC had the highest rate of change, while WMWM had the highest average % C increase. The systems with WCWL and WWCL had the lowest changes in soil organic C in both methods. The systems which included medics in the rotation had similar changes in average C between years. This is in line with what Syswerda, et al., (2011) said; rotational systems which include pastures are expected to have the highest increase in C.

Table 1: The rate of change (%C per year)and average % C increase between 2002-2020 in the top 15 cm of the soil for each system at Langgewens. The system with WWWW is wheat monoculture, WWWC is wheat and canola rotation, WCWL and WWCL is wheat, canola, and lupin rotation, WMWM is wheat and medic rotation, WMcWMc is wheat and medic/clover rotation, WMWC is wheat, medic, and canola rotation, and WMcWMc+saltbush is wheat and medic/clover rotation with saltbush

System	Rotation	Rate of change (%C per year)	Avg. % C increase 2002-2020
A	WWWW	0.0247	0.0185
B	WWWC	0.0280	0.0237
C	WCWL	0.0154	0.0147
D	WWCL	0.0182	0.0197
E	WMWM	0.0269	0.0197
F	WMcWMc	0.0258	0.0218
G	WMCM	0.0257	0.0202
H	WMcWMc+saltbush	0.0229	0.0249

At Tygerhoek the comparison of the two methods (Table 2), the systems with CCC and PCPC had a higher change in soil C and PCCP and PPC had the lowest change each time. This can be explained by looking at the C content at the beginning of the trial. PPC (1.96%) had the highest followed by PCCP with 1.73% soil organic C.

Table 2: The rate of change (%C per year)and average % C increase between 2002-2020 in the top 15 cm of the soil for each system at Tygerhoek. The system with PPC is 33% crop and 67% pasture rotation, PCPC and PCCP is 50% crop and 50% pasture rotation, and CCC is 100% cash crop rotation. The crops included wheat, barley, canola, and oats.

System	Rotation	Rate of change (%C per year)	Avg. % C increase 2002-2020
2	PPC	-0.00003	-0.011
3	PCPC	0.0087	0.017
4	PCCP	0.002	0.009
5	CCC	0.0045	0.012

When comparing the increase of the different crop rotational systems at Langgewens and Tygerhoek a common occurrence is the system which had with the lowest C content at the beginning of the trial had the highest rate of change and average % increase over the trial period. At Langgewens this is WWWC and WMWM, while at Tygerhoek this is CCC and PCPC. Both have a 100% crop and 50/50 crop-pasture/medic system. The lowest rotational systems were WCWL and WWCL at Langgewens, and PCCP and PPC at Tygerhoek. The systems at Langgewens and Tygerhoek had high soil C contents at the start of the trial which could explain the low increase in SOC. Another observation at Langgewens is all systems that included medics had a similar C content at the end of the trial and changes per year throughout the trial. This points to the importance of medics in C sequestration. At Tygerhoek the 50/50 crop-pasture systems also ended in the same soil C content, but the PCPC had a lower C content at the start which resulted in a higher yearly change in C. The system with 33% crop and 66% pastures had the highest C content in each of the years. This is in line with what is found at Langgewens as well. This is also what was found by Franzluebbers, et al., (2012) where they state that one of the fastest ways to sequester C in the soil is by conversion of an arable cropping system to perennial grasslands.

The increase of the C content through the trial gives a clear indication that there are confounding factors that will limit the amount of C that the soil can sequester and store. This could explain why there is no significant difference between the C content at Langgewens, but some of the systems had a significantly higher increase in C than others. It could also explain why at Tygerhoek the 100% cropping system had the highest C increase when the systems which included 66% pastures were expected to have a significantly higher increase, only increased by 0.84%, but consistently had the highest C content throughout the trial. This shows that there might be a limit to the amount of C sequestered which will depend on the soil properties, but also the climate. The trial which had the higher rainfall and lower temperature also showed higher C through the trial.

3.3.5 Effect of crop rotational system on wheat yield

Various factors can affect the yield of crops, which include nutrient availability, climate, soil physical properties, biological properties, and management practices. The management practices include the differing crops included in a rotational system. In the trial done at Langgewens, it was found that there are significant differences between the rotational systems. The system with WWWW was significantly lower than all the other systems except WWWC and WMcWMc. The systems that had a higher yield were the WMcWMc+saltbush and WMCM with 3569.3kg and 3561.1kg, and, closely followed by WMWM with 3520.7kg. The systems following that were WCWL (3428.7kg), WWCL (3285.9kg), WMcWMc (3244.2kg), WWWC (3093.7kg), and the lowest being WWWW (2789.1kg). The results are shown in Figure 40. In a study done by Angus et al. (2015), they found that all the rotational crops (canola, lupins, and pastures) implemented in their study had positive effects on the yield of wheat. This study shows that when implementing 50% pastures into the rotational system there will be a positive influence on the yield, compared to 75 and 100% crops. The positive effect of the inclusion of medics in the rotational system was also observed by Smith et al. (2020).

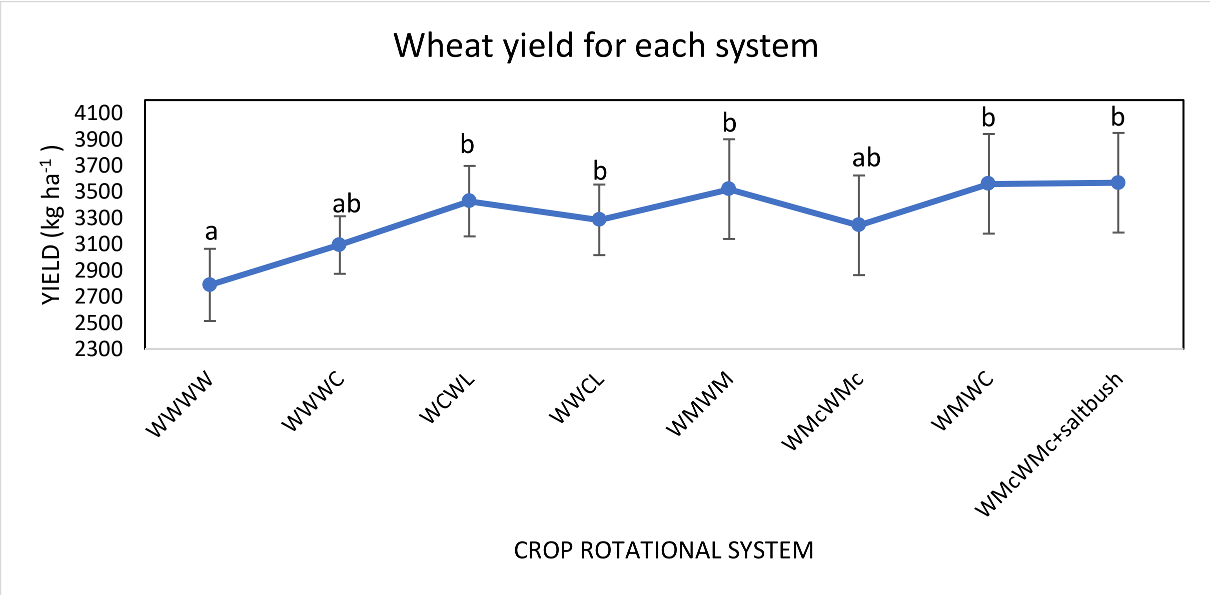

Figure 40: Average wheat yield (kg ha^{-1}) for each system at Langgewens from 2002 to 2020. The system with WWWW is wheat monoculture, WWWC is wheat and canola rotation, WCWL and WWCL is wheat, canola, and lupin rotation, WMWM is wheat and medic rotation, WMcWMc is wheat and medic/clover rotation, WMWC is wheat, medic, and canola rotation, and WMcWMc+saltbush is wheat and medic/clover rotation with saltbush

At Tygerhoek, there was also a significant difference in the average wheat yield between the rotational systems (*Figure 41*). The wheat in the pure cash crop rotation has a significantly lower yield (3380kg) than PCPC (3671.7kg) and PCCP (3593.8kg). The systems with PPC had an average yield of 3589.1kg. This shows the positive influence that pastures play on yield. Ernst et al. (2018) looked at the effect of continuous cropping after pastures and found a steady decline in wheat yield. They also found that the deterioration of the soil quality could only be corrected for the first five years after pastures with supplemental fertilizers.

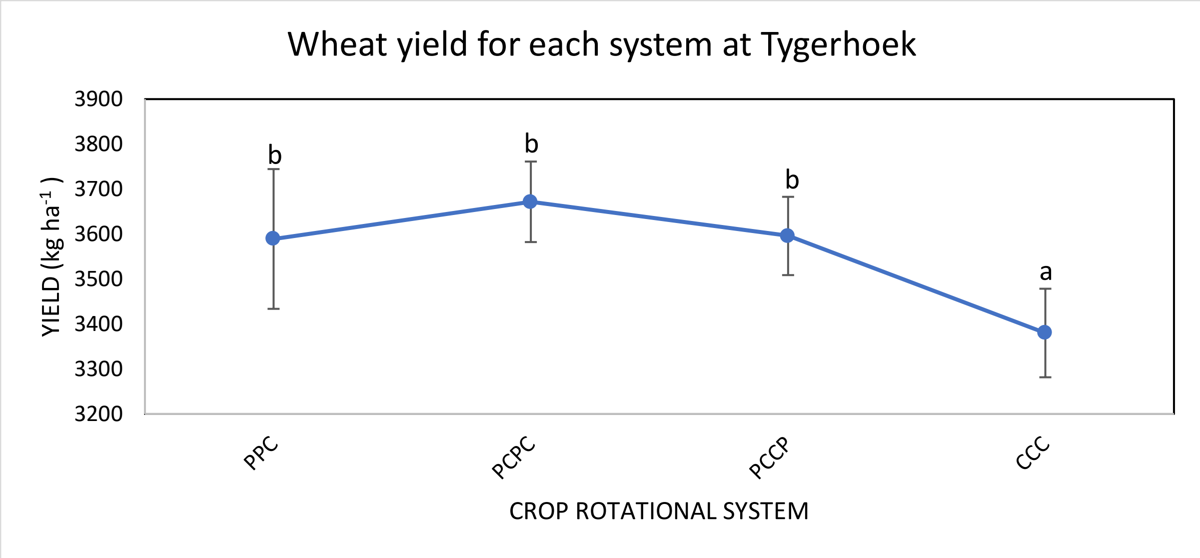

Figure 41: Average wheat yield (kg ha^{-1}) for each system at Tygerhoek from 2002 to 2020. The system with PPC is 33% crop and 67% pasture rotation, PCPC and PCCP is 50% crop and 50% pasture rotation, and CCC is 100% cash crop rotation. The crops included wheat, barley, canola, and oats.

At both Langgewens the system which had wheat monoculture and at Tygerhoek the system with which had pure cash crop was significantly lower than the other systems. Possible reasons for this are the nutrients in the soil are depleted when these same crops are grown in this way year after year. The loss of these soil nutrients, particularly nitrogen, causes the soil to become weak and unable to support the healthy growth of plants, while the other systems have legumes included in the rotation which will fix nitrogen for the following crop (Pranagal & Woźniak, 2021). This means that to grow plants at their maximum potential, we must continually add additional vital nutrients to the soil. The increased application of fertilizer will negatively impact the ecology. There is also the increased risk of pests, diseases, and weeds when monoculture is implemented. Since the plants on monoculture farms are nearly identical to one another, if one of them were to become vulnerable to a pest, the others would likewise be (Andow, 1983). When there are different crops in the rotational system the same diseases and pests will not be found in consecutive seasons.

3.4 Conclusions

During the 18-year trial period, there were significant differences in SOC between the years at both Langgewens and Tygerhoek, but only a significant increase in soil organic C at Langgewens (SOC increased by 0.4%) attributed to its much lower starting SOC content. The change between the years shows that some years had a much higher increase in SOC, while some of the changes in years were negative. It was found that, in accordance with the literature, there is a 'saturation point' in SOC that was reached at Langgewens after 2013 and was 1.33%, while it is hypothesized that at Tygerhoek this point is 1.7% and was reached after 2006.

The overall average SOC content of Tygerhoek was seen to be higher than that of Langgewens. The climate and soil physical properties also influence the SOC content. The results suggest that the average rainfall is higher, there is a lower average temperature (17°C compared to

18ºC), higher average yield, the pH is more alkaline (average of 6.03 compared to 5.76), a lower amount of lime and gypsum applied, lower N fertilizer applied, and a higher clay content (21% compared to 13%) across the trial period when comparing Tygerhoek and Langgewens.

At Langgewens when comparing the yield of different crops to the SOC the results point to a correlation between the previous one or two seasons' yield and the C content of the soil. It also points to wheat and lupins having a greater influence on the soil C content than canola. At Tygerhoek for wheat, canola, and barley there is a better correlation between the previous seasons' yield and for oats and lupin the previous one to two seasons' when looking at the effect on the SOC content. Wheat, lupin, and barley had a greater influence on the SOC than oats and canola. These results can be explained by the rate of decomposition of the plant biomass, and the fact that cereal crops produce higher biomass.

The quality and quantity of biomass produced and left in the soil are different between certain crops and subsequently different crop rotational systems. At Langgewens no significant differences were observed in average SOC content over the 19-year period between the rotational systems. The WWCL and WMcWMc+saltbush rotational systems showed the highest average C. At Tygerhoek there was a significant difference between the systems, with the PPC system having a significantly higher average SOC than PPCC, CCC, and PCPC. This could be because it was only cropped for 33% of the time. This is in accordance with most studies that found that the incorporation of pastures into a cropping system will result in a higher soil C content, which was found at both sites.

When comparing the change in SOC between the crop rotational systems at Langgewens WWWC had the highest rate of change, while WMWM had the highest average % C increase. The systems with WCWL and WWCL had the lowest changes. The systems which included medics in the rotation had similar changes. At Tygerhoek the comparison of the two methods, the systems with CCC and PCPC had a higher change in soil C. This can be explained by looking at the C content at the beginning of the trial which is explained by the saturation point.

At Langgewens WMcWMc+saltbush, WMCM, WMWM, WCWL, and WWCL, were significantly higher than WWWW. At Tygerhoek the pure cash crop rotation has a significantly lower yield than PCPC and PCCP, but not PPC. This points to the positive influence that pasture/medics have on the yield of wheat. The results at both trial sites show the positive effect that a crop rotation system with different crops has on yield. At both sites, the wheat monoculture had a significantly lower yield.

When considering both the C and yield between the rotational systems at Langgewens the system with WMcWMc+saltbush consistently performed better than the rest, while at Tygerhoek it was PPC. This shows that the incorporation of natural vegetation (pastures and saltbush) into the rotational system has many benefits.

There is a good correlation between soil C content and soil health, due to its influence on soil chemical, physical and biological properties. It is expected for healthier soil to result in a bigger crop yield. From the results in this chapter, the rotational systems that had a higher C content also showed a higher yield. To confirm these findings the effect that SOC has on the yield of wheat will be further explored in the next chapter.

Chapter 4: Effect of soil organic carbon content on yield and quality of wheat

4.1 Introduction

The SOC has a variety of impacts on the chemical and physical environment of the soil. These will significantly impact crop productivity (FAO, 2015). A much more sustainable method of farming can be achieved by using SOC as a means of ensuring stable and long-lasting crop productivity and by reducing the over-reliance on external inputs like mineral fertilizer (King, et al., 2020). The effects of SOC accumulating in the soil may vary according to the region and environment. This may result in less demand for fertilizer and irrigation in places with higher rainfall, while in drier areas, it may result in drought protection and mineral release. All these elements will have an indirect impact on crop yield (FAO, 2015).

Over the last few decades, increases in wheat production have kept up with rising global demand. To meet the anticipated demand for wheat caused by a rise in global population, changes in food preferences, and a decline in the wheat production area, wheat yields must continue to increase (Ransom, et al., 2007), and thus increased productivity is essential. There is a multitude of management practices that can impact yield. Sustainable yield increases necessitate using management practices that preserve or improve the productivity of the natural resources used in production. Erosion, nutrient depletion, organic matter loss, salinity, acidification, and physical deterioration are all factors that can lower soil health and subsequent production. The sustainability of the soil can be impacted by important practices such as crop rotation, N fertilizer management, and conservation agriculture (Liebig, et al., 2004; Ransom, et al., 2007; Cardoso, et al., 2013).

Soil health is defined as "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans" (Natural Resources Conservation Services: Soil Health, 2012). Cation exchange capacity, buffering capacity, resistance to compaction, aggregate formation and stability, water retention and infiltration, microbe population, and the release of nutrients like N, P, and S are some of the factors that are impacted by soil health (Murphy, 2015). To increase soil health various factors needs to be considered, which include management practices, soil physical, chemical, and biological properties, and the climate (Lehmann, et al., 2020). Central to this is the retention of SOM (Six, et al., 2000). The SOC content of the soil is correlated to the amount of SOM retained in the soil (Lal, 2006). Low yield, a weak soil structure, and a decreased ability to absorb mineral inputs efficiently are the effects of significant SOC depletion in the soil (Lal, 2011).

Lal (2006) proposed mechanisms through which the yield can be increased, and one is by an increase in SOC of degraded soils. This is through increasing the amount of water that is available, improving the supply of nutrients, and enhancing the structure of the soil and other physical properties. Larney, et al., (2000) observed a decrease in wheat yield when there was a decrease in the SOC content of the soil. The effect of increasing SOC on yield is limited (Lal, 2006; Oldfield, et al., 2019). Literature from the Americas, Asia, and tropical-, North-, and West Africa shows a positive relationship, with little research done in arid and semi-arid regions. Feng et al. (2018) reviewed the semi-arid regions in Australia, while Smith, et al., (2020) briefly touched on the effect on yield in the Overberg region of South Africa.

This chapter will focus on the factors which have an influence on the yield and quality of wheat in a semi-arid region of South Africa. Central to this will be the relationship between SOC and yield. Research data was obtained from two long-term trials (18 years) with no-till and crop rotations being implemented to maximise the SOM returned and preserved in the soil to increase the SOC content.

4.2 Materials and methods

Soil samples of the top 15 cm of the soil at both Langgewens and Tygerhoek were collected in late December to mid-January of each year for the duration of the trial. The methods which were used to determine the soil characteristics and yield and quality of wheat have been discussed in detail in Chapter 3, under materials and methods.

4.2.1 Statistical analysis

The same data will be used in this chapter as in the previous one. Statistical analysis was done using Statistica Version 14.0.0.15. A mixed model ANOVA was used to determine if the difference between the carbon and yield of each system and year are statistically different at both locations. Partial correlation was used to see if there is a correlation between the SOC and the yield of a specific year (Kunihiro, et al., 2004). A panel regression was done for yield against each of the variables (Brugger, 2021).

4.3 Results and discussion

4.3.1 Soil characteristics

4.3.1.1 Soil nutrients

Soil nutrients are essential for the plant to produce a yield. The nutrients which were evaluated in this study included phosphorus, potassium, calcium, magnesium, sodium, and sulfur. At Langgewens the overall average for calcium (Ca) is 790 mg kg^{-1}, magnesium (Mg) is 122 mg kg^{-1}, sodium (Na) is 24 mg kg^{-1}, potassium (K) is 153 mg kg^{-1}, phosphorus (P) is 79 mg kg^{-1}, and Sulphur (S) is 7.25 mg kg^{-1}. The critical limits for the nutrients were found. Ca is limiting below 400 mg kg^{-1}, Mg at 60 cmol kg^{-1}, K at 40 mg kg^{-1}, Na needs to be lower than 222 mg kg^{-1}, and P lower than 17 mg kg^{-1} (Fertilizer Association of Southern Africa, 2016). The only nutrient that was lower than the critical level was S. According to Yesmin, et al. (2021) the critical level of S for wheat is 11 mg kg^{-1}. S-deficient wheat plants show a bright chlorotic, yellow-green color and stunted growth on the young leaves. At Tygerhoek the average for Ca is 1522 mg kg^{-1}, Mg is 208 mg kg^{-1}, Na is 71.8 mg kg^{-1}, K is 248.66 mg kg^{-1}, P is 49.71 mg kg^{-1}, and S is 8.37 mg kg^{-1}. The level of S is also limiting at Tygerhoek. The soil characteristics is shown in Table A 1 and Table A 2 in the Appendix.

4.3.2 Yield across the trial period

Every producer strives for the highest yield through the management practices which they implement. The wheat yield for dryland agriculture is lower than that under irrigation. Various factors play a role in the determination of wheat yield. The fertility of the soil, the amount of water available to the crop, and the climate in which the crop is produced are the most important factors. According to Pittelkow, et al., (2015) the yield of crops declined for the first 1-2 years after no-till is implemented. At Langgewens, which is dryland, the wheat yield varied through most years between 1.5 and 4.5 tons per hectare (Figure 42). There are significant differences between the different years ($p<0.01$). During 2002-2003, 2007-2008, 2014-2015, and 2016-2017 there was a significant decrease in yield, and an increase during each season during 2003-2004, 2004-2005, 2005-2006, 2011-2012, 2015-2016, 2018-2019, and 2019-2020. The following years were drought years: 2003, 2004, 2015, and 2017, with 2019 also being drier. During the 2018 season, there were strong winds that caused damage to nearly half the crops, thus the yield was low. The rate of change shows a decrease of 34.989 kg ha^{-1} per year, but the R^2 is only 0.0473 which means 4.73% of the variance in yield is explained by the years.

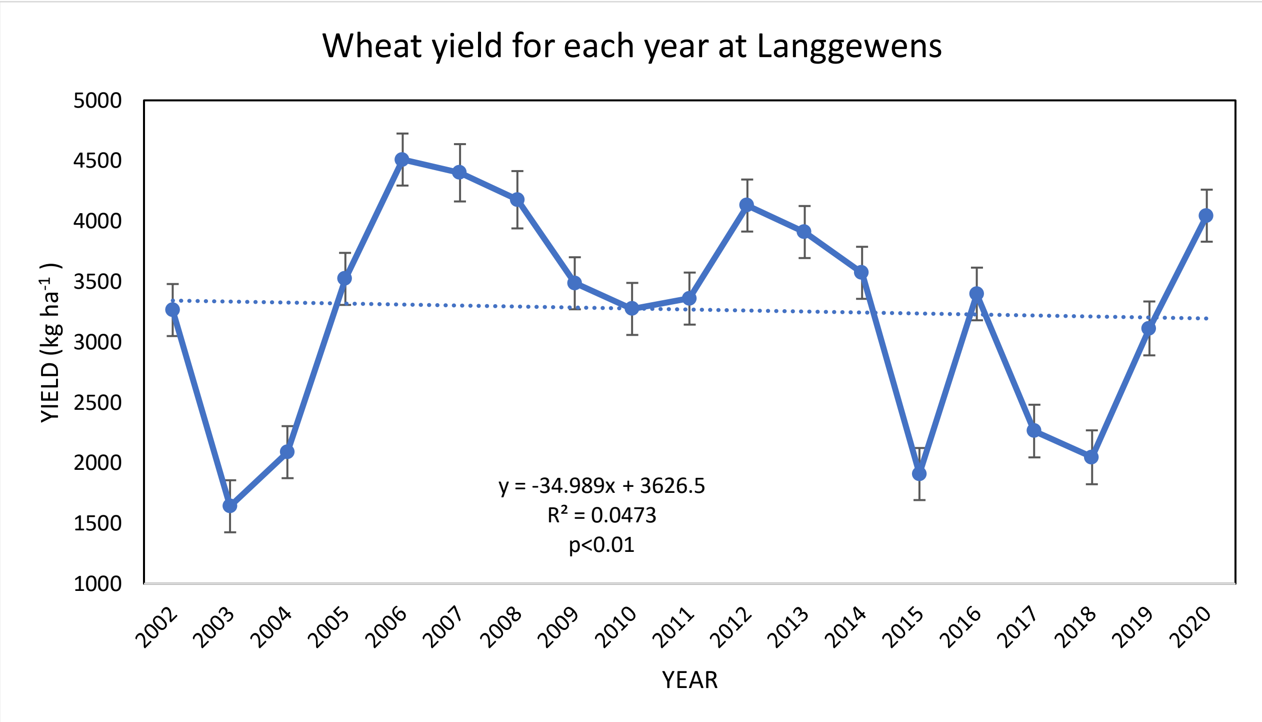

Figure 42: The wheat yield (kg ha^{-1}) for each year at Langgewens from 2002 to 2020

At Tygerhoek there is a higher average yield with a range between 1 and 6 tons of wheat yield per hectare (Figure 43). The yield shows a significant decrease during 2003-2004, 2006-2007, 2007-2008, 2009-2010, 2012-2013, 2014-2015, 2016-2017, and 2018-2019, with an increase during 2002-2003, 2004-2005, 2005-2006, 2008-2009, 2010-2011, 2013-2014, 2017-2018, and 2019-2020.

There was also a decrease between 2012 and 2019. The final yield was also significantly higher than that of the first. For this reason, the trendline shows a 12.657 kg ha^{-1} increase per year, with a R^2 of 0.0042. Before planting there was 300 mm of rain in one day which delayed planting and caused a late season with subsequent a low yield.

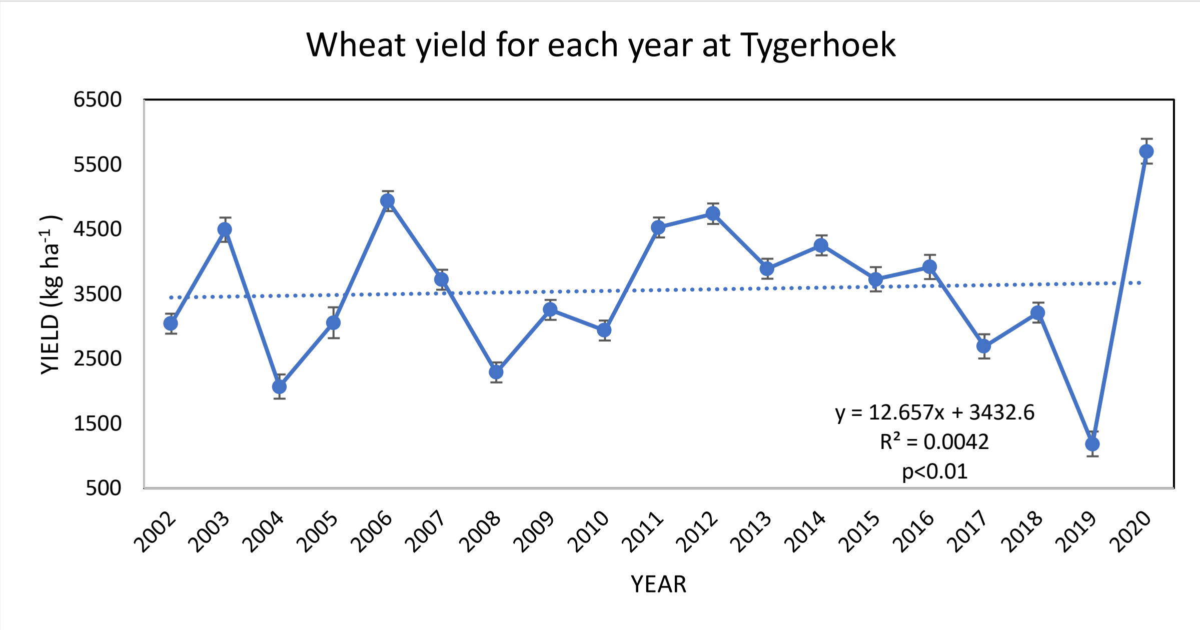

Figure 43: The wheat yield (kg ha^{-1}) for each year at Tygerhoek from 2002 to 2020

4.3.3 Factors affecting wheat yield

Various factors influence the yield, but according to Liebig's Law of minimum, the nutrient (or factor) that is most limiting will determine the yield. The most important factors affecting yield are the soil's fertility and the climate in which the crop is grown (Liliane & Charles, 2020). Crop failures can result from insufficient rainfall, whereas plant damage, soil compaction, erosion, or nutrient leaching might result from excessive rainfall (Kahlon, et al., 2013). Wheat production is impacted by high temperatures in one of two ways: either chronic stress from prolonged, moderately high temperatures up to 32°C or heat shock from an abrupt, but brief, exposure to 33°C and higher (Paulsen, 1994). The pH of the soil is correlated with soil fertility (Jones & Jacobsen, 2005). Low pH levels can be harmful because they will convert nutrients into forms that the plant cannot absorb. Additionally, the solubility of plant-toxic metals increases, which may cause stunted growth or lack of vigour. The plant cannot achieve its full yield or, in extreme cases, complete its life cycle, which includes germination, developing roots, stems, leaves, and flowers, and producing seeds, if any of the nutrients are deficient or if an external stressor is applied. The same is true for a nutritional surplus, which will result in toxicity. When looking at the nutrient content of the soil, the only nutrient that might be limiting in the study at Langgewens and Tygerhoek is S. When Soinne et al. (2020) examined factors affecting crop yield, they discovered a negative link between the clay to C ratio and grain yield in both fertilized and unfertilized fields. This was discovered particularly in regions with clay-to-C ratios greater than 15. This influence can be explained by the influence that not only SOC but also soil texture has on soil physical properties (Kay, 1998). The biggest is aggregate stability. To maintain the same level of aggregate stability when clay content increased, a higher SOC content was required (Johannes, et al., 2017). This relationship is expressed by the clay-to-C ratio. Johannes, et al., (2017) found that a reasonable goal is 1:10 and the optimal value for soil structure quality is 1:8.

4.3.3.1 Rainfall

Higher rainfall does not equate to a higher yield, there are various factors which is affected by higher rainfall. Rainfall is most important for replenishing the water stored in the soil, which the crop will utilize once the growing season begins. For this reason, it is important to look at the rainfall during the growing season as well and not just total rainfall. From Figure 44it is evident that the rainfall and wheat yield follows the same trend across the trial period. During 2002-2003 both yield and rainfall show a decrease, with both increasing until 2007 when the highest rainfall and yield averages were recorded. The decrease in yield from 2013-2015 can also be seen in the lower rainfall during this period, as well as the increase during 2016. The rainfall is not the only factor that should be looked at. The statistics show a significant linear correlation between yield and yearly and seasonal rainfall with p= 0.002 and p= 0.001. There is a weak positive correlation with R^2= 0.44 and R^2= 0.48 between yearly and seasonal rainfall and yield for the current season. This shows the importance of the current season's rainfall and especially the rainfall during the season for yield.

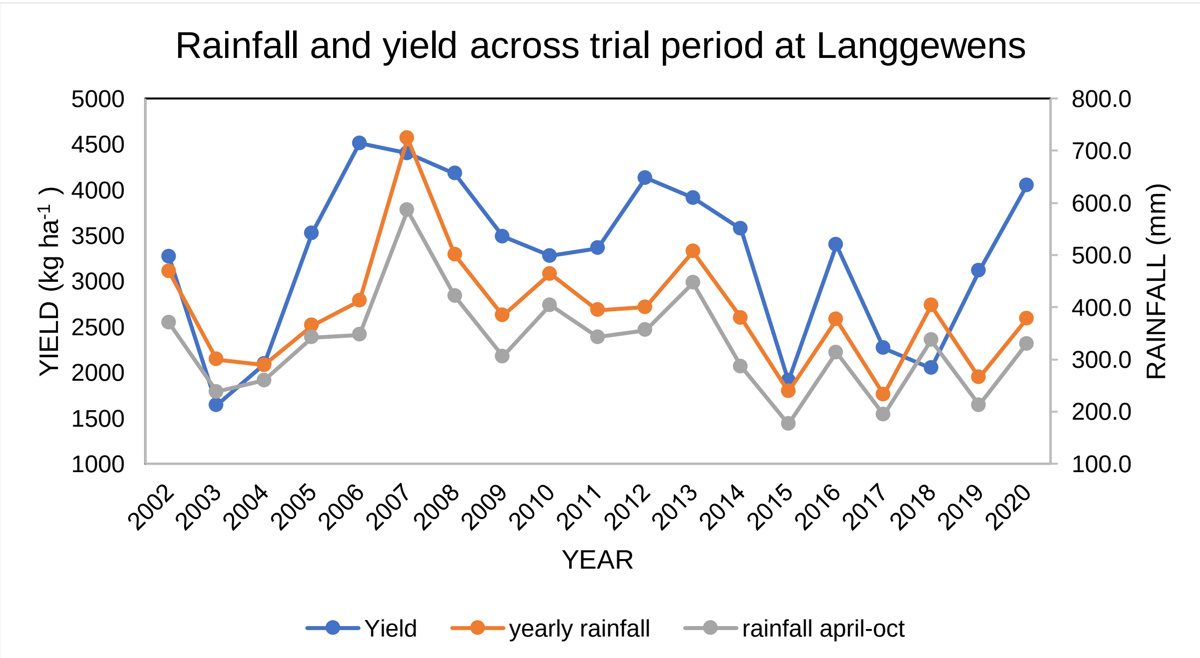

Figure 44: Wheat yield (kg ha^{-1}) against yearly- and seasonal rainfall (mm) at Langgewens from 2002 to 2020

At Tygerhoek (Figure 45), the growing season rainfall corresponded better with yields than the annual rainfall. There is a decrease in rainfall from 2006-2007 along with the yield in 2006-2008, then a yearly increase in both until 2012 and a decrease until 2019. The statistics show no significant interaction between yield and yearly or seasonal rainfall with p= 0.989 and p= 0.17. There is a negligible positive correlation with R^2= 0.00001 and R^2= 0.11 between yearly and seasonal rainfall and yield for the current season. The rainfall was very variable during the trial period, with seasonal rainfall being better correlated to yield.

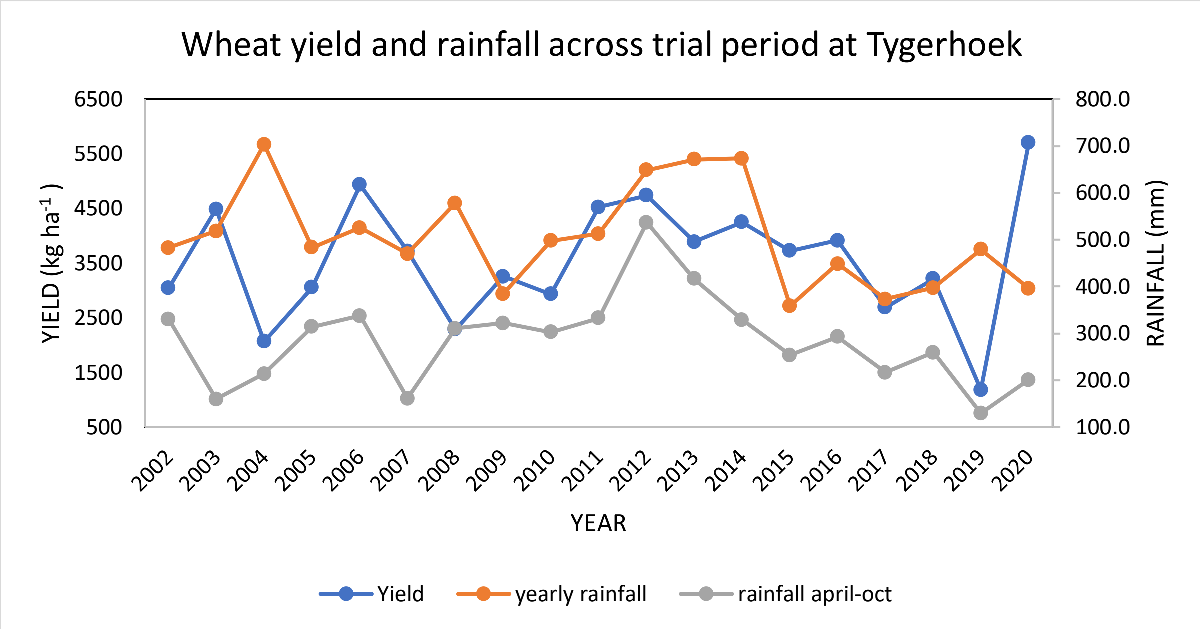

Figure 45: Wheat yield (kg ha^{-1}) against yearly- and seasonal rainfall (mm) at Tygerhoek from 2002 to 2020

4.3.3.2 Soil pH, liming, and gypsum

Crop yield is indirectly improved by liming through enhancing the physical, chemical, and biological properties of the soil, which increases the availability and mobility of many essential nutrients by modifying the soil pH (Li, et al., 2019). At the beginning of the trial at Langgewens, there were large amounts of lime and gypsum added to the soil after which an increase in yield can be seen (Figure 46). After the application during 2009-2014 and 2017-2018, there was also a corresponding increase in yield. The statistics show no significant linear correlation between yield and calcitic- and dolomitic lime, and gypsum with p= 0.09, p= 0.25, and p= 0.85. There is a negligible positive correlation with R^2= 0.16, R^2= 0.08, and R^2= 0.002 for calcitic- and dolomitic lime, and gypsum respectively for the current season's wheat yield. This shows that the effect of lime and gypsum is not seen in the current season, but according to the graph, it could be two years later.

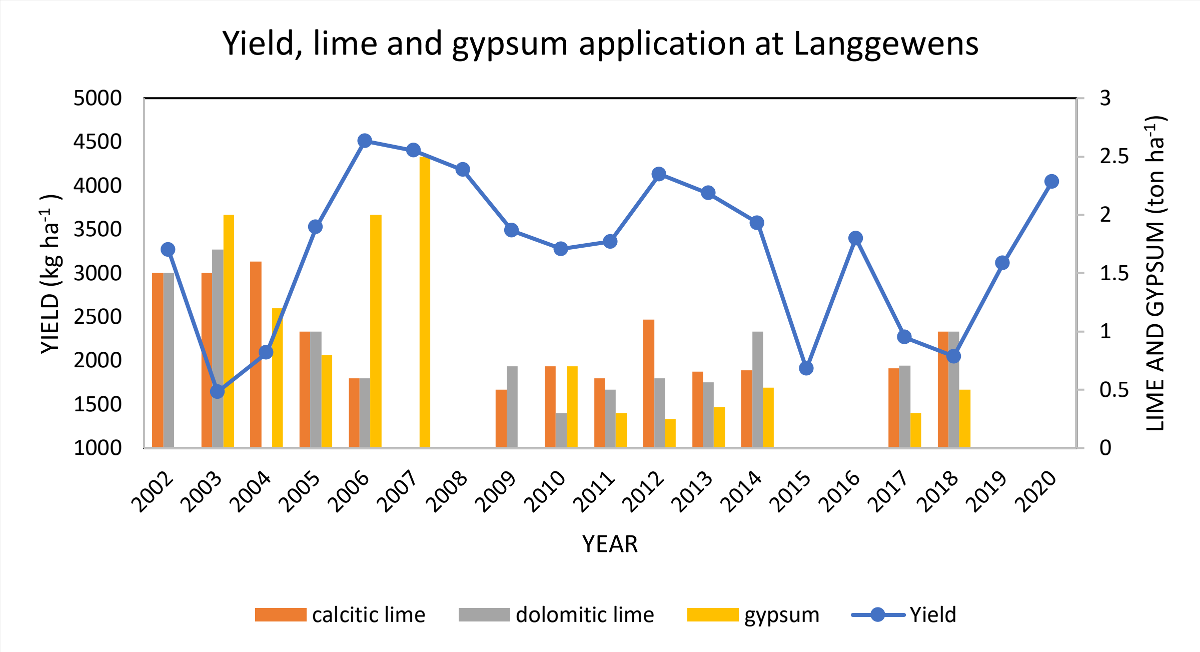

Figure 46: Wheat yield (kg ha^{-1}) against lime and gypsum application (tonnes ha^{-1}) at Langgewens from 2002 to 2020

At Tygerhoek the pH showed an increase after 2011, while the addition of lime and gypsum happened in 2007, 2009, 2010, and 2011. An increase in yield is visible between 2008 and 2012, during the years when lime and gypsum were applied (Figure 47). The statistics show no significant linear correlation between yield and calcitic lime with p= 0.24, while gypsum did not have enough data points to apply statistical analysis. There is a high positive correlation with R^2= 0.87 for calcitic lime for the current season's yield.

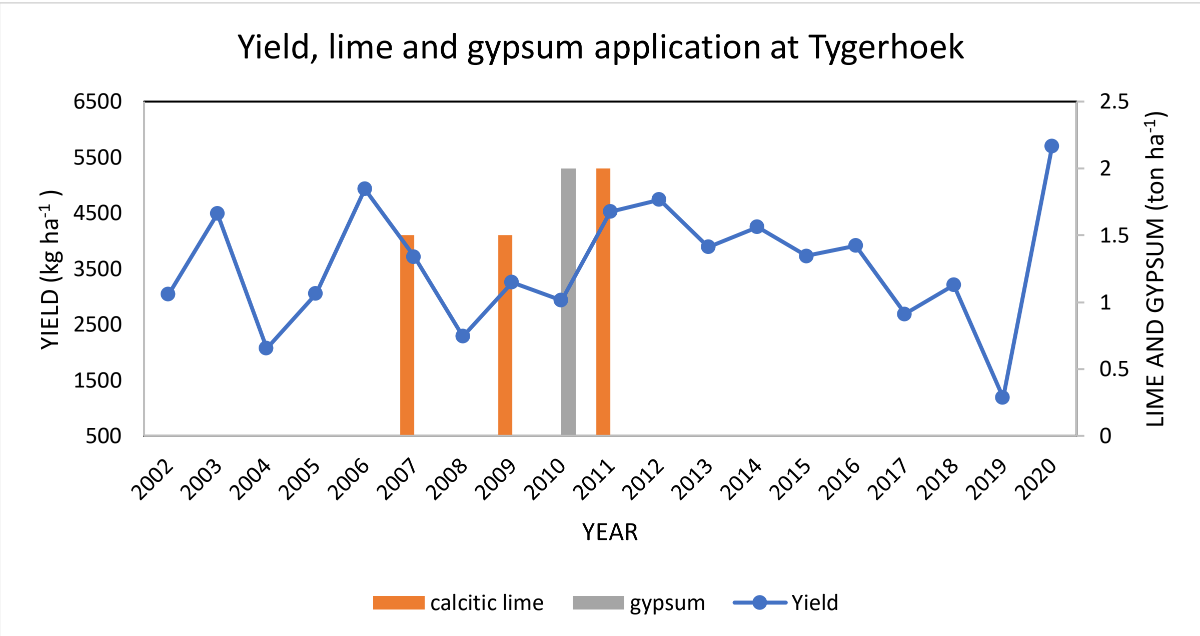

Figure 47: Wheat yield (kg ha^{-1}) against lime and gypsum application (tonnes ha^{-1}) at Tygerhoek from 2002 to 2020

It is well known that liming will increase the pH of the soil (Conradi Jr, et al., 2020). The pH of the soil affects soil fertility (Queensland Government, 2013). Low pH levels can be harmful because they cause nutrients to be converted into forms that the plant cannot absorb (Conradi Jr, et al., 2020). Toxic metals are more soluble, which can lead to stunted development or a lack of plant vigor. Wheat requires a pH of 5.5 to 6.5 for maximum micronutrient availability and growth (Department: Agriculture, Forestry and Fisheries, 2022). At Langgewens there is a dramatic increase in both pH (5.4 to 5.8) and wheat yield during the first five years of the study (Figure 48). Thereafter, the soil pH remains between 5.7-6.0 due to regular liming, thus we can see no more effects that it had on yield. The statistics show no significant linear correlation between yield and pH with p= 0.07. There is a negligible positive correlation with R^2= 0.18 for pH against yield, with it being for the current season. To see significant results, the pH should be significantly higher or lower than the optimum range.

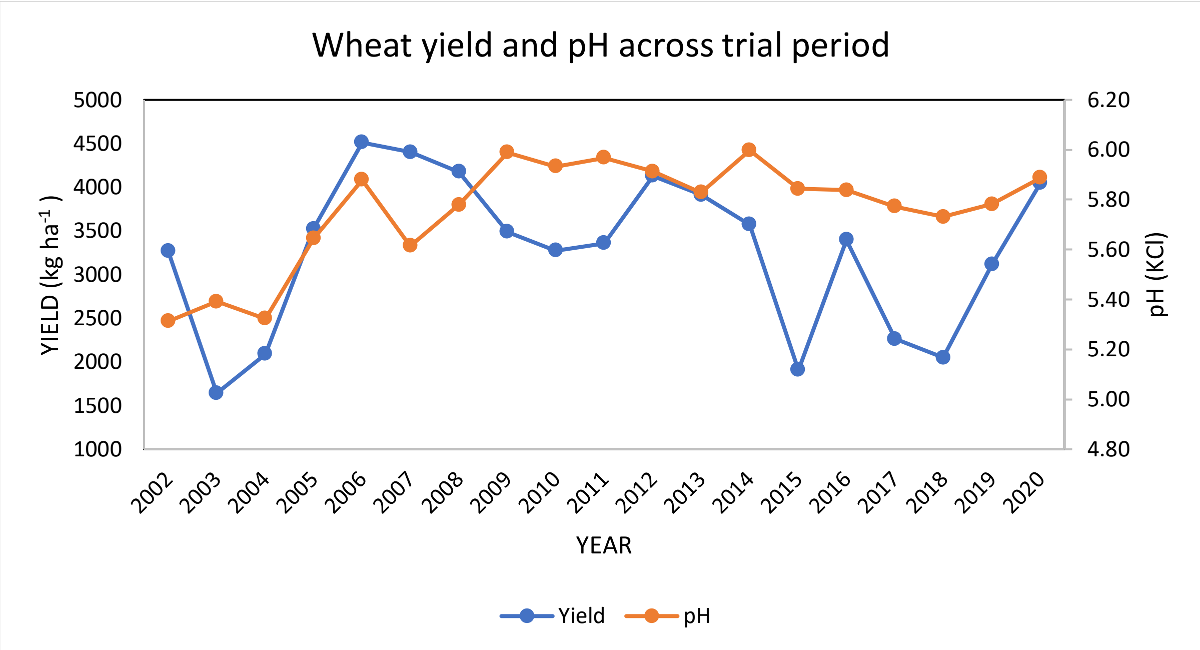

Figure 48: Wheat yield (kg ha^{-1}) against pH (KCl) of the top 15 cm of the soil at Langgewens from 2002 to 2020

At Tygerhoek, soil pH decreased (6.0 to 5.6) during the first five years of the study, then stayed constant for the next four years, with a constant increase from 6.0 to 6.4 during 2011-2017 (Figure 49). During the period when the pH increased the yield decreased. This is not what is expected as the literature states the target pH level is 6.4, and a lower pH level can make toxic metals more soluble. The yield shows a significant increase from 2019-2020. The pH data is not available for 2020. The yield that is obtained for the years following the conclusion of the trial might show more significant results for the pH against the yield as the pH is at the target value. The statistics show no significant linear correlation between yield and pH with p= 0.67. There is a negligible positive correlation with R^2= 0.01 for pH against yield. Graphically the effect of pH is rather seen in the next season's yield.

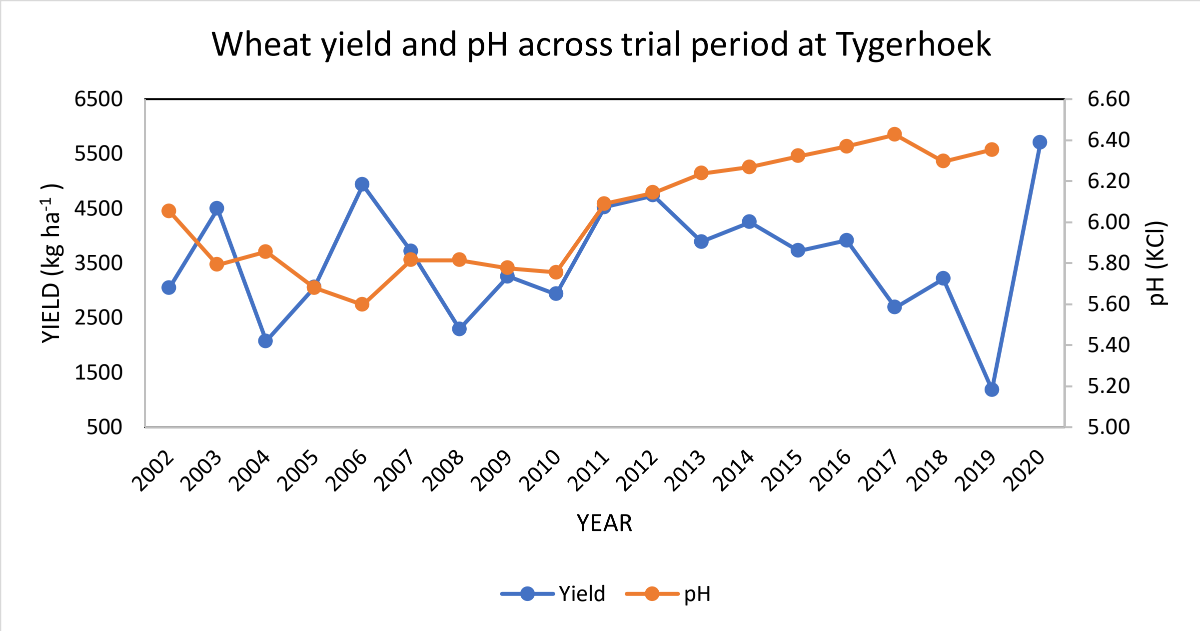

Figure 49: Wheat yield (kg ha^{-1}) against pH (KCl) of the top 15 cm of the soil at Tygerhoek from 2002 to 2020

4.3.3.3 Nitrogen application

Nitrogen is one of the most important nutrients in wheat production, which is also the most limiting (Belete, et al., 2018). At Langgewens the application of N correlates well with the yield (Figure 50). Both the highest yield and N application were in 2007, while there was a slight decrease in from 2008-2011, with the N applied also lower than in 2007. The statistics show no significant linear correlation between yield and the application of N with p= 0.24. There is a negligible positive correlation with R^2= 0.11 for N application against yield, with it being for the current season. This shows that the effect of the amount of N applied has on the current season's yield, but a greater variation in the amount of N applied was needed for a significant result.

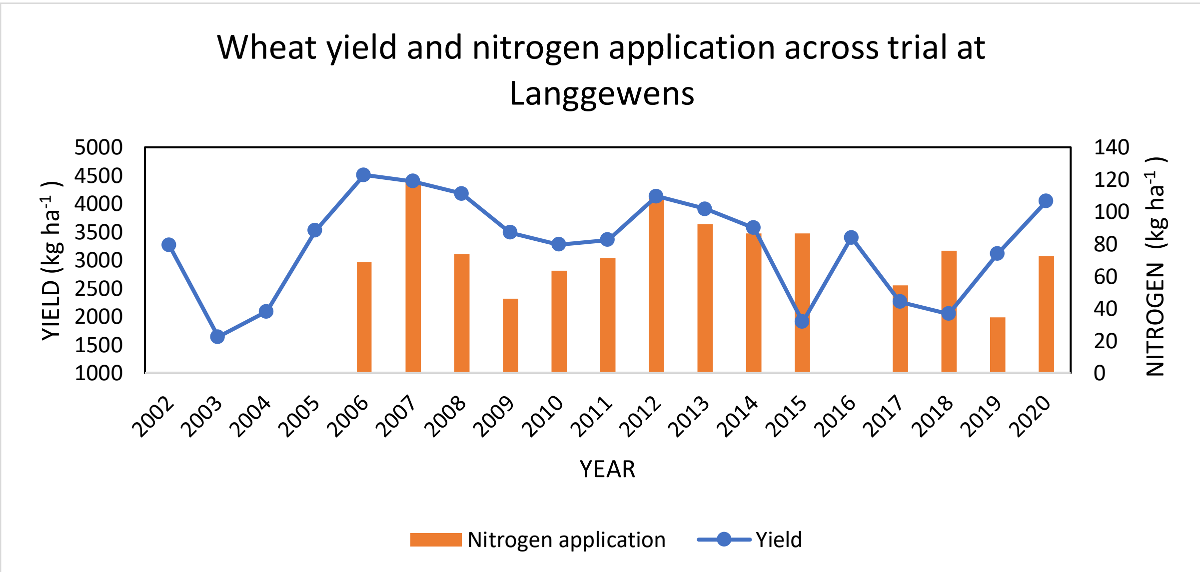

Figure 50: Wheat yield (kg ha^{-1}) against nitrogen application (kg ha^{-1}) at Langgewens from 2002 to 2020

At Tygerhoek there was not a clear correlation seen between the amount of N applied and wheat yield (Figure 51). This can be explained by the trial being designed to obtain the N from the legume pastures rather than N from fertilizers. It was easier to see when comparing the N application to that of the previous year. This can be explained by the lower average amount of N applied through the trial compared to Langgewens. Ali, et al., (2011) found that the number of tillers, plant height, spike length, the number of grain spikes, 1000-grain mass, and grain yield all increased significantly if there was an increase in N application. Both yield and N application were higher than in the previous years 2009, 2011, and 2016, while both were lower during 2008, 2010, and 2017. The statistics show no significant linear correlation between yield and the application of N with p= 0.50. There is a negligible negative correlation with R^2= 0.04 for N application against yield, with it being for the current season.

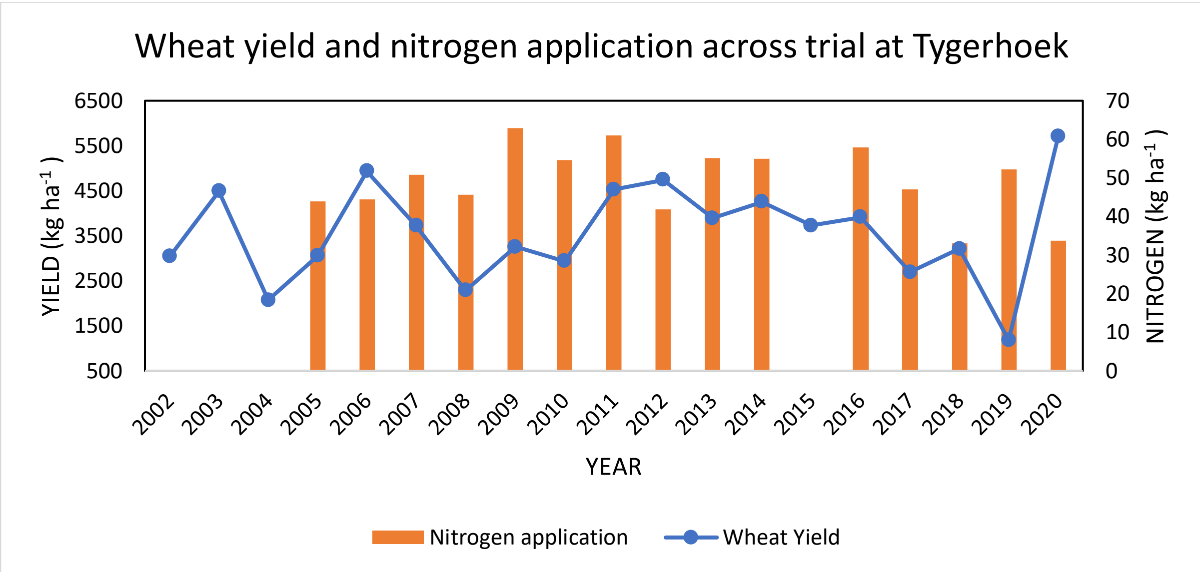

Figure 51: Wheat yield (kg ha^{-1}) against nitrogen application (kg ha^{-1}) at Tygerhoek from 2002 to 2020

4.3.3.4 Soil available nutrients

When looking at the Ca, Mg, K, P, and S all show the same trend at the beginning of the trial at Langgewens (Figure 52). There is an increase in the soil nutrient content during the first three years. This might have been due to the increase of OM deposited in the topsoil from the plant residue left from the no-till practice. Another influence is that 2003-2004 was drought years which resulted in lower yields, thus subsequent lower nutrient use. Nutrients are released back into the soil as plant residues decompose, with higher quantities at the soil surface. Due to less soil mixing by tillage, stratification, both vertical and horizontal, is expected to occur more in no-till and minimum-till systems (Dinkins, et al., 2014). All the nutrients then show an increase which was at its highest during 2010-2011. Thereafter most of the nutrient levels started to stabilize and most increased during 2018-2020. Trendlines were fitted to the soil nutrients which showed which nutrients increased at faster rates. The gradient of the trendlines showed that Ca increased with 0.124 cmol kg^{-1} per year (R^2=0.578), Mg increased with 0.014 cmol kg^{-1} per year (R^2=0.178), K increased with 1.725 mg kg^{-1} per year (R^2=0.313), P increased with 1.928 mg kg^{-1} per year (R^2=0.704), S increased with 0.549 mg kg^{-1} per year (R^2=0.271). These results suggest that Ca had the fastest rate of increase per year, followed by P. The trendline which explained the most variation between the years was also P with 70.4%.

When the nutrient status is compared to the yield graphically, the nutrient status influences the yield of the following year. With the nutrients increasing during the first 3 years there is a significant increase in yield from 2003-2006. Thereafter both the yield and nutrients decreased. The nutrient increase during 2010-2011 is also seen in the yield during 2011-2013, and the increase in both at the end of the trial. Not all the variation in yield can be explained by the nutrient status of the soil, but it is a major factor (Burstrom, 1968; Schjønning, et al., 2018; Yu, et al., 2018; Burkitbayev, et al., 2021). This can be seen in the trial at Langgewens. The statistics show no significant linear correlation between yield of the current season and Ca, Mg, K, P, and S with $p= 0.96$, $p= 0.61$, $p= 0.28$, $p= 0.48$, and $p= 0.07$ respectively. There is a negligible positive correlation for all the nutrients with the current season’s yield.

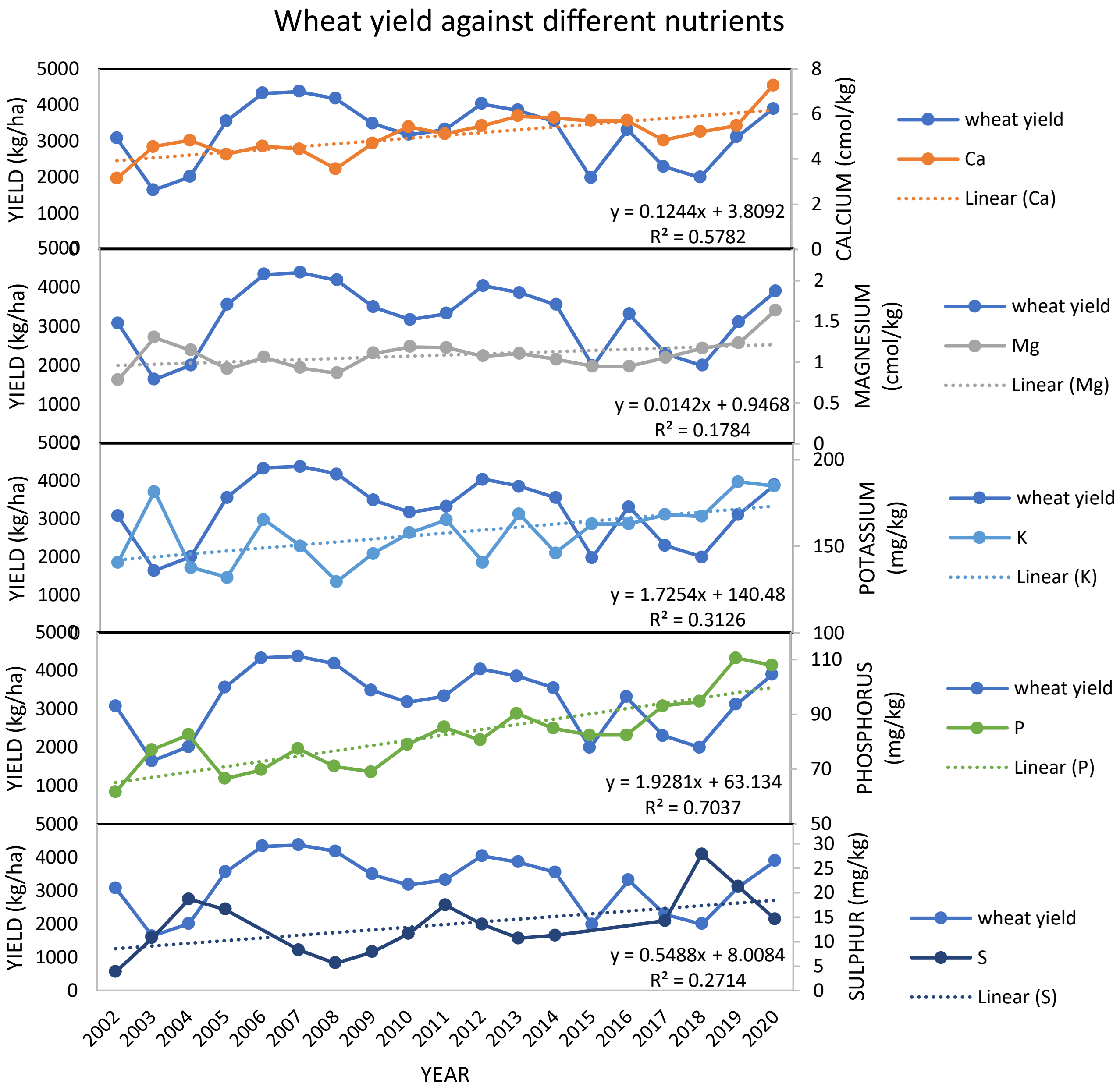

Figure 52: Wheat yield against nutrient content of the top 15 cm of the soil at Langgewens from 2002 to 2020

At Tygerhoek the level of S in the soil is limiting. The nutrient status of all the nutrients was variable at the start of the trial (Figure 53). The nutrients started to stabilise at a certain point thereafter. This can be seen with Mg, K, P, and S. Sodium increased and then decreased, while Ca increased steadily throughout the trial period. The gradient of the trendlines showed that Ca increased with 0.283 cmol kg^{-1} per year (R^2=0.597), Mg increased with 0.003 cmol kg^{-1} per year (R^2=0.015), K decreased with 1.453 mg kg^{-1} per year (R^2=0.136), P increased with 0.172 mg kg^{-1} per year (R^2=0.017), S decreased with 0.185 mg kg^{-1} per year (R^2=0.149). These results suggest that Ca had the fastest rate of increase per year. There was also a decrease across the trial period for K and S. The trendline which explained the most variation between the years was also Ca with 59.7%.

When looking at the nutrient status against the yield it is visible that the yield is also variable at the start of the trial. The same trend can be seen as was at Langgewens with the yield corresponding to the previous season's nutrient status. All the nutrients showed a decrease during 2002-2003 and yield 2003-2004. Nutrients increased in 2003-2004 and yield 2004-2005. Thereafter no trend can be seen between all the nutrients thus it is not possible to attribute further increases or decreases in yield to the observed nutrients. The statistics show no significant linear correlation between the yield of the current season and Ca, Mg, K, and S with p= 0.50, p= 0.16, p= 0.24, and p= 0.10 respectively, while P showed a significant linear correlation for the current season's yield with a p-value of 0.03. There is a negligible positive correlation for all the nutrients with the current season's yield.

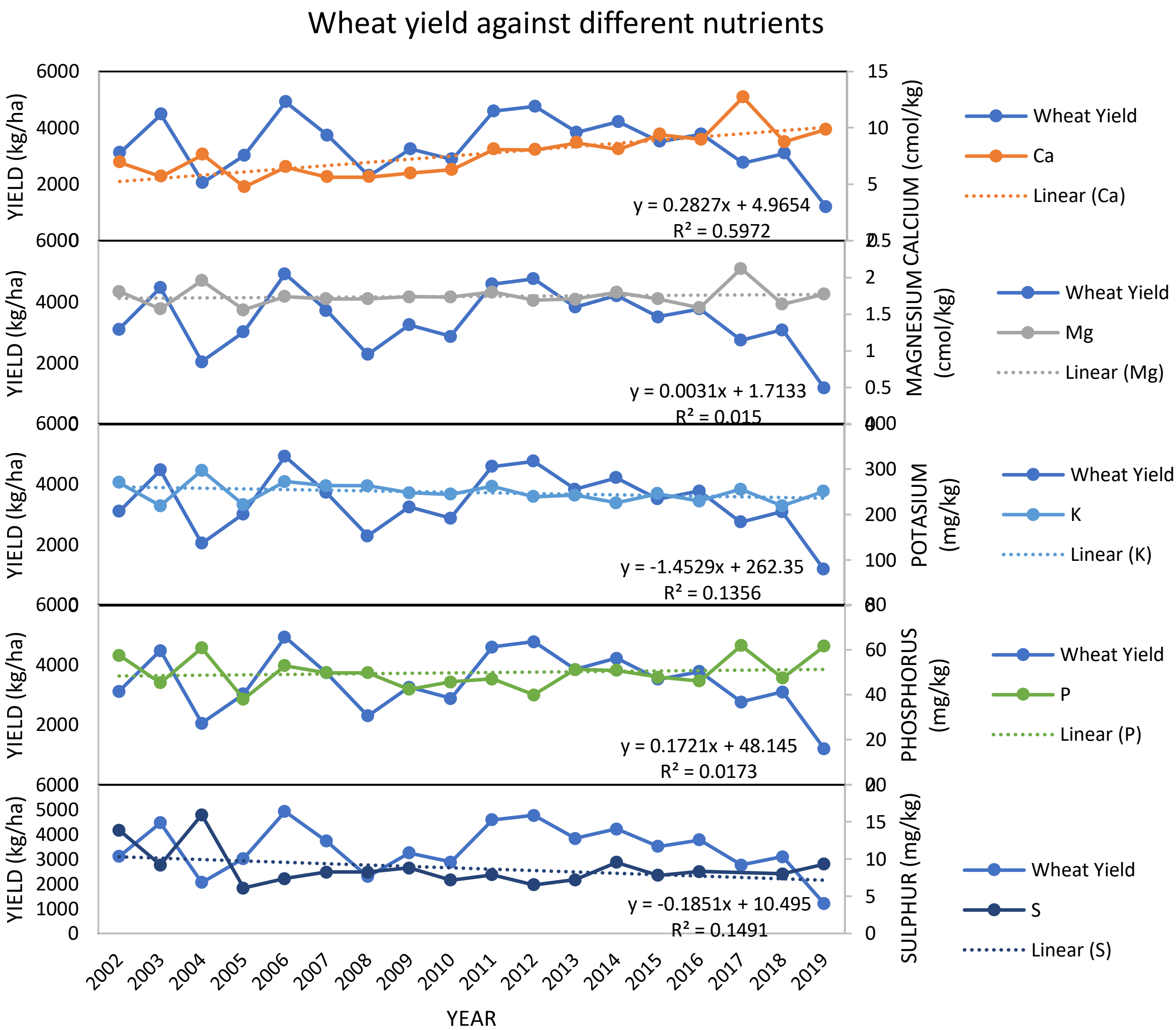

Figure 53: Wheat yield against nutrient content of the top 15 cm of the soil at Tygerhoek from 2002 to 2019

4.3.3.5 Clay-to-carbon ratio

The texture of the soil might not have a direct influence on the yield, but it will determine the water holding capacity, infiltration, permeability, aeration, aggregate stability, and organic matter- and nutrient availability (He, et al., 2014). To maintain the same level of aggregate stability when clay content increased, a higher SOC content was required (Johannes, et al., 2017). Soinne et al. (2020) found that when looking at the clay-to-C ratio there is a negative correlation with grain yield, especially when the ratio is higher than 15. Johannes, et al., (2017) found that a reasonable goal is 1:10 and the optimal value for soil structure quality is 1:8. During the trial at Langgewens, there is a decrease in the clay:C ratio from about 12 to 8 (Figure 54). The highest clay:C ratio was observed in the first two years, with the two lowest yields being in 2003 and 2004. The ratio is then at the reasonable goal and then reaches the optimum. The statistics show no significant linear correlation between yield and the clay-to-carbon ratio with p= 0.92. There is a negligible correlation. To see significant results the clay:C ratio should be far greater than the reasonable goal.

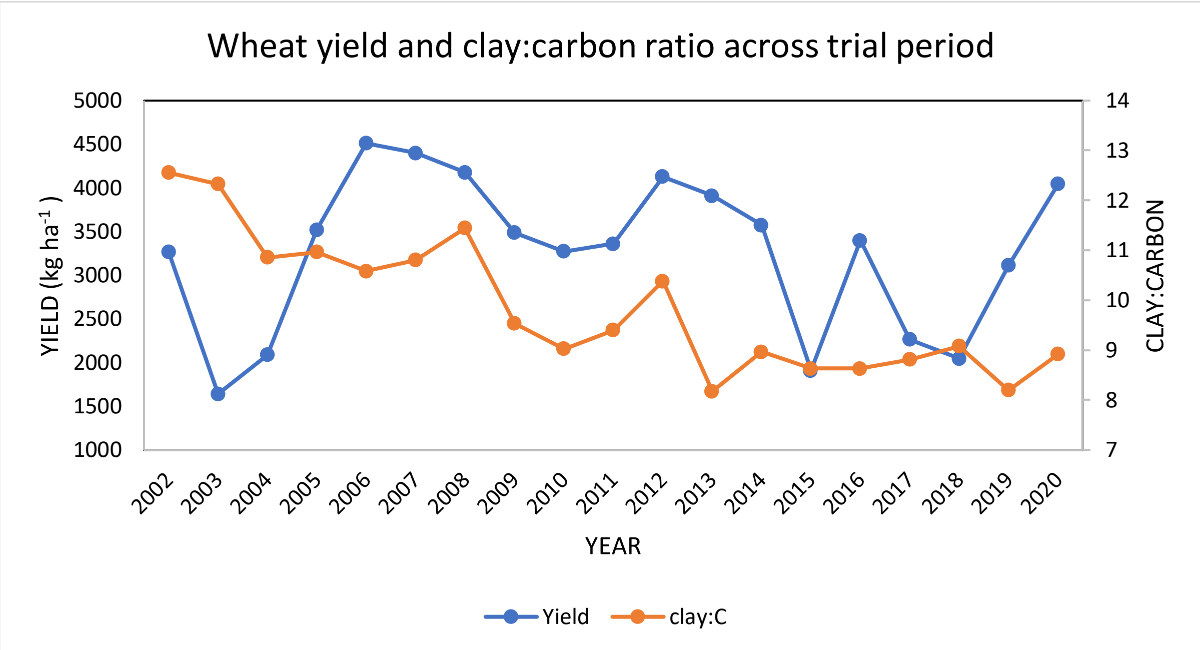

Figure 54: Wheat yield against the clay-to-carbon ratio at Langgewens from 2002 to 2020

When looking at the clay:C ratio at Tygerhoek it is difficult to see any correlation. The ratio is always between 10 and 13 and does not increase or decrease significantly (Figure 55). It is also not higher than 15 where Soinne et al. (2020) found a significantly negative correlation, but also not at the reasonable goal that Johannes, et al., (2017) found. This means that the SOC content needs to be higher to reach the optimal value of 8. The clay:C ratio is not a limiting factor in either of the trials. The statistics show no significant linear correlation between yield and the clay-to-carbon ratio with p= 0.49. There is a negligible positive correlation with R^2= 0.0.03 for clay:C.

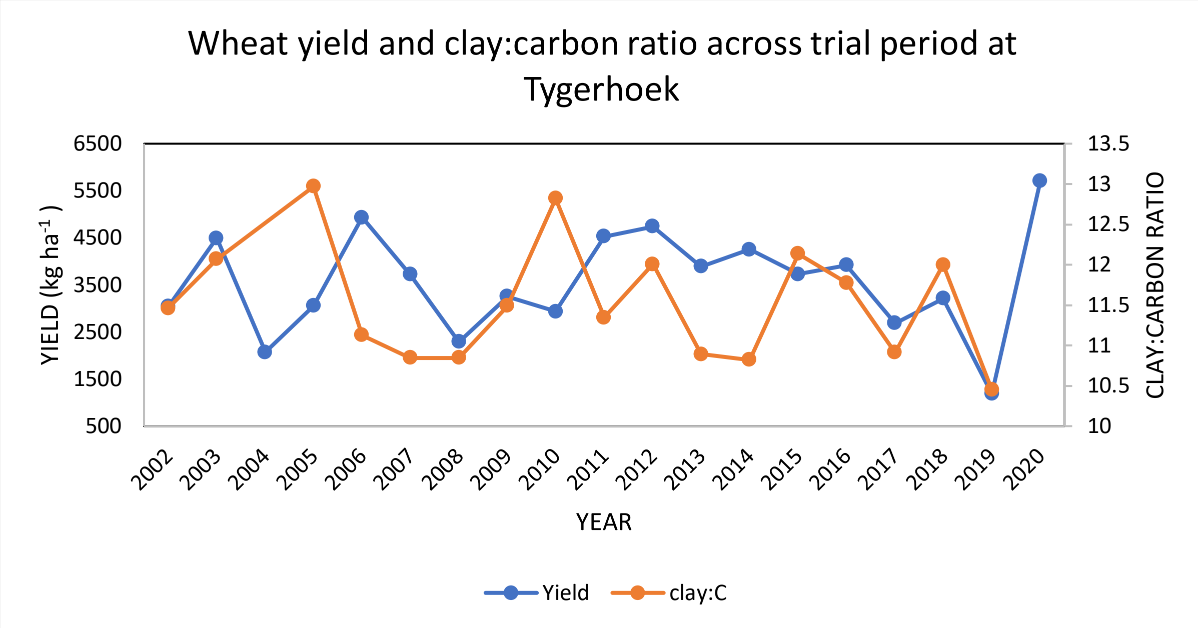

Figure 55: Wheat yield against the clay-to-carbon ratio at Tygerhoek from 2002 to 2020

4.3.4 Soil organic carbon and yield correlation

Soil quality and productivity can be improved by an increase in the SOC content of the soil (Àlvaro-Fuentes et al., 2008; Lal, 2011). It is then expected for the SOC content of the soil to have a positive relationship with the yield of the crop produced. A possible reason for this positive relationship is the addition of SOM (SOC) contributes to soil fertility through external nutrient supply. E, et al., (2018) found a positive relationship between wheat yield and SOC in a long-term study but also found that both increased at first while yield started to plateau off after some time. This study was conducted in the Loess Plateau in China where the threshold in SOC for the increase in yield was 6.8%. According to a meta-analysis done by both Oldfield, et al., (2019) and Sun, et al., (2020) an increase of both SOC and yield is expected in semi-arid regions when conservation agriculture is implemented, while semi-arid to humid regions has no change in yield with increase in SOC, and cold humid and tropical humid climates does not gain SOC and a negative correlation with yield. This applies to both trials in this study. Smith, et al., (2020) also found a significant positive relationship between SOC and yield at Tygerhoek during the 2012 season.

4.3.4.1 Relationship between soil organic carbon and wheat yield

When the SOC content of the soil is graphically shown against the yield it can give a trend for the relationship. At Langgewens no linear correlation ($p>0.01$) was found between the SOC content and yield. From Figure 56 a negligible interaction between SOC and yield is seen with a R^2 value of 0.0031, which tells us that only 3% of the variance in yield can be explained by the SOC. The visual representation also shows another trend: there is an increase in yield with an increase in the SOC content of the soil until a certain point, which is about 1.1% SOC, and then a decrease thereafter. There is also a higher degree of variability of yield between 0.9% and 1.4%.

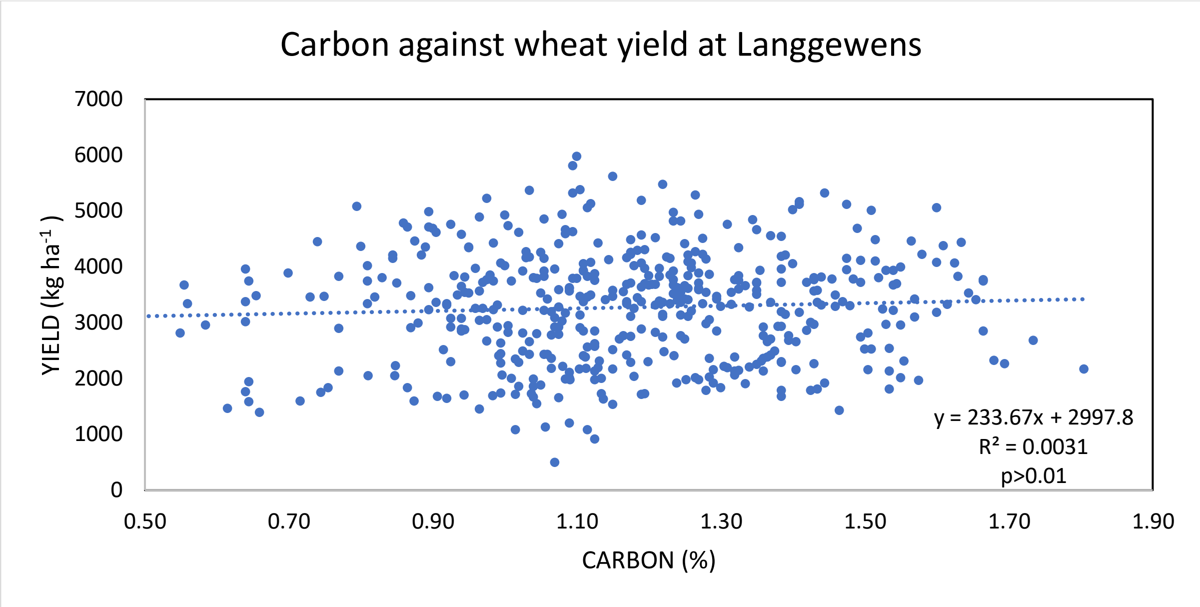

Figure 56: Soil organic carbon (%) in the top 15 cm of the soil against wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

At Tygerhoek the trend with many of the data points being clustered in a certain range can be seen in Figure 57. The most yield is between 1.2% and 2.1% SOC. There is also a slight increase in yield between 0.6% and 1.6% SOC and a decrease between 2.1% and 3.1%. There was also no linear correlation found ($p>0.01$) and a negligible interaction between the yield and SOC (R^2=0.005).

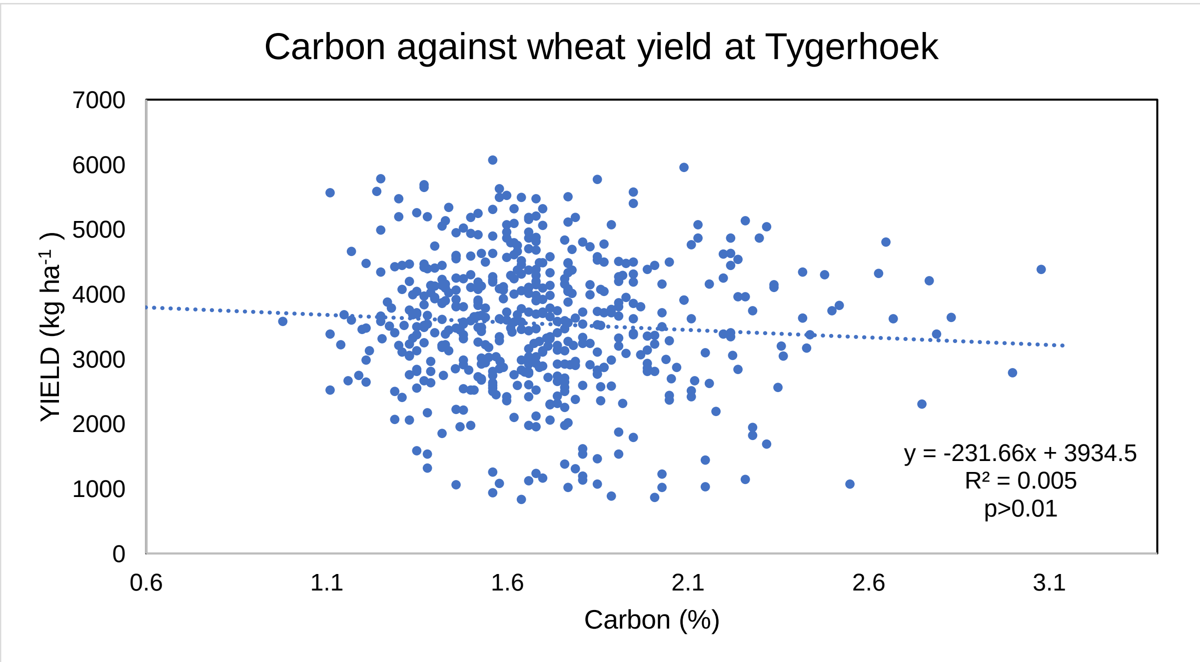

Figure 57: Soil organic carbon (%) in the top 15 cm of the soil against wheat yield (kg ha^{-1}) at Tygerhoek from 2002 to 2020

4.3.4.2 Effect of different crop rotational systems on SOC and yield relationship

The crops which are planted in the rotational system will influence the yield of wheat and the SOC content. From the previous chapter at Langgewens the system with WWCL and WMcWMc+saltbush had the highest SOC content, and WMcWMc+saltbush and WMWC had the highest wheat yield. Figure 58 shows that the systems which had a higher average SOC generally had a higher wheat yield. The obvious exception is the system with WWWC. The relationship between the SOC content and wheat yield for the crop rotational systems shows an increase in SOC will increase wheat yield, with y = 2998,3x - 181,04. According to the statistics, there is not a significant linear relationship between wheat yield and SOC content for the crop rotational systems, with a p-value of 0.09. The R^2 value shows a low positive correlation of 0.41.

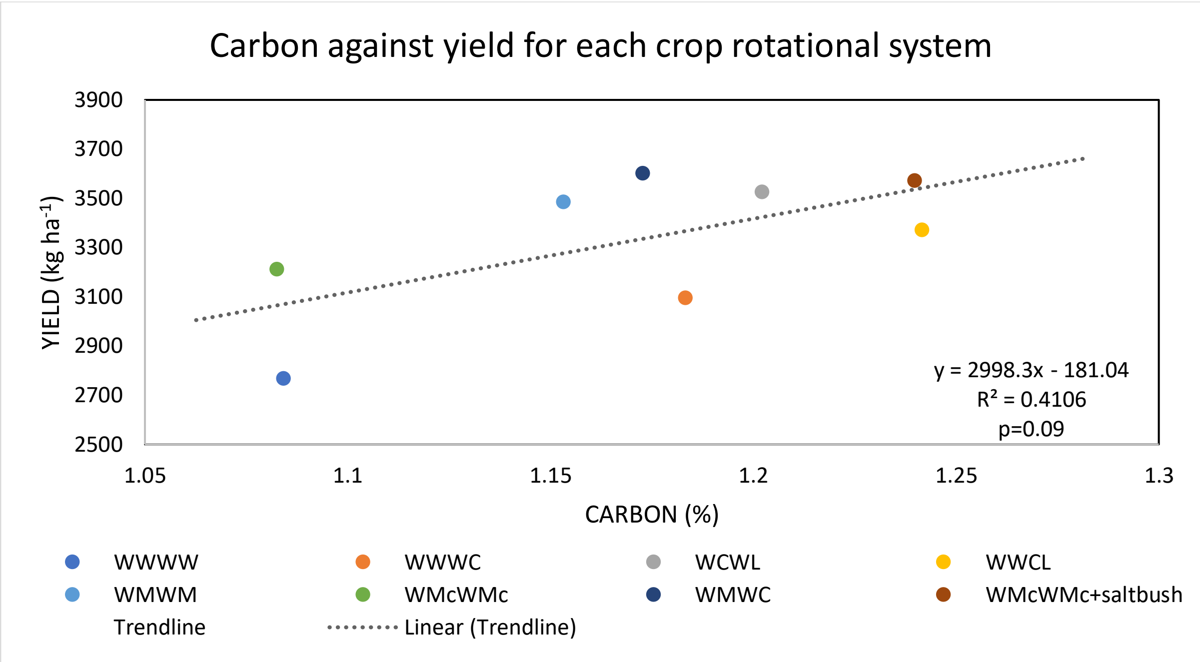

Figure 58: The average soil organic carbon content (%) in the top 15 cm against wheat yield (kg ha^{-1}) for each crop rotational system at Langgewens from 2002 to 2020. The system with WWWW is wheat monoculture, WWWC is wheat and canola rotation, WCWL and WWCL is wheat, canola, and lupin rotation, WMWM is wheat and medic rotation, WMcWMc is wheat and medic/clover rotation, WMWC is wheat, medic, and canola rotation, and WMcWMc+saltbush is wheat and medic/clover rotation with saltbush

At Tygerhoek the system with PPC had a significantly higher SOC content, and PCPC and PPC had the highest average wheat yield across the trial period. The SOC content against the wheat yield (Figure 59) shows an increase in both SOC and yield in the CCC, PCCP, and PPC systems, while the system with PCPC had the highest yield with a low SOC content. The trendline shows an increase in SOC will increase wheat yield, with y = 674,67x + 2432,8. According to the statistics, there is not a significant linear relationship between wheat yield and SOC content for the crop rotational systems, with a p-value of 0.61. The R^2 value is 0.15, which shows a negligible positive correlation between SOC content in the soil and wheat yield for the crop rotational systems.

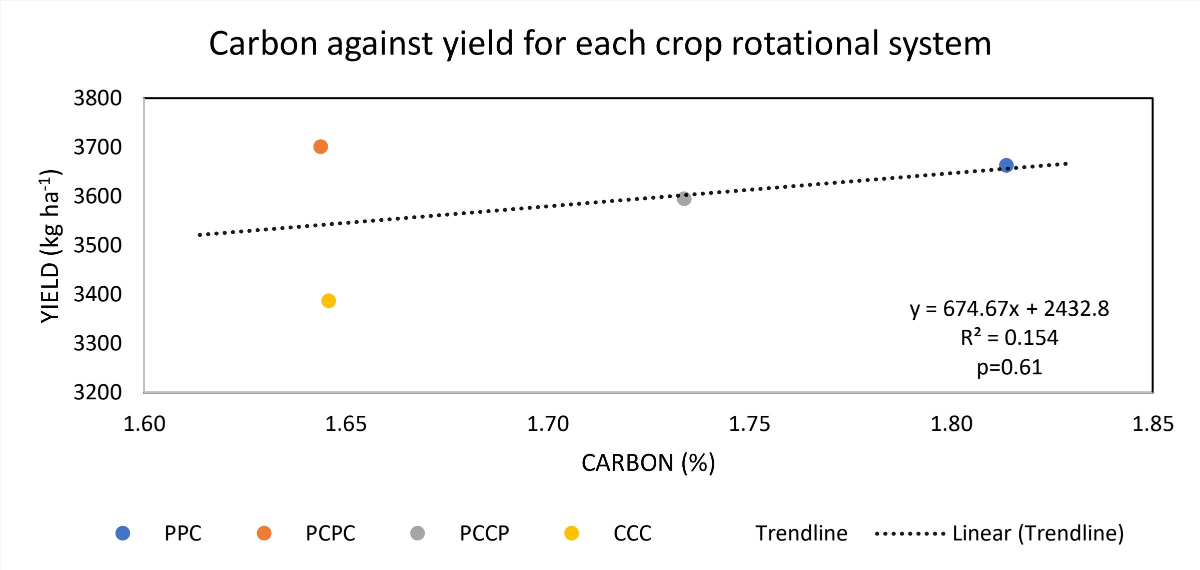

Figure 59: The average soil organic carbon content (%) in the top 15 cm of the soil against the wheat yield (kg ha^{-1}) for each crop rotational system at Tygerhoek from 2002 to 2020. The system with PPC is 33% crop and 67% pasture rotation, PCPC and PCCP is 50% crop and 50% pasture rotation, and CCC is 100% cash crop rotation. The crops included wheat, barley, canola, and oats.

The different systems have different crops which are in rotation. Central to this is the root architecture, biomass produced, and yield removed (Rasse, et al., 2005). At a depth of 5 to 10 cm, lucerne and medic/clover had the largest root densities, whereas barley had the lowest, according to Smith, et al., (2020). Medic/clover also have complete dieback and reestablishment in winter which results in new roots forming. This explains the higher SOC content of the rotation systems with medics. When compared to medic/clover residues, wheat above- and below-ground residue has a broader C:N ratio, which means that breakdown is slower and the residue stays in the soil for longer, but the medic/clover SOM could be lost quite soon (Brady & Weil, 2014). Due to the increased N content of legume residue compared to other crops, lucerne and medic/clover have higher nitrogen levels. This could influence the high biomass (C) producing crops as this could increase the range of the C:N ratio.

When considering the differences in yield, the crops in the rotational system can influence the yield of the wheat. Angus et al. (2015) found no significant difference when using barley as a rotation crop, canola showed a positive response, and legumes will result in N fixation, thus the yield of the wheat did increase after lupines were grown. Connor et al. (2011) found that there is also an effect on the yield when implementing a fallow season. Smith et al. (2020) found that implementing medics increases the yield and protein content of wheat when implementing.

By considering which systems should result in the higher SOC content and wheat yield from the literature we can compare the finding in this study. At Langgewens WMWC, WMcWMc+saltbush, WCWL, WMWM, and WWCL had a higher SOC content and wheat yield. These systems included medics/clover and lupin for a higher SOC, and canola, lupin, and medics which had a positive influence on yield. at Tygerhoek the systems with PPC and PCCP had a high yield and SOC content, while PCPC had only a high yield. here the effect of the abovementioned crops and pastures are visible. The finding in this study is in line with other literature.

4.3.4.3 Effect of SOC on yield

The SOC has a variety of impacts on the chemical and physical environment of the soil, which will determine soil health. These will significantly impact crop productivity and can include reduced dependence on fertilizers through mineral release, and drought resistance. To see what the effect of SOC is on yield it can be visualized by plotting the average SOC content and yield for each year against each other. The effect that yields, thus the amount of residue left, has on SOC was looked at in Chapter 3. At Langgewens wheat yield had a significant increase during 2003-2004, 2004-2005, 2005-2006, 2011-2012, 2015-2016, 2018-2019, and 2019-2020, and a decrease during 2002-2003, 2007-2008, 2014-2015, and 2016-2017 (Figure 60). The SOC content had a significant decrease in C between 2011-2012 and 2013-2014, and an increase between 2008-2009, 2012-2013, and 2018-2019. By comparing the changes in wheat yield with that of SOC content it becomes clear that there is a possible effect of SOC on wheat yield. There was a significant increase in SOC during 2008-2009, 2012-2013, and 2018-2019, while the wheat yield increased during 2011-2012, 2015-2016, and 2019-2020. The decrease in SOC was seen during 2011-2012 and 2013-2014, with yield decreasing during 2014-2014 and 2016-2017. This effect on wheat yield is seen two to three years after there was a significant change in SOC content of the top 15 cm of the soil. The statistics also show that there is no linear correlation between SOC and the current season's yield, with a p-value of 0.83, and an R^2-value of 0.003.

This effect can be referred to in literature, as a higher SOC content has a positive correlation to the health of the soil (Lal, 2016). Healthier soil will then produce a higher yield (Nunes, et al., 2018). Soil health is rather built over time; thus, it will explain the time lag which is observed in this study between the significant changes in SOC content and the yield of wheat.

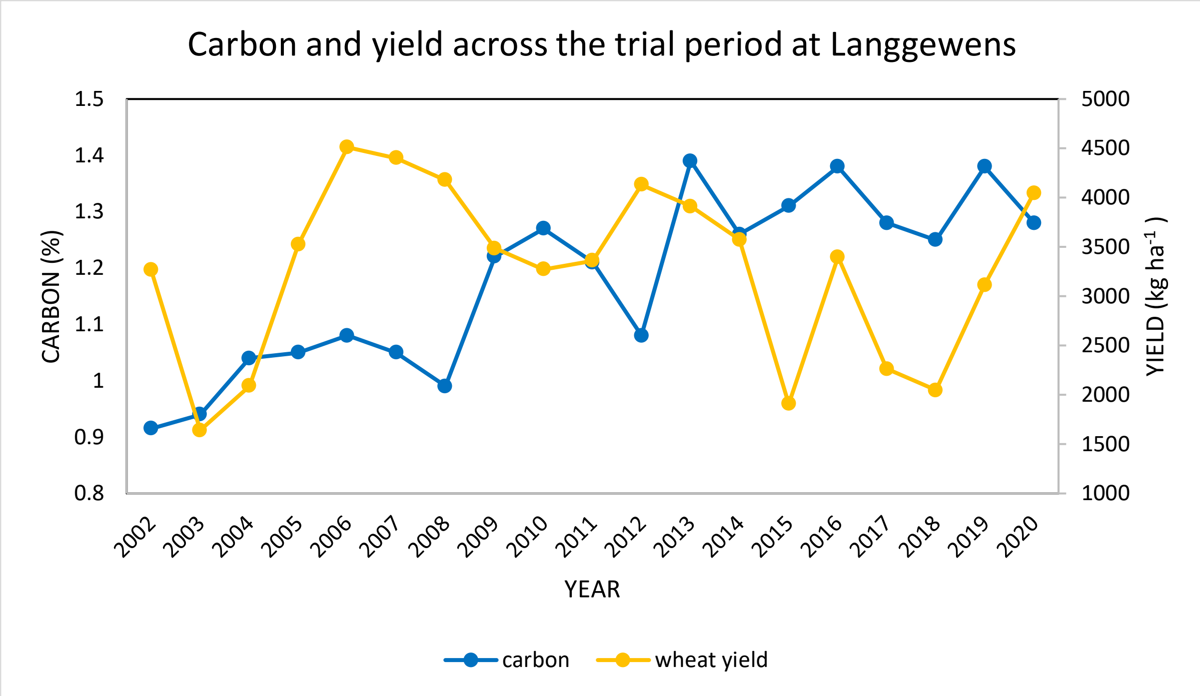

Figure 60: Average soil organic carbon (%) in the top 15 cm of the soil and wheat, canola, and lupin yield at Langgewens from 2002 to 2020

At Tygerhoek the wheat yield shows a significant decrease during 2003-2004, 2006-2007, 2007-2008, 2009-2010, 2012-2013, 2014-2015, 2016-2017, and 2018-2019, with an increase during 2002-2003, 2004-2005, 2005-2006, 2008-2009, 2010-2011, 2013-2014, 2017-2018, and 2019-2020 (Figure 61). The SOC content was significantly lower in 2003-2005, 2008-2009, 2014-2015, and 2017-2018. The significantly higher years were: 2005-2006, 2012-2013, 2016-2017, and 2018-2019. The effect of changes in SOC content against wheat yield is not as pronounced at Tygerhoek compared to Langgewens. Some of the years show a two-to-three-year lag. SOC increased significantly during 2005-2006, 2012-2013, 2016-2017, and 2018-2019 while the corresponding wheat yield increase was seen during 2008-2009,2013-2014, 2017-2018, and 2019-2020. There was a significant decrease observed in SOC during 2002-2005, 2008-2009, 2014-2015, and 2017-2018, with wheat yield during 2006-2008, 2009-2010, 2016-2017, and 2018-2019. The significant changes in wheat yield are seen one to three after there was a significant change in SOC. The statistics also show that there is no linear correlation between SOC and the current season's yield, with a p-value of 0.54, and an R^2-value of 0.03.

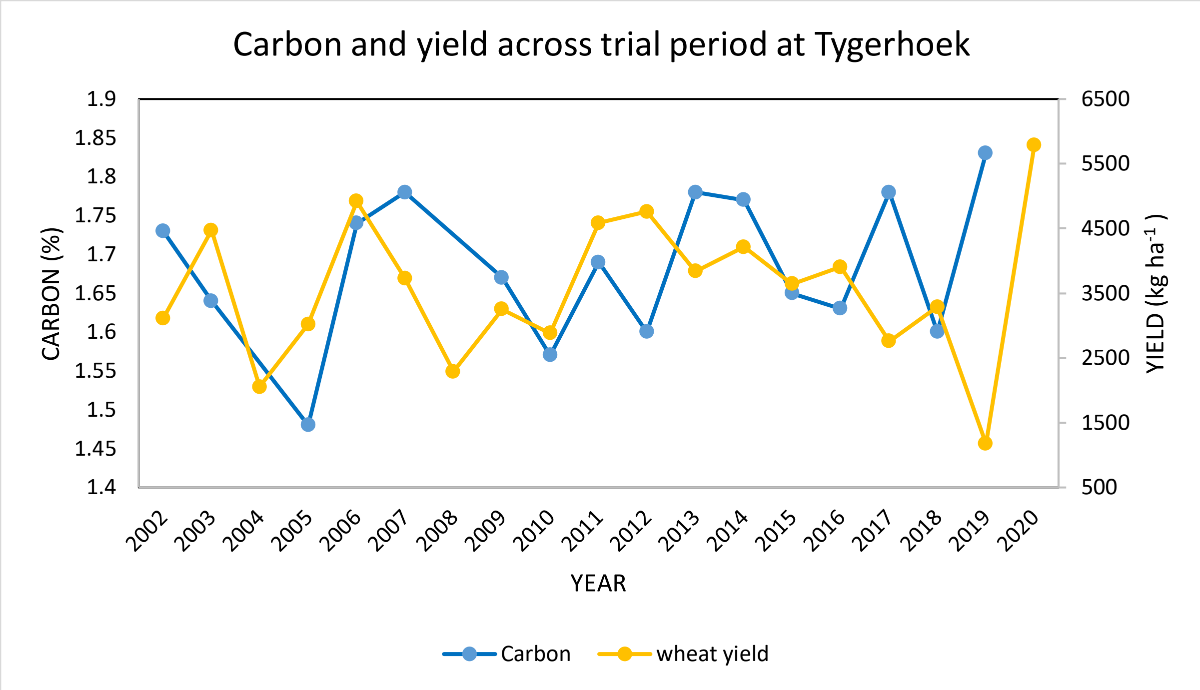

Figure 61: Average soil organic carbon (%) in the top 15 cm of the soil and wheat yield at Langgewens from 2002 to 2020

4.3.4.4 Partial correlation of SOC and yield

The partial correlation measures the degree of association between two random variables, in this case, SOC content and wheat yield. From the previous section, it was concluded that the effect that SOC has on yield is seen two to three years after a significant change was observed. This is further proved by looking at the partial correlation between SOC and yield (Table 3). A partial correlation of SOC and yield was done for both Langgewens and Tygerhoek for the current and next season's yield. the results show positive, negative, and no correlation for certain years throughout the trial period. For the current season's partial correlation there was a significantly positive partial correlation for 2006, 2007, 2012, 2013, 2016, and 2020. The next season's yield only showed a significantly negative partial correlation in 2019.

When looking at the partial correlation results against what was found when showing SOC content and yield over time some of the significant results can be explained. At both Langgewens and Tygerhoek, there was a higher SOC content and wheat yield in 2006, 2007, 2013, 2016, and 2020 at Langgewens. At Tygerhoek the SOC was highest in 2019, with the highest yield in 2020, and Langgewens that both SOC and yield high in 2019 and 2020 respectively. Thus, this result does not match what was found in the partial correlation of the following year's yield.

Table 3: Partial correlation between the soil organic carbon and wheat yield for both Langgewens and Tygerhoek from 2002 to 2020

	Yield		Following year's yield	
Year	Partial correlation	p-value	Partial correlation	p-value
2002			0.02	0.88
2003	0.27	0.11	-0.19	0.07
2004	0	0.97		
2005	0.14	0.33	-0.02	0.85
2006	0.63	<0.01	0.03	0.8
2007	0.36	<0.01	-0.05	0.63
2008			-0.05	0.62
2009	0.5	<0.01	0.07	0.49
2010	0.35	<0.01	-0.02	0.82
2011	-0.1	0.46	0.06	0.59
2012	0.39	<0.01	0.19	0.06
2013	0.48	<0.01	-0.05	0.62
2014	0.26	0.05	0.11	0.29
2015	-0.26	0.06	0.13	0.24
2016	0.45	<0.01	0.1	0.35
2017	-0.02	0.86	-0.09	0.41
2018	-0.11	0.41	0.02	0.82
2019	0.09	0.52	-0.28	<0.01
2020	0.43	<0.01		

4.3.5 Panel regression: What affects yield?

The results of the previous section show that there is no direct (linear) correlation between SOC content and wheat yield. This points to a more complex relationship where more of the variables needs to be included. This gives rise to the use of a panel regression. In contrast to standard linear regression models, panel data regression effectively manages the dependencies of unobserved independent variables on a dependent variable that can result in biased estimators (Brugger, 2021). The statistics software selects the model fit which best explains the data. In this case, it is the fixed two-way model. This model includes both unit-fixed and time-fixed effects in ordinary least squares estimation. Three models were evaluated: (1) current seasons yield against SOC, soil nutrients, and seasonal rainfall, (2) the following year's yield against the variables, and (3) the previous year's rainfall against the current yield and variables. The adjusted R2 values for the three models are 0.10, 0.06, and 0.09. This shows that the amount of variation explained by the independent variables that affect the dependent variable is rather low. These three models were used as in previous sections it was concluded that some factors are better correlated to the following year's yield, and from this, the rainfall was significant which led to the third model of what is the effect of the previous year's rainfall on the different factors. The rainfall was also selected as the most limiting factor will determine the yield according to Liebig's law (Liebig, et al., 2004), which in the case of dry land agriculture is most often soil moisture, which is influenced by the rainfall. The variance inflation factor (VIF) (Table 4) for all the variables in the panel regression is calculated, and there is no multicollinearity between the regression variables as the VIF is smaller than 5.

Table 4: Variance inflation factor (VIF) for all the variables in the panel regression

VIF	Current yield	Following year's yield	Previous years rainfall
Carbon	2.4	2.1	2.5
pH	1.9	1.9	1.8
Resistance	1.5	1.3	1.4
Calcium	2.3	2.5	2.3
Magnesium	2.4	2.5	2.3
Sodium	1.8	1.7	1.6
Potassium	1.5	1.5	1.5
Phosphorus	1.2	1.3	1.3
Sulphur	1.1	1.1	1.1
Rainfall	1.2	1.2	1.2

The panel regression shows which variables have a significant effect on the yield. When looking at the yield in the current season resistance ($p<0.01$) and K ($p=0.01$) are significant, and Na ($p=0.07$) also has an effect (Table 5). Resistance has a standard coefficient of 0.243 which shows a positive correlation, while K and Na have a negative correlation with -0.127 and -0.075 respectively. These results point to the possible toxicity and subsequent lower yield that these nutrients could have. It could also be explained by what is seen when yield and nutrients were compared with the previous one or two seasons' nutrients affected the yield. The higher resistance of the soil will mean a higher soil salinity; thus, it will not result in a higher yield. An explanation for seeing this might be that the camps that had a higher salinity also had a higher yield.

When all the variables are correlated to the next year's yield resistance shows a significant negative correlation ($p<0.01$) with a standard coefficient of -0.124, while rainfall and magnesium have a significant positive correlation ($p<0.01$ and $p=0.05$) and a standard coefficient of 0.388 and 0.107. Here the effect of salinity is highlighted against the yield. Magnesium deficiency cause stunted growth (thus positive correlation) and magnesium can also be added through lime; thus, the results are seen in the following year's yield. The rainfall correlates to the following year's yield can be explained by a great need for moisture by the wheat after emergence and during the growth stages of the season. This is true for Tygerhoek and not Langgewens, as there is nearly no moisture in the soil during the summer months. This is influenced by the moisture stored during the summer months of that and the previous year's rainfall.

As the current rainfall influences the next year's yield, it is important to look at what effect the previous year's rainfall had on the yield and other variables of the current year. The previous year's rainfall was positively significant ($p<0.01$ and 0.194). Resistance had a positive significant correlation ($p<0.01$ and 0.197) again. Potassium had a negative significant ($p=0.03$ and -0.113) correlation. This could be the result of toxicity because potassium increases crop yields as it increases root growth and improves drought tolerance.

Table 5: Regression summary of the significance that each of the variables has on yield with regard to the p-value

Variables	Current yield		Following year's yield		Previous years rainfall	
	p-value	Std Coeff	p-value	Std Coeff	p-value	Std Coeff
Carbon	0.43	0.042	0.91	-0.005	0.16	0.074
pH	0.14	0.062	0.13	-0.059	0.68	0.017
Resistance	<0.01	0.243	<0.01	-0.124	<0.01	0.197
Calcium	0.53	-0.028	0.32	-0.046	0.95	-0.003
Magnesium	0.28	0.055	0.05	0.107	0.79	0.015
Sodium	0.07	-0.075	0.38	-0.033	0.2	-0.05
Potassium	0.01	-0.127	0.63	0.023	0.03	-0.113
Phosphorus	0.21	0.068	0.47	0.035	0.29	0.059
Sulphur	0.78	0.008	0.83	0.006	0.96	0.002
Rainfall	0.81	0.011	<0.01	0.388	<0.01	0.194

In statistics, standardized coefficients are the estimates that come from a regression analysis where the underlying data have been standardized so that the variances of dependent and independent variables are equal to 1. For the current and next year's yield, SOC had a positive and negligible standard coefficient, pH had positive and negative, the nutrients had varied outcomes, with Sulphur having the smallest standard coefficients, and rainfall had positive coefficients, which is expected as higher rainfall will result in a higher yield but spread over the season and up to a certain point.

4.3.6 Factors affecting the quality of wheat

Depending on the wheat class, region, type, and quality of the soil and fertilizer, the protein content will vary significantly. In the context of South Africa, 11.5 % wheat protein is the desired level (Department: Agriculture, Forestry and Fisheries, 2022). The wheat protein level is an excellent general indicator of the quality of the wheat. The two key nutrients which affect the protein content of wheat are nitrogen and sulphur. Both sulphur and nitrogen are essential macronutrients and building blocks of protein biosynthesis (Yu, et al., 2018).

At Langgewens the average protein content across the trial period was 12.29%. The years that were significantly lower than the previous ones were: 2005, 2009, 2016, 2018, and 2020. While 2003, 2006, 2010, 2015, and 2017 were significantly higher than the previous (Figure 62).

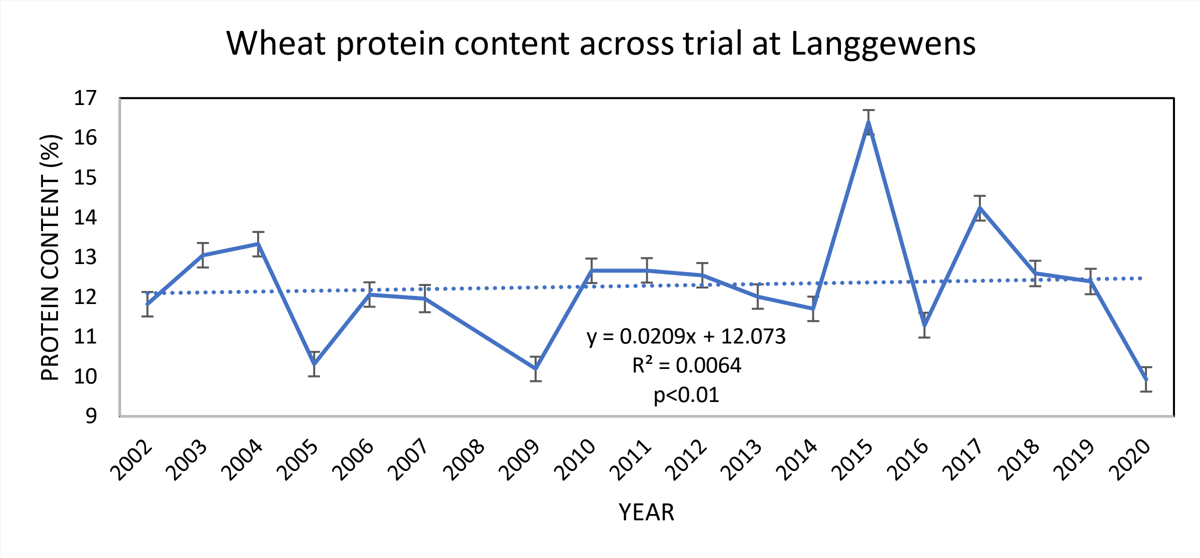

Figure 62: Average wheat protein content (%) at Langgewens from 2002 to 2020

The grade of the wheat protein differs between the years (Table 6). The year which had the lowest grade was 2020 with B4, while 2005 and 2009 were B3. Grade B2 was seen in 2002, 2006, 2007, 2013, and 2014. The best grade is B1 which was in 2003-2004, 2010-2012, and 2015-2019. This correlates to the significant changes in protein content, especially in 2002, 2005, 2009, and 2020 being lower.

Table 6: Wheat protein content and grade for each year at Langgewens from 2002 to 2020.

Year	Protein content (%)	Grade
2002	11.82	B2
2003	13.05	B1
2004	13.33	B1
2005	10.31	B3
2006	12.06	B2
2007	11.96	B2
2009	10.19	B3
2010	12.66	B1
2011	12.67	B1
2012	12.55	B1
2013	12.01	B2
2014	11.70	B2
2015	16.39	B1
2016	11.29	B1
2017	14.23	B1
2018	12.59	B1
2019	12.39	B1
2020	9.93	B4

At Tygerhoek the years that were significantly lower than the previous were 2003, 2012, 2016, 2018, and 2020 (Figure 63). The years that were significantly higher than the previous ones were 2004, 2006, 2010, 2015, 2017, and 2019. The average protein content across the trial period was 12,35%.

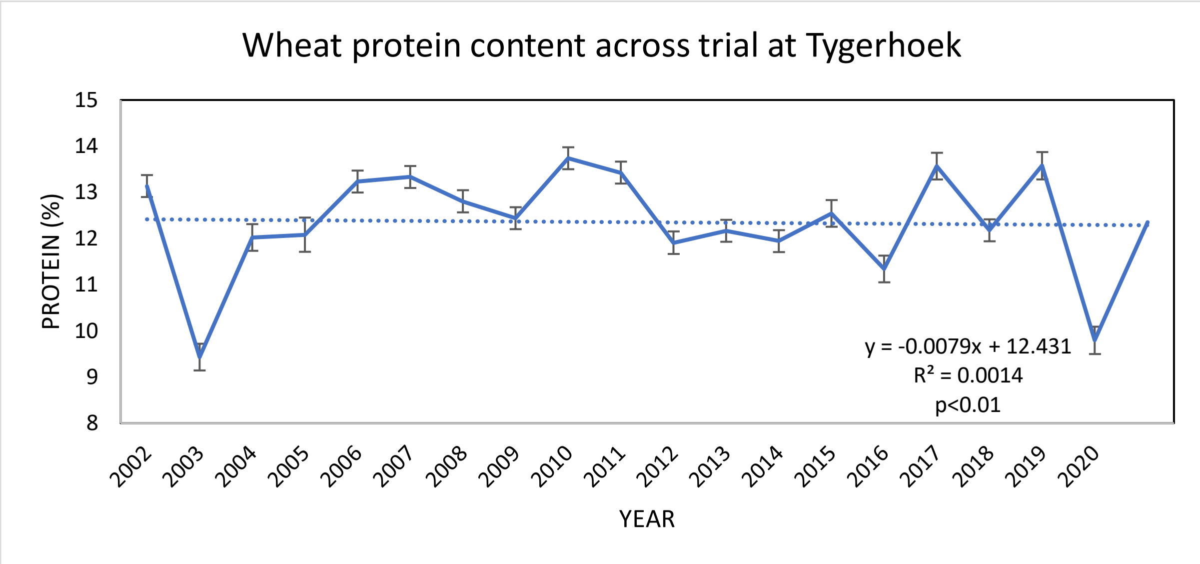

Figure 63: Average wheat protein content (%) at Tygerhoek from 2002 to 2020

The protein grade showed differences between the different years (Table 7). A grade of B4 was seen in 2003 and 2020. There were no B3, with B2 in 2004-2005, 2012, 2014, and 2016. Grade B1 was seen in 2002, 2006-2011, 2013, 2015, and 2017-2019. When comparing the grade to the significant changes it correlates to 2003, 2012, 2014, 2016, and 2020.

Table 7: Wheat protein content and grade for each year at Tygerhoek from 2002 to 2020

Year	Protein content (%)	Grade
2002	13.14	B1
2003	9.43	B4
2004	12.02	B2
2005	12.08	B2
2006	13.23	B1
2007	13.33	B1
2008	12.81	B1
2009	12.44	B1
2010	13.74	B1
2011	13.43	B1
2012	11.91	B2
2013	12.17	B1
2014	11.94	B2
2015	12.54	B1
2016	11.34	B2
2017	13.57	B1
2018	12.18	B1

2019	13.58	B1
2020	9.79	B4

4.3.6.1 Effect of yield on wheat protein

A higher yield will constitute the crop taking up higher amounts of nutrients which might result in lower protein content. The protein content and hectoliter mass (HLM), which is a measure of the volume of grain per unit, of wheat, are inversely correlated which can explain why higher yields will have a lower protein content. This can be seen at Langgewens (Figure 64). For each season the relationship is negatively proportionate. 2002-2004 shows a decrease in yield and an increase in protein, increase in yield between 2004-2009 sees a lower protein content, while the lower yield between 2009-2011 showed an increase in protein content. For each of the years between 2014-2020, the yield and protein content show the opposite result.

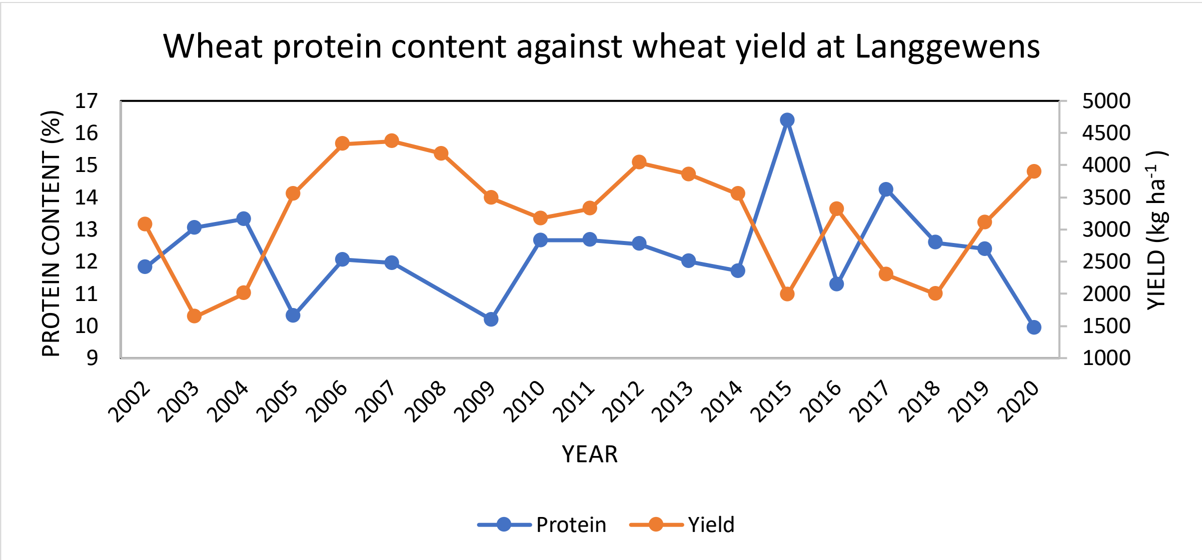

Figure 64: Average wheat protein content (%) and wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

At Tygerhoek the trend is not as pronounced between the wheat yield and protein content (Figure 65). The opposites are seen between 2002-2004 and 2016-2020.

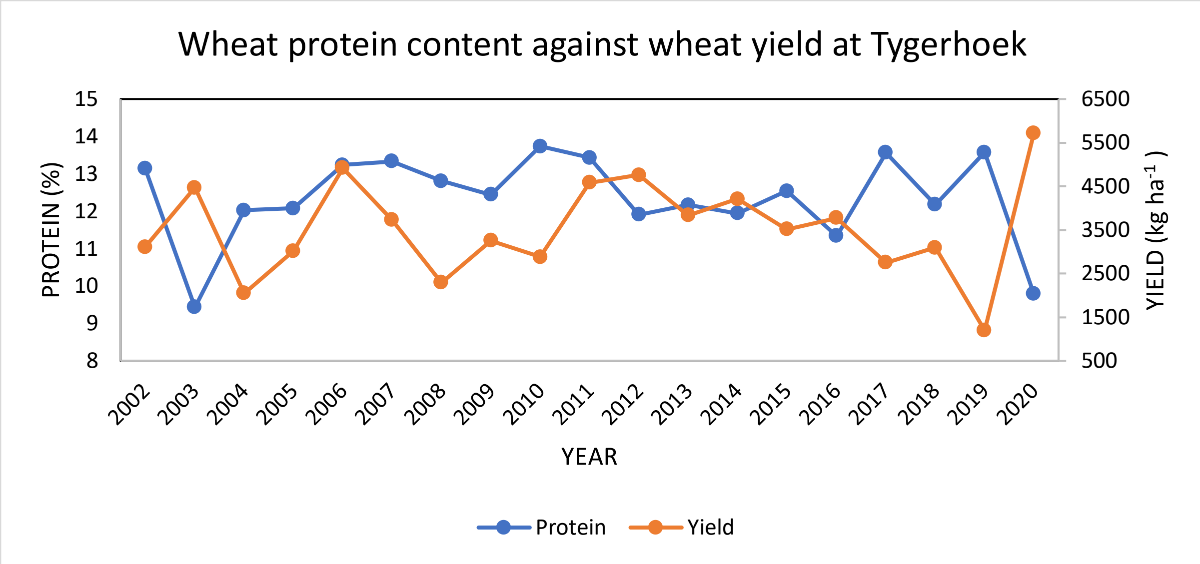

Figure 65: Average wheat protein content (%) and wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

4.3.6.2 Effect of rainfall and drought on wheat protein

The crops' ability to synthesize carbohydrates is reduced when there is an insufficient water supply, which reduces yield. Protein content and carbohydrate content are negatively related (Sehgal, et al., 2018). So, in times of drought, the protein content rises while the carbohydrate content falls. At Langgewens this inverse relationship can be observed (Figure 66) between the yearly rainfall and protein content. The increase in protein and decrease in rainfall is seen during 2002-2003, 2004-2005, 2006-2007, 2009-2010, 2012-2013, 2014-2015, 2015-2016, 2016-2017, 2017-2018, and 2019-2020. This relationship is also observed when looking at the seasonal rainfall against the protein content (Figure 67).

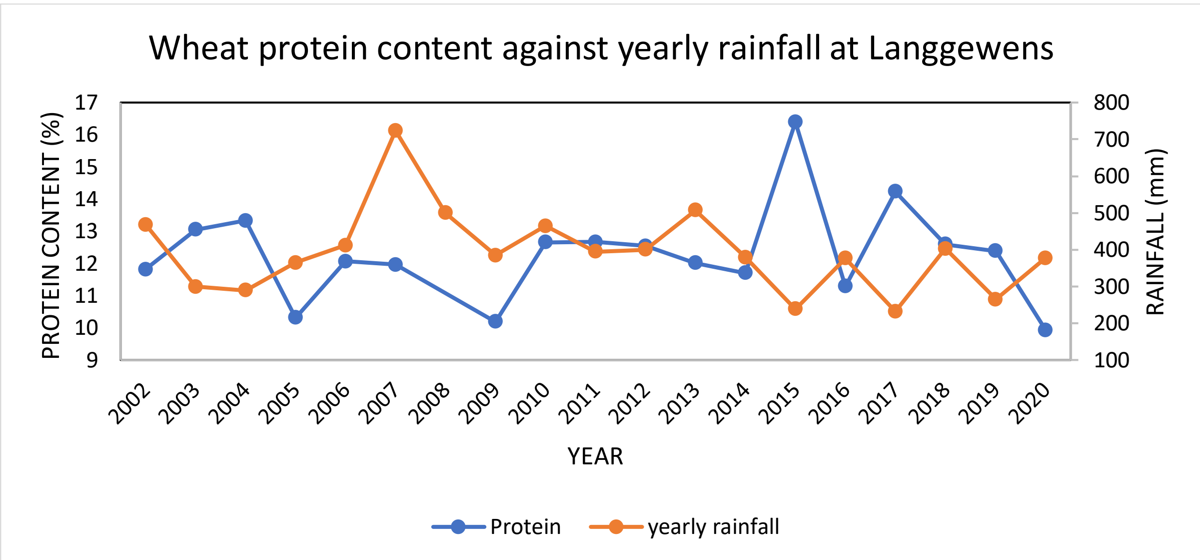

Figure 66: Average wheat protein content (%) and yearly rainfall (mm) at Langgewens from 2002 to 2020

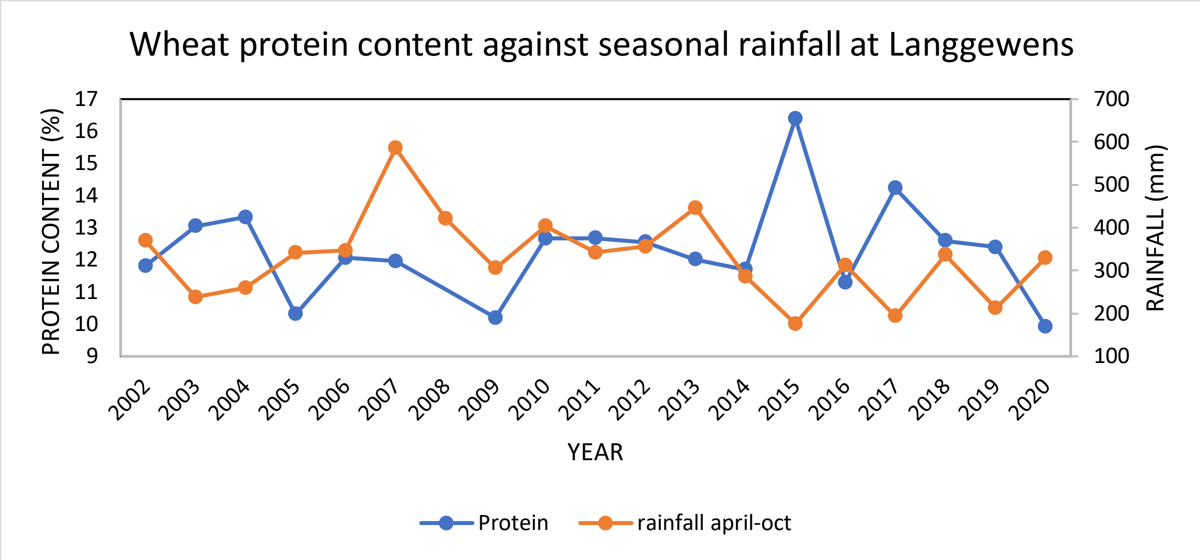

Figure 67: Average wheat protein content (%) and rainfall (mm) from April to October at Langgewens from 2002 to 2020

At Tygerhoek the inverse relationship is also observed for the yearly (Figure 68) and seasonal rainfall (Figure 69) against the protein content. For the yearly rainfall this is observed during 2002-2003, 2004-2005, 2007-2008, 2010-2011, 2011-2012, 2014-2015, 2015-2016, 2016-2017, 2017-2018, and 2019-2020.

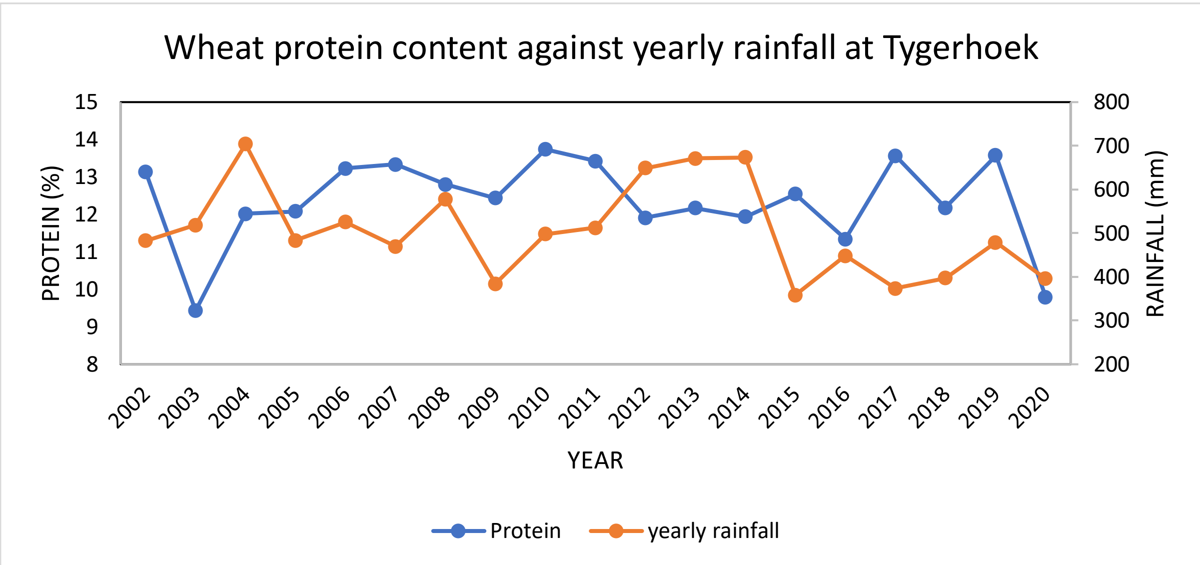

Figure 68: Average wheat protein content (%) and yearly rainfall (mm) at Langgewens from 2002 to 2020

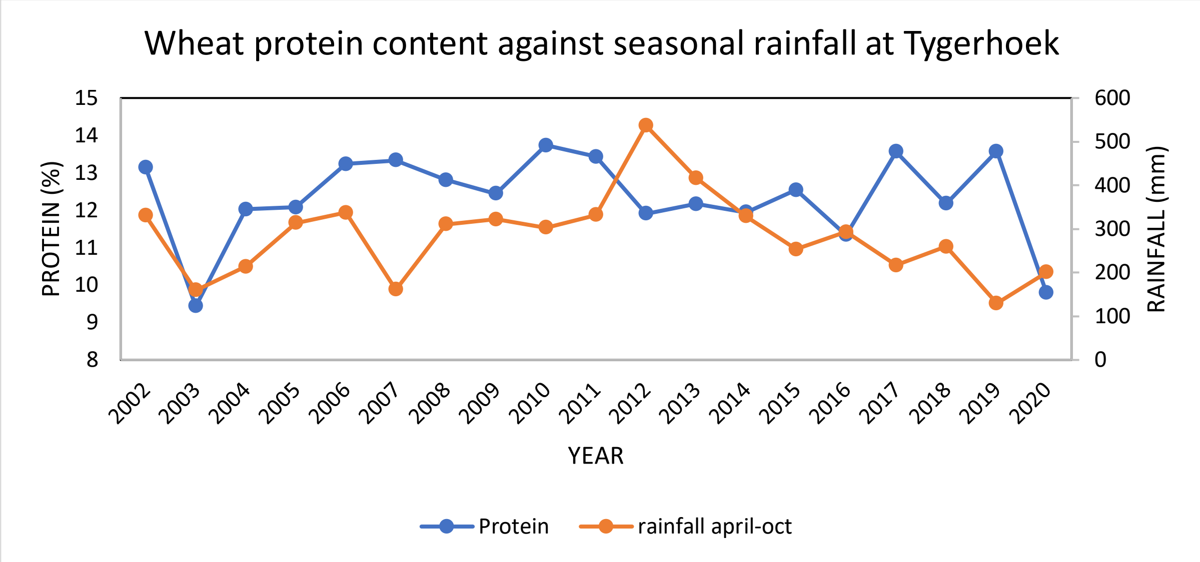

Figure 69: Average wheat protein content (%) and rainfall (mm) from April to October at Langgewens from 2002 to 2020

4.3.6.3 Effect of nitrogen application on wheat protein

Wheat protein is made of amino acids which consist of N; thus, the wheat protein content is correlated to the amount of N in the soil, and thus the amount of N fertilizer applied. Wheat protein significantly increases with an increase in N application, as was found by Zang, et al., (2017). At Langgewens the protein content was significantly lower in 2009 and 2016, while the N applied was the second lowest and zero for those years respectively (Figure 70). When the N application was lower, the protein content was also lower compared to the previous year, as can be seen in 2008, 2009, 2013, 2014, and 2019. The protein content was significantly higher in 2010 and 2015 when the N applied was also higher.

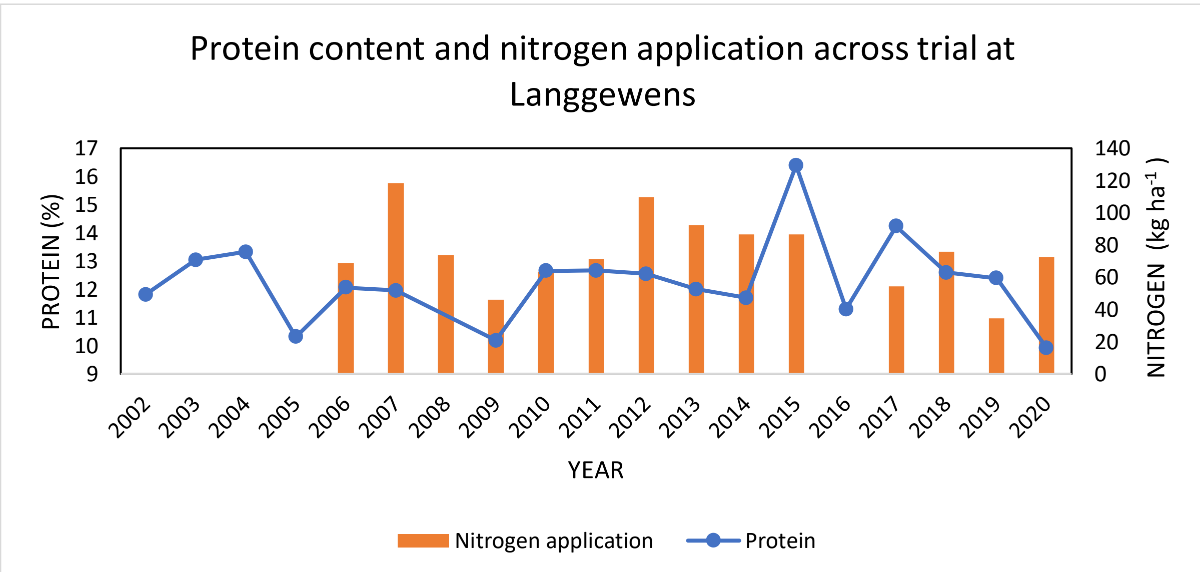

Figure 70: Average wheat protein content (%) and nitrogen application (kg ha^{-1}) at Langgewens from 2002 to 2020

At Tygerhoek the protein content was significantly lower in 2012, 2018, and 2020 when the N applied was also lower (Figure 71). The higher N applied did not correlate as well with the protein content, except in 2010 and 2019, which were both drier years. The effect of lower N application on protein content is much more visible than an increase compared to the previous year, as can be seen also in 2008 and 2011.

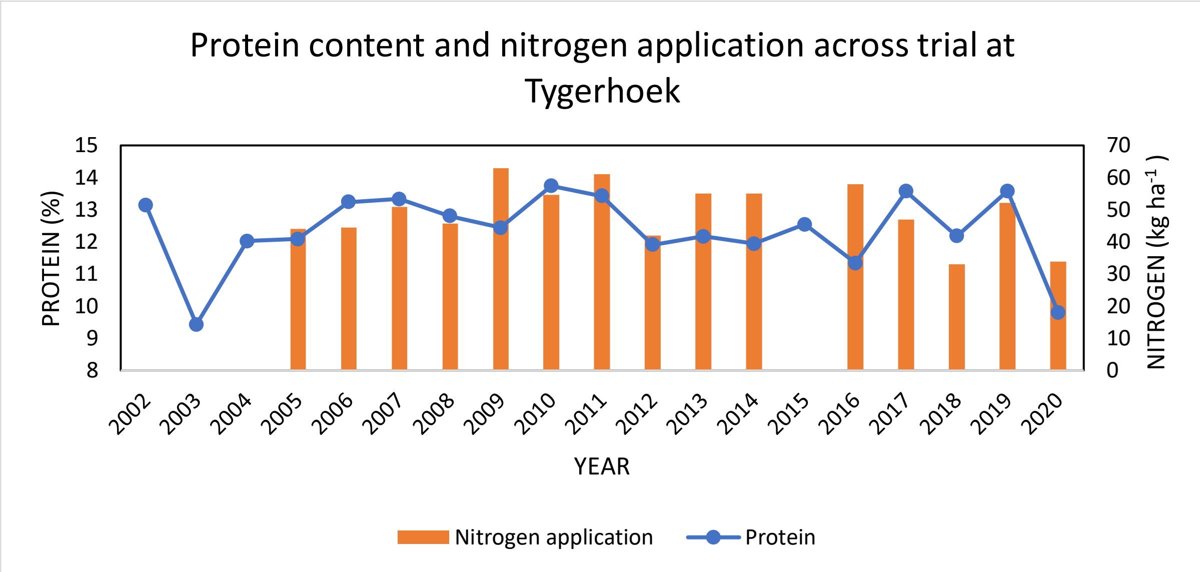

Figure 71: Average wheat protein content (%) and nitrogen application (kg ha^{-1}) at Tygerhoek from 2002 to 2020

4.3.6.4 Effect of soil sulphur content on wheat protein

According to Yesmin, et al. (2021), the critical level of S for wheat is 11 kg ha^{-1}. At Langgewens S is limiting during 2002, 2003, 2007, 2008, and 2013. Sulphur plays a major role in the efficient uptake and use of N in the soil. When wheat protein is shown graphically against sulphur content in the soil (Figure 72) over time, the curves have similar shapes. At the start of the trial, both increased, decrease after 2004, and increase from 2008/2009 until 2011, with a slight decrease and increase at the end. Sulphur is not the only factor that will affect protein content, thus some of the variability cannot be explained by sulphur.

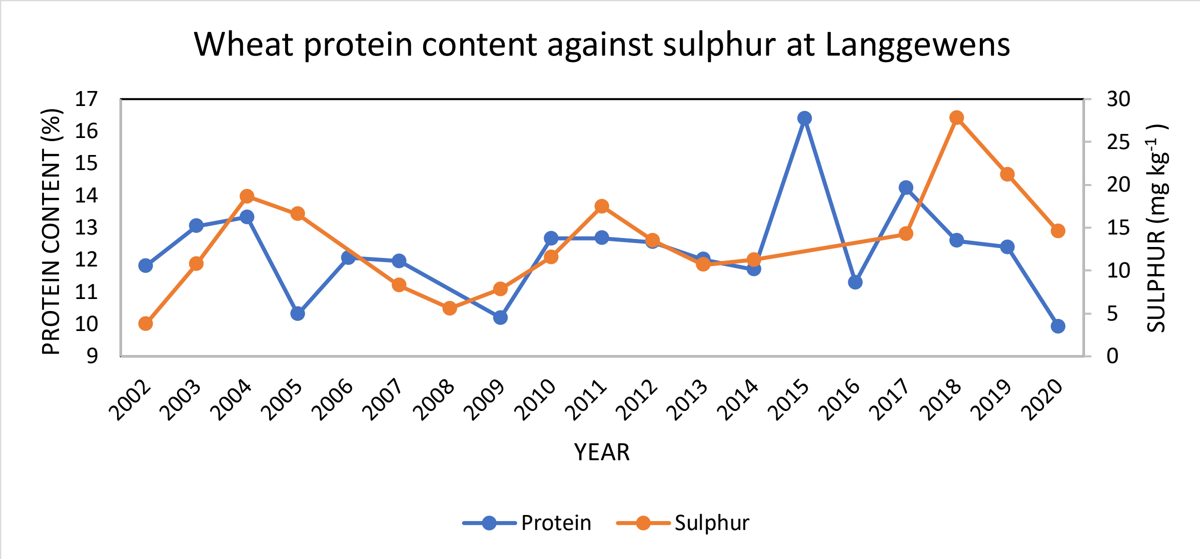

Figure 72: Average wheat protein content (%) and sulphur content (mg kg^{-1}) of the top 15 cm of the soil at Langgewens from 2002 to 2020

At Tygerhoek S was limiting in 2003, and from 2005 to 2019. The shapes of the curves (Figure 73) are also similar. The decrease and increase in the first three years with both protein content and sulphur. After 2005 both are rather stable until 2019. Even though S is limiting for most of the trial it does not seem to majorly affect the protein content of the wheat.

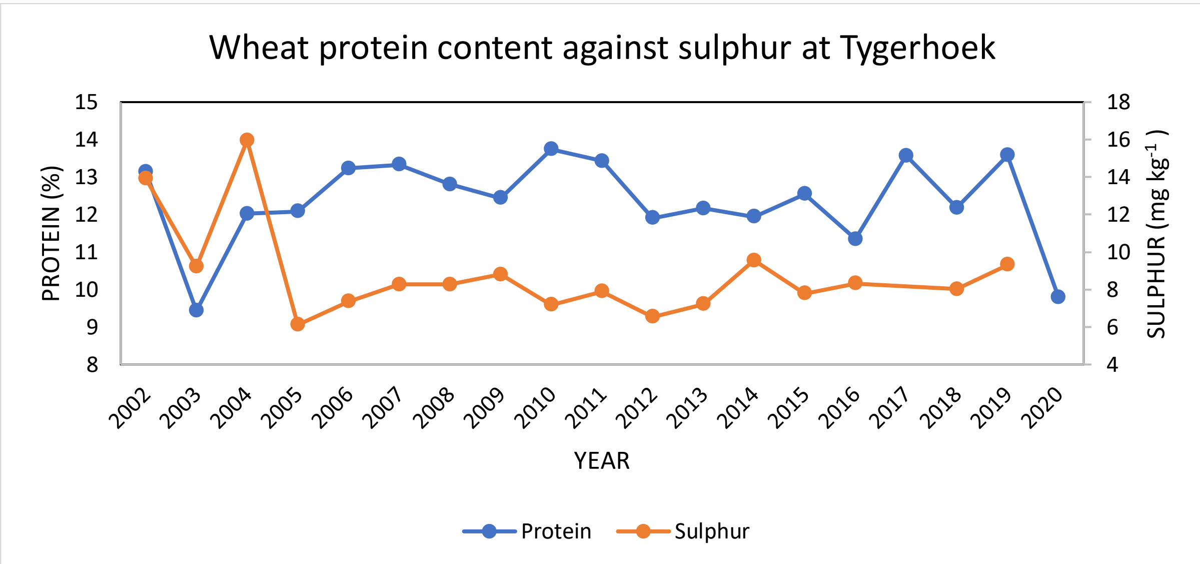

Figure 73: Average wheat protein content (%) and sulphur content (mg kg^{-1}) of the top 15 cm of the soil at Tygerhoek from 2002 to 2020

4.3.6.5 Effect of SOC on wheat protein

The SOC content of the soil will influence the health of the soil, thus the CEC and the nutrient availability (He, et al., 2014). In terms of N and S availability, it is expected for the SOC content of the soil to influence the protein content. At Langgewens the change in wheat protein content seems to follow the changes in SOC content (Figure 74). This trend seems to be one or two years preceding the change in protein content. There is a decrease in SOC between 2006-2008 which is seen in protein content between 2007 and 2009 and an increase between 2008 and 2010 and 2009 and 2011 respectively. The significant increase between 2012-2013 in SOC correlates to a significant increase in protein between 2014-2015. This is supported by the better soil health affecting the protein content found in the literature.

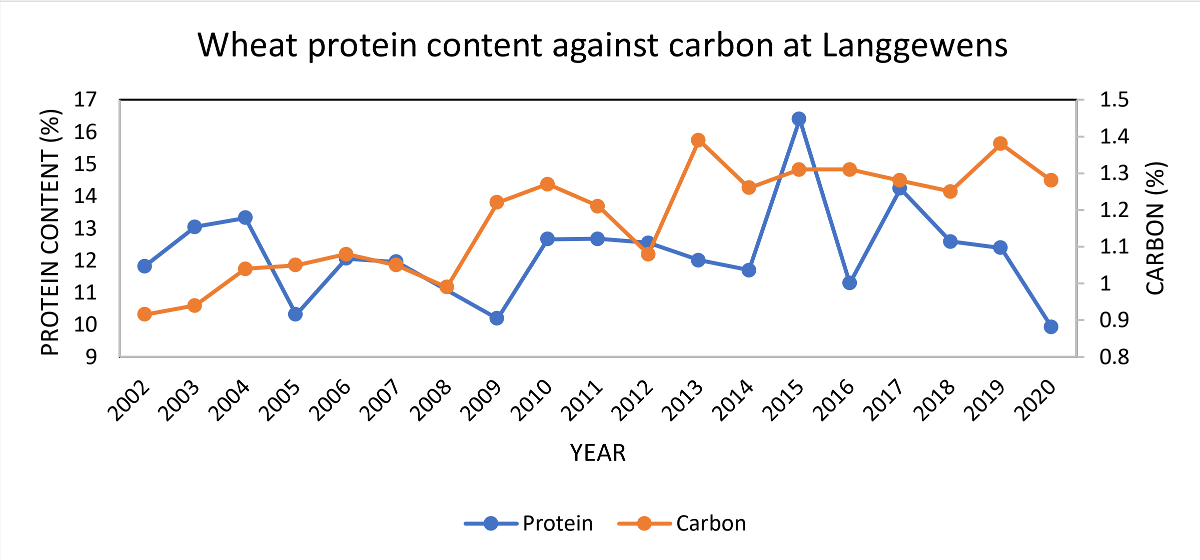

Figure 74: Average wheat protein content (%) and soil organic carbon content (%) of the top 15 cm of the soil at Langgewens from 2002 to 2020

At Tygerhoek the trend of change is also observed, but more pronounced for the next season (Figure 75). The seasons where the SOC content was significantly lower were 2008-2009, 2014-2015, and 2017-2018, while wheat protein content was 2011-2012, 2015-2016, and 2019-2020. When the SOC content was significantly higher in 2012-2013 and 2016-2017, the protein content showed an increase in 2014-2015 and 2018-2019.

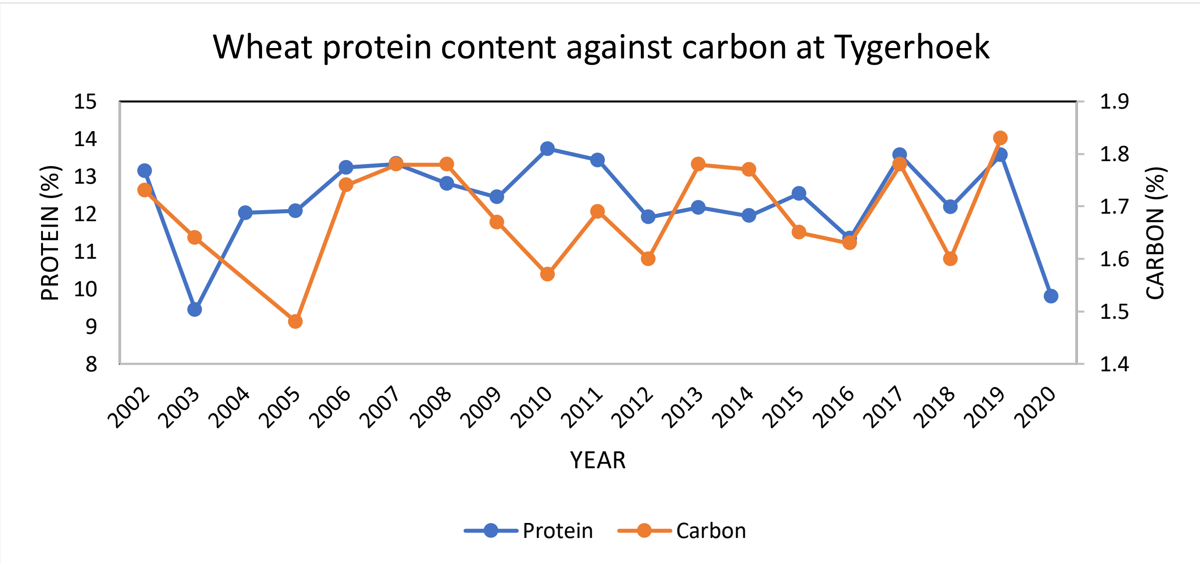

Figure 75: Average wheat protein content (%) and soil organic carbon content (%) of the top 15 cm of the soil at Tygerhoek from 2002 to 2020

4.3.6.6 Effect of crop rotations on wheat protein

The effect that the crop rotational system has on the protein content of wheat is not readily found in the literature. The crop rotational system combines soil N and SOC, as the different crops will have different inputs of above and belowground biomass (Smith, et al., 2020), with differing C:N ratios for the different crops (Brady & Weil, 2014), and higher N content for the legumes (Raphaela, et al., 2016). At Langgewens there are statistical differences between the different rotational systems (Figure 76). The wheat monoculture has the lowest protein content, followed by WWWC. Both these systems are statistically lower than the rest. The two systems with 50% wheat have the same protein content and are statistically lower than the systems which included medics/clover, which have a similar protein content.

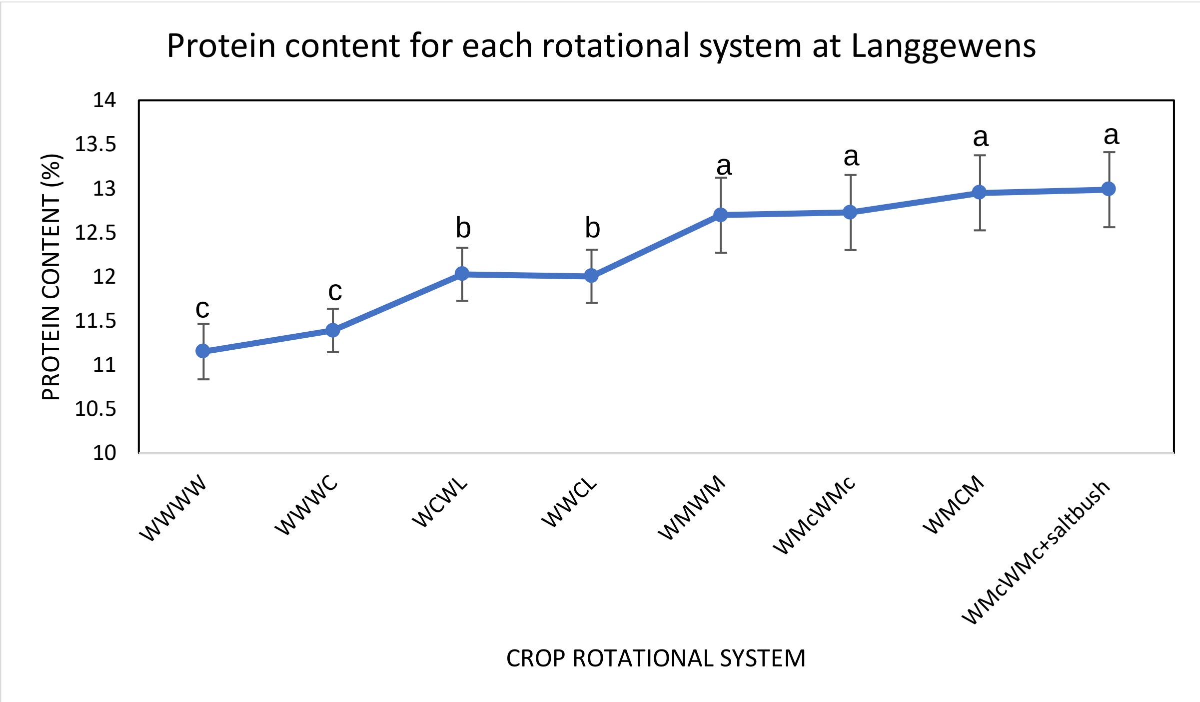

Figure 76: Average wheat protein content (%) for each system at Langgewens from 2002 to 2020. The system with WWWW is wheat monoculture, WWWC is wheat and canola rotation, WCWL and WWCL is wheat, canola, and lupin rotation, WMWM is wheat and medic rotation, WMcWMc is wheat and medic/clover rotation, WMWC is wheat, medic, and canola rotation, and WMcWMc+saltbush is wheat and medic/clover rotation with saltbush

The grade for the wheat protein shows similar results (Table 8). The systems with WWWW and WWWC are classed as B2, while the rest of the systems are all B1. This shows that even though the systems with medics are statistically higher they are still classed together with WCWL and WWCL.

Table 8: Wheat protein content and grade for each of the crop rotational systems at Langgewens from 2002 to 2020

Crop rotational system	Protein content (%)	Grade
WWWW	11,15	B2
WWWC	11,39	B2
WCWL	12,03	B1
WWCL	12,00	B1
WMWM	12,70	B1
WMcWMc	12,73	B1
WMCM	12,95	B1
WMcWMc+saltbush	12,99	B1

At Tygerhoek the same trend can be seen (Figure 77). The system which had 100% crops is significantly the lowest, with 50% crop/50% pasture having similar contents, and the system with PPC had a significantly higher protein content than the rest.

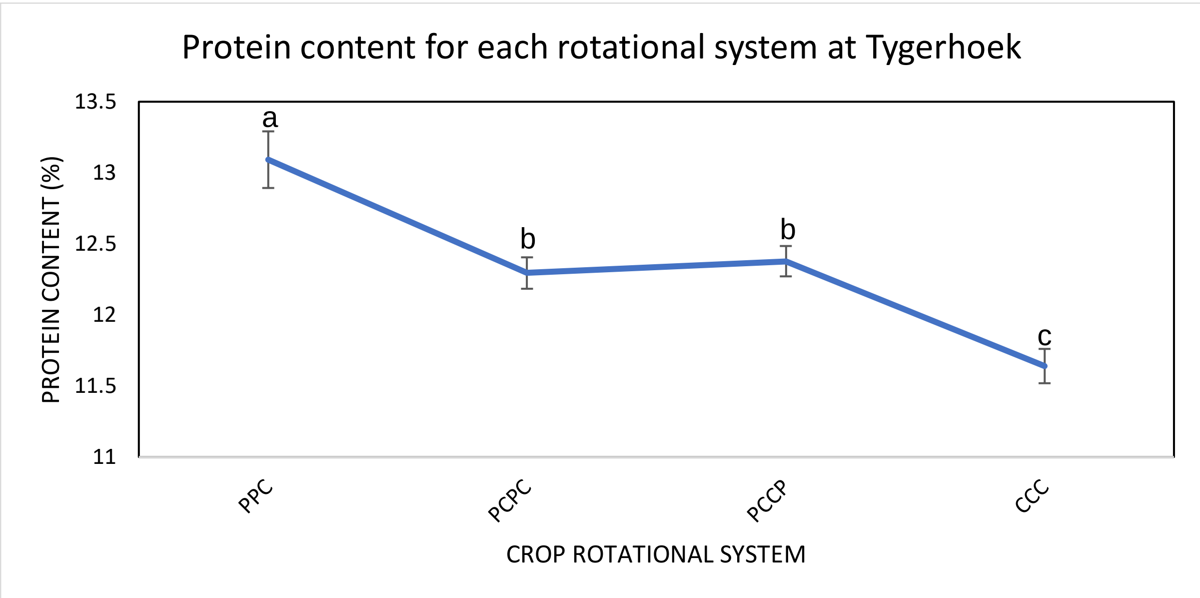

Figure 77: Average protein content (%) for each system at Tygerhoek from 2002 to 2020. The system with PPC is 33% crop and 67% pasture rotation, PCPC and PCCP is 50% crop and 50% pasture rotation, and CCC is 100% cash crop rotation. The crops included wheat, barley, canola, and oats.

The grade of the wheat protein showed similar results to the significant changes in protein content (Table 9). The system with CCC had a B2 while the rest was graded as a B1.

Table 9: Wheat protein content and grade for each crop rotational system at Tygerhoek from 2002-2020

Crop rotational system	Protein content (%)	Grade
PPC	13,09	B1
PCPC	12,29	B1
PCCP	12,38	B1
CCC	11,64	B2

4.4 Conclusions

Soil fertility, water availability, climate, and diseases or pests are the four main variables that influence crop yield. When these factors are not properly monitored and handled, they can pose a serious risk to producers. The SOC content of the soil influences the soil fertility and water availability, thus it will affect the yield. This section looked at the relationship between and the effect of SOC on wheat yield.

At both Langgewens and Tygerhoek, the yield was variable throughout the trial period, while the yield ranged between 1.5 - 4.5 tonnes ha^{-1} and 1 - 6 tonnes ha^{-1} respectively. The rainfall and yield showed the same trends at both farms, along with a significant linear correlation for both yearly and seasonal rainfall. This is expected as the farms are rain-fed and in semi-arid regions.

At Langgewens the pH was between 5.8 and 6 for large periods of the trial, and a positive relationship can be seen when there are changes in pH and yield. At Tygerhoek the pH showed a decrease at the start of the trial, with a constant increase from 6.0 to 6.4 during the latter stages of the trial period. At both farms, an increase in yield can be seen after the application of lime and gypsum.

The application of N to the soil with mineral fertilizers showed a strong positive correlation to the wheat yield, with the highest yield and N application during the same season being observed more than once, while the opposite was also observed. At both Langgewens and Tygerhoek, the nutrients played a role in the yield of wheat. The yield followed the same trend of the nutrient content of the topsoil and was most visible after one to two years. Only P showed a significant linear correlation for the current season's yield at Tygerhoek. The clay:C ratio will show a negative correlation to the yield only above 15. During the trial at both farms the clay:C ratio did not reach 15, thus there was no correlation seen with the wheat yield.

There was no linear correlation between SOC and yield at either farm. A similar trend was seen at both farms, with an increase in both wheat yield and SOC up to a certain point after which yield decreased. This point is about 1.1% SOC at Langgewens and 1.6% at Tygerhoek. The main reason for the difference between the farms can be attributed to the climate, and soil's physical and chemical aspects. The relationship between the SOC and wheat yield for the different crop rotational systems showed a higher yield with a higher SOC content. At both Langgewens and Tygerhoek, there was a lag of one to two years between the significant changes in SOC and wheat yield. Soil health is rather built over time which will explain this lag. For this reason, a partial correlation was used. There was a significantly positive partial correlation for some seasons for SOC on the current season's yield, while a significant partial negative correlation was seen once on the following season's yield. The partial correlation shows that there is a relationship between SOC and yield.

A panel regression was done. There was no multicollinearity between the regression variables for either model. The current season's yield and variables showed a significant positive correlation for resistance and a negative for K and S. When looking at the next season's yield resistance shows a significant negative correlation, while rainfall and Mg have a significant positive correlation. The previous year's rainfall against the current yield and variables showed a significantly positive correlation with rainfall and resistance, and a negative with K. These results show that not all the variables have significant influences on the current or even the next year's yield.

Part of the research question was to look at the effect of SOC on the quality of wheat yield. At both farms, there were statistical differences between years for the protein content. The protein content correlated well with the amount of N applied to the soil through fertilization. The effect on protein content was more pronounced when the N application was lower than higher. A similar trend was observed for Sulphur and protein for the same year. At Langgewens the change in protein content seems to follow the change in SOC, but one or two years after. At Tygerhoek the change in the following season was more pronounced. This can be ascribed to soil health being built over time. A proportionately negative relationship was observed between yield and protein content. At both trial sites, an inverse relationship was observed for yearly and seasonal rainfall against protein content. At Langgewens the wheat monoculture had a significantly lower protein content and a lower grade. The two systems with 50% were significantly higher than monoculture but significantly lower than the systems which included medics/clover. At Tygerhoek the system with 100% crops had a significantly lower protein content and grade, while the system with 50% crop/50% pasture was significantly higher than 100% crop but significantly lower than 33% crop/66% pasture.

These results show that there is an advantage to implementing conservation agricultural practices – no-till and crop rotation – to increase the SOC content of the soil, concerning the yield and quality of wheat. This is especially pertinent to producers in arid and semi-arid regions. Further studies need to be conducted to explore at which SOC content the maximum wheat yield would be obtained. This will be explored in the next chapter.

Chapter 5: Boundary line analysis of relationships between wheat yields and quality, soil organic C content and environmental factors

5.1 Introduction

Precision agriculture is something that has gained much attention in the past few decades. The goal is to make sure that the soil and crops get exactly what they require for optimum health and productivity while also looking to achieve profitability, sustainability, and environmental preservation. Analysis of the relationship between crop yield and factors affecting it have led to the establishment of optimal values and ranges for the different factors which can be controlled by the producer to maximize yields (Schillinger, et al., 2008; Austin, et al., 2009; Yesmin, et al., 2021). The usage of Boundary line analysis is one such approach in which to obtain these values using producers field data obtained across seasons and within major production areas.

Boundary line analysis (BLA) of soil nutrient and crop yield data was first proposed by Walworth et al. (1986), which enables derivation of critical values and sufficiency ranges will affect the yield of a crop. This is done by using enough data that includes growing conditions variability, and creating a scatter plot with yield (or any crop physiological property) as the dependent variable against the growth factor (such as soil or foliar nutrient content) as the independent variable, showing the optimum for the factor at the peak. A line is fitted to the maximum dependent variable in certain intervals of the independent variable. This “boundary line” would give the maximum yield for any value of the growth factor. The line would represent the optimal yield at a certain level of the independent variable, and the chances of the yield being on this line are very small. Anything under this line has external influences which have resulted in a sub-optimal yield. This approach has been used to attain sufficiency ranges for mangoes (Ali, 2018), bananas (Maia & de Morais, 2015), grapevines (Myburgh & Howell, 2014), and soybeans (de Souza, et al., 2020) among other crops.

Several factors affect crop yield. These factors are divided into three broad categories: technological (such as managerial decisions and agricultural methods), biological (such as diseases, insects, pests, and weeds), and environmental (climatic condition, soil fertility, topography, water quality, etc.) (Liliane & Charles, 2020). The technological factor can be altered according to the desires of the producer. These include crop rotation, type and amount of tillage per season, and integration of livestock. It will also determine the SOC content of the soil, which according to Lal (2006) is a mechanism through which the yield of degraded soils can be increased. The biological category will determine what types of fungicides, pesticides, and herbicides will be applied to obtain the least competition and waste for a higher yield. The environmental category will be different for each producer. The climate is different in one country, and even to the level of one farm, as well as the topography, type of soil, and nutrient content of the soil. This will firstly determine the type of crop planted and secondly the amelioration of the growing conditions of the crop. This will include the additions of fertilizers to the soil to increase the nutrient content, or lime to correct the soil pH. The target amount of nutrients for the crop and the amount which should be applied will differ between regions. This shows the importance to give the crops exactly what it needs when it is needed (Austin, et al., 2009).

The quality of the crop is of great importance. This will determine the price for which it can be sold, and thus the profit which will be made by the producer. For wheat, the protein content and hectolitre mass will determine the quality of the wheat (Lusse, 2016). The protein content will vary widely depending on the wheat cultivar, region, type, and quality of the soil and the fertilizer (Xue, et al., 2019). The protein content of the wheat is also directly affected by the amount and timing of nitrogen availability during the growing season, as well as the amount of sulphur present in the soil. This shows that the producer can influence the protein content of the wheat through managerial decisions, such as the fertilizer application, if all the abiotic factors are favourable, such as rainfall and temperature.

The SOC content of the soil is greatly affected by the amount of SOM added to the soil via plant biomass (Culman, et al., 2013; de Moraes Sa, et al., 2014). One of the key elements affecting the amount of SOM/SOC in the soil is the climate. Low temperatures and high soil water content prevent organic matter from decomposing quickly, leading to greater SOM concentrations but slowing SOC accumulation (Wagai, et al., 2008). A higher SOM benefits many soil properties, including nutrient exchange and availability, water infiltration and retention, physical resistance, and biotic activity (Lal, 2011). The clay content of the soil will also influence the amount of SOC stored in the soil through mineral association (Keber, et al., 2005). The management practices, such as the addition of fertilizers, lime, and gypsum, will also influence the SOC content (Wattel-Koekkoek, et al., 2001). Many of these factors have some form of control that can be asserted by the producer. For this reason, the BLA will show the numeric amounts needed for the highest SOC which can be attained in the different areas.

The optimum values and sufficiency ranges for most nutrients, the pH, rainfall, temperature, and the application of N fertilizer, lime, and gypsum have been obtained for wheat. The problem that producers can face is that these values are not specific to their region, or even farm. There are a lot of variabilities that can drastically change the optimal values, such as the type of soil, the clay, silt, sand, and coarse fraction content, the climate, and even the management practices implemented, which include the type of tillage and crop rotation. All of these are different for each producer and will affect the potential yield obtained by the producer. The use of the BLA to obtain optimal value and sufficiency ranges will eliminate many of these problems if the producer can supply enough data. This will lead to a more precise application of soil and plant amendments and potentially change the management practices, which will ultimately lead to a higher yield, with less loss and more economic benefits.

The main objective which will be covered in this chapter will be to obtain optimal values and sufficiency ranges of various environmental factors (rainfall, soil properties) in order to obtain maximum wheat yields and protein content through the use of BLA. These results should show the importance of more precise application of soil and plant amendments and whether there is a difference in optimal values and sufficiency ranges between the two trial sites which have different climate and soil physical properties.

5.2 Materials and methods

Soil samples of the top 15 cm of the soil at both Langgewens and Tygerhoek Research farms were collected in late December to mid-January of each year for the duration of the trial. The methods which were used to determine the soil characteristics and yield and quality of wheat have been discussed in detail in Chapter 3, under materials and methods.

5.2.1 Boundary line analysis

The same data will be used in this chapter as in the previous one. The data will be used in creating a boundary line analysis (BLA), as stipulated by Schnug et al. (1996), which will consist of a scatter plot with yield or protein content as the dependent variable against the growth factor as the independent variable, showing the optimum for the factor at the peak. There are five steps to determine the upper boundary line. Step 1 is to identify and remove the outliers in the data set using box and whiskers plots. The next step is to divide the scatter plot into 10-15 intervals and only the highest point in each interval is selected. These scatter plots with the highest points selected can be found in Figure A 1 to Figure A 30 in the Appendix. From the scatter plot with the new data points a second-degree polynomial function is generated at significance level of $p<0.05$. The last step is to determine the optimum values and range for the independent variable. The optimum concentration can be obtained by solving the first derivation of the regression equation. To obtain the minimum and maximum range which will be at 90% of the maximum yield. This is done by using the confidence interval.

5.3 Results and discussion

In the previous chapters, a good correlation between soil health and the SOC content was found which proposed that there is also an increase in yield and led to the next topic: the effect of SOC on yield and quality of wheat. The results show that there is an increase in the yield and quality of wheat when there was an increase in SOC. This chapter will look at what level the highest level of wheat yield, protein, and SOC content observed for the different factors that were looked at in the previous chapters using boundary-line analysis. The BLA will give the optimum value and the range for the factor to obtain the highest yield, protein content, and SOC content.

5.3.1 Boundary line analysis for factors affecting yield

Numerous factors can affect yield, but Liebig's Law of Minimum states that the most limiting nutrient (or factor) will ultimately determine yield. The fertility of the soil and the climate in which the crop is cultivated are the main factors influencing yield. In the previous chapter, the effect that each factor had on the wheat yield, over the trial period (18 years) was explored. The results showed whether the factor affected the current, next, or the yield of two years later. The relationship between the wheat yield and SOC content was best seen when looking at the SOC content one to three years before the current wheat yield. The current yield and rainfall are well correlated, especially the seasonal rainfall. The target pH is well known for wheat. There was a strong positive correlation between the current season's N application and wheat yield. The nutrient status of the soil was best correlated to the next seasons yield. Soinne et al. (2020) found that when looking at the clay-to-C ratio there is a negative correlation with grain yield when the ratio is higher than 15. All these findings will give an indication of which years needs to be looked at when the BLA is done for the different factors against the yield.

5.3.1.1 Soil organic carbon

At Langgewens there is a distinct quadratic relationship between the maximum yields and SOC content (Figure 78), with an R^2-value of 0.89. This implies that below and above a certain SOC content the wheat yield will decrease. The 90% confidence interval for SOC is [1.03:1.39], with the optimum value being 1.13%. The highest yield at Langgewens across the trial period was 5967 kg ha^{-1} when the SOC content of the field was 1.10%, while the second highest was at 1.15%. This range contains 54.8% of the SOC data throughout the trial, while the average was lower in 2002, 2003, and 2008. According to the statistics, SOC has a significant influence on wheat yield (p= 0.00000005), and SOC has a strong positive correlation with yield.

The increase in yield with an increase in SOC was also found in wheat, maize, mustard, sunflower, and groundnut (Shankar, et al., 2002; Ghosh, et al., 2003; Singh Brar, et al., 2015). The decrease in yield at higher SOC content was also observed by Singh Brar, et al., (2015), and can be explained by the management practices which lead to the higher SOC contents. The stubble left on the field by the conservation agriculture and NT methods can reduce evaporation (Lal, 2018), decreased soil temperatures can delay plant maturity (Zhang, et al., 2014), in drier regions there could be soil structural issues inadequate residue cover/biomass production (Giller, et al., 2015), and the possibility that the high SOC contents will create soil where there is a deficiency in mineral N, P, and S, as found by Kirkby, et al., (2016).

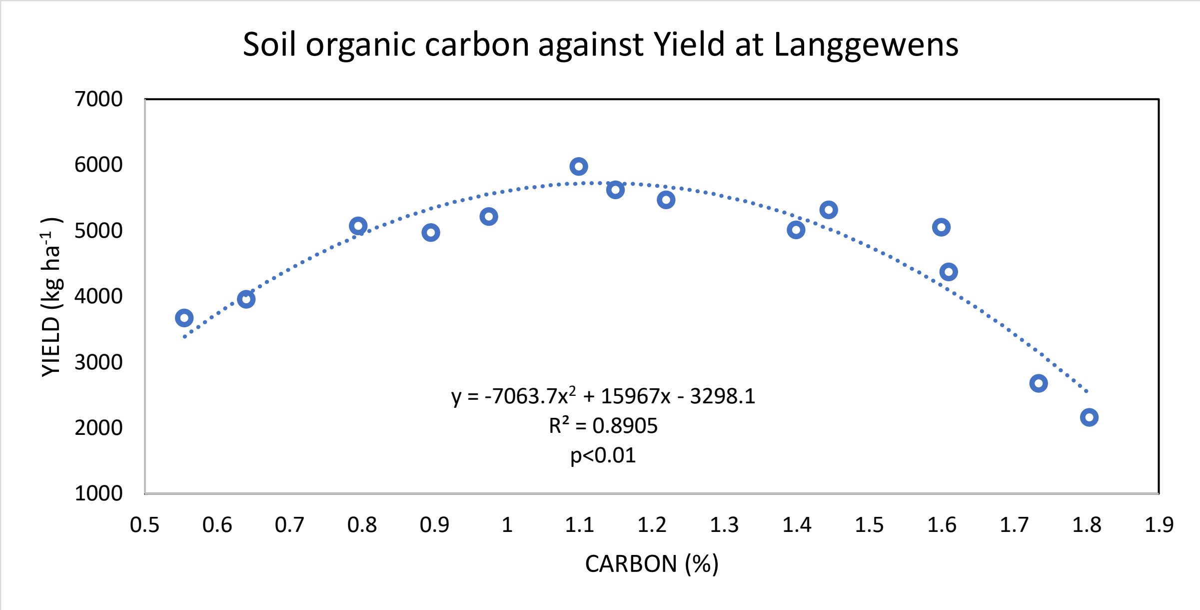

Figure 78: Boundary line analysis of wheat yield (kg ha^{-1}) against soil organic carbon (%) at Langgewens from 2002 to 2020

At Tygerhoek the relationship is also quadratic with the R^2-value of 0.54 which shows that the second order polynomial is of relatively good fit (Figure 79). The data show the lowest yield when the SOC is below 1% and slightly lower above 2.2%. The rest of the data points are similar in yield. The 90% confidence interval is between [1.51:1.88] and the optimum value is 1.72% SOC. The highest yield at Tygerhoek across the trial period was 6063 kg ha^{-1} with the SOC content being 1.56% for the field in the particular season. This value falls within the 90% confidence interval. This range contains 49.4% of the SOC data throughout the trial, while the average was lower only in 2005. According to the statistics, SOC has a significant influence on wheat yield (p= 0.014), and SOC has a moderate positive correlation with yield.

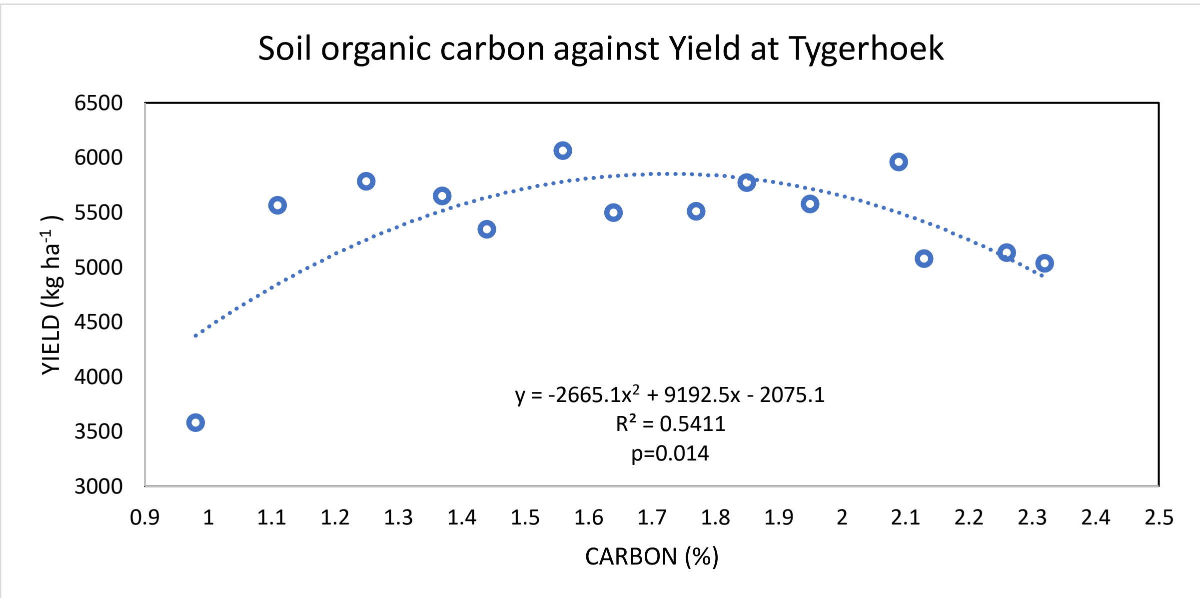

Figure 79: Boundary line analysis of wheat yield (kg ha^{-1}) against soil organic carbon (%) at Tygerhoek from 2002 to 2020

When looking at the combined BLA for the yield against the SOC content (Figure 80), a good fit is observed (R^2=0.85). The optimum value obtained from the BLA is 1.60% SOC, with the confidence interval being between [1.21:1.83]. The increase in yield between SOC of 0.50% and 1.10% can be observed, which was seen at Langgewens. The decrease in yield when the SOC is higher is not as pronounced in this BLA. According to the statistics, SOC has a significant influence on wheat yield (p= 0.001), and SOC has a strong positive correlation with yield.

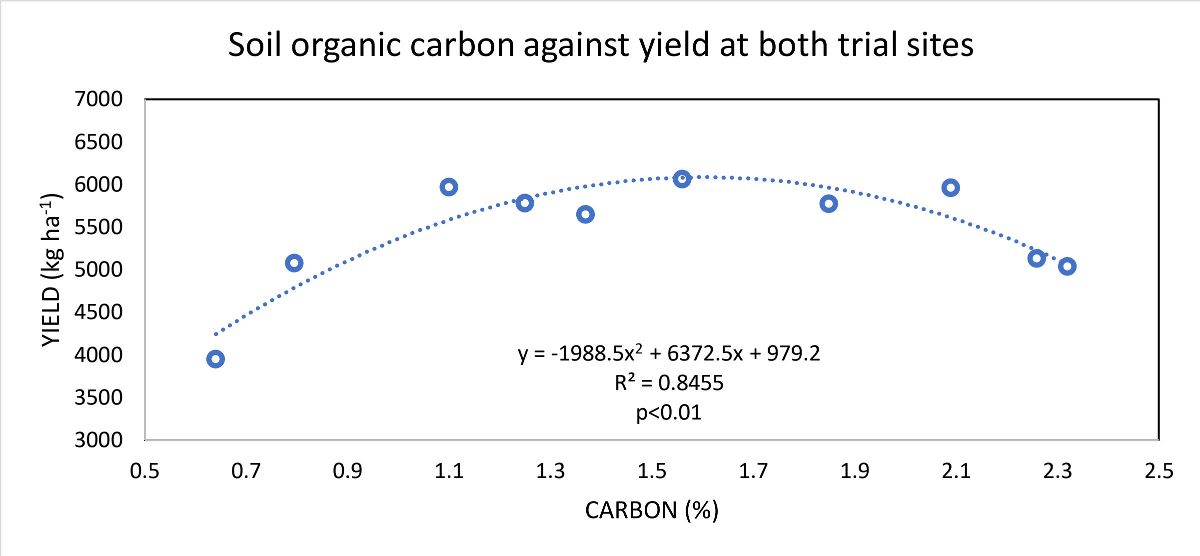

Figure 80: Boundary line analysis of wheat yield (kg ha^{-1}) against soil organic carbon (%) at Langgewens and Tygerhoek from 2002 to 2020

These results show that there is a difference between the SOC contents of the two farms and their effects on the yield. When looking at the combined effect the decrease in yield at higher SOC contents is not as pronounced, but rather an increase with a plateau. This was found in the literature (Culman, et al., 2013; de Moraes Sa, et al., 2014), and in a study by Oldfield et al. (2019), they found that the effect of the SOC starts to level off at ~2%. At Langgewens this figure is ~1.6% while at Tygerhoek it is ~2.1%. This shows that there is a combination of factors that will determine the optimum level for SOC to increase the yield and this level will be different as the level of the other factors differs. Another possibility for the decrease in yield is that C (or SOM) returns to the soils increase with primary production (yield), but the restitution (the unharvested aboveground plant parts) or yield ratio decreases as the yield increases (Basile-Doelsch, et al., 2020). The When the data of the two farms have been combined the increase in yield with SOC when the SOC is below 1.00% can be observed, with a plateau thereafter. The confidence range is also much larger and contains the ranges of both trial sites as well.

Another aspect that needs to be considered is that SOC does not have a direct influence on yield. This relates to Liebig's law where SOC does not directly address/fix the most limiting crop growth factor, but rather increase soil health. Hijbeek (2017) argued that increasing SOM (SOC) does not always directly benefit soil fertility or crop yields because external nutrient supply, or other management practices (e.g. irrigation and tillage) can mimic, supplement or substitute for some of the contributions that SOM (SOC) makes to soil fertility. According to Giller, et al., (2021), only if additional SOM (SOC) removes an immediate constraint to crop growth will it boost crop yields in the short term.

5.3.1.2 Rainfall

From the previous chapters, it is evident the significant effect that rainfall has on yield. The BLA gives a good representation of the effect that rainfall has on yield at Langgewens (Figure 81). The yearly rainfall shows an increase in yield as the rainfall increases. The optimum value for yearly rainfall according to the BLA at Langgewens is 648 mm, with the confidence interval being [572:723]. The BLA also shows that yield will only increase up to a certain point with an increase in rainfall, which is also found in the literature. According to the statistics yearly rainfall has a significant influence on wheat yield (p= 0.0399) and has a moderate positive correlation with wheat yield. The R^2-value is 0.60 for yearly rainfall.

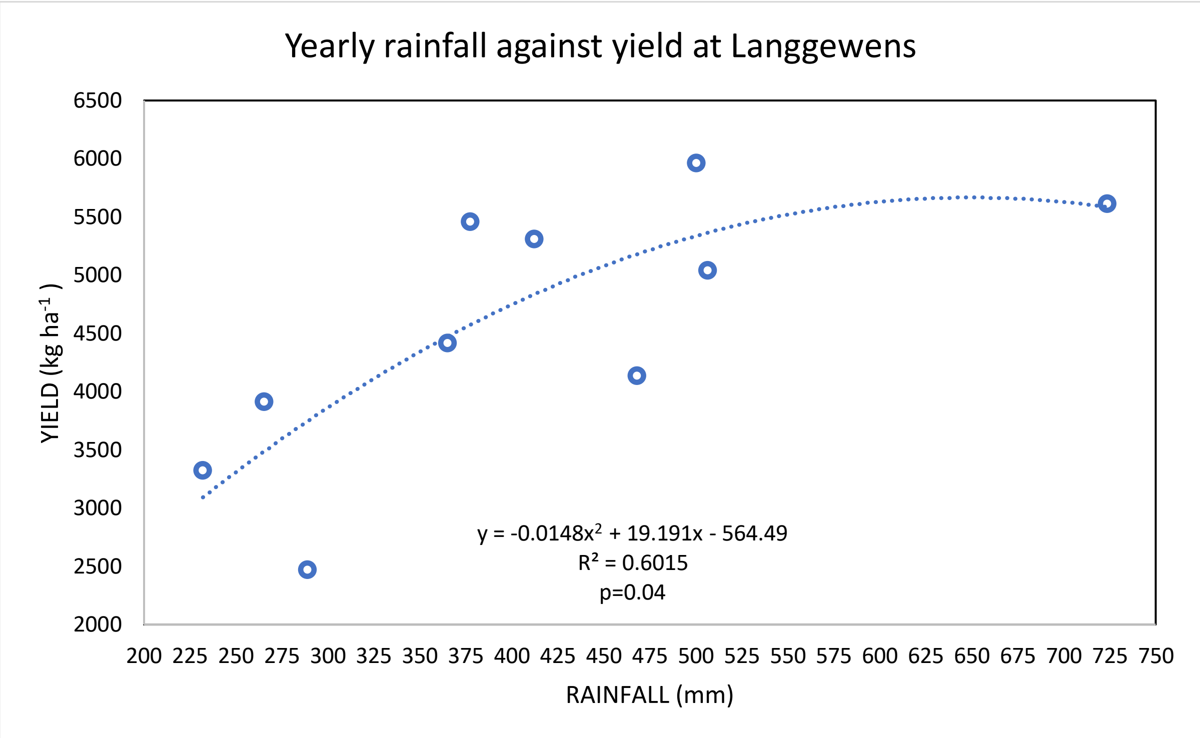

Figure 81: Boundary line analysis of wheat yield (kg ha^{-1}) against yearly rainfall (mm) at Langgewens from 2002 to 2020

Seasonal rainfall gives a distinct picture of the water available to the crops during growth. The BLA gives a similar polynomial function, with the optimum value being 542 mm and the confidence interval between 484 and 600 mm (Figure 82). According to the statistics, seasonal rainfall has a significant influence on wheat yield (p= 0.02) and has a moderate positive correlation with wheat yield. The R^2-value is 0.62 for yearly rainfall.

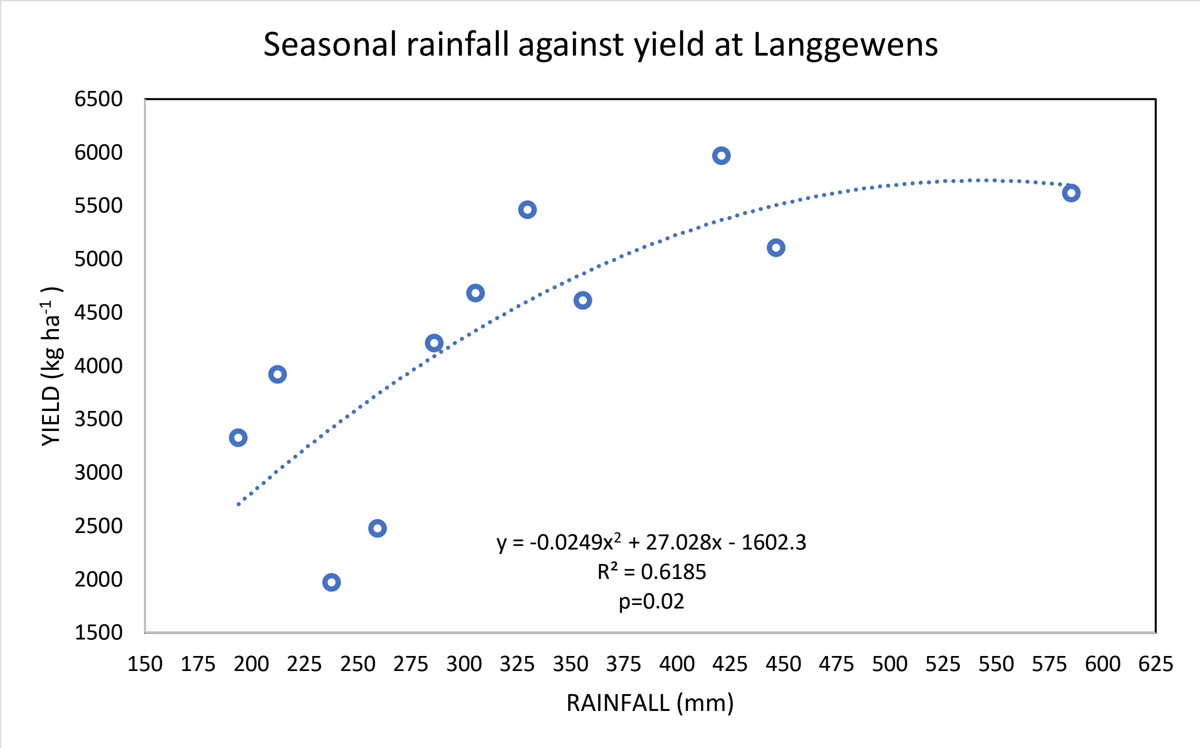

Figure 82: Boundary line analysis of wheat yield (kg ha^{-1}) against seasonal rainfall (mm) at Langgewens from 2002 to 2020

At Tygerhoek and the combined data, a weak fit is seen for the polynomial function against both the yearly and seasonal rainfall. The trend of a decrease in yield when the rainfall is too high was also be observed. According to the statistics yearly rainfall and seasonal does not have a significant influence on wheat yield and the correlation is negligible.

On both farms, the trend of a decrease in yield when the rainfall is too high was observed. The rainfall during the season is much better correlated to yield, especially at Langgewens where eighty percent of rainfall occurs during the growing season. The amount of rainfall is not the only aspect that should be evaluated. The timing of rainfall will determine when the season can commence if germination and emergence will be good, and lack of rain during grain filling. The amount of rain per day will influence the infiltration and runoff, where less per day but more over the season is better.

5.3.1.3 Soil pH (KCl)

At Langgewens the BLA quadratic function fit soil pH data versus yields fairly well, with an R^2 value of 0.76 (Figure 83). The confidence interval for pH to give the highest yield is [5.47:6.11], and the optimum value is 5.83, which is between the prescribed value of 5.5 to 6.5 (Department: Agriculture, Forestry and Fisheries, 2022). In the data points, there is a clear decrease below pH 5.00. The highest yield across the trial period was 5967 kg ha^{-1} and had a pH of 5.40. This falls outside the confidence interval as the yield was much lower at the lower pH values. The second-highest yield had a pH of 5.60, which is in the confidence interval and closer to the optimum level. According to the statistics, pH has a significant influence on wheat yield (p= 0.003) and has a moderate positive correlation with wheat yield.

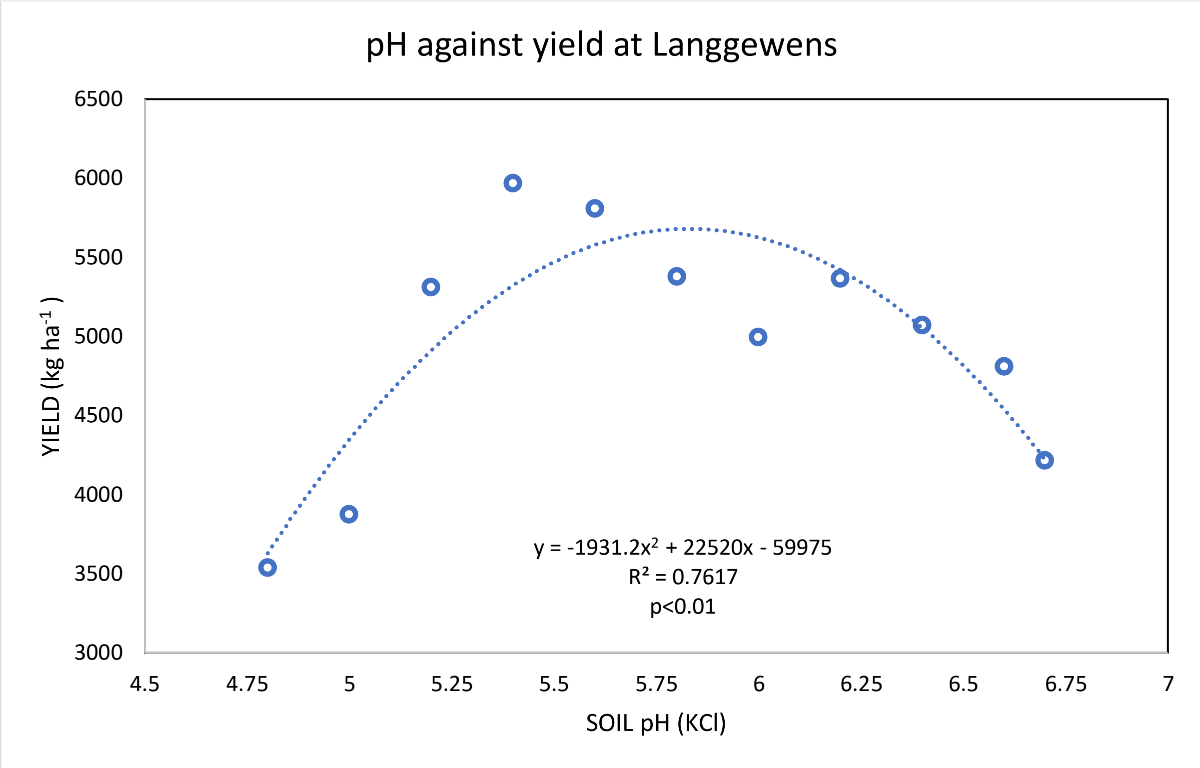

Figure 83: Boundary line analysis of wheat yield (kg ha^{-1}) against soil pH measured in KCl at Langgewens from 2002 to 2020

At Tygerhoek the polynomial line is of a much better fit with an R^2 value of 0.83 (Figure 84). The optimum value has a pH of 5.90 and a confidence interval of [5.66:6.43]. The highest yield across the trial period was 6463 kg ha^{-1} with the pH of the field being 6.4, which falls in the confidence interval. According to the statistics, pH has a significant influence on wheat yield (p= 0.002), and pH has a strong moderate correlation with yield.

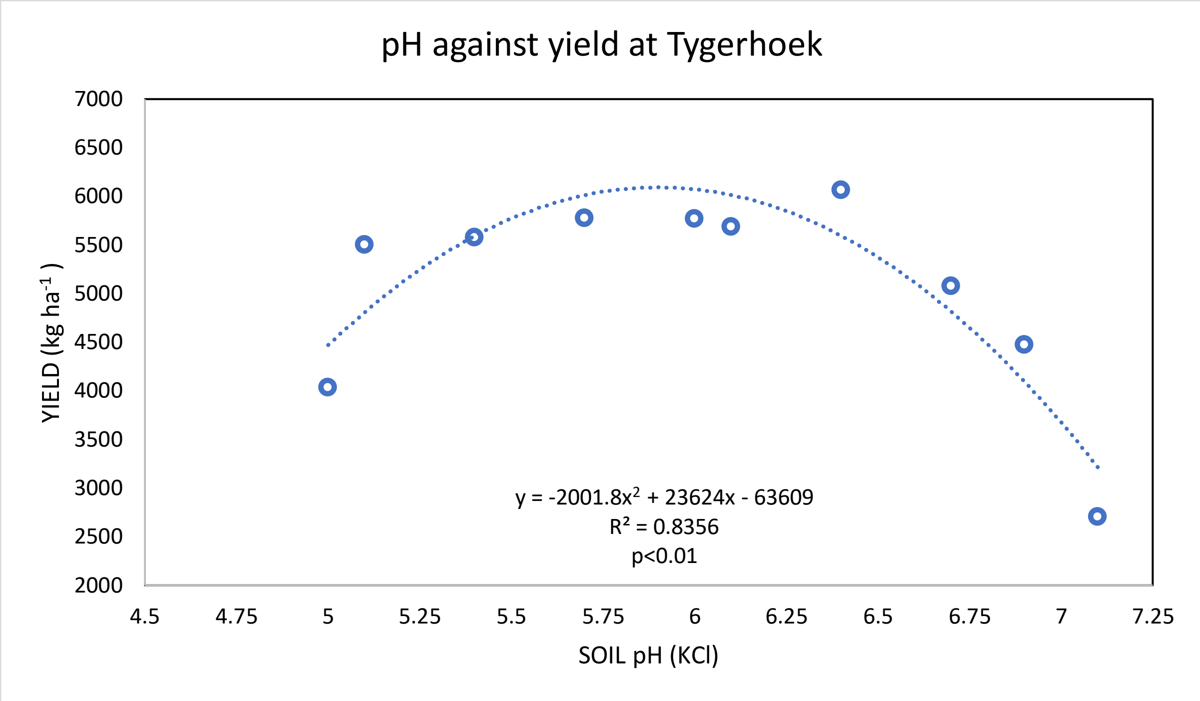

Figure 84: Boundary line analysis of wheat yield (kg ha^{-1}) against soil pH measured in KCl at Tygerhoek from 2002 to 2020

When the BLA for both trial sites is done, the same trend can be observed (Figure 85). There is a slight increase in both yield and pH, after which there is a plateau, and after a pH of 6.50, there is a decrease in yield. The optimum value according to the BLA is 5.89 with the confidence interval being between [5.64:6.42]. This confidence interval correlates well with that of the two trial sites, as well as the optimum values being within 0.1 pH point from each other. According to the statistics, pH has a significant influence on wheat yield (p= 0.002), and pH has a strong moderate correlation with yield. The R^2-value is 0.84 for pH.

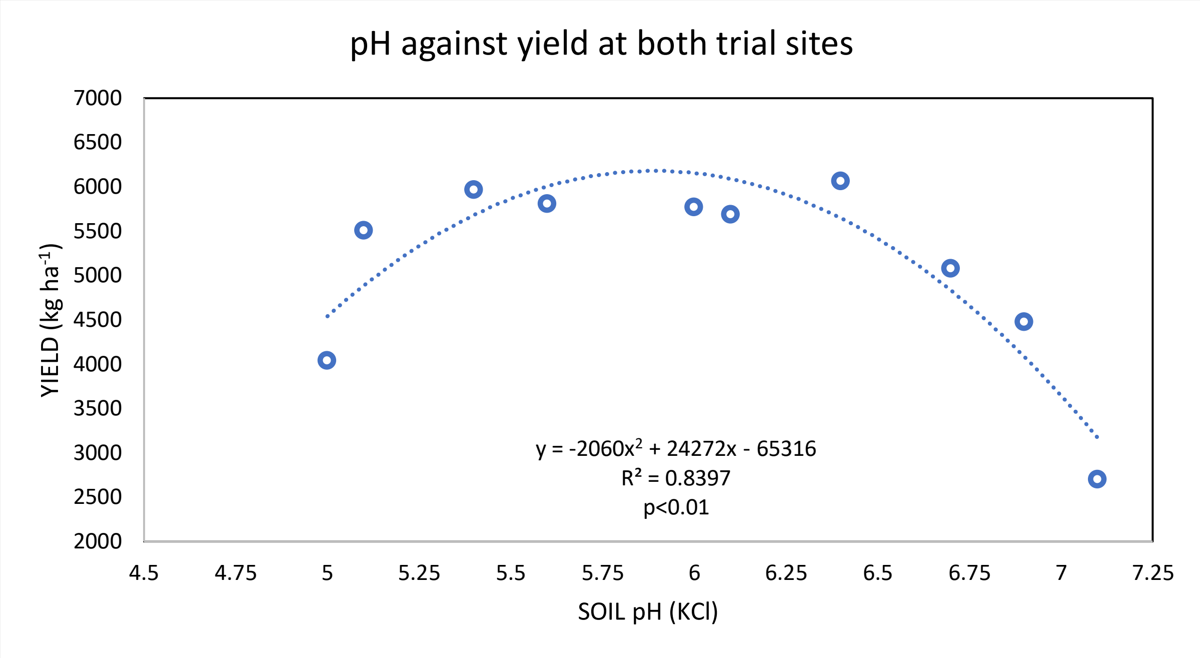

Figure 85: Boundary line analysis of wheat yield (kg ha^{-1}) against soil pH measured in KCl at Langgewens and Tygerhoek from 2002 to 2020

The pH levels for the two farms differ, along with the range where the highest wheat yield is produced. According to Government (2022), wheat should ideally be produced in soils with a pH range of between 5.5 to 6.5. Both these farms have their confidence intervals in this range. This shows the validity of the results along with the BLA approach.

5.3.1.4 Nitrogen application

Nitrogen affects plant growth and the subsequent grain yield (Belete, et al., 2018). Nitrogen is added to the soil in the form of inorganic fertilizer. The amount of N present in the fertilizer was quantified for each of the fields. At Langgewens there is a clear trend of higher N application resulting in a higher yield, but the R^2 value is 0.33, which points to a bad fit for the BLA. At Tygerhoek the polynomial did not show a good fit either, with an R^2 value of 0.04. a possible reason for this is the inclusion of legumes in the rotational system, which will lower the N fertilizer demands.

There is no prescribed amount of nitrogen that should be applied. The amount of N applied will depend on the target yield. For the two farms which had most of the high-yielding fields between 3000 and 7000 kg ha^{-1} in yield, the amount of N applied can vary between 80 and 180 kg N per ha (Department: Agriculture, Forestry and Fisheries, 2022). A higher amount of N applied will result in a higher yield. To see the effect that N application has on yield, a higher variation in N, along with higher amounts had to be applied. Various other factors will have an influence that was not constant for the experiment. Different crop rotational systems had significant differences in the yields, which was seen in Chapter 3.

5.3.1.5 Soil nutrient content

When the BLA was performed on soil available Ca, Mg, P, and S there was a poor fit with all the R^2 values being below 0.5, which resulted in nonsignificant results. This is likely due to these soil nutrients being above critical concentration values in the carefully managed long-term field trials.

Potassium is required in large quantities by crops (similar to N) and has a positive effect on wheat yield by Improving photosynthesis and photosynthate Translocation (Wang, et al., 2020), while SOM and K can increase plant tolerance to drought (Bader, et al., 2021). At Langgewens K gives a polynomial function for the BLA (Figure 86). The optimum value is 155 mg kg^{-1}, and the confidence interval is [127:188]. Literature states that K is limiting below 40 mg kg^{-1}which correlates to our findings, where yield decreases rapidly below 105 mg $kg^{-1}$and above 231 mg kg^{-1}. According to the statistics, K has a significant influence on wheat yield (p= 0.0004) and has a strong positive correlation with wheat yield. The R^2-value is 0.85 for yearly rainfall.

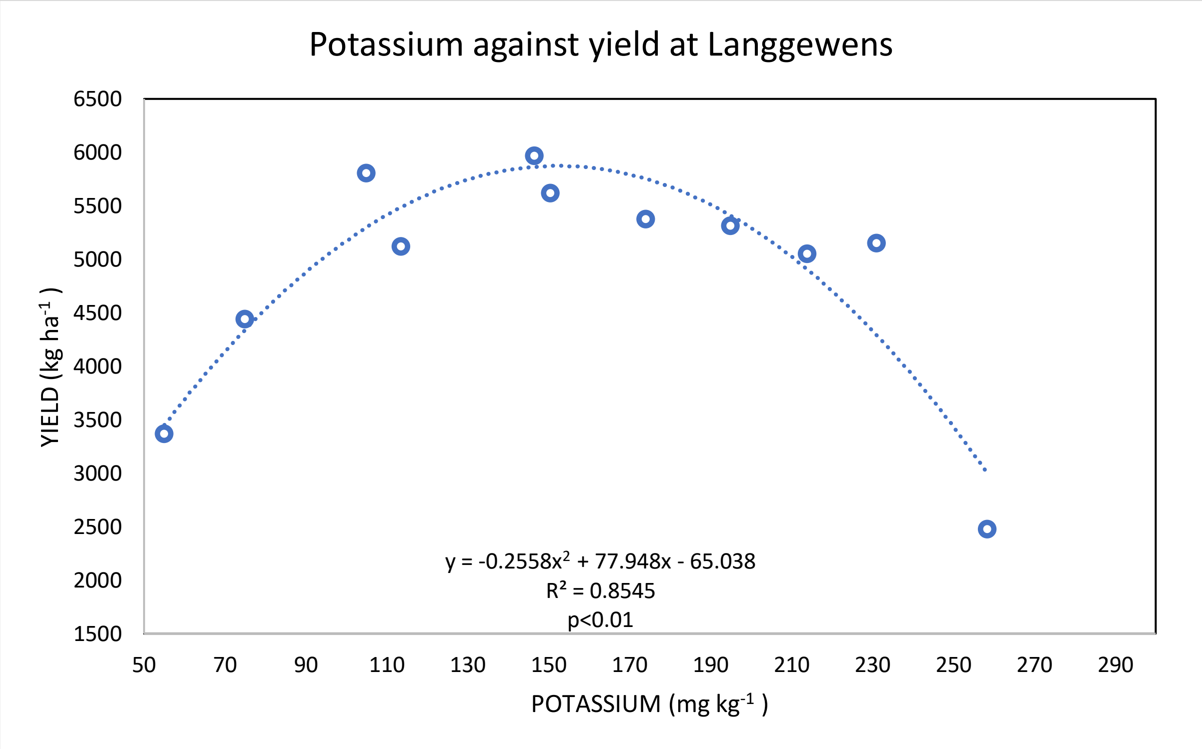

Figure 86: Boundary line analysis of wheat yield (kg ha^{-1}) against potassium (mg kg^{-1}) at Langgewens from 2002 to 2020

The potassium also shows a good polynomial function for the BLA at Tygerhoek (Figure 87). There is a decrease in yield below when K is 95 mg kg^{-1}, with the critical level being 40 mg kg^{-1}in literature. The optimum level is 274 mg kg^{-1} and the confidence interval is [220:328]. According to the statistics, K has a significant influence on wheat yield (p= 0.004) and has a moderate positive correlation with wheat yield. The R^2-value is 0.0.63 for K.

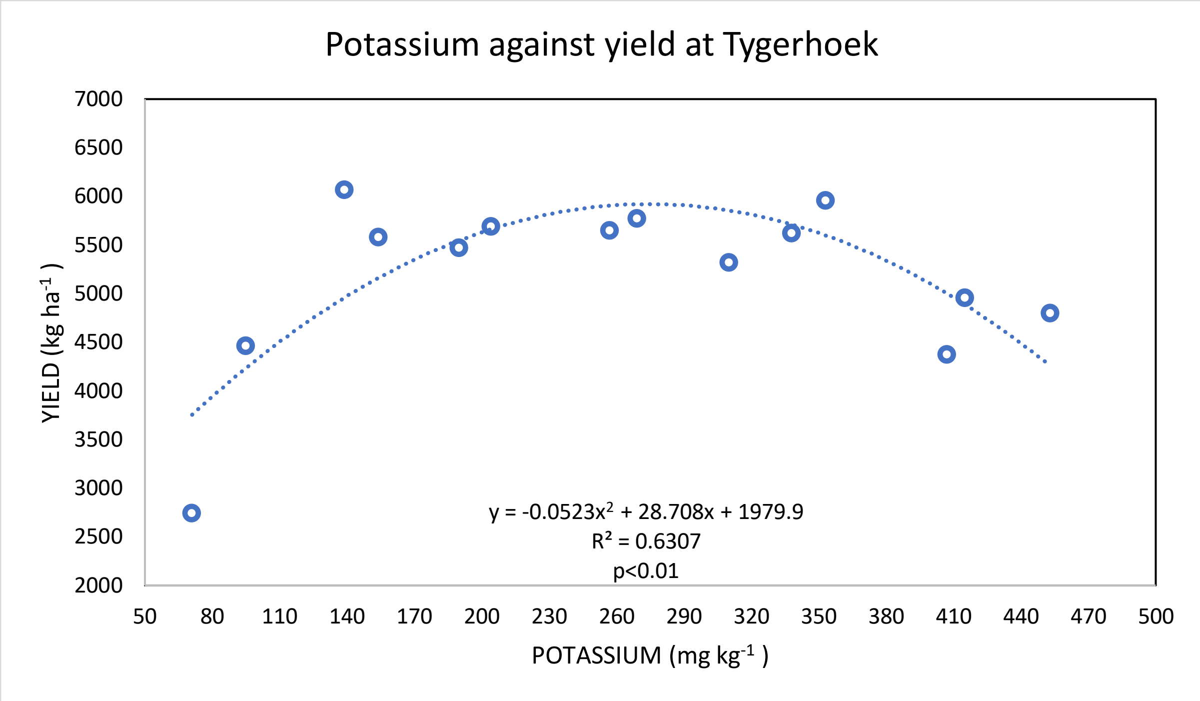

Figure 87: Boundary line analysis of wheat yield (kg ha^{-1}) against potassium (mg kg^{-1}) at Tygerhoek from 2002 to 2020

At both trial sites, there was an increase in yield as the amount of K increased, up to a certain point, after which it stayed constant. There was then a decrease in yield, seen more distinctly at Langgewens. This decrease in yield can be due to the increase in potassium which can lead to an increase in cadmium and lead contents and reduced amounts of chromium and iron in the soil (Wyszkowski & Brodowska, 2020). Too high K will also result in the leaching of P from the soil. The sufficiency range according to the literature is 80 – 160 mg kg^{-1} for grain crops (Fertilizer Association of Southern Africa, 2016). In the two experimental trials, the sufficiency ranges were higher than that of the literature.

5.3.1.6 Clay-to-Carbon ratio

Soinne et al. (2020) found that when looking at the clay-to-C ratio there is a negative correlation with grain yield, especially when the ratio is higher than 15, while Johannes, et al., (2017) found that a reasonable goal is 1:10 and the optimal value for soil structure quality is 1:8. At Langgewens the BLA gives a good polynomial function (Figure 88), with an R^2 value of 0.88. The optimum value is 9.5, while the confidence interval is [9.3:12.7]. There is a decrease in yield at a clay:carbon ratio above 13.3. According to the statistics the clay:C ratio has a significant influence on wheat yield (p= 0.00007) and has a strong positive correlation with wheat yield. The R^2-value is 0.88 for yearly rainfall.

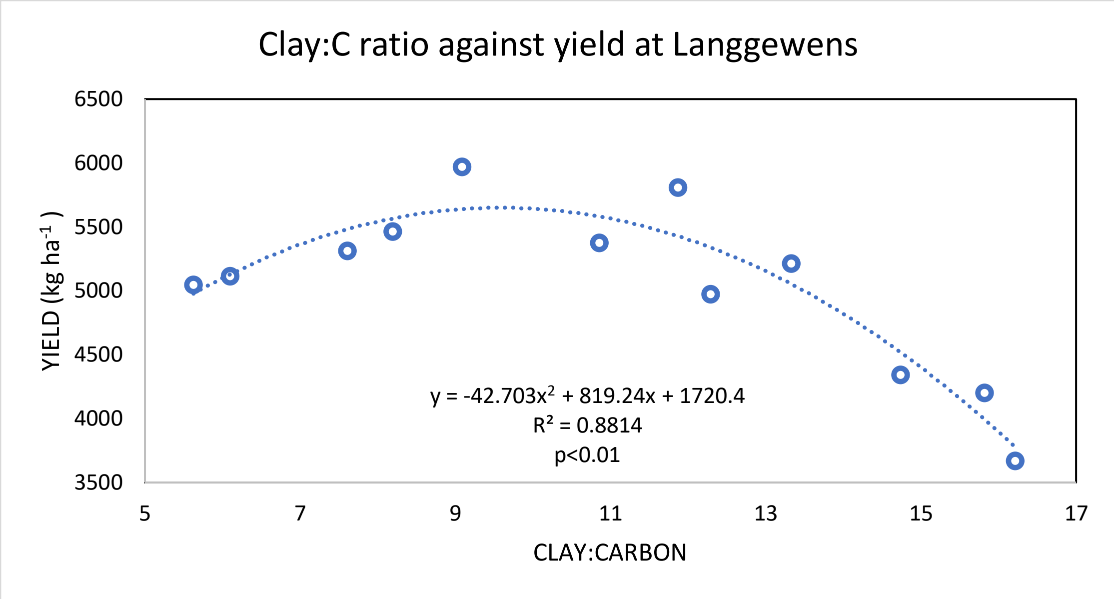

Figure 88: Boundary line analysis of wheat yield (kg ha^{-1}) against clay:carbon ratio at Langgewens from 2002 to 2020

At Tygerhoek the BLA is also a good fit and in line with what Soinne et al. (2020) state. There is a decrease in yield when the clay:carbon ratio is below 6.6 and above 16.9, which is a little high. The optimum value is 12 and the confidence interval is between [10.3:14]. According to the statistics the clay:C ratio has a significant influence on wheat yield (p=0.001) and has a moderate positive correlation with wheat yield. The R^2-value is 0.71 for clay: C.

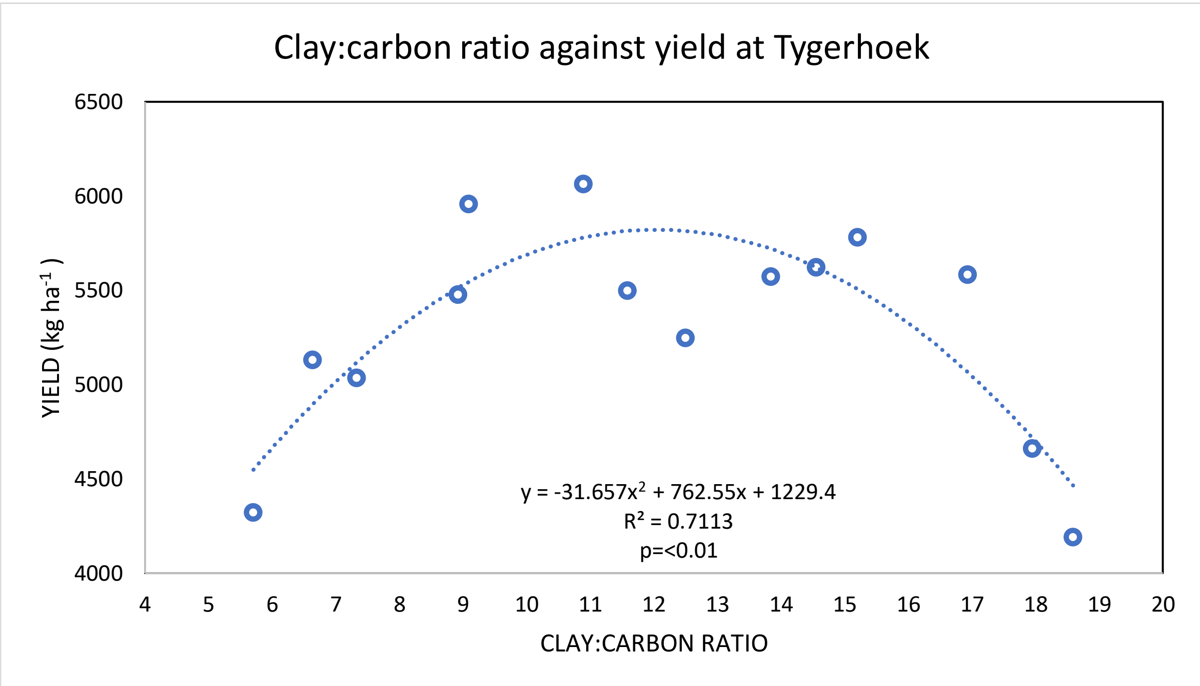

Figure 89: Boundary line analysis of wheat yield (kg ha^{-1}) against clay:carbon ratio at Tygerhoek from 2002 to 2020

The BLA for both trial sites shows the same trend; there is an increase in the clay:C ratio with an increase in yield, with a plateau, and then a decrease in yield after the clay:C ratio increases above 17 (Figure 90). This was observed at Langgewens and Tygerhoek. The optimal value is 12.35 with the confidence interval being between [9.29:13.84]. This is interval is between those of the two trial sites, but the optimal values are further away from one another. According to the statistics the clay:C ratio has a significant influence on wheat yield (p=0.007) and has a moderate positive correlation with wheat yield. The R^2-value is 0.76 for clay: C.

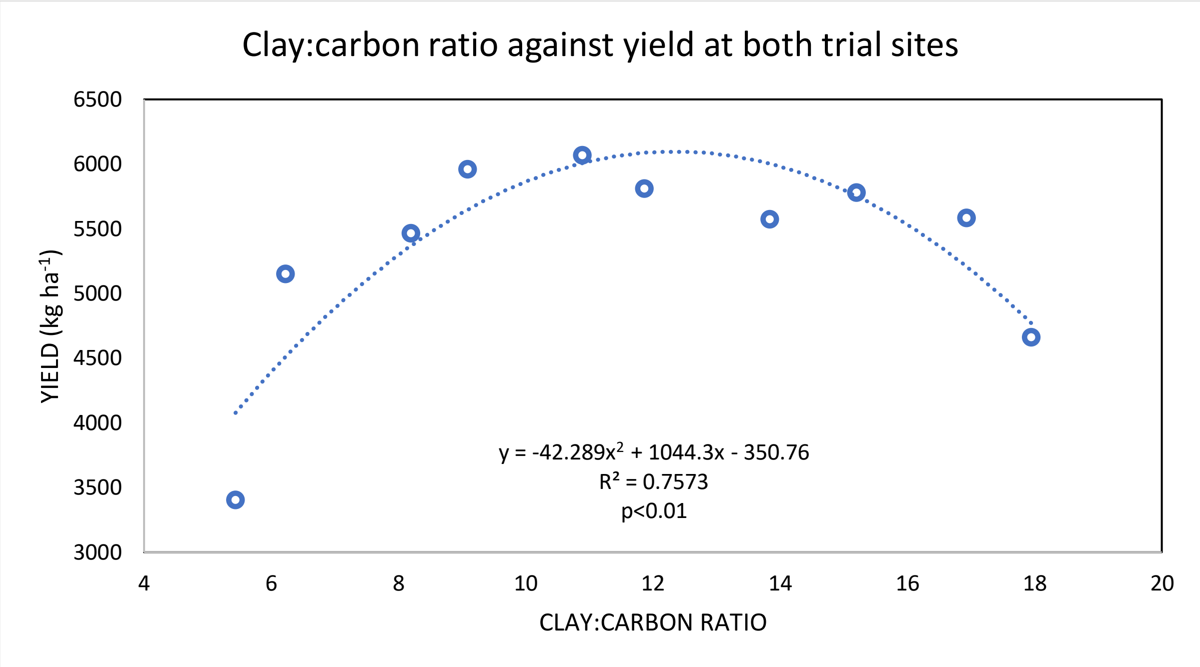

Figure 90: Boundary line analysis of wheat yield (kg ha^{-1}) against clay:carbon ratio at Langgewens and Tygerhoek from 2002 to 2020

The more stable the soil aggregates are, the better the productivity will be (Government of Western Australia, 2021). To maintain the same level of aggregate stability when clay content increases, a higher SOC content was required. Therefore, the clay:C ratio is important. Thus, a lower ratio will be better for productivity, and this is what was found in the BLA of both farms. According to the literature a ratio of 8 is optimal and 10 is a reasonable goal, and in this study, the optimum was 9.5 at Langgewens, and at Tygerhoek it was 12, but the highest yield was observed at 10.9.

5.3.2 Boundary line analysis for factors affecting wheat protein content

The wheat protein level is an excellent general indicator of the quality of the wheat. In South Africa, the desired level of wheat protein is 11.5 % (Barnard, et al., 2002). The BLA is not able to determine a certain level of the factor investigated as it shows the highest level for a certain factor. From the previous chapter, the amount of N applied will influence that season’s protein level. It was also observed for the Sulphur content of the soil. The SOC content of the soil influences the protein content of the next season or two seasons later. The wheat yield is negatively proportionate to the protein content of the current season.

5.3.2.1 Nitrogen application

Wheat protein significantly increases with an increase in N application, as was found by Zang, et al., (2017). At both trial sites, the BLA did not show a significant result, with R^2-values of 0.33 and 0.09 for Langgewens and Tygerhoek respectively. A possible reason for the low R^2-values is urea volatilization. This is the loss of N from the soil and is most prominent when fertilizers are applied through broadcasting (Jones, et al., 2013). An increase in crop residue can also increase volatilization. Jones, et al., (2013) attributed this to (1) crop residues having a higher pH than soil, which increases ammonia in solution and makes it more volatile (Holcomb, et al., 2011); (2) crop residues frequently have a higher pH than the soil, which raises the concentration of ammonia in solution; (3) residues may increase soil moisture, which also raises the concentration of ammonia in solution and makes it more volatile; (4) residues can prevent N from penetrating the soil. No-till systems, as opposed to bare soil and conventional tillage systems, have higher volatilization potential, and need more irrigation or rainfall sooner after urea application to reduce loss of N (Engel, et al., 2011).

5.3.2.2 Sulphur content

Sulphur plays a major role in the efficient uptake and use of N in the soil by the plant. At Langgewens the level of S in the soil for maximum protein is 9 mg kg^{-1}, with the confidence interval being [1.1:15]. This is shown in Figure 91. There is a slight decrease in protein content when the S is above 20 mg kg^{-1}. According to the statistics, S has a significant influence on protein content (p=0.022), and S has a moderate positive correlation with protein content. The R^2-value is 0.61 for S.

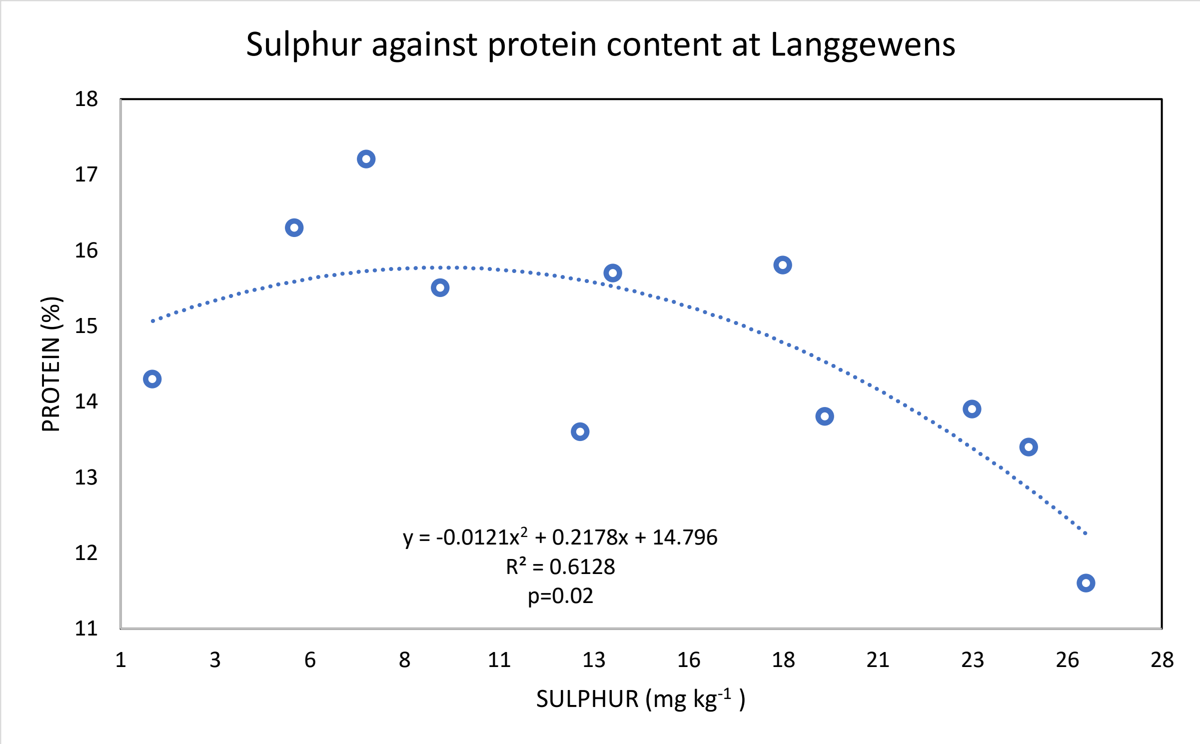

Figure 91: Boundary line analysis of wheat protein (%) against sulphur (mg kg^{-1}) in the soil at Langgewens from 2002 to 2020

At Tygerhoek the optimum value for the amount of S in the soil to have a positive effect on the protein content needs to be 6.98 mg kg^{-1}, with the confidence interval being [6.9:10.5]. There is much less variation in the S content for the BLA, with all the protein content being between 13% and 16% (Figure 92), compared to Langgewens. This could explain why the R^2 value is much less and the confidence interval is more narrow. According to the statistics, S does not have a significant influence on protein content (p=0.08), and S has negligible interaction with protein content. The R^2-value is 0.39 for S.

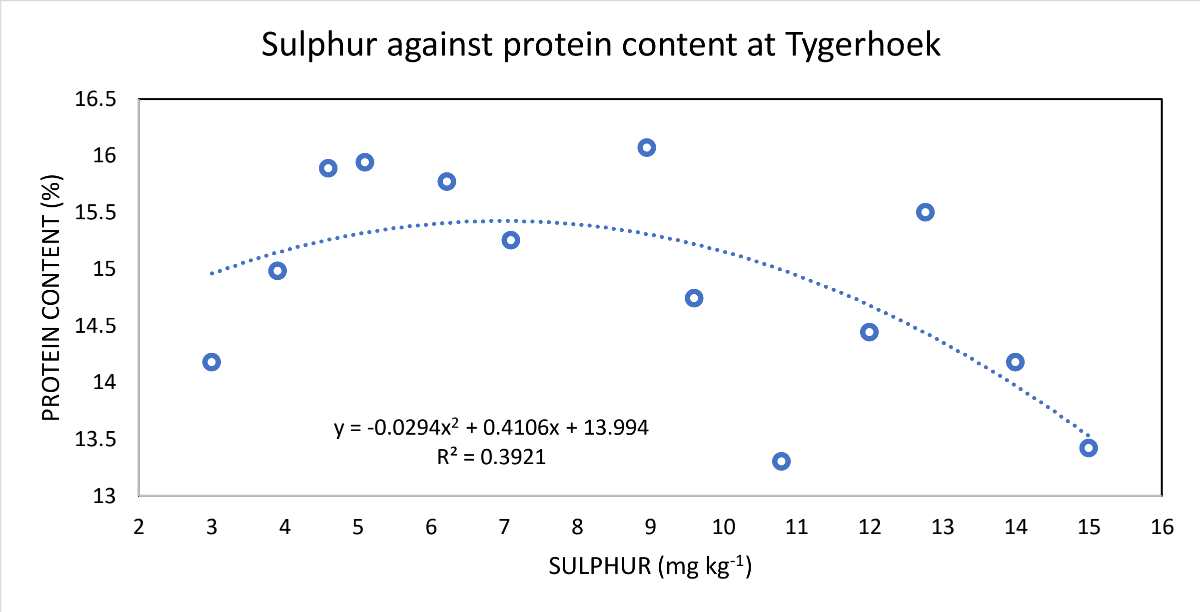

Figure 92: Boundary line analysis of wheat protein (%) against sulphur (mg kg^{-1}) in the soil at Langgewens from 2002 to 2020

5.3.2.3 Soil organic carbon

The SOC content of the soil will influence the health of the soil, thus the CEC and the nutrient availability (He, et al., 2014). In terms of N and S availability, it is expected for the SOC content of the soil to influence the protein content. At Langgewens there is a good polynomial function for the BLA (Figure 93), with the optimal value for SOC being 1.25% and the confidence interval being [0.93:1.39]. There is an increase in protein as the SOC increases up to a certain point, with a decrease thereafter. According to the statistics, SOC has a significant influence on protein content ($p=0.005$), and SOC has a moderate positive correlation with rainfall. The R^2-value is 0.76 for SOC.

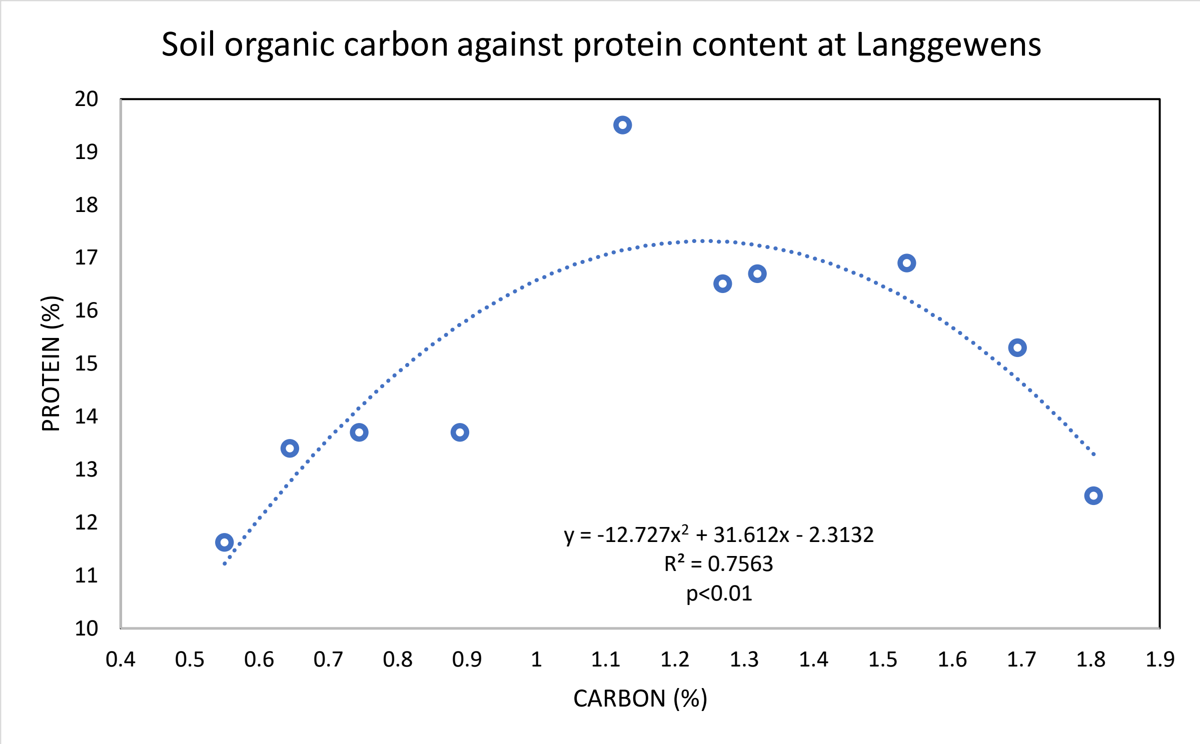

Figure 93: Boundary line analysis of wheat protein (%) against soil organic carbon content (%) at Langgewens from 2002 to 2020

At Tygerhoek the BLA also gives a good polynomial function (Figure 94), with the optimum value being 1.77% and the confidence interval being [1.46:1.93]. There is a slight increase in protein as the SOC increases up to a certain point, after which the protein stays relatively constant. According to the statistics, SOC has a significant influence on protein content ($p=0.0003$), and SOC has a moderate positive correlation with rainfall. The R^2-value is 0.90 for SOC.

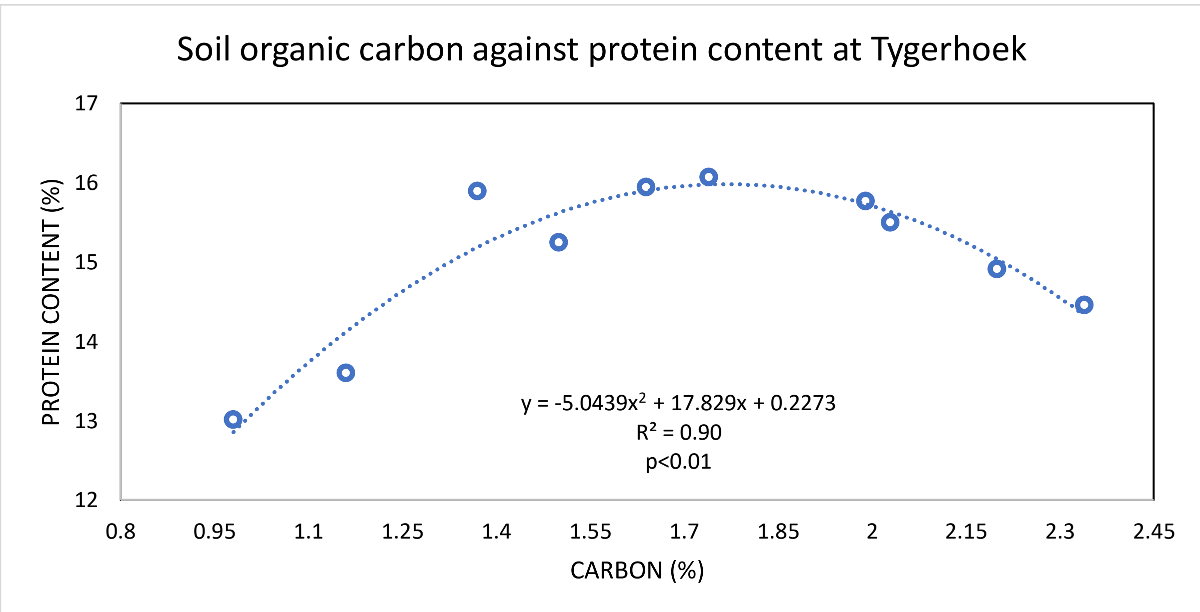

Figure 94: Boundary line analysis of wheat protein (%) against soil organic carbon content (%) at Tygerhoek from 2002 to 2020

There is a difference between the polynomial functions of the two trial sites, which could be due to the SOC content being higher at Tygerhoek. For this reason, it is important to look at the trial sites together. This is presented in Figure 95. There is a slight increase in protein as the SOC increases, after which the protein stays relatively constant. According to the BLA, the optimal value is 1.46% SOC and the sufficiency range is [1.16:1.77]. This is between the two trial sites. When looking at the BLA graph, the SOC value which resulted in the highest protein content would be between 0.9 and 1.3%. According to the statistics, SOC does not have a significant influence on protein content (p=0.06), but SOC has a moderate positive correlation with rainfall. The R^2-value is 0.55 for SOC.

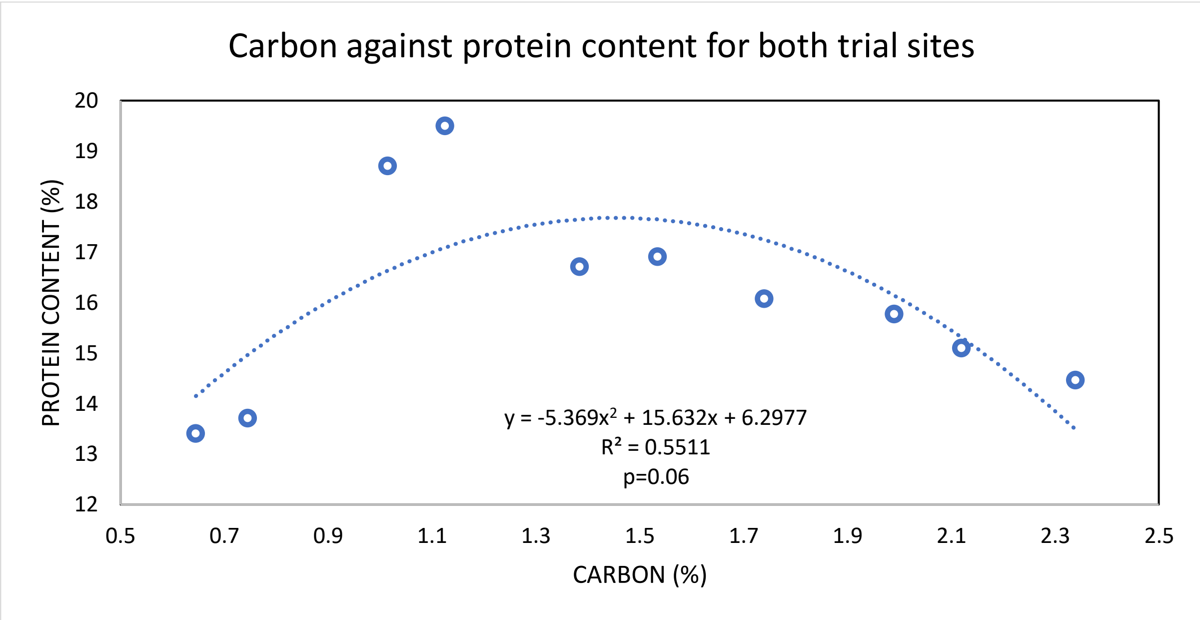

Figure 95: Boundary line analysis of wheat protein (%) against soil organic carbon content (%) at both Langgewens and Tygerhoek from 2002 to 2020

There is good evidence that the SOC content when at the optimum value will influence the quality of the wheat. The target value for the protein content is 11.5%. This needs to be considered by the producer as the grain can be mixed to obtain a value closer to this. This is because not all the fields will have the same SOC content or the same effect of SOC on protein.

5.3.2.4 Yield

A higher yield will constitute the crop taking up higher amounts of nutrients which might result in lower protein content. The protein content and hectoliter mass (HLM), which is a measure of the volume of grain per unit, of wheat, are inversely correlated which can explain why higher yields will have a lower protein content. At Langgewens this negative relationship between the yield and protein content can be seen (Figure 96). The highest protein content was seen when the yield was below 1000 kg ha^{-1}. The optimum range for the yield is between [197:3089]. According to the statistics, the wheat yield has a significant influence on protein content (p<0.01), and yield has a strong positive correlation with rainfall. The R^2-value is 0.97 for yield.

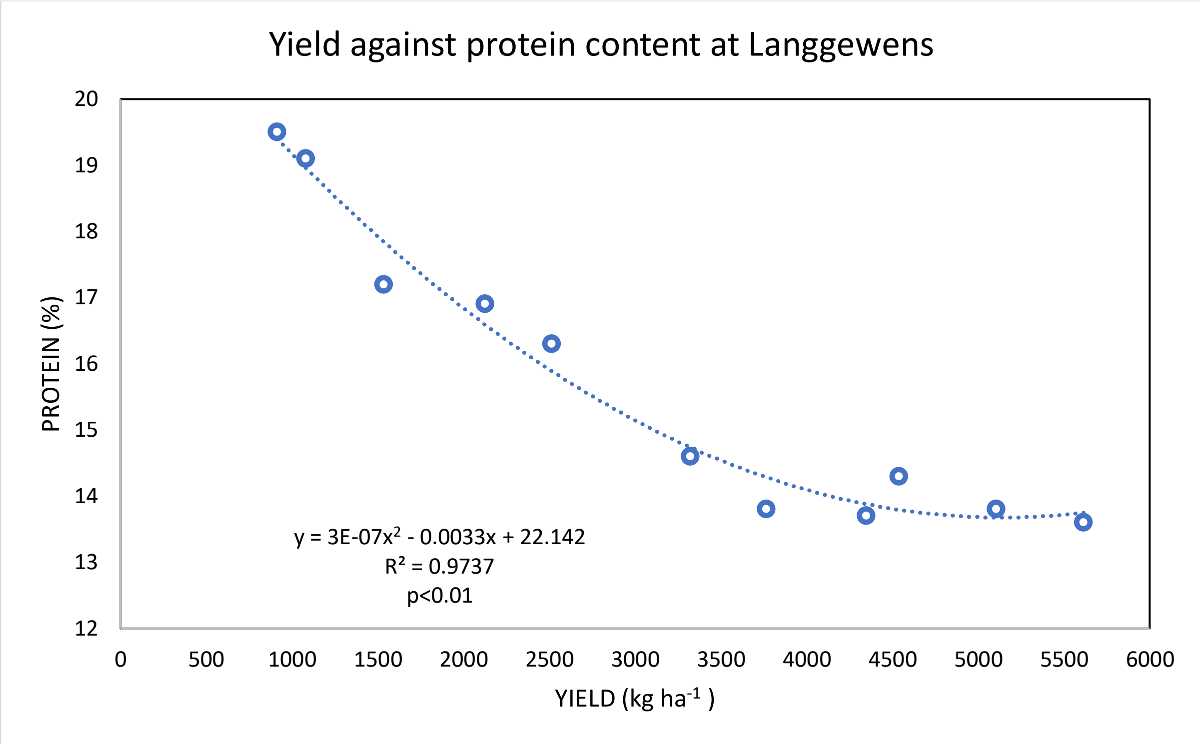

Figure 96: Boundary line analysis of wheat protein (%) against wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

The negative relationship between the yield and protein content is also visible at Tygerhoek (Figure 97). The highest protein content is obtained when the yield is below 3500 kg ha^{-1}, after which the protein content decreases. The confidence interval is between [2722:3777]. According to the statistics, the wheat yield has a significant influence on protein content (p=0.0009), and yield has a strong positive correlation with rainfall. The R^2-value is 0.76 for yield.

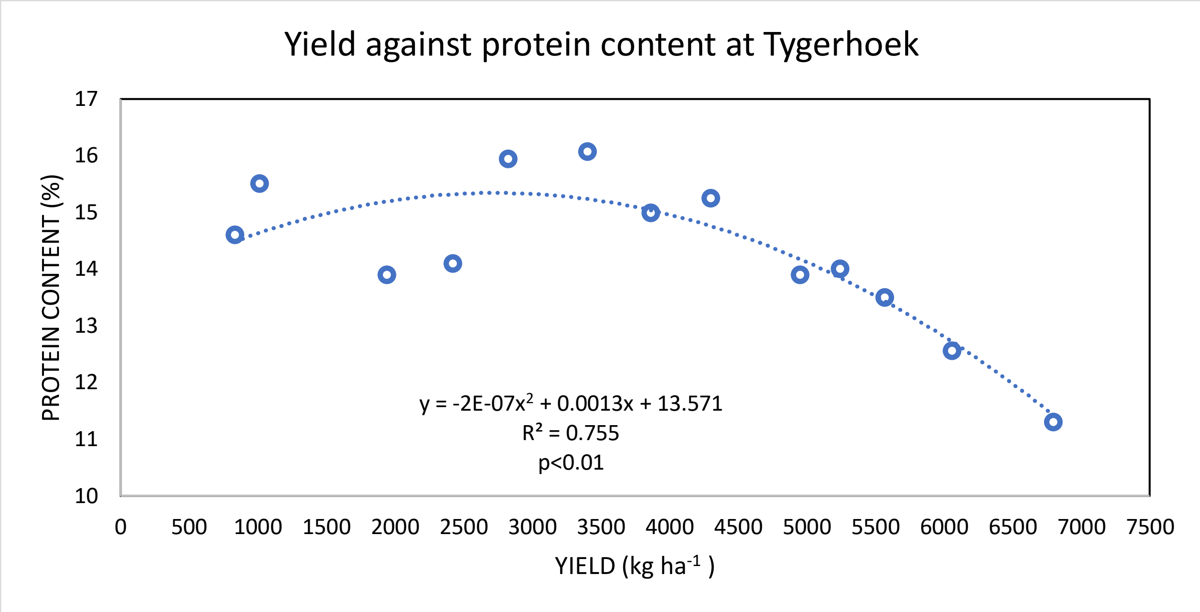

Figure 97: Boundary line analysis of wheat protein (%) against wheat yield (kg ha^{-1}) at Tygerhoek from 2002 to 2020

During the 18-year trial, the wheat yield at Tygerhoek was higher than that of Langgewens. For this reason, it is important to look at the combined yield data against the protein content. This will visualize the relationship better, as shown in Figure 98. A negative relationship was observed with the BLA giving an R^2-value of 0.95. According to the statistics, the wheat yield has a significant influence on protein content (p=0.000006), and yield has a strong positive correlation with rainfall.

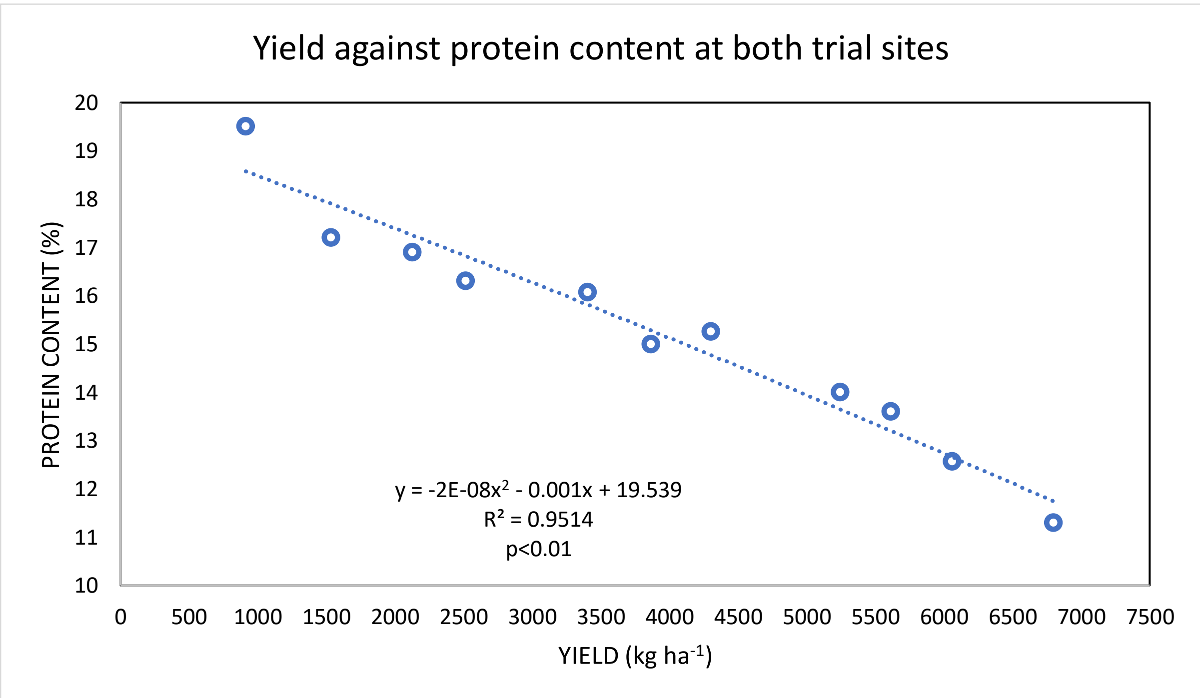

Figure 98: Boundary line analysis of wheat protein (%) against wheat yield (kg ha^{-1}) at both Langgewens and Tygerhoek from 2002 to 2020

The HML is correlated to the yield and is inversely correlated to the protein. This was observed at both farms. The decrease in protein content is not too low to affect the target content of 11.5%, except when the yield was 6800 kg ha^{-1} at Tygerhoek with a protein content of 11.3%. This is on the BLA line which means that it is not the norm and usually the protein content will be lower. This was not seen at Langgewens as the yield had a maximum of 5600 kg ha^{-1}.

5.3.2.5 Rainfall

The protein content of wheat is negatively correlated to rainfall (Sehgal, et al., 2018). So, in times of drought, the protein content rises while the yield falls. In both trials, the protein content showed a weak inverse relationship with rainfall and was better correlated to the seasonal rainfall. The R^2 values were all below 0.5, which is why it is not shown. A reason for this is the positive relationship that rainfall and yield have. Thus, a lower rainfall will result in a lower yield (lower HML) and higher protein content.

5.3.3 Factors affecting soil organic carbon content: Boundary line approach

Although BLA was first used to study the relationship between biological response (mainly plant physiological parameters) and independent factors using field data gathered under different environmental conditions (Webb, 1972), it has also been used to study microbiology process response (denitrification) and the soil properties affecting it (Elliot & de Jong, 1993). Soil organic C levels are a type of biological response that is controlled by primary production (plants) and decomposers (soil fauna), thus the use of BLA would still be appropriate for evaluating its relationship with soil and climatic factors. In the previous section of this chapter, it was found that when looking at the relationship between SOC and yield that there were lower yields when the SOC was higher or lower than a certain point. This shows that the performance of SOC can be quantified. Webb (1972) stated that if a deficiency in yield due to an inferior performance can be quantified, a BLA can be used, as well as when a cause-and-effect relationship exists between two variables. It is known that SOC is well correlated to soil health (Six, et al., 2000; Lal, 2006; Lal, 2011; Murphy, 2015), which in turn will deliver a higher yield. Thus, by quantifying the factors that affect SOC and obtaining sufficiency ranges, this might lead to an indirect increase in yield.

The factors that affect the SOC content can include climate, crop productivity, and soil pH. Rainfall and temperature have a significant effect on the SOM content, with higher rainfall and cooler temperature resulting in higher SOM (Deiss, et al., 2021). From the previous chapter, the rainfall of the previous year has a bigger influence than the current rainfall on the SOC, and it is better to look at the rainfall during the growing season than the yearly rainfall. The average temperature pointed to a lower temperature resulting in a higher SOC. The results point to a correlation between the previous one or two season’s yield and the C content of the soil. There is a complex relationship between the pH of the soil and the SOC content. There was no effect between the addition of lime and gypsum and the SOC content of the soil, while the addition of N fertilizer influenced the SOC, but one to two years after the addition. Most of these factors can be influenced by the producer, thus the optimum values obtained from the BLA are important.

5.3.3.1 Rainfall

The amount of rainfall will determine the decomposition rate of the SOM (Schimel, et al., 2007). It will also influence the amount of SOM returned to the soil in the form of plant biomass, as a higher rainfall will result in greater yield. The R^2 values were all below 0.5, which is why it is not shown. According to the BLA, there is a slight increase in SOC as the rainfall increases, but it is mostly constant, with a slight decrease at the highest rainfall once again. The BLA also gave an optimum value that was 50 mm higher than the average seasonal rainfall. The rainfall (soil moisture) will affect the decomposition of the plant biomass left on the fields, but these results show that this will only be the case up to a certain point. Basile-Doelsch, et al., (2020) found that mineralization rates rise linearly with moisture as soil water content rises, reaching a maximum before plateauing and decreasing due to an oxygen shortage.

5.3.3.2 Temperature

A higher temperature will result in warmer soils and thus an increase in the rate of decomposition. The BLA did not show a good fit for the maximum average annual temperatures, with R^2 values of 0.04 and 0.03 for Langgewens and Tygerhoek respectively. Where there is a rather significant result is at the average yearly minimum temperatures for Langgewens (Figure 99), while Tygerhoek had an R^2 of 0.35. The BLA gives a polynomial function with an R^2 value of 0.519. The average minimum temperature is 12.37°C, while the BLA gives the optimum as 11.48°C. This can be explained by the high SOC at lower temperatures. The confidence interval is [12.06:12.68], which gives a good representation of the relationship between minimum temperatures and SOC content. According to the statistics, the minimum temperature does not have a significant influence on SOC ($p= 0.0879$), and SOC has a moderate positive correlation with rainfall. The R^2-value is 0.52 for minimum temperature.

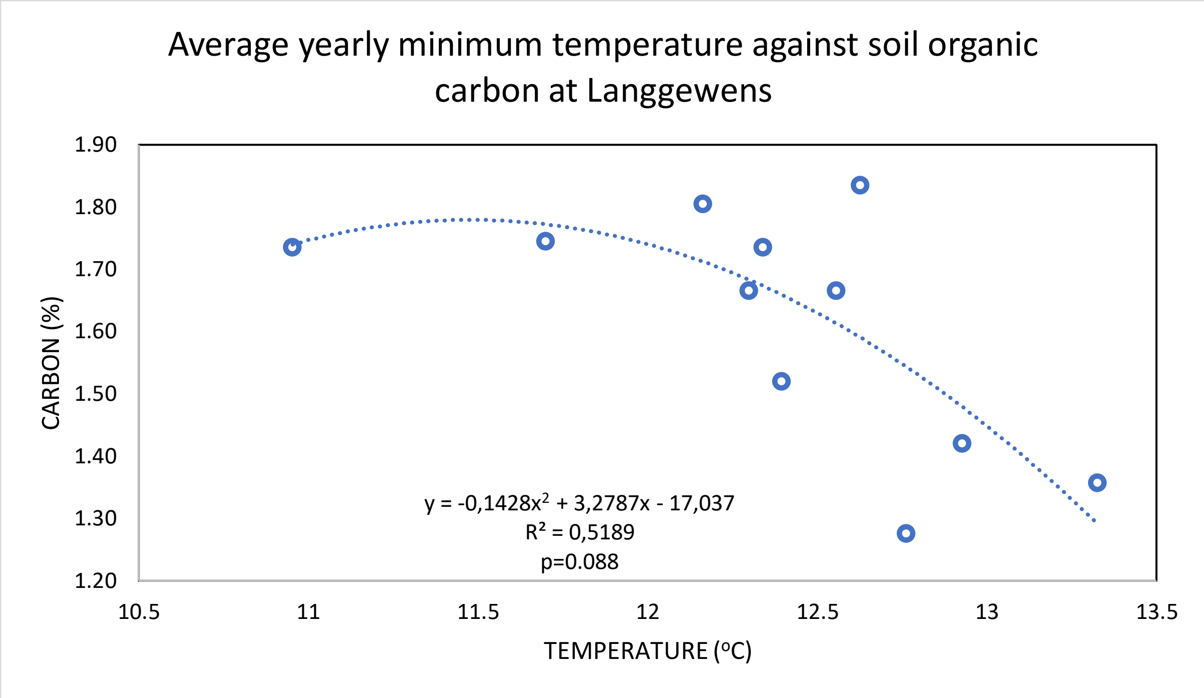

Figure 99: Boundary line analysis of soil organic carbon (%) against average yearly minimum temperatures (ºC) at Langgewens from 2002 to 2020

To give a clearer view of the relationship between the average yearly minimum temperature and SOC the data of the two trial sites are combined to give a wider range of temperature data. The relationship is shown in Figure 100. No optimum value or confidence range could be deduced from the BLA graph, but the relationship between the average minimum temperature and SOC content is portrayed very well. According to the statistics, the minimum temperature has a significant influence on SOC (p= 0.000004), and SOC has a strong positive correlation with rainfall. The R^2-value is 0.90 for minimum rainfall.

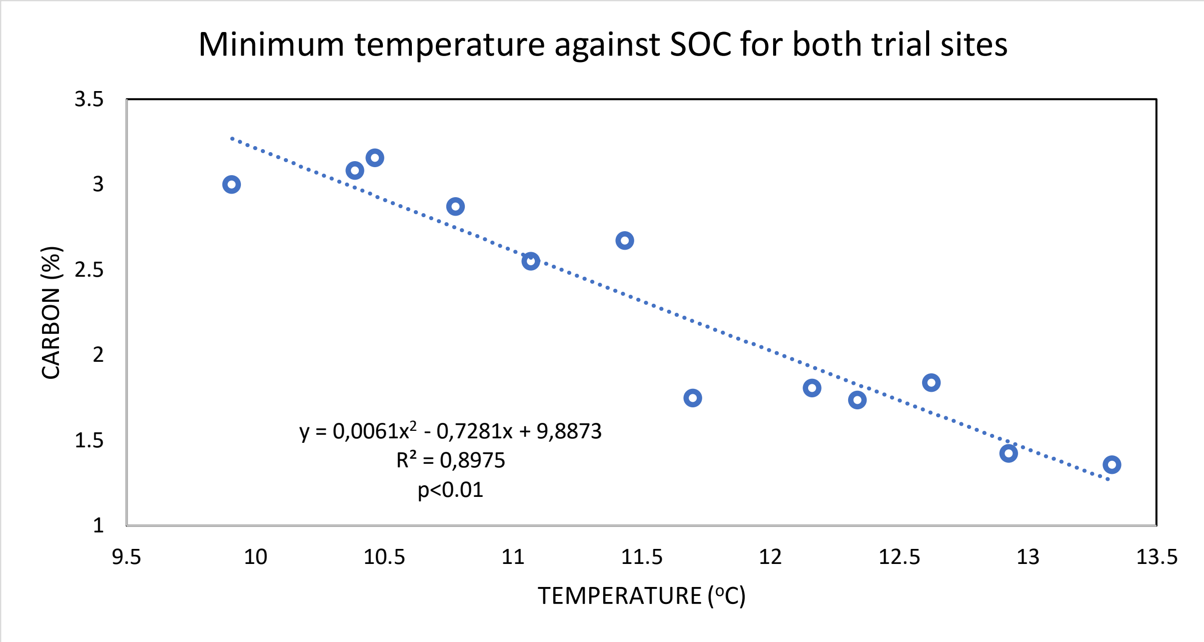

Figure 100: Boundary line analysis of soil organic carbon (%) against average yearly minimum temperatures (ºC) at Tygerhoek from 2002 to 2020

The temperature cannot be influenced by the producer; thus the actual values are not of great importance. What can be concluded from these findings is that the minimum temperature influences the SOC content of the soil, much more so than the maximum temperature. Zhao, et al., (2017) and Follet, et al., (2012) also found that there is an increase in SOC with a decrease in mean annual temperature. This can be attributed to the increased rate of decomposition of the plant biomass because of an increase in microbial activities and biochemical processes. The increase in decomposition can then lead to an increased loss of SOC from the soil.

5.3.3.3 Yield

There is a positive correlation between yield and the amount of biomass produced by the plant (Agegnehu, et al., 2014). At Langgewens there is an increase in SOC as the yield increases up to a certain point, after which the SOC decreases (Figure 101). The optimum yield to obtain the highest SOC content according to the BLA is 3750 kg ha^{-1}, while the confidence interval is between [2230:3858]. According to the statistics, the wheat yield has a significant influence on SOC (p= 0.0076), and SOC has a strong positive correlation with yield. The R^2-value is 0.66 for wheat yield.

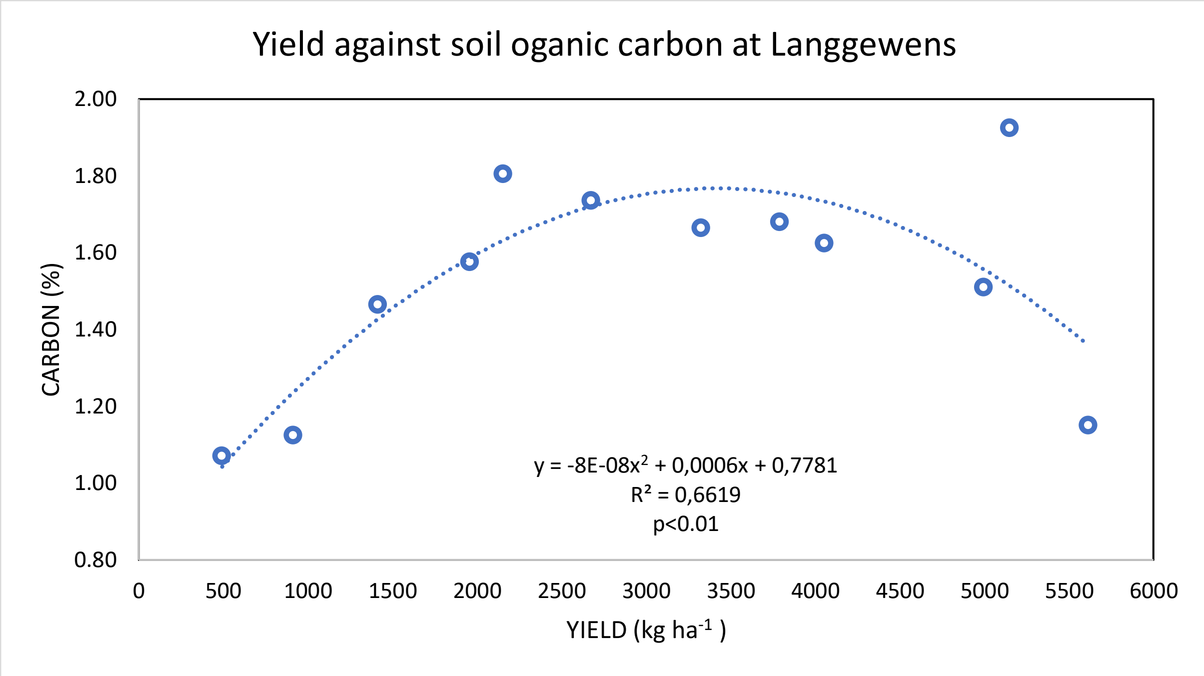

Figure 101: Boundary line analysis of soil organic carbon (%) against wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

At Tygerhoek there is a good fit for the polynomial function for the BLA (Figure 102), with the same trend observed as at Langgewens. The confidence interval is between [2645:4351] with the average being 3498 kg ha^{-1}. The effect of a higher yield on the SOC content is much more pronounced at Tygerhoek with the lowest SOC being at a yield of 6063 kg ha^{-1}. According to the statistics, the wheat yield has a significant influence on SOC (p= 0.0007), and SOC has a strong positive correlation with yield. The R^2-value is 0.80 for wheat yield.

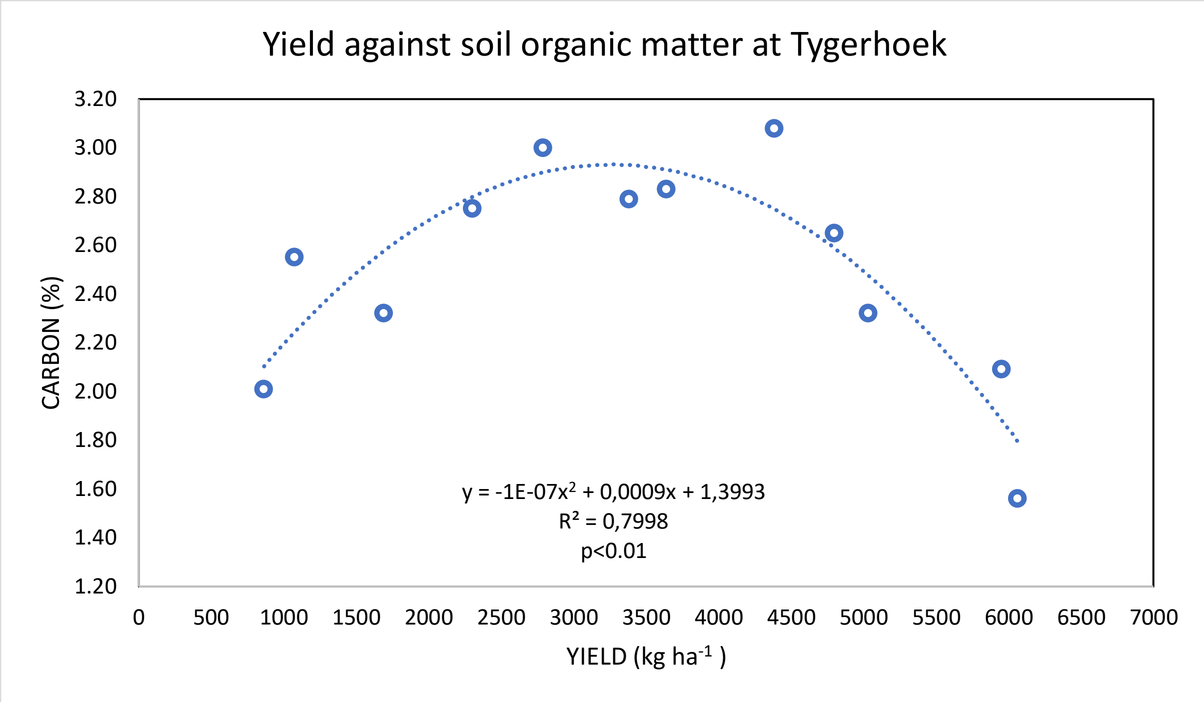

Figure 102: Boundary line analysis of soil organic carbon (%) against wheat yield (kg ha^{-1}) at Tygerhoek from 2002 to 2020

The wheat yield observed at Tygerhoek was higher, along with a higher SOC content across the trial period. This is the reason to combine the data to give a more concise BLA model for the effect that wheat yield has on SOC. This BLA is shown in Figure 103. The optimum value according to the BLA is 3000 kg ha^{-1}, with a confidence interval of [2409:4283]. When the values are compared to the two trials, the optimum value is much lower, while the confidence interval is between but very similar to the two trial sites. According to the statistics, the wheat yield has a significant influence on SOC (p= 0.001), and SOC has a strong positive correlation with yield. The R^2-value is 0.81 for wheat yield.

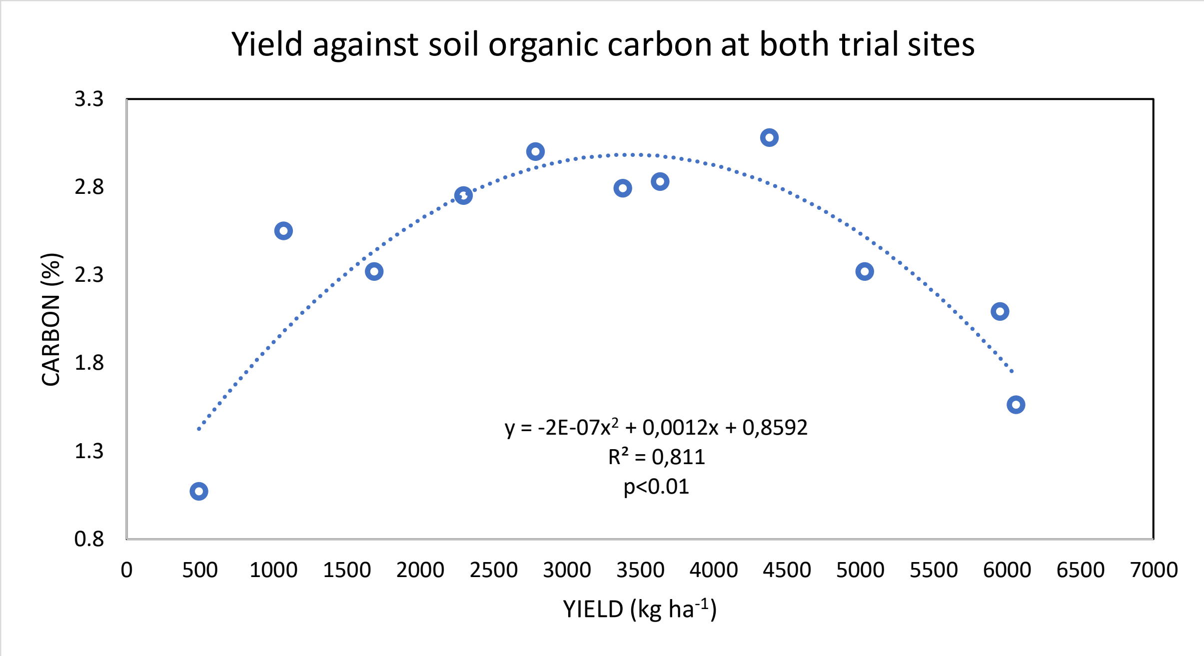

Figure 103: Boundary line analysis of soil organic carbon (%) against wheat yield (kg ha^{-1}) at both Langgewens and Tygerhoek from 2002 to 2020

The yield is correlated to the amount of plant biomass returned to the soil which will be the organic matter and after C sequestration it can be quantified as SOC content. This statement is backed up by the findings in this study as at both farms when the yield is below 1500 kg ha^{-1} the corresponding SOC content is lower. There is another observation that can be made from the BLA. When the yield is higher than a certain point there is also a decrease in SOC. According to Kirkby, et al., (2016) when high-energy C-rich crop residue is added to the soil and there is a lack of nutrient supply may negatively affect the SOM and cause a loss of new SOM added to the soil. To correct this Kirkby, et al., (2016) proposed the addition of supplementary nutrients – N, P, and S – after which they found that the SOC content increased and only 24% of the initial residue load was present after the season when nutrients were added compared to 88% when left on the fields.

5.3.3.4 Soil pH

The effect that the pH of the soil has on SOC can be contradicting. Various sources in the literature found a negative correlation between soil pH and SOC (Zhou, et al., 2019; Zhou, et al., 2020). At Langgewens there is a good fit for the polynomial function to the BLA. There is an increase in SOC as the pH increases until it reaches a maximum SOC where the pH is 5.8 (Figure 104). The optimum value is close to the maximum at 5.87 and the confidence interval is [5.43:6.08]. According to the statistics, pH has a significant influence on SOC (p= 0.0036), and SOC has a strong positive correlation with rainfall. The R^2-value is 0.755 for soil pH.

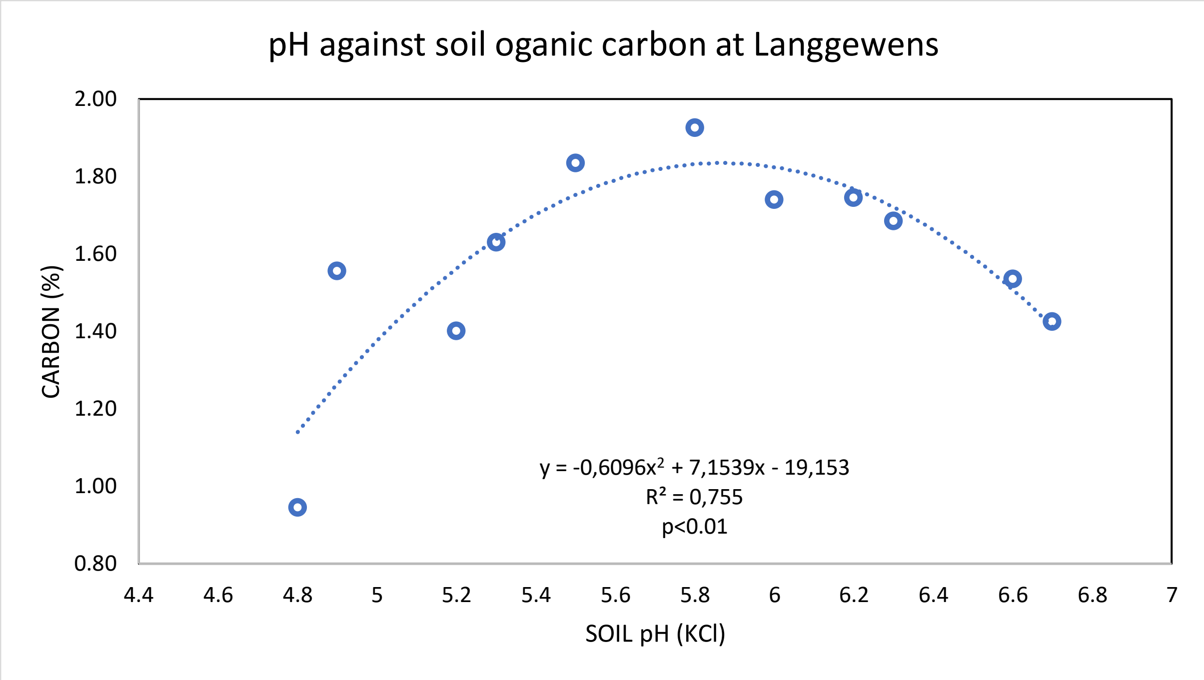

Figure 104: Boundary line analysis of soil organic carbon (%) against soil pH measured in KCl at Langgewens from 2002 to 2020

At Tygerhoek the polynomial function has a near-perfect fit with an R^2 value of 0.93 (Figure 105). The optimal value according to the BLA is 6.23, and the confidence interval is between [5.68:6.41]. According to the statistics, pH has a significant influence on SOC (p= 0.00009), and SOC has a strong positive correlation with soil pH.

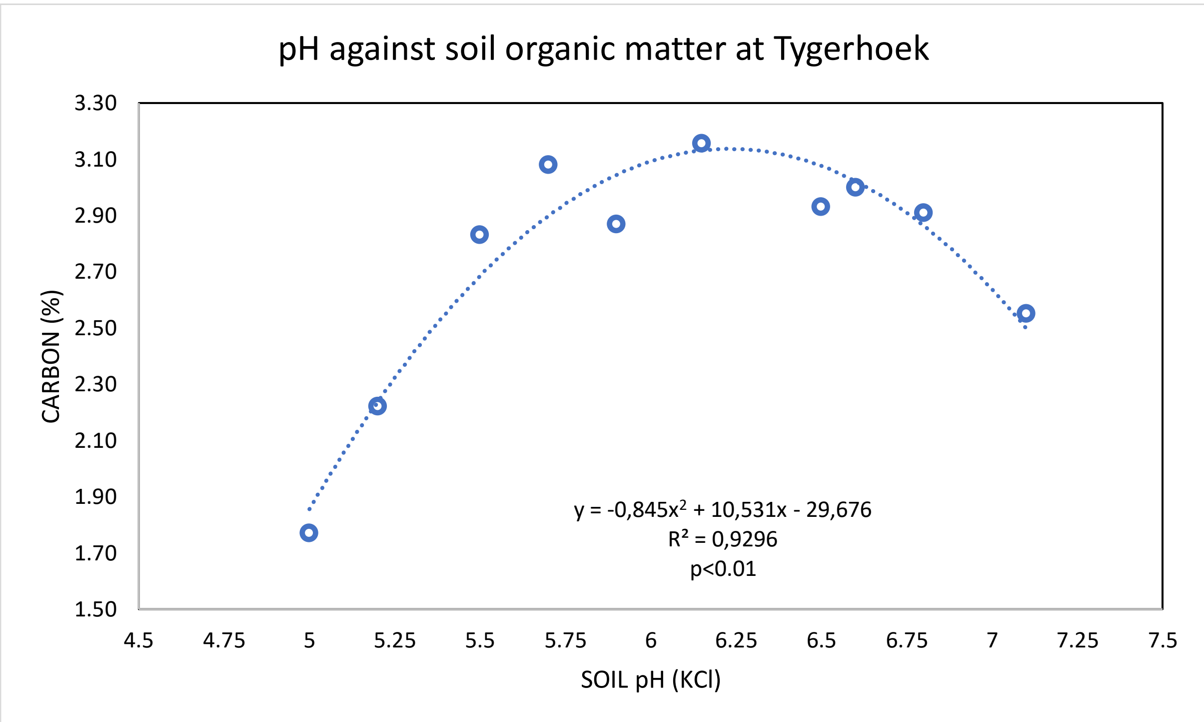

Figure 105: Boundary line analysis of soil organic carbon (%) against soil pH measured in KCl at Tygerhoek from 2002 to 2020

To show the relationship between soil pH and SOC it must be looked at over a wider range of pH values. There was a lower pH observed at Langgewens. The combined pH and SOC showed a similar trend, with an increase in both up to a certain point and then a decrease in SOC at higher pH levels (Figure 106). The BLA gives an optimal value of 6.23 and a significance range of [5.55:6.31]. According to the statistics, pH has a significant influence on SOC (p=0.000006), and SOC has a strong positive correlation with pH. The R^2-value is 0.95 for soil pH.

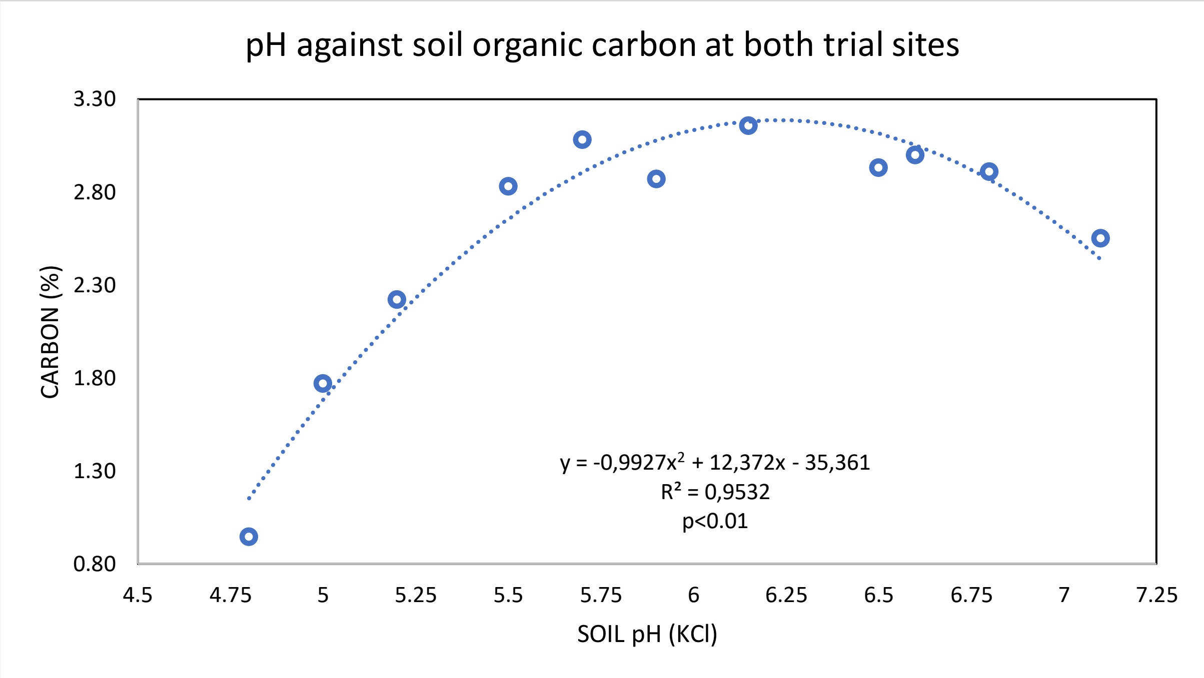

Figure 106: Boundary line analysis of soil organic carbon (%) against soil pH measured in KCl at Langgewens and Tygerhoek from 2002 to 2020

The BLA shows that there is a rapid decrease in SOC when the soil pH goes below 5.5, and also a slight decrease when it is above 6.6 at Langgewens and 7 at Tygerhoek. At pH above 5, Ca and Mg ions in solution tends to insolubilize OM and adsorb it by electrostatic interactions, thus reducing its biodegradation (Rowley, et al., 2018). These findings could influence the management practices, such as the addition of lime to the soil to increase the pH. According to Cornell University (1996), the best range for microorganisms for the decomposition of OM is between 5.5 and 8. This could be a reason for the decrease in SOC at the two farms.

5.3.3.5 Clay content

The clay content of the soil will have an influence on the storage of SOM, in particular SOC, by mineral association (Keber, et al., 2005). This is known as occlusion. Keber, et al., (2005) further found that with a clay content between 5 and 30%, occlusion is most prominent and a further increase would result in a decline in the occluded POM. At neither Langgewens nor Tygerhoek, there were significant results for the clay content against SOC. This could be due to there not being a large variation in clay content, with the range for both trial sites being between 9 and 30%, which is the prominent range according to Keber, et al., (2005).

The BLA showed a good fit (R^2=0.75) for the polynomial function when the data is combined for Langgewens and Tygerhoek (Figure 107). There is an increase in SOC and the clay content increases, with a slight decrease as the clay content reaches 30%. This is in accordance with what was found in the literature. According to the statistics, the clay content of the soil has a significant influence on SOC (p=0.008), and SOC has a moderate positive correlation with clay content. The R^2-value is 0.75 for pH.

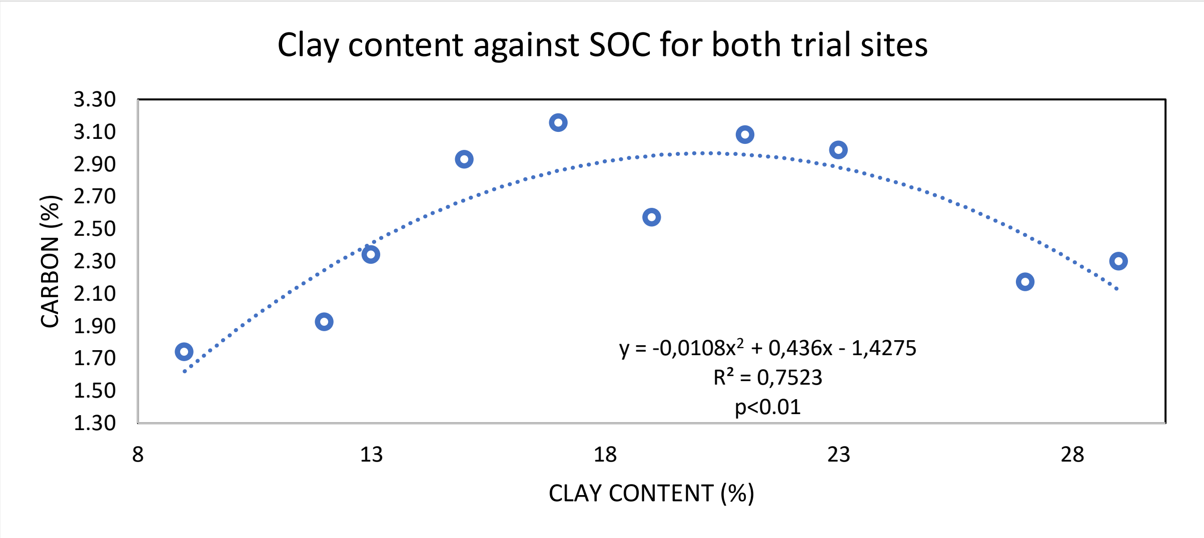

Figure 107: Boundary line analysis of soil organic carbon (%) against clay content (%) of the top 15cm of the soil at Langgewens and Tygerhoek from 2002 to 2020

5.3.3.6 Lime and gypsum application

According to the literature addition of lime can either have a positive or negative impact on soil C. At Tygerhoek there were only three amounts of calcitic lime (0.75, 1.5, and 2 tone ha^{-1}) added and one amount for gypsum. There are too few data points for the BA to give a significant result. At Langgewens the BLA suggests there be a negative relationship between the amount of lime and gypsum applied to the soil and the SOC content (Figure 108). For gypsum applied there is a positive polynomial function for the BLA. The highest SOC was observed when 0.5 to 2 tons per hectare was applied. There is a stable SOC content above 2 tonnes per ha. For calcitic lime, the same trend can be observed. The range for the calcitic lime is between 0.3 and 1 tone per hectare before it is at the same level where the gypsum ended. The dolomitic lime showed the same trend as well. Between 0.25 and 1 tone per hectare, the highest SOC was observed, and thereafter it decreased to the same level as the rest. The level at which calcitic and dolomitic lime and gypsum decreased was between a SOC content of 1.03 and 1.38%, which compared to the averages of 1.48%, 1.54%, and 1.50% for the optimal ranges for the calcitic and dolomitic lime, and gypsum respectively. According to the statistics, calcitic lime and gypsum do not have a significant influence on SOC (p= 0.07 and 0.09), while dolomitic lime has a significant influence on SOC (p=0.012). There is a strong positive correlation between SOC and dolomitic lime (R^2 = 0.72), while calcitic lime and gypsum have a moderate positive correlation (R^2 = 0.58 and 0.56).

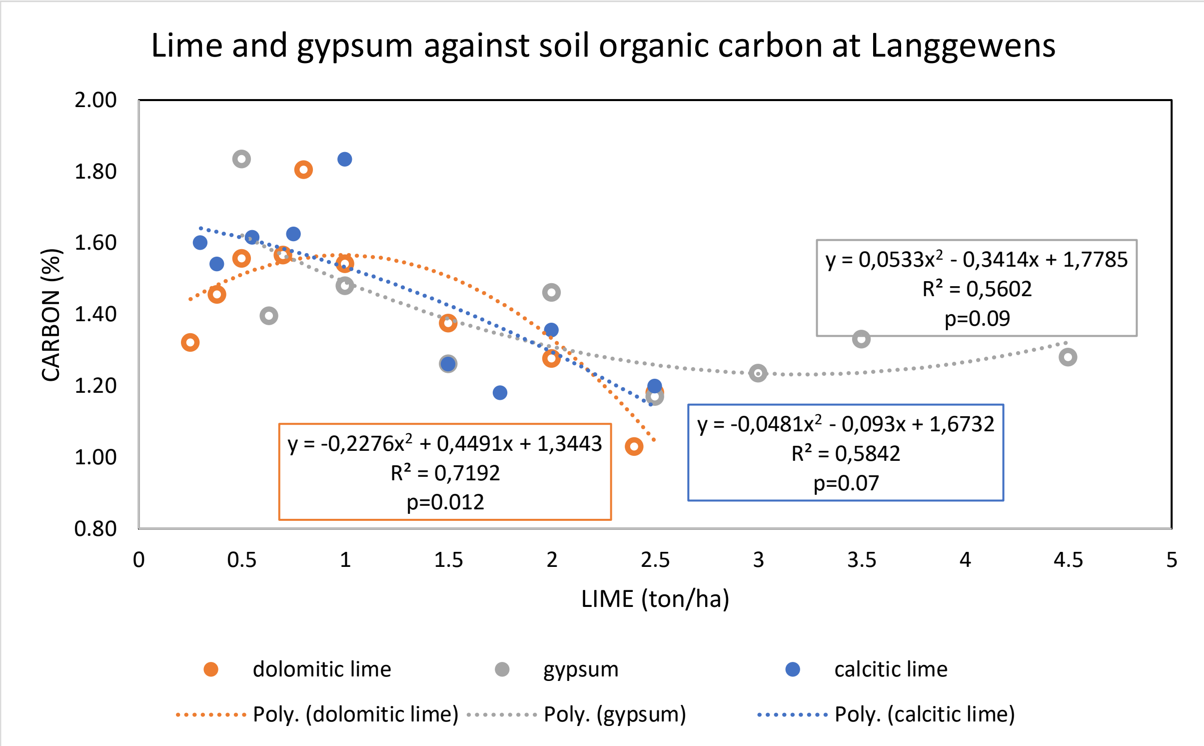

Figure 108: Boundary line analysis of soil organic carbon (%) against the addition of calcitic and dolomitic lime, and gypsum (tone ha^{-1}) at Langgewens from 2002 to 2020

The results at Langgewens are of significant importance when it comes to the application of lime and gypsum. The BLA suggests that the application of gypsum should be between 0.5 and 2 tone ha^{-1}, and lime should be between 0.25 and 1 tonnes ha^{-1} to obtain the benefits of SOC. A possible reason for the higher SOC contents at lower lime applications is that Liming increases soil biological activity, which enhances the mineralization of organic matter, which might cause CO^2 losses from the soil, and a subsequent decrease in SOC (Paradelo, et al., 2015).

5.3.3.7 Nitrogen application

A higher amount of N applied to the soil will increase the crop biomass, thus the amount of OM. It will also influence the soil microbial populations and their respiratory and enzymatic activities (De Forest, et al., 2004). At both Langgewens and Tygerhoek, the BLA for the SOC against the amount of N applied to the soil is relatively stable, with a slight negative relationship, but it does not show a significant result (R^2=0.40 and 0.15). It was found by Heenan & Taylor, (1995) that a larger SOC content is typically associated with greater rates of nitrogen mineralization combined with the leaching of nitrate-nitrogen.

5.4 Conclusions

When looking at the yield, we showed that above and below a certain SOC level wheat yield will decrease. The optimum points differ between Langgewens (1.13%) and Tygerhoek (1.72%), but when it is looked at together the decrease is not as pronounced. This indicates that the climate, the soil's physical and chemical properties, and the management practices will play a larger role than SOC. The yield shows an increase with an increase in yearly and seasonal rainfall, while it plateaued off at the highest rainfall. The effect of pH on yield is in the prescribed range on the farms; at Langgewens (5.83) it is a little lower than Tygerhoek (5.90), which is both between 5.5 and 6.5. The soil nutrient status for yield is in line with what is found in literature, with Langgewens and Tygerhoek showing similar results. The clay:C ratio is also in agreement with the literature, where too low or high a ratio will result in a lower yield.

The target protein content is 11.5% and knowing how different factors affect the protein will determine the management practices. The yield and S stay constant up to 20 mg kg^{-1} when the yield decreases. The SOC content will influence the N and S availability, and soil moisture that will determine the protein content. At Langgewens the optimal SOC content is 1.25%, while at Tygerhoek it is 1.82%, while there was a decrease in protein content above and below a certain SOC content. The BLA shows a negative correlation between yield and protein content, which can be explained by the protein content and HLM being inversely correlated. There is also a negative correlation between protein content and rainfall, which can be due to a higher rainfall resulting in a higher yield (higher HLM).

The yield and protein content both showed that when the SOC content was above or below a certain point both will decrease. This shows the importance of the SOC content and that there is a cause-and-affect between the factors that will influence yield. There was no definitive result found when comparing the average yearly maximum temperature with SOC, but when the average yearly minimum is looked at there is a clear negative correlation with SOC content. This can be attributed to the increased rate of decomposition of the plant biomass because of an increase in microbial activities and biochemical processes. The increase in decomposition can then lead to an increased loss of SOC from the soil. There is a decrease in SOC when the wheat yield is above and below a certain point. When the yield is low there is a low biomass input into the soil, while there is not an adequate supply of nutrients to sequester the SOM to SOC. The soil pH can be influenced by lime application. The optimum soil pH values for SOC content are 5.87 at Langgewens and 6.23 at Tygerhoek. The application of lime and gypsum shows that when lower amounts are applied during the season it will result in higher SOC content. This is below 2 ton ha^{-1} for gypsum and below 1 ton ha^{-1} for calcitic and dolomitic lime. The SOC shows a slight decrease when the clay content is near the upper and lower limits described in the literature.

The specific climatic, soil physical and chemical, and plant production factors and management practices influence the wheat yield and protein content. By applying the BLA to these factors an optimal value and range has could be obtained. This can be implemented by the producers to obtain a higher yield and a more optimal protein content, as well as economic and ecological advantages.

Chapter 6: General conclusions and further studies

6.1 General conclusion

The Western Cape produces roughly 60% of South Africa's dryland wheat with the two biggest production areas being the Swartland and the Overberg. This shows the importance to implementing management practices that will not only ensure a stable yield but might also improve the yield of wheat. One such practice is the implementation of conservation agriculture, which has positive results on SOM accumulation and C sequestration. This will lead to greater soil health and resilience and will support subsequent greater yield. Previous studies done in South Africa looked at the impact of management practices of SOC, but very little was done on the effect it has on yield.

The first objective of this research project was to look at the long-term effect of no-till crop rotation systems on SOC and the effect of different enviromental factors on SOC. The different crops in the rotational systems had different biomass inputs, as well as root architectures. It is important, especially under dryland production in semi-arid conditions where the decomposition of SOM is reduced. The main objective was to explore whether there is an effect of and relationship between the SOC content in the soil and the yield and protein content of wheat. This involved using different statistical methods to quantify the relationship during the 18-year trial period at both trial sites. Finally, Boundary Line Analysis (BLA) data analysis was used to obtain optimum values and sufficiency ranges for the factors which affect wheat yield, protein content, and SOC content.

The SOC content of the soil is greatly correlated to the health of the soil. For this reason, it was important to look at the different factors that had a positive effect on SOC, to implement this through management practices. There was a significant increase between the start of the trial and conclusion in SOC content at Langgewens, with an average increase of 0.02% per year across the trial period, with a total average increase of 0.4% over the 19-year period, while at Tygerhoek there is only a slight average increase of 0.0035 % per year, with a total average increase of 0.06% over the 18-year period. The average SOC content across the trial periods was seen to be higher at Tygerhoek (1.68% SOC) compared to Langgewens (1.17% SOC). Possible reasons for a higher SOC at Tygerhoek could be due to the average rainfall being higher, there was a lower average temperature (17^{o}C compared to 18^{o}C), a higher average yield, the soil pH is more alkaline (average of 6.03 compared to 5.76), a higher clay content (21% compared to 13%), but a lower amount of lime, gypsum and N fertilizer was applied. The difference in SOC accumulation between the sites was also attributed to the soils reaching a SOC 'saturation point', which was proposed to be 1.33% at Langgewens and 1.70% at Tygerhoek, and reached after 2013 and 2006 respectively.

It was proposed that the yield of the crops in the rotational system would influence the amount of above- and below-ground biomass produced on the SOC. At both trial sites, it was found that the SOC content is best correlated to the yield of the previous one to two years. Wheat, lupin, and barley had a greater influence on the SOC than oats and canola. This could be explained by cereal crops having greater biomass. These statements could not be backed up as there was no statistical difference between the SOC contents of the different crop rotational systems at Langgewens. The WWCL and WMcWMc+saltbush rotational systems showed the highest average C. At Tygerhoek there was a significant difference between the systems, with the PPC system having a significantly higher average SOC than PPCC, CCC, and PCPC. The findings at both trial sites were supported by scientific literature, as it was found that the incorporation of pastures into a cropping system will result in a higher soil C content.

Besides the important effect of climatic on SOC content, it was found in the literature that there is a plateau that is reached after 11 years, which means that the soil reaches a saturation point. At Langgewens after 13 years SOC content was seen to be rather stable between 1.24% and 1.38%. This also means that the rate of SOC accumulation will be higher when the SOC content was low at the start of the trial. This could potentially explain why WWWC and WMWM at Langgewens and CCC and PCPC at Tygerhoek had the greatest increase in SOC. The rotational systems which included the medics at Langgewens all had similar changes between the years. At Langgewens the wheat yield of WMcWMc+saltbush, WMCM, WMWM, WCWL, and WWCL, were significantly higher than WWWW. At Tygerhoek the pure cash crop rotation has a significantly lower yield than PCPC and PCCP, but not PPC. This points to the positive influence that pasture/medics have on the yield of wheat. At both sites, the wheat monoculture had a significantly lower yield. These results from both trial sites show that the incorporation of natural vegetation (pastures and saltbush) into the rotational system not only has a benefit on the SOC content of the soil but also wheat yield.

There are also other factors that will influence the yield. At both Langgewens and Tygerhoek, the yield was variable throughout the trial period, while the yield ranged between 1.5 - 4.5 tonnes ha^{-1} and 1 - 6 tonnes ha^{-1} respectively. The rainfall and yield showed the same trends at both farms, along with a significant linear correlation for both yearly and seasonal rainfall. This is expected as the farms are rain-fed and in semi-arid regions. The other factors, which included pH, lime, gypsum, N fertilizer, soil nutrients, and the clay:C ratio did not show a significant linear correlation, but the factors had the same trends as the yield. These trends varied between the current, next, and yield two seasons later. Only P showed a significant linear correlation for the current season's yield at Tygerhoek.

At neither experimental site a linear correlation was found between wheat yield and the SOC content of the soil. There was a one to two year lag between the significant changes in SOC and wheat yield. The proposed reason for this was that soil health is built over time. For this reason, a partial correlation was used. There was a significantly positive partial correlation for some seasons for SOC on the current season's yield, while a significant partial negative correlation was seen once on the following season's yield. The partial correlation shows that there is a relationship between SOC and yield. This gave rise to use a panel regression, which effectively manages the dependencies of unobserved independent variables on a dependent variable that can result in biased estimators. The current season's yield and variables showed a significant positive correlation for soil resistance and a negative for soil K and S. When looking at the next season's yield resistance shows a significant negative correlation, while rainfall and soil Mg have a significant positive correlation. The previous year's rainfall against the current yield and variables showed a significantly positive correlation with rainfall and soil resistance, and a negative with soil K. These results show that not all the variables have significant influences on the current or even the next year's yield. The three types of statistical analysis showed interesting results, with a possible explanation being the 'saturation point' that the SOC content reached.

Part of the research question was to look at the effect of SOC on the quality of wheat yield. A good positive correlation was seen for N fertilizer applied and the soil S content to the current protein content, SOC was seen best one to two years prior to changes in protein content, the wheat yield was negatively correlated, and rainfall had an inverse relationship. The crop rotational system implemented showed that wheat monoculture had a significantly lower protein content than 50% wheat, which was significantly lower than those with medics/clover at Langgewens. At Tygerhoek the system with 100% crops had a significantly lower protein content and grade, while the system with 50% crop/50% pasture was significantly higher than 100% crop but significantly lower than 33% crop/66% pasture.

The factors that influence yield and protein content were compared by looking at the averages across the trial period of the two experimental sites. The averages can be misleading and underlying factors could improve which leads to higher yields. For this reason, it is important to use BLA to conceptualize the relationships. A scatter plot with yield or protein content as the dependent variable against the growth factor as the independent variable was made, showing the optimum for the factor at the peak of the polynomial function. The BLA for SOC against wheat yield showed that above and below a certain point wheat yield will decrease, but when it is looked at together the decrease is not as pronounced. The optimum points were 1.13% at Langgewens and 1.72% at Tygerhoek. This is explained by the SOC content reaching a 'saturation point' where the positive effect of SOC is no longer seen on yield, but also SOC is not directly addressing the most limiting factors, which in the case of dryland wheat production is the climate and soil depth/texture. Wheat yield increased as expected with an increase in yearly and seasonal rainfall, with a plateau when the rainfall was at its highest. The optimum pH values were in line with what is prescribed in literature, along with the nutrient status of the soil, and the clay:C ratio.

The BLA for soil S against the protein content showed that above 20 mg kg^{-1} there is a decrease in protein content. The BLA showed a decreased protein content above and below a certain SOC point, with the optimums being 1.25% at Langgewens and 1.82% at Tygerhoek. According to the literature, a higher yield will result in a lower protein content because the protein content and HLM (higher HLM is a higher yield) are inversely correlated, with this negative correlation also observed at both trial sites. A negative correlation between protein content and rainfall was also observed. This can be explained by the yield increasing with rainfall, and the subsequent negative correlation between yield and protein content.

The use of BLA to look at the factors which affect SOC was proposed, as there is an indirect effect on the yield. BLA has also been used determine the effect of soil properties on denitrification rates, which is also not a plant biological response. The results showed that there is a significant effect of average minimum temperatures rather than maximum temperatures on SOC content, with a negative correlation observed. An explanation was the increased rate of decomposition due to an increase in microbial activity and biochemical processes. Yield led to lower SOC when it was either above or below a certain point. The optimum pH was in the range of the target pH for wheat production. The application of lime and gypsum showed that it is better for the accumulation of SOC when the amounts applied is below 2 ton ha^{-1} for gypsum and below 1 ton ha^{-1} for calcitic and dolomitic lime. The clay content showed similar results to what was found in the literature.

Results in this study can be used by producers to predict how certain factors – crop rotation, rainfall, temperature, yields, pH, and lime, gypsum, and N application – will influence the SOC content of the soil under CA in semi-arid grain-producing regions of the Western Cape. The factors that affect wheat yield were also explored with SOC and yield following a similar trend across the trial periods and the crop rotational systems which had a higher SOC content also had a higher yield, but no significant linear or partial correlation was found. Through BLA optimum values and sufficiency ranges were made for the factors which had a significant influence on wheat yield and protein content.

6.2 Further studies

As conservation agriculture (no-tillage and crop rotation) has more recently started being implemented and studied in South Africa, further research is required to establish a solid scientific foundation. While this study concluded the benefits of implementing crop rotation on yield, a significant effect of SOC on yield was not observed while the trend of higher SOC with a higher yield was observed between the crop rotation systems. This might be seen on different farms in these regions. The results for the may be different is if the different C functional pools were used, as well as their change across the trial period. The effect of integrating livestock could not be looked at in this study as not enough systems had grazing. This could have interesting results as the root system has a great influence on the SOC input, with grazing potentially stimulating root growth. Another aspect that was lacking in this study was the effect of crop residue on the SOM and subsequent SOC of the soil. The breakdown of crop residue, amount left in the soil, and amount sequestered as C was not found in local literature. Lastly, the soil type needs to be considered when looking at the SOC accumulation, as a more clayey soil will be able to accumulate more SOC than sandy soil.

This study showed great strides in the right direction for CA in the major grain-producing areas of the Western Cape. The results show that there is great potential in increasing the yield through NT and crop rotation, with a great capacity for increasing the SOC content.

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Appendix

Soil characteristics

Table A 1: Descriptive statistics for soil carbon, pH, resistance, T-value, calcium, magnesium, sodium, potassium, phosphorus, and sulphur at Langgewens from 2002 to 2020

Soil characteristic	Mean	Std. deviation	Sample variance	Range
Carbon (%)	1.18	0.24	0.06	0.48-1.93
pH (KCl)	5.76	0.37	0.14	4.8-6.8
Resistance (ohm)	752.89	407.41	165982.26	45-5200
T-value (cmol kg^{-1})	6.90	2.00	3.95	2.76-23.26
Calcium (cmol kg^{-1})	5.05	1.70	2.89	1.88-18.68
Magnesium (cmol kg^{-1})	1.09	0.38	0.14	0.40-4.19
Sodium (mg kg^{-1})	35.87	62.98	3966.50	0.62-1420
Potassium (mg kg^{-1})	157.70	45.41	2062.24	55-431.5
Phosphorus (mg kg^{-1})	82.39	21.98	482.92	39.5-181.5
Sulphur (mg kg^{-1})	14.34	36.83	1356.69	0.48-685

Table A 2: Descriptive statistics for soil carbon, pH, resistance, T-value, calcium, magnesium, sodium, potassium, phosphorus, and sulphur at Tygerhoek from 2002 to 2020

Soil characteristic	Mean	Std. deviation	Sample variance	Range
Carbon (%)	1.68	0.32	0.10	0.21-3.16
pH (KCl)	6.03	0.39	0.15	5-8
Resistance (ohm)	596.52	258.85	67002.23	60-1760
T-value (cmol kg^{-1})	10.28	2.89	8.34	5.06-40.78
Calcium (cmol kg^{-1})	7.61	3.15	9.89	2.98-60
Magnesium (cmol kg^{-1})	1.74	0.63	0.40	0.68-10.49
Sodium (mg kg^{-1})	71.80	87.90	7725.61	17-1503
Potassium (mg kg^{-1})	248.66	78.32	6135.30	71-614
Phosphorus (mg kg^{-1})	49.71	15.79	249.33	15-209
Sulphur (mg kg^{-1})	8.37	5.99	35.90	1.2-78

Soil texture and coarse fragments

Table A 3: Sand, silt, clay, and stone content (%) for each camp at Tygerhoek

Camp	Sand %	Clay %	Silt %	Stone %	Camp	Sand %	Clay %	Silt %	Stone %
1,1	57	21	22	40	13,1	61	23	16	58
1,2	61	21	18	40	13,2	57	23	20	40
1,3	63	19	18	60	13,3	65	17	18	50
1,4	55	21	24	49	13,4	67	15	18	57
2,1	55	21	24	53	14,1	54	25	21	73
2,2	53	21	26	49	14,2	60	21	19	57
2,3	55	21	24	40	14,3	58	21	21	47
2,4	55	19	26	38	14,4	60	21	19	57
2,5	53	21	26	49	14,5	64	17	19	56
2,6	53	21	26	57	14,6	60	21	19	53
2,7	51	21	28	46	15,1	64	17	19	40
2,8	53	23	24	43	15,2	64	15	21	65
3,1	55	21	24	49	15,3	49	27	24	66
3,2	51	21	28	46	15,4	53	27	20	60
3,3	55	19	26	50	15,5	53	25	22	69
3,4	61	17	22	40	15,6	49	29	22	60
3,5	63	15	22	50	15,7	55	23	22	73
3,6	57	19	24	63	15,8	57	23	20	70
4,1	55	21	24	80	16,1	59	21	20	34
4,2	61	21	18	60	16,2	65	17	18	53
4,3	59	21	20	67	16,3	67	15	18	53
4,4	59	19	22	63	16,4	61	19	20	41
5,1	63	17	20	59	17,1	63	17	20	57
5,2	57	19	24	57	17,2	63	17	20	53
5,3	57	19	24	67	17,3	65	15	20	60
5,4	51	23	26	65	17,4	67	13	20	54
6,1	61	17	22	62	18,1	61	17	22	47
6,2	63	15	22	63	18,2	63	17	20	50
6,3	61	19	20	51	18,3	65	15	20	46
6,4	65	17	18	51	18,4	65	15	20	46
7,1	57	19	24	65	19,1	61	17	22	60
7,2	67	17	16	66	19,2	61	19	20	53
7,3	61	19	20	60	19,3	59	21	20	49
7,4	63	17	20	66	19,4	59	21	20	56
8,1	61	19	20	77	20,1	63	17	20	39
8,2	63	17	20	53	20,2	65	15	20	57
8,3	61	19	20	54	20,3	59	23	18	46
8,4	63	17	20	60	20,4	53	25	22	46
8,5	59	21	20	57	21,1	65	15	20	63
8,6	63	17	20	55	21,2	63	17	20	46
8,7	59	19	22	55	21,3	65	15	20	64
8,8	63	17	20	64	21,4	63	17	20	70
9,1	63	17	20	65	21,5	61	17	22	67
9,2	63	17	20	68	21,6	65	15	20	59
9,3	63	17	20	70	21,7	61	19	20	40
9,4	61	15	24	63	21,8	57	21	22	40
10,1	63	15	22	50	22,1	61	15	24	40
10,2	63	15	22	64	22,2	63	17	20	40
10,3	63	17	20	65	22,3	61	19	20	40
10,4	63	15	22	62	22,4	61	17	22	49
11,1	59	15	26	63	23,1	61	19	20	43
11,2	65	15	20	74	23,2	63	19	18	38
11,3	63	19	18	63	23,3	63	19	18	40
11,4	63	15	20	83	23,4	59	21	20	37
12,1	63	17	20	57	24,1	63	17	20	50
12,2	65	15	20	64	24,2	61	21	18	41

Table A 4: Sand, silt, clay, and stone content (%) for each camp at Langgewens

Camp	Sand %	Clay %	Silt %	Stone %	Fine gravel %	Course gravel %
38	69	14	17	0	15	5
46/1	70	14	16	0	15	0
49/3	77	9	14	0	15	15
53/3	76	10	14	5	15	15
39/1	66	15	19	10	25	5
39/2	67	16	17	10	25	5
46/2	71	12	17	5	15	0
46/3	70	11	19	5	15	0
49/1	77	9	14	0	15	15
49/2	80	9	11	0	15	15
53/1	76	11	13	10	15	15
53/2	74	11	15	5	15	15
40/3	70	14	16	30	15	5
40/4	72	14	14	30	15	5
45/1	72	14	14	5	15	5
45/2	74	9	17	5	15	5
50/3	74	10	16	5	15	5
50/4	77	9	14	5	15	5
52/3	73	11	16	5	15	5
52/4	73	11	16	5	15	5
40/1	70	15	15	30	25	5
40/2	72	11	17	30	25	5
45/3	73	10	17	5	15	5
45/4	73	11	16	5	15	5
50/1	74	10	16	5	15	5
50/2	73	12	15	5	15	5
52/1	73	12	15	5	15	5
52/2	73	11	16	5	15	5
36	72	11	17	15	15	15
48	75	9	16	0	15	5
57	79	10	11	10	15	5
59	81	9	10	25	25	15
37	73	11	16	0	15	5
44	73	12	15	10	5	15
54	78	9	13	0	15	5
55	82	9	9	10	15	15
42/1	75	13	12	0	15	15
42/2	71	14	15	0	15	15
47/1	75	9	16	10	15	15
47/2	72	10	18	5	15	15
56/1	80	9	11	0	15	5
56/2	82	9	9	0	5	5
58/1	83	9	8	30	5	0
58/2	79	10	11	30	5	0
41	75	13	12	25	15	15
43	75	13	12	5	15	5
51	72	12	16	12	15	5
60	80	9	11	53	5	5

Fertilizer application

Table A 5: Average fertilizer application (tonne ha^{-1}) at Langgewens from 2006 to 2020

Fertilizer (ton/ha)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
2-1-0 (29)	0.14	0.16											0.05		
2-1-0 (35)			0.09												
1-0-0 (40)	0.09	0.13	0.12												
3-1-1 (31)S		0.16													
1:4:2(24)						0.12							0.05		
2.3.0(31)+3.6% S												0.05			
MAP	0.1	0.1	0.08	0.05	0.08	0.07	0.08	0.07	0.05	0.05				0.03	
Kysan 27%N 3.5%S				0.16	0.08	0.19	0.15								
Nitro 24:24:0					0.07	0.08									
Alpha magic 3.3%N 13.1%P 6.6%K 4.6%S					0.13										
Geoflo 10.3%N 5.1%P 2.6%K 1.4%S							0.22	0.23	0.23	0.23		0.12	0.1	0.1	0.1
Cura A44 50:0:0							0.14	0.14	0.14	0.14		0.12	0.12		0.11
Amiplus 48:16:0					0.1			0.1	0.08	0.08			0.08	0.1	0.13
Calciumsulphate	0.08														
Turbophos	0.24	0.2	0.2	0.15											
Spraybor	1														
Bortrac			1	1.22	1	1	1	1	2	2	1	2	1	1	
Coptrac							0.5	0.5	1	0.5		0.4			
Mantrac							0.5		0.5	0.5		0.5	0.5		
Zintrac								0.5	0.5	0.5					
Alpha 36				0.17											
Turbo					0.11	0.2									

Table A 6: Average fertilizer application (tonne ha^{-1}) at Tygerhoek from 2005 to 2020

Fertilizers (ton/ha)	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2016	2017	2018	2019	2020
1.0.0 (40)														0.11	
1.0.0 (33.5)												0.13	0.09		0.08
1.0.0 (24)											0.13				
Mengsel 3.1.0 (27)											0.12				
Mengsel 23 N 20 P 15 S									0.15						
Mengsel 20 N 20 P 5 S								0.06							
Mengsel 20 N 15 P 10 S	0.11	0.11	0.12	0.12	0.12	0.15	0.15			0.15					
KAN 28% N	0.11														
Nitrosul 26% N		0.12	0.14	0.12	0.14	0.13	0.15	0.12	0.13	0.12					
MAP (35)					0.21	0.05	0.07	0.06	0.09	0.1	0.04	0.06	0.05		
Timac DC 70 (9:14:4)														0.07	0.06
Sodiummolibdinum	0.15	0.15	0.15	0.15	0.15	0.15	0.15		0.18						
Agribor	0.2	0.2	0.2	0.2											
Supers	0.1	0.1													
Liquibor					0.5	0.13	0.18		0.15	0.5					
U Plant 31 S												0.1			

Lime and gypsum application

Table A 7: Average lime and gypsum application (tonne ha-1) at Langgewens from 2002 to 2020

	2002	2003	2004	2005	2006	2007	2009	2010	2011	2012	2013	2014	2017	2018
Calcitic lime	1.5	1.5	1.6	1	0.6		0.5	0.7	0.6	1.1	0.7	0.7	0.7	1
Dolomitic lime	1.5	1.7		1	0.6		0.7	0.3	0.5	0.6	0.6	1	0.7	1
Gypsum		2	1.2	0.8	2	2.5		0.7	0.3	0.3	0.4	0.5	0.3	0.5

Table A 8: Average lime and gypsum application (tonne ha^{-1}) at Tygerhoek from 2002 to 2020

	2007	2009	2010	2011
Calcitic lime	1.5	1.5		2
Gypsum			2	

Boundary line analysis scatter plots

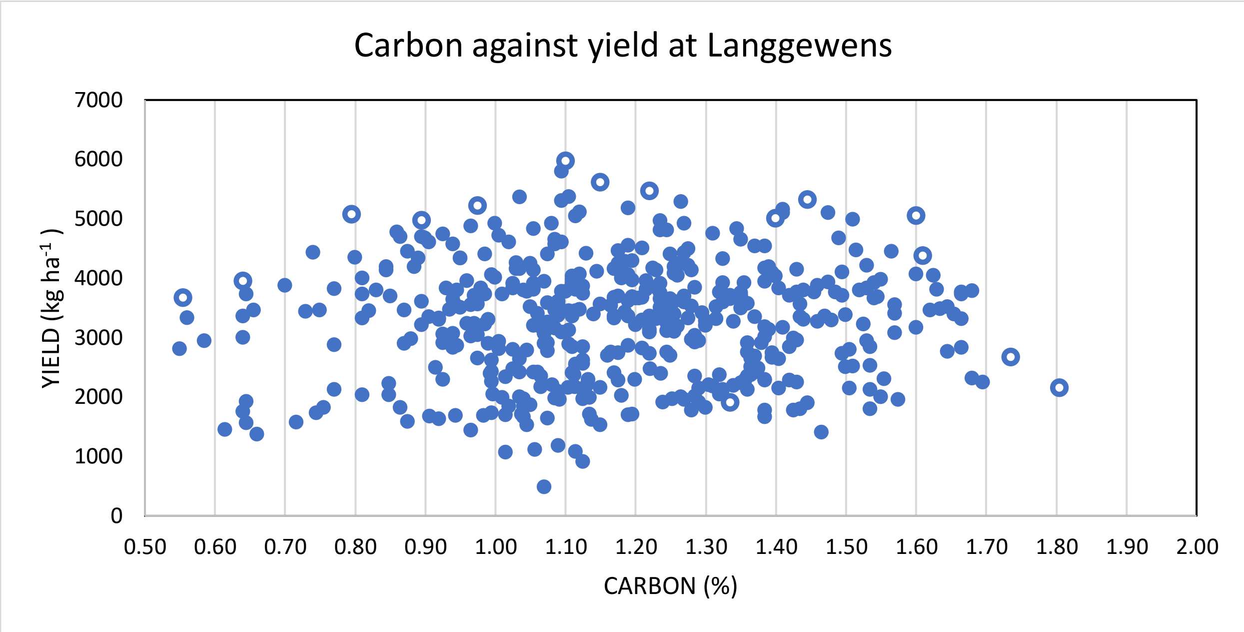

Figure A 1: Boundary line analysis of soil organic carbon (%) against wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

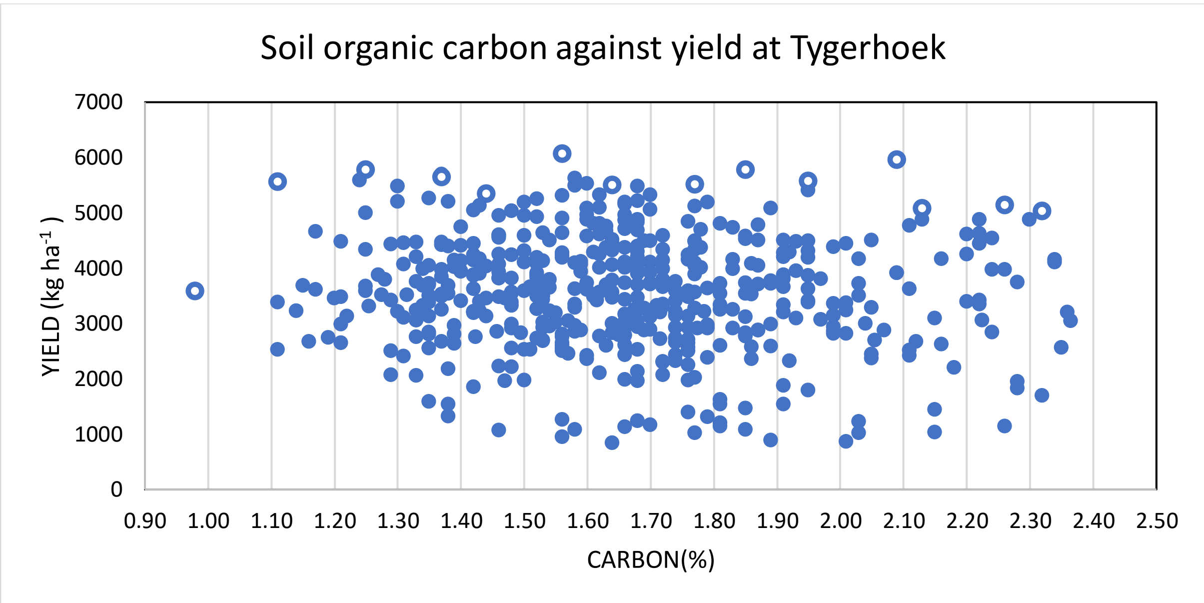

Figure A 2: Boundary line analysis of soil organic carbon (%) against wheat yield (kg ha^{-1}) at Tygerhoek from 2002 to 2020

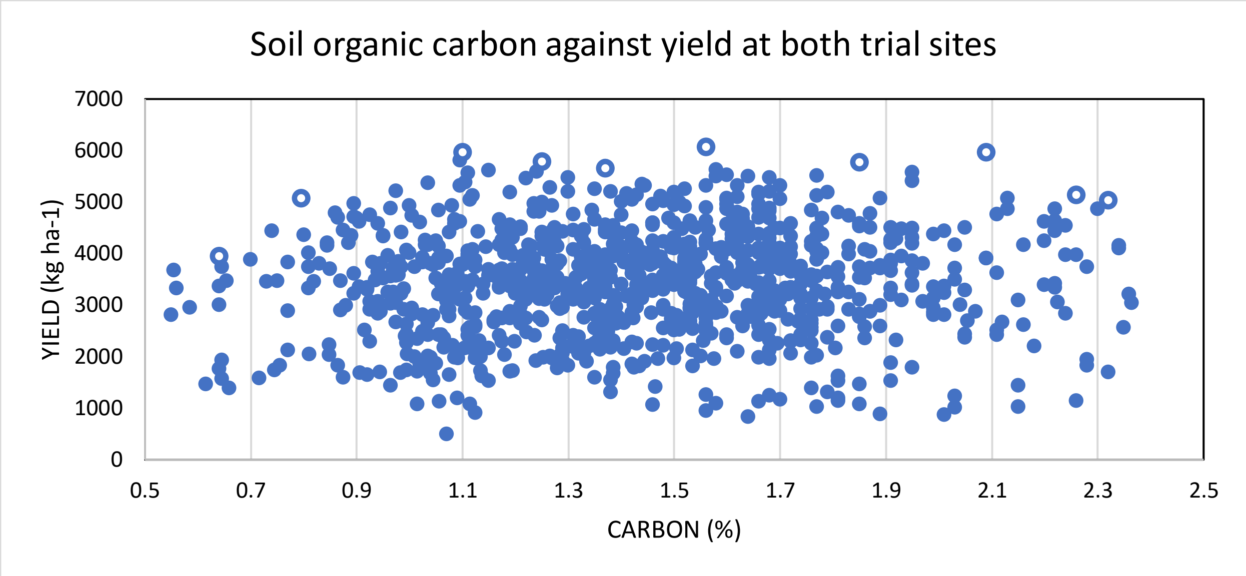

Figure A 3: Boundary line analysis of soil organic carbon (%) against wheat yield (kg ha^{-1}) at both Langgewens and Tygerhoek from 2002 to 2020

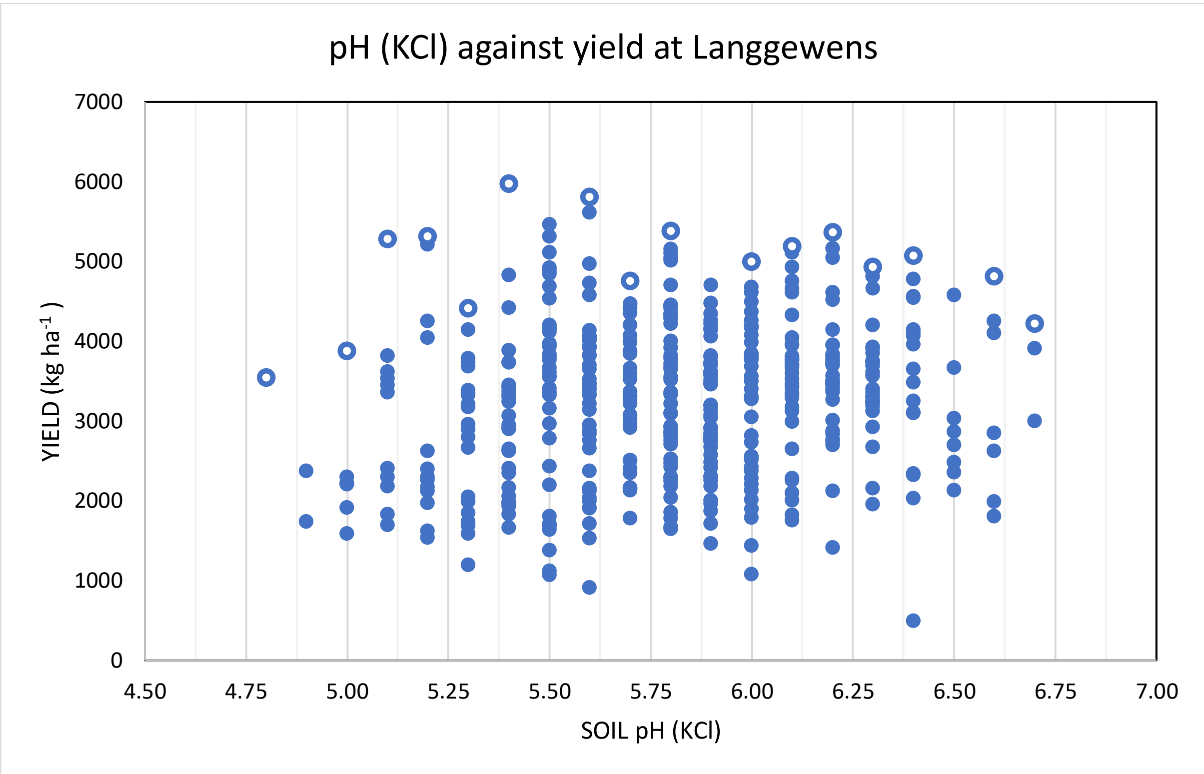

Figure A 4: Boundary line analysis of soil pH (KCl) against wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

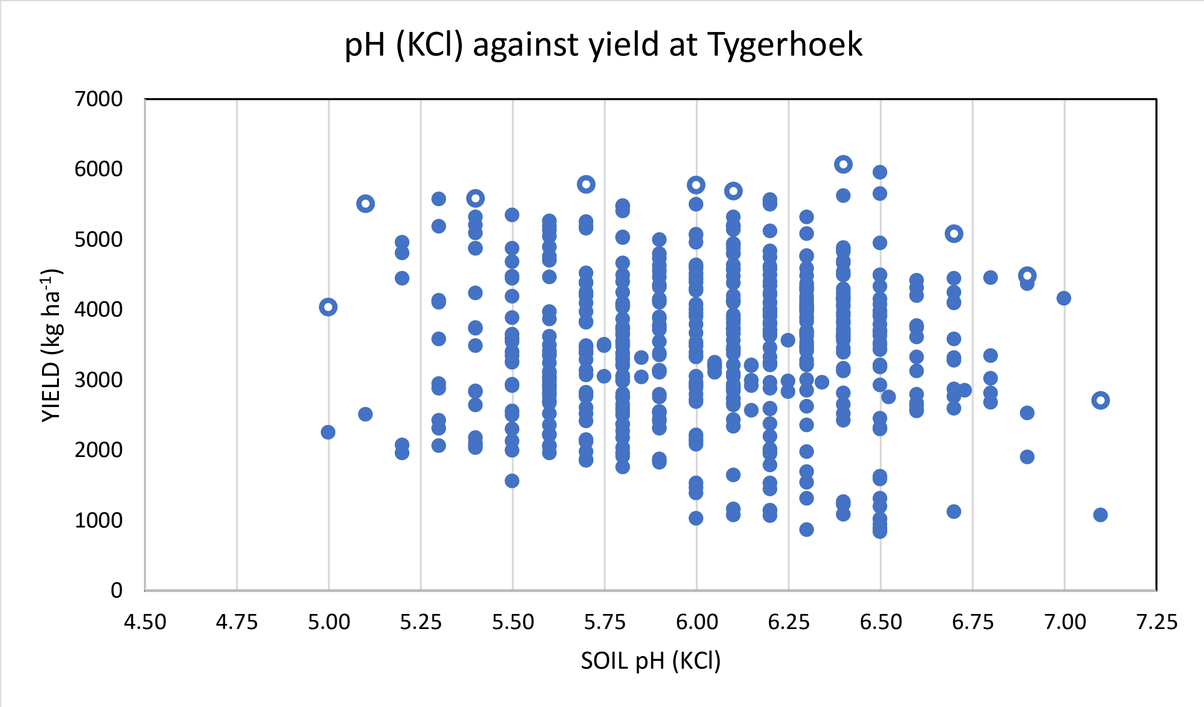

Figure A 5: Boundary line analysis of soil pH (KCl) against wheat yield (kg ha^{-1}) at Tygerhoek from 2002 to 2020

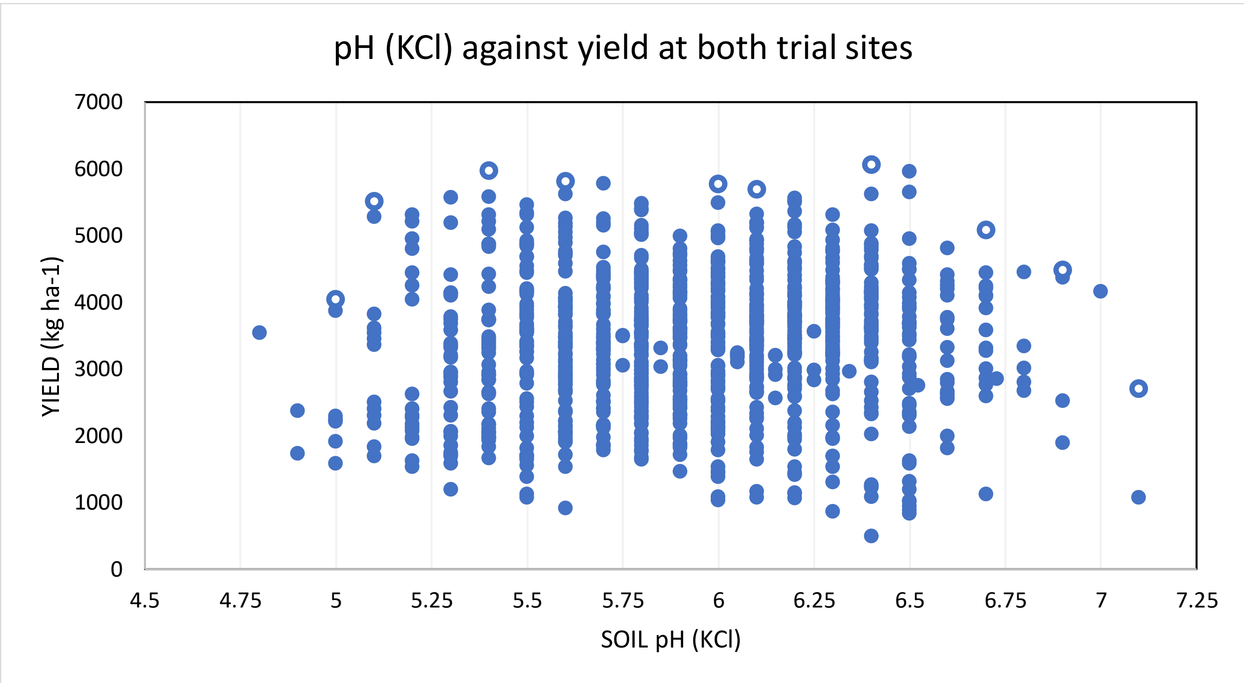

Figure A 6: Boundary line analysis of soil pH (KCl) against wheat yield (kg ha^{-1}) at both Langgewens and Tygerhoek from 2002 to 2020

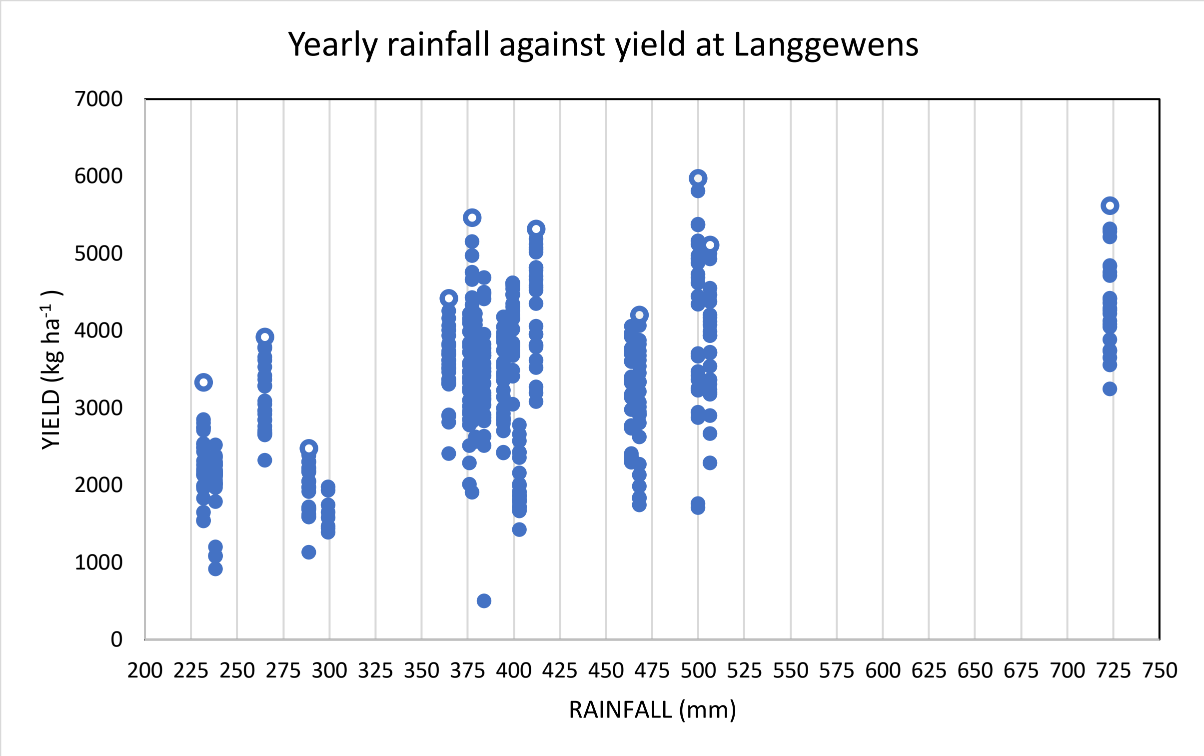

Figure A 7: Boundary line analysis of average yearly rainfall (mm) against wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

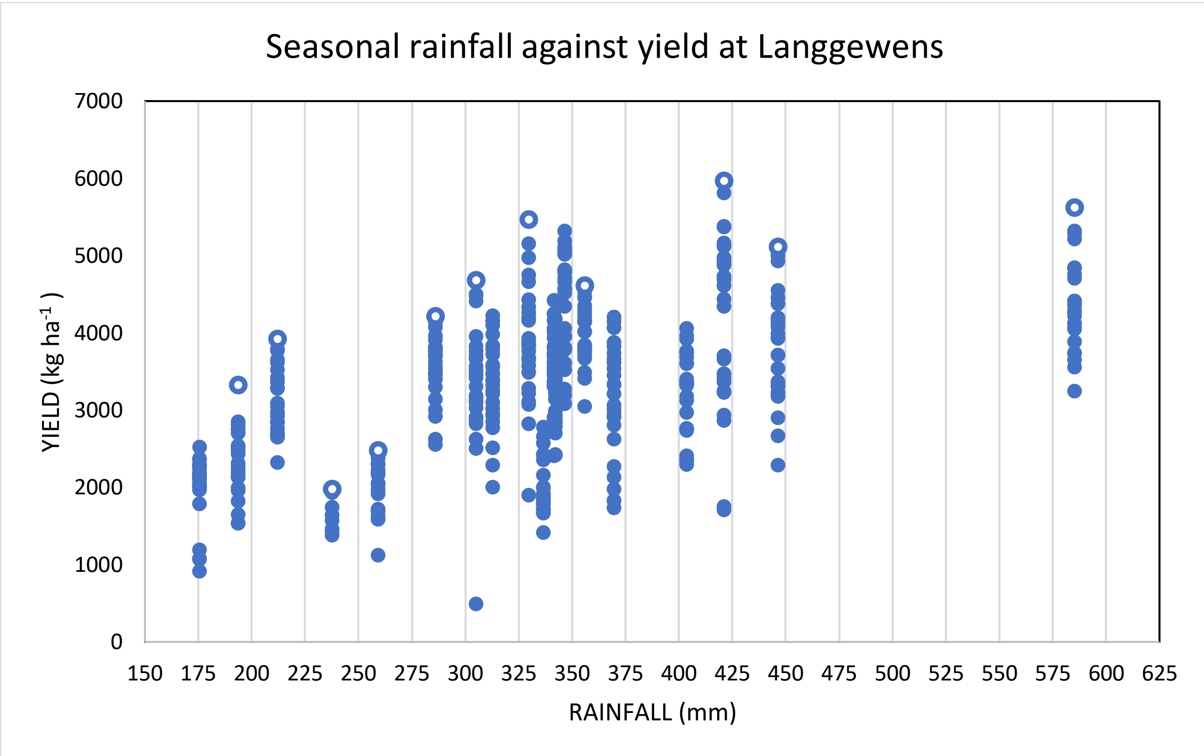

Figure A 8: Boundary line analysis of average seasonal rainfall (mm) against wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

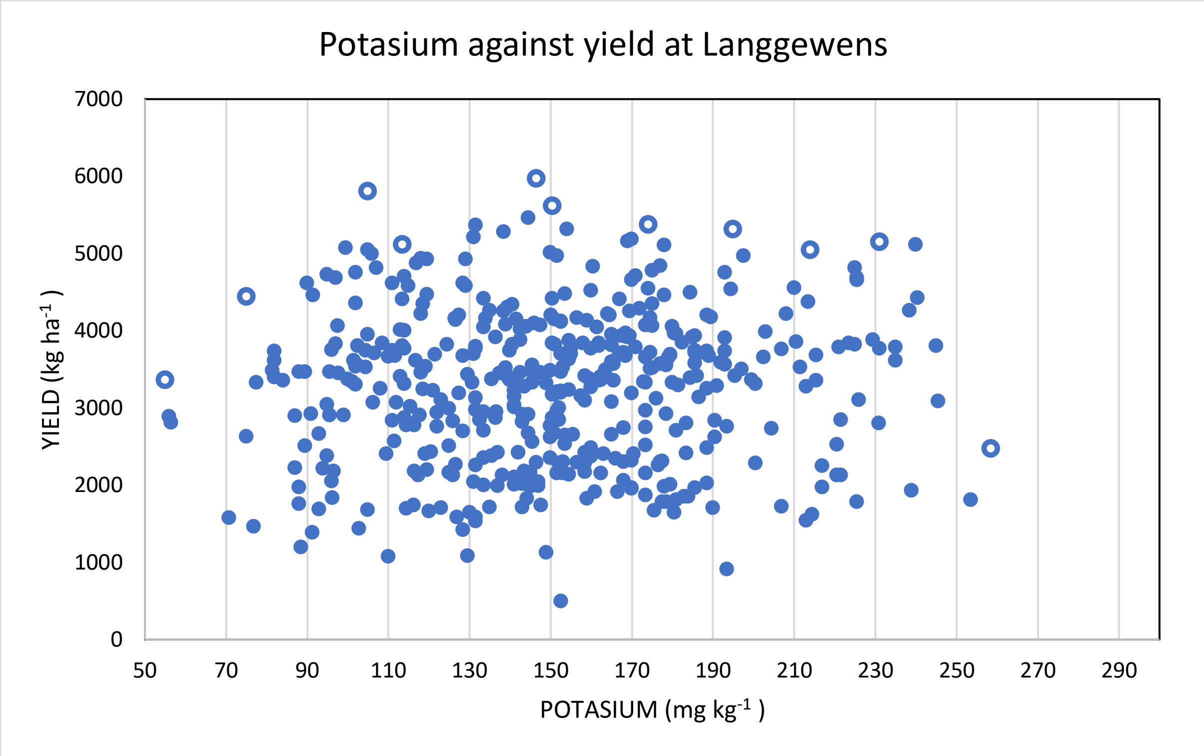

Figure A 9: Boundary line analysis of potassium content (mg kg^{-1}) against wheat yield (kg ha^{-1}) at Langgewens from 2002 to 2020

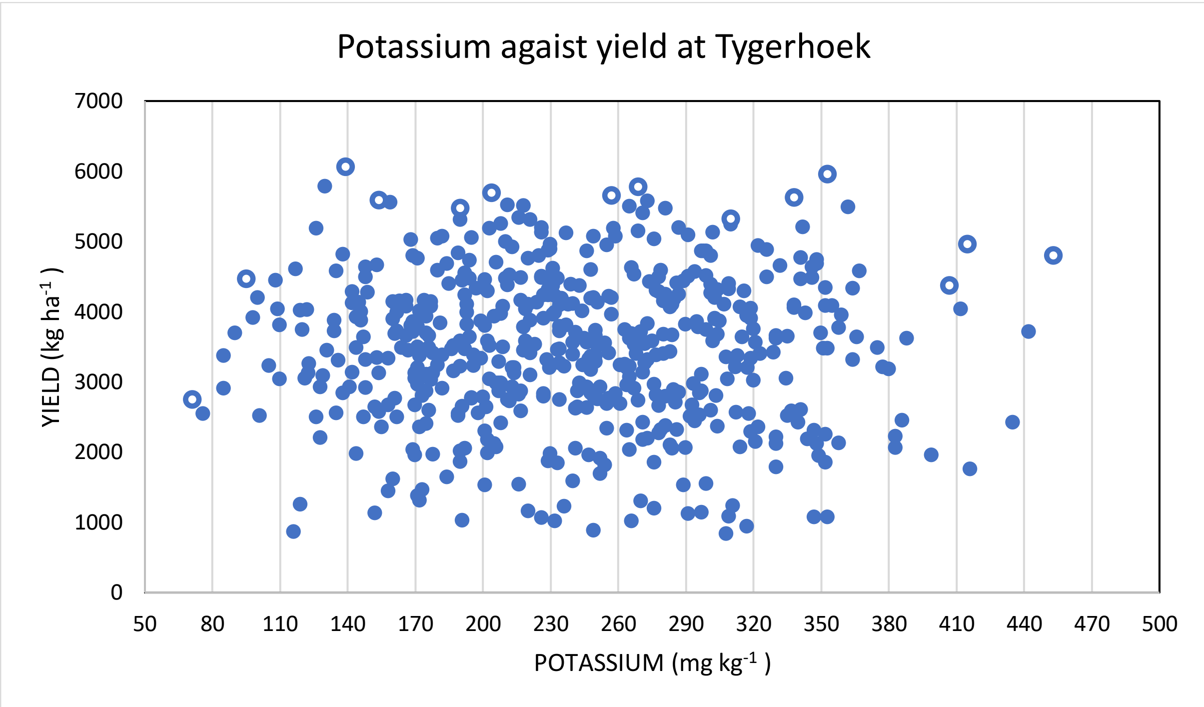

Figure A 10: Boundary line analysis of potassium content (mg kg^{-1}) against wheat yield (kg ha^{-1}) at Tygerhoek from 2002 to 2020

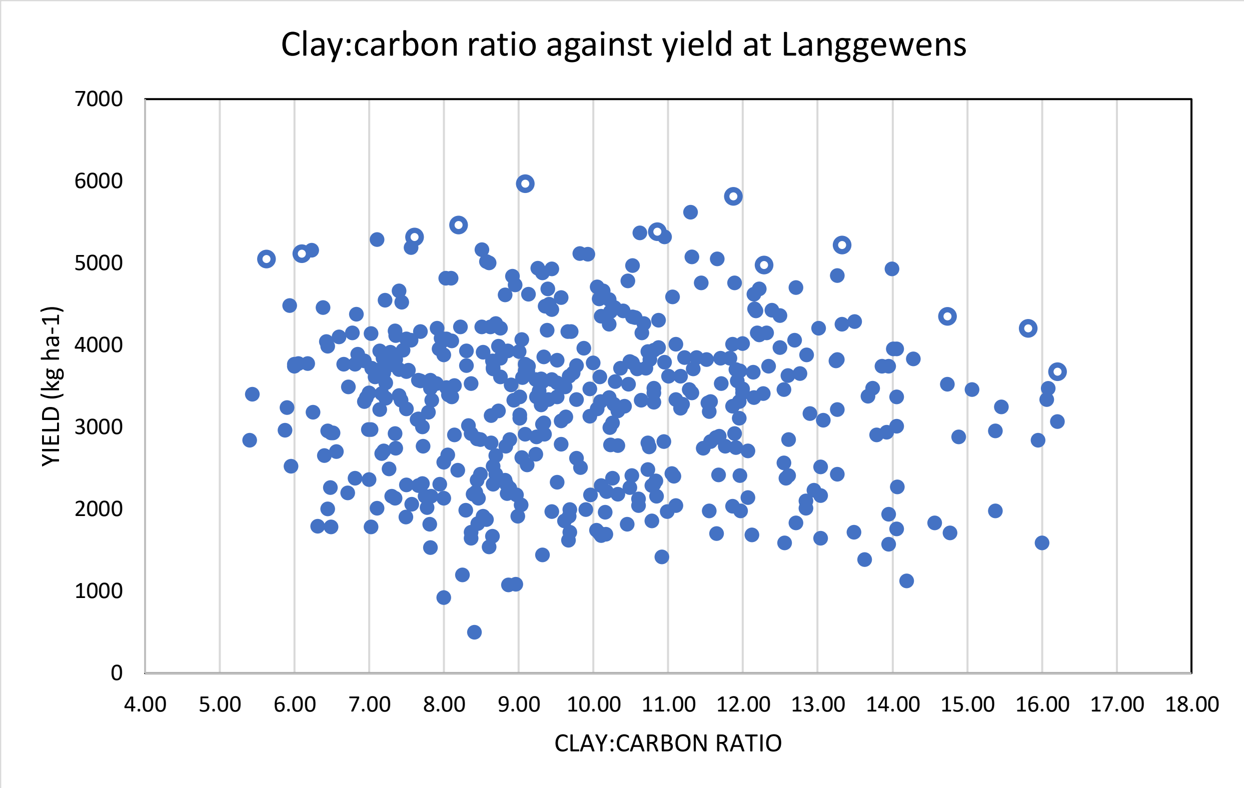

Figure A 11: Boundary line analysis of clay:carbon ratio against protein content (%) at Langgewens from 2002 to 2020

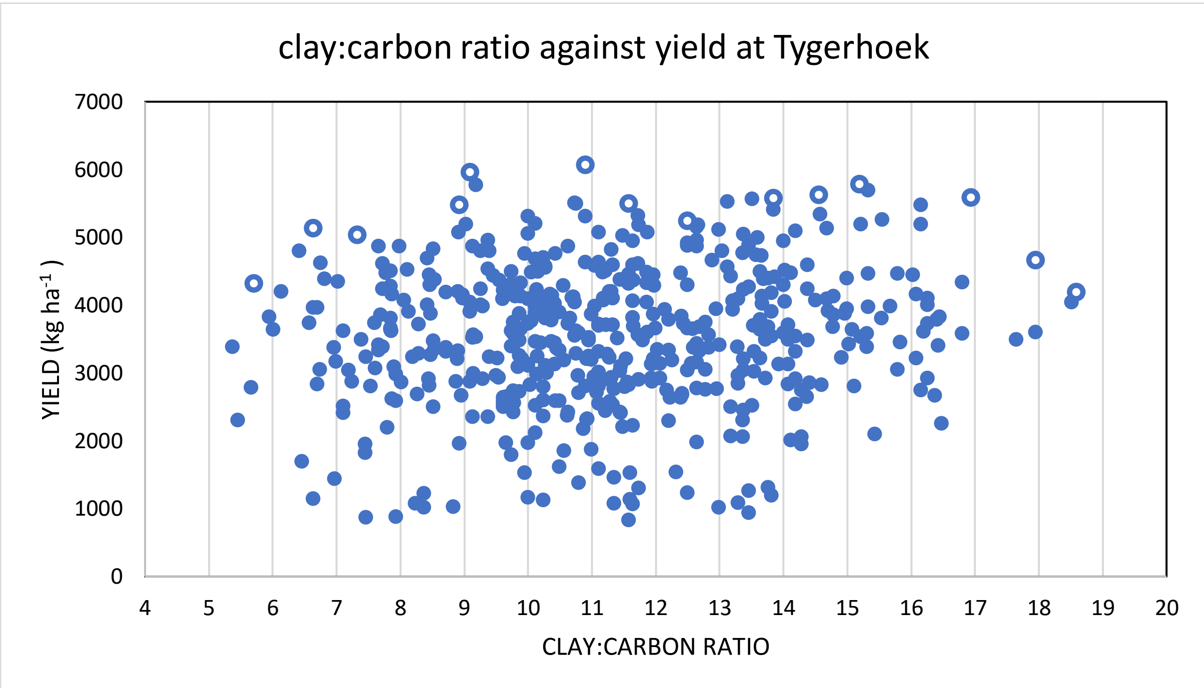

Figure A 12: Boundary line analysis of clay:carbon ratio against protein content (%) at Tygerhoek from 2002 to 2020

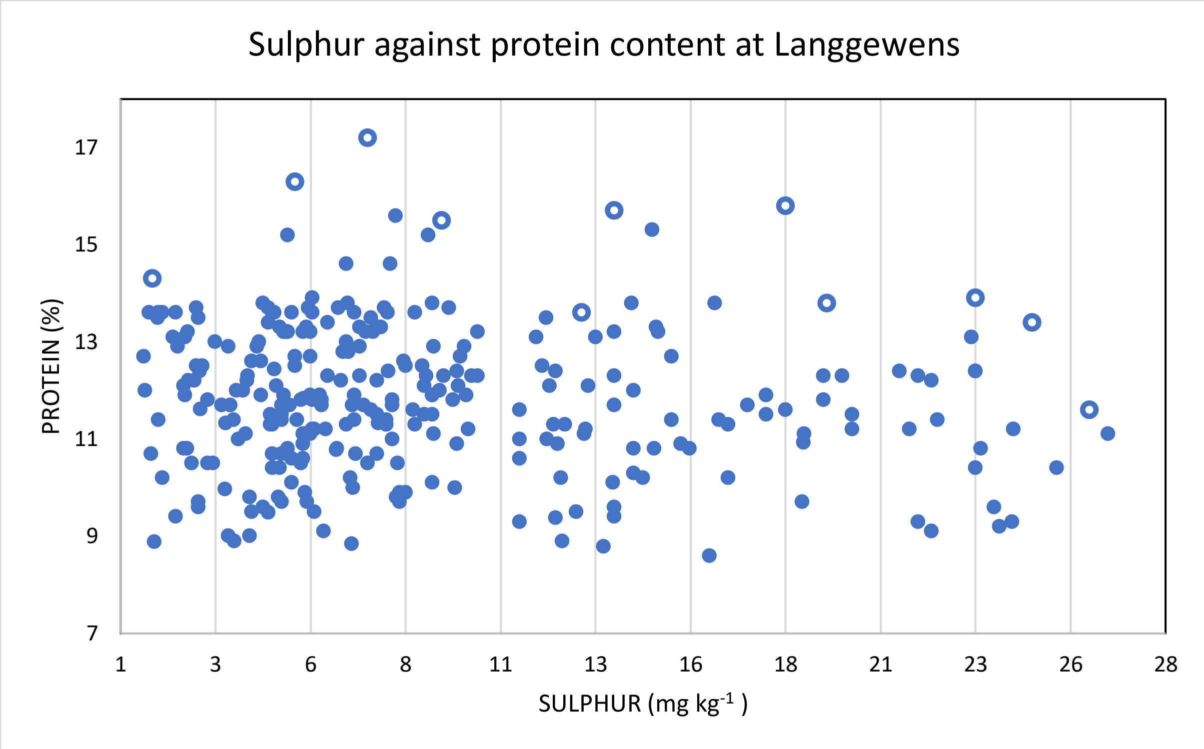

Figure A 13: Boundary line analysis of sulphur content (mg kg^{-1}) against protein content (%) at Langgewens from 2002 to 2020

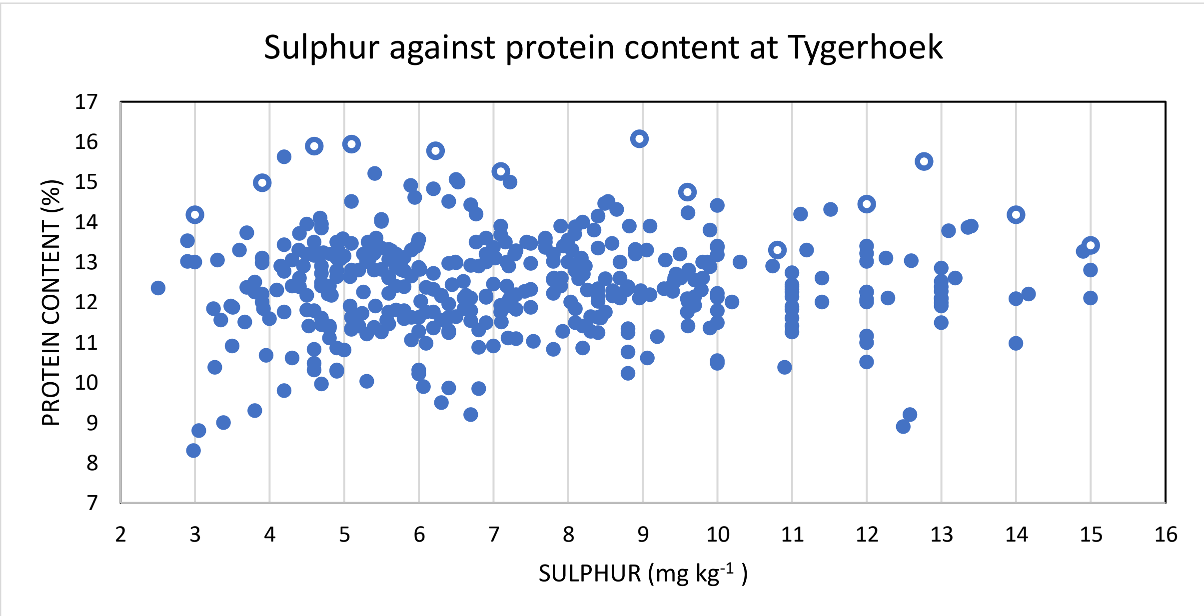

Figure A 14: Boundary line analysis of sulphur content (mg kg^{-1}) against protein content (%) at Tygerhoek from 2002 to 2020

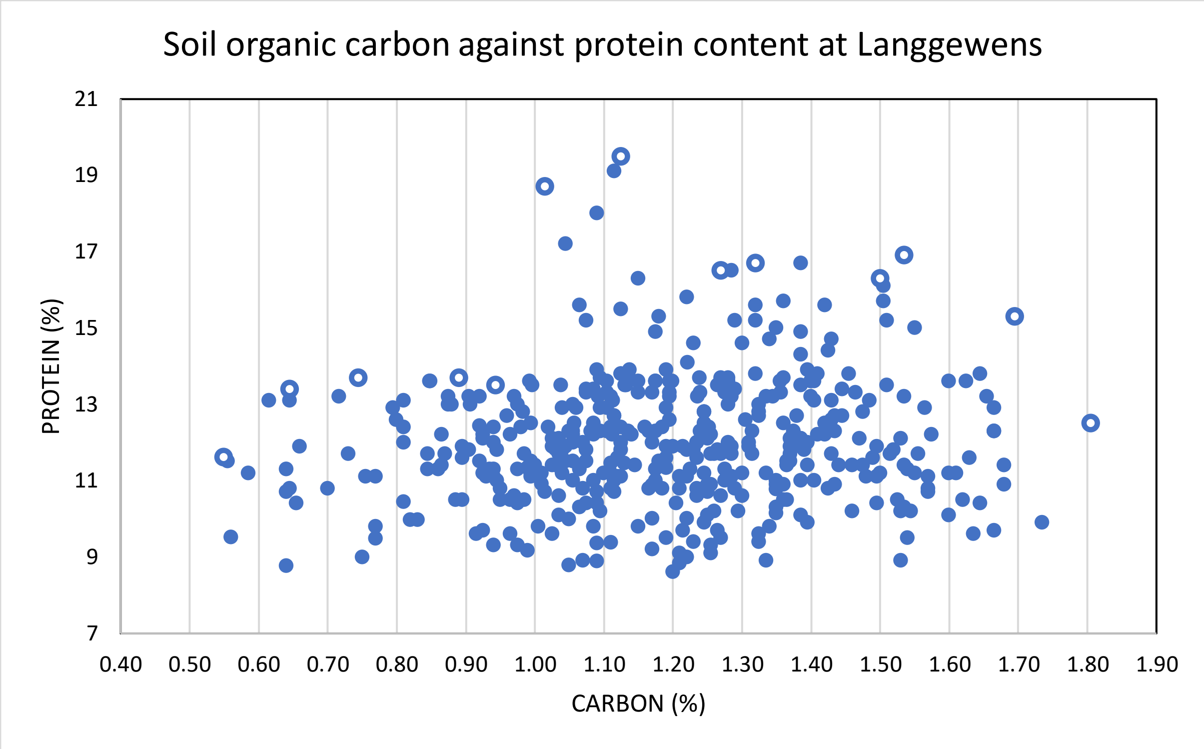

Figure A 15: Boundary line analysis of soil organic carbon (%) against protein content (%) at Langgewens from 2002 to 2020

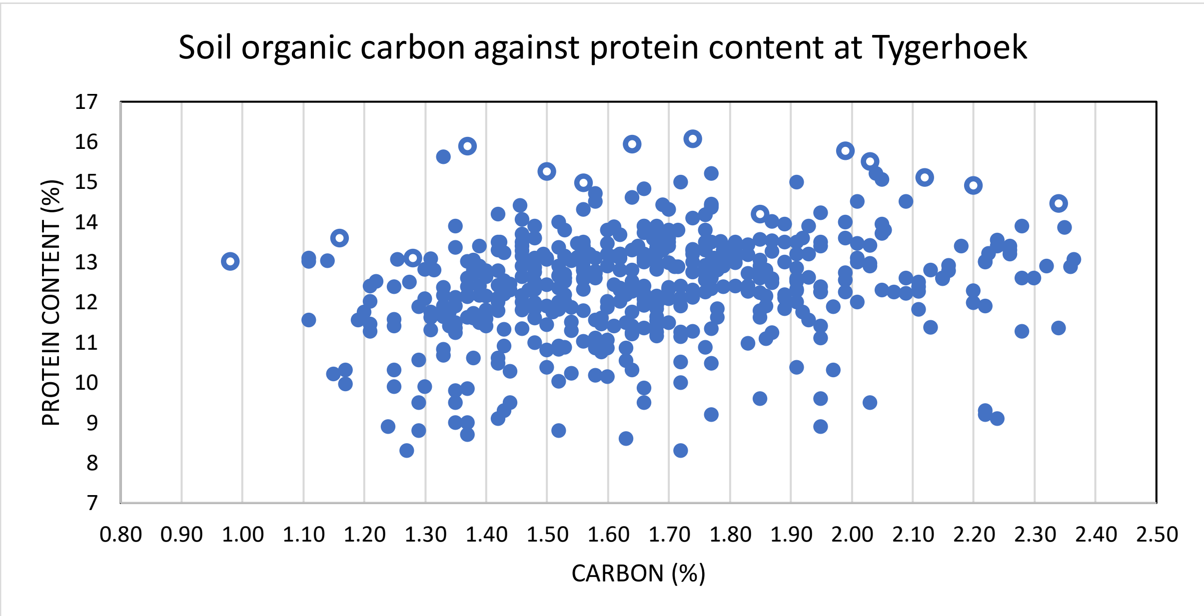

Figure A 16: Boundary line analysis of soil organic carbon (%) against protein content (%) at Tygerhoek from 2002 to 2020

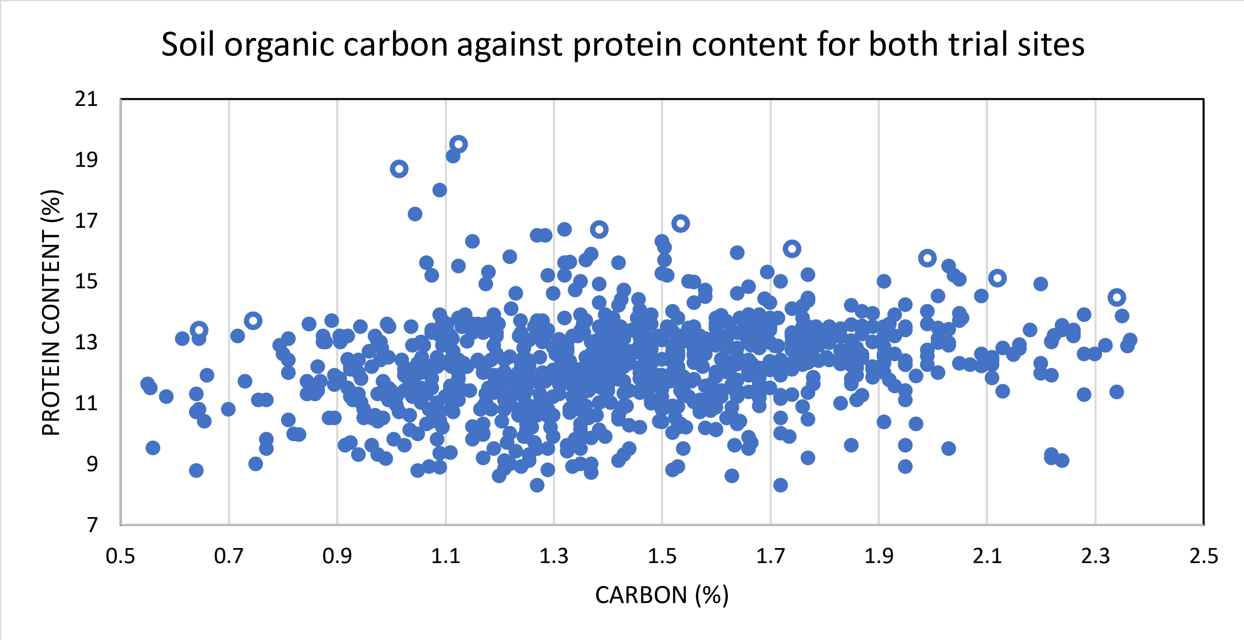

Figure A 17: Boundary line analysis of soil organic carbon (%) against protein content (%) at both Langgewens and Tygerhoek from 2002 to 2020

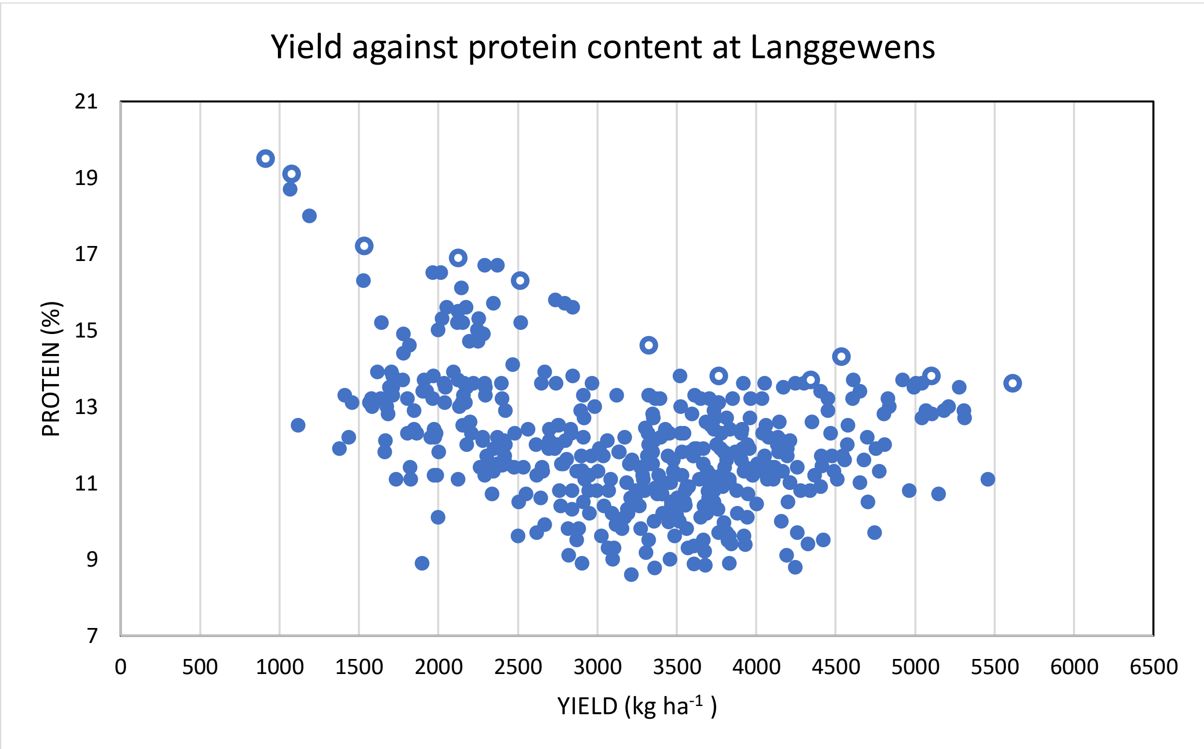

Figure A 18: Boundary line analysis of wheat yield (kg ha^{-1}) against protein content (%) at Langgewens from 2002 to 2020

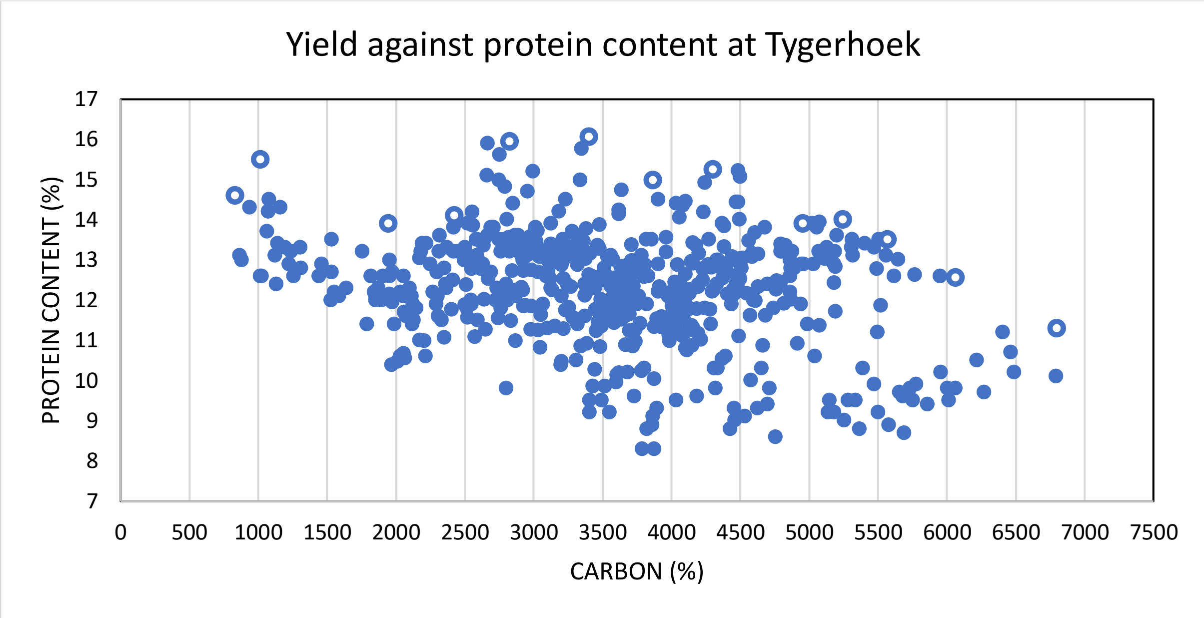

Figure A 19: Boundary line analysis of wheat yield (kg ha^{-1}) against protein content (%) at Tygerhoek from 2002 to 2020

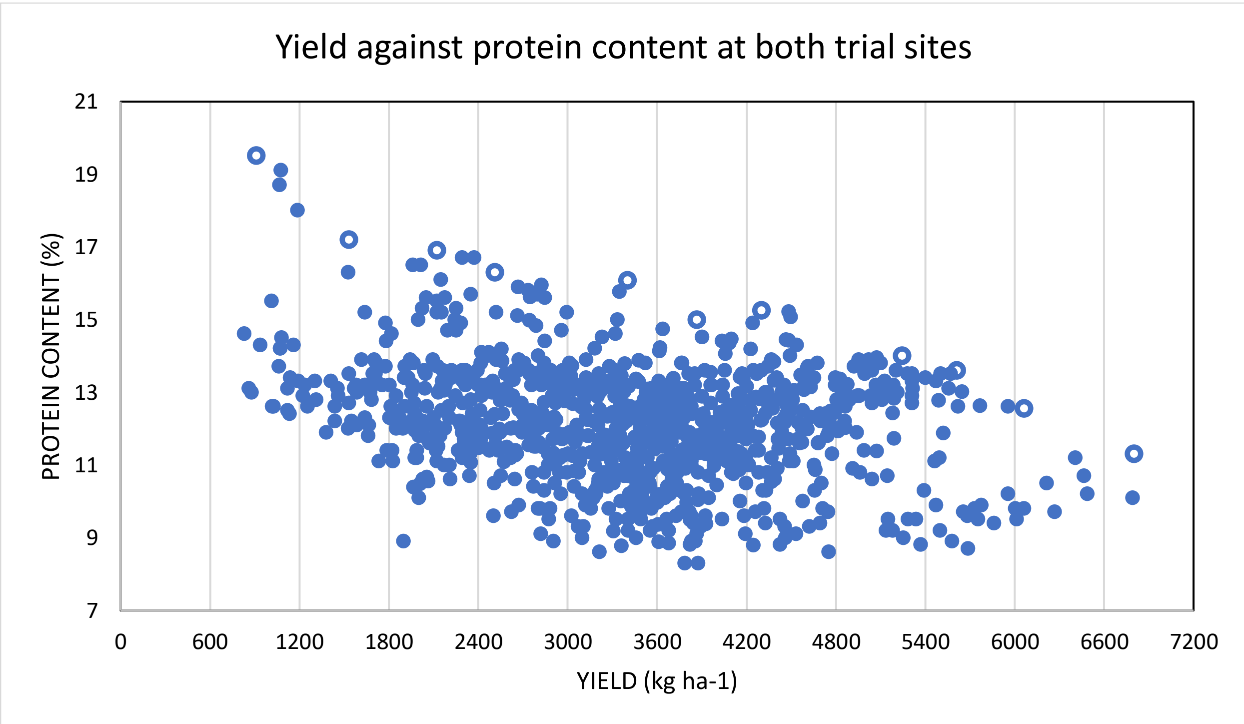

Figure A 20: Boundary line analysis of wheat yield (kg ha^{-1}) against protein content (%) at both Langgewens and Tygerhoek from 2002 to 2020

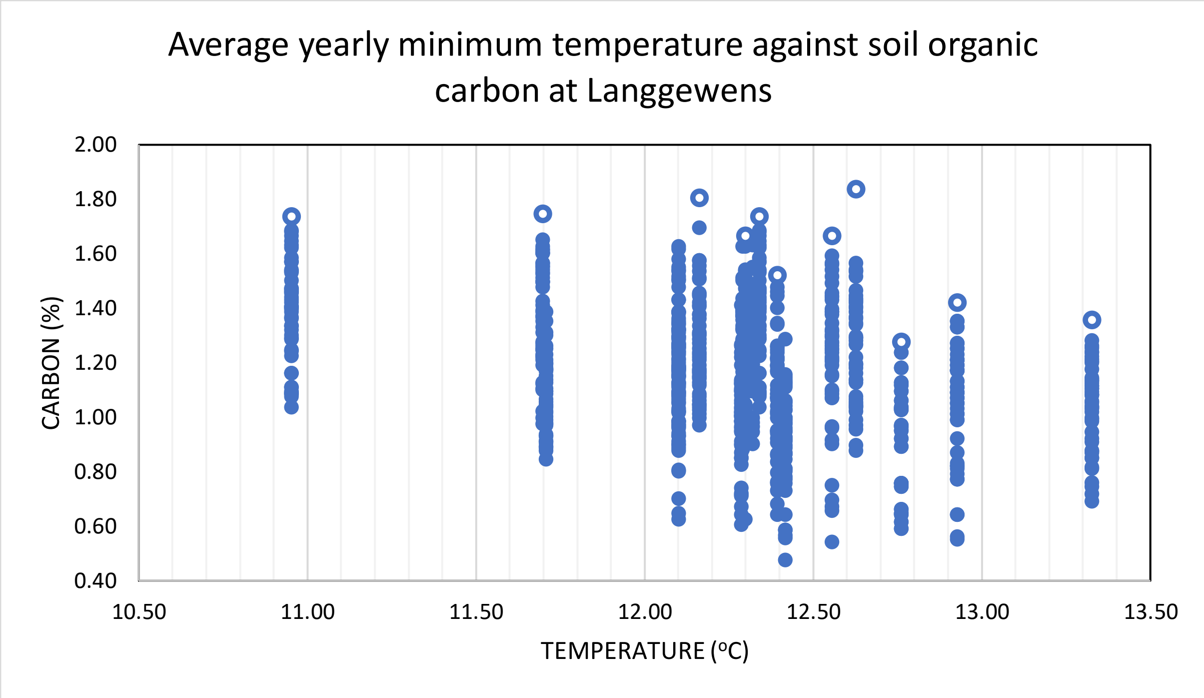

Figure A 21: Boundary line analysis of average yearly minimum temperature (ºC) against soil organic carbon (%) at Langgewens from 2002 to 2020

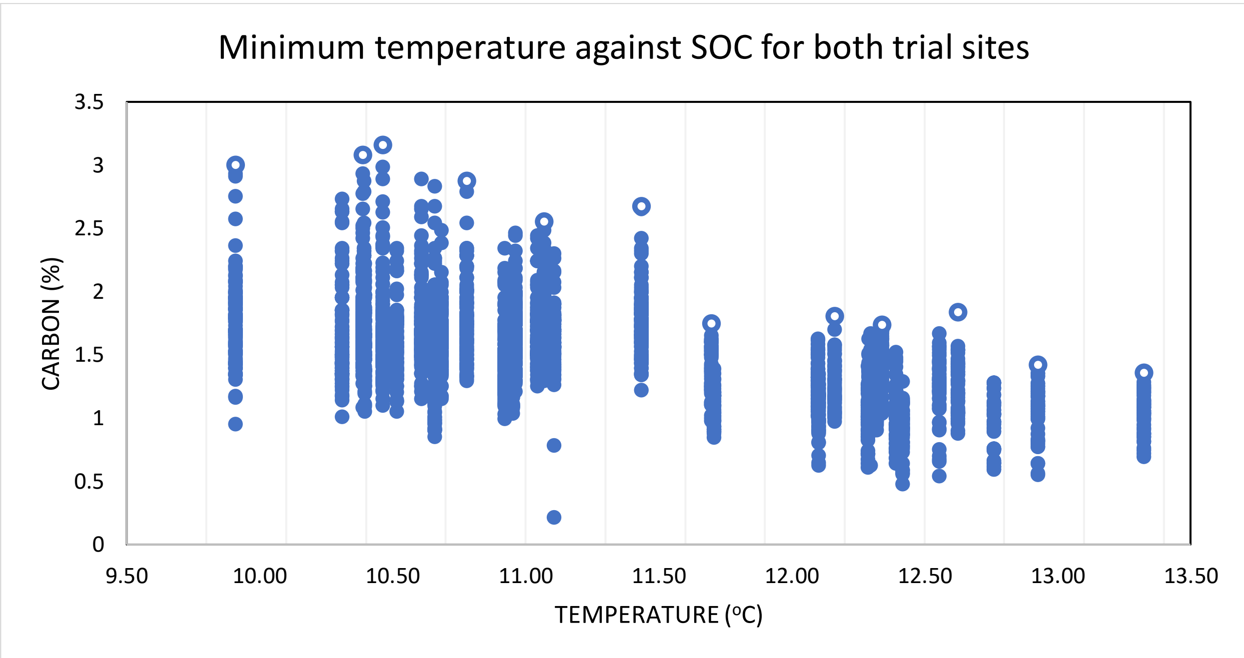

Figure A 22: Boundary line analysis of average yearly minimum temperature (ºC) against soil organic carbon (%) at both Langgewens and Tygerhoek from 2002 to 2020

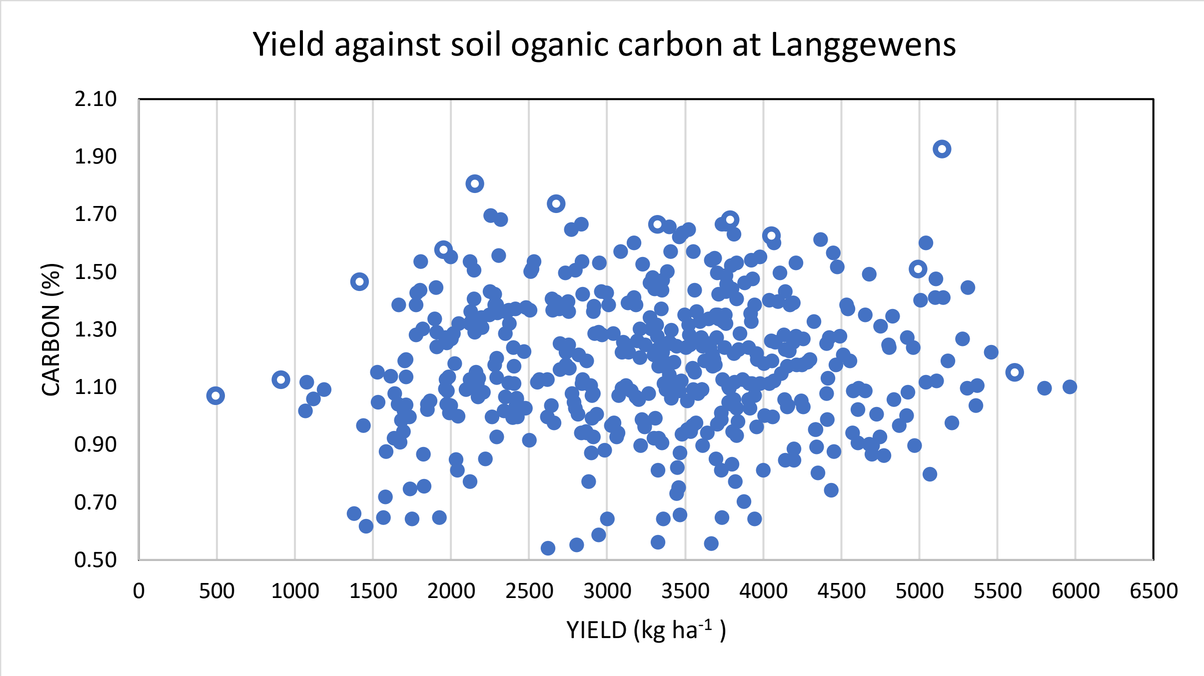

Figure A 23: Boundary line analysis of wheat yield (kg ha^{-1}) against soil organic carbon (%) at Langgewens from 2002 to 2020

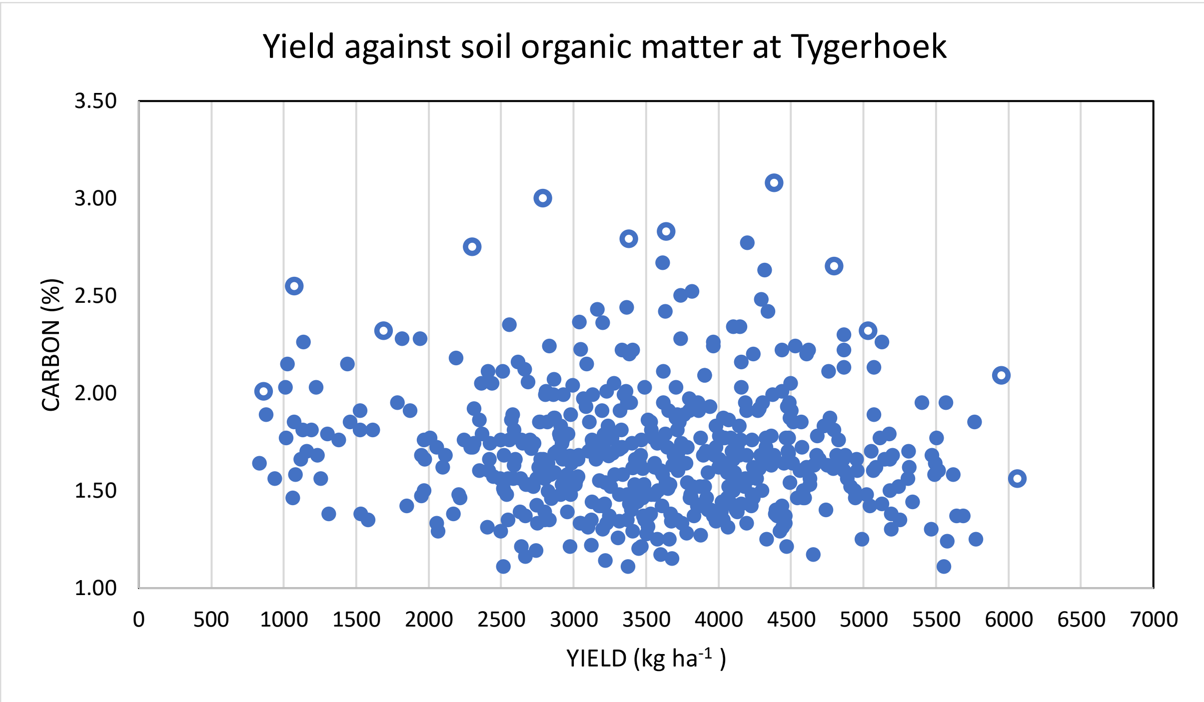

Figure A 24: Boundary line analysis of wheat yield (kg ha^{-1}) against soil organic carbon (%) at Tygerhoek from 2002 to 2020

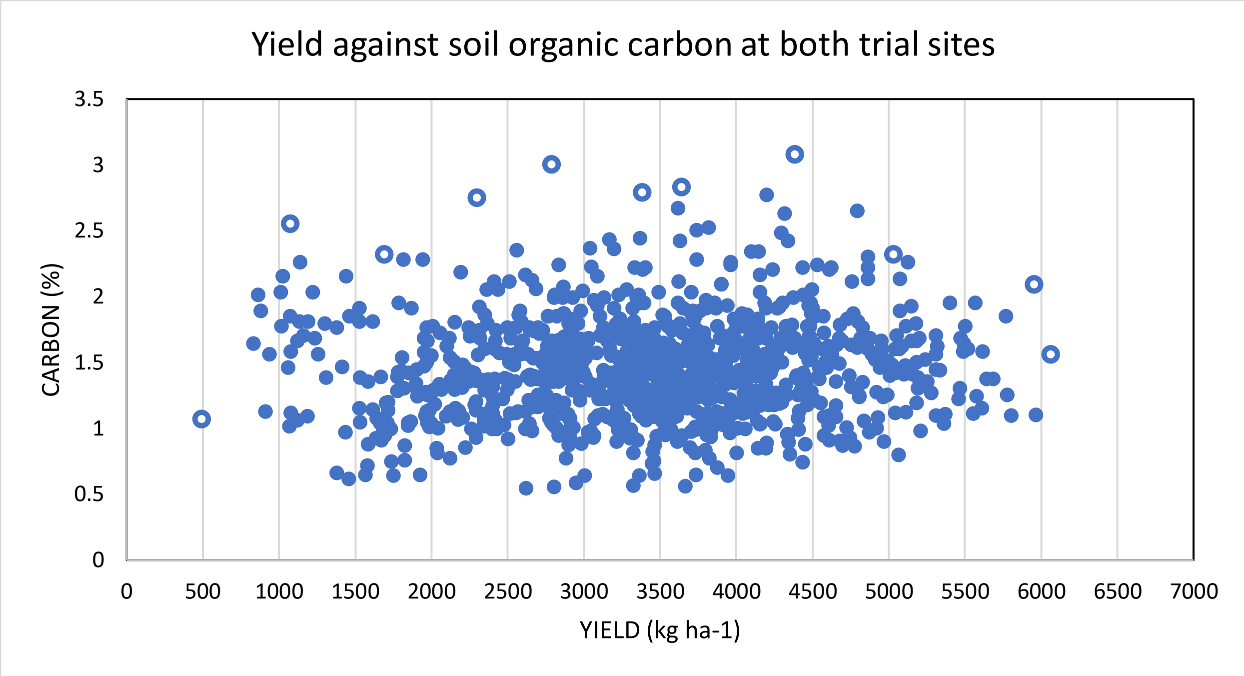

Figure A 25: Boundary line analysis of wheat yield (kg ha^{-1}) against soil organic carbon (%) at both Langgewens and Tygerhoek from 2002 to 2020

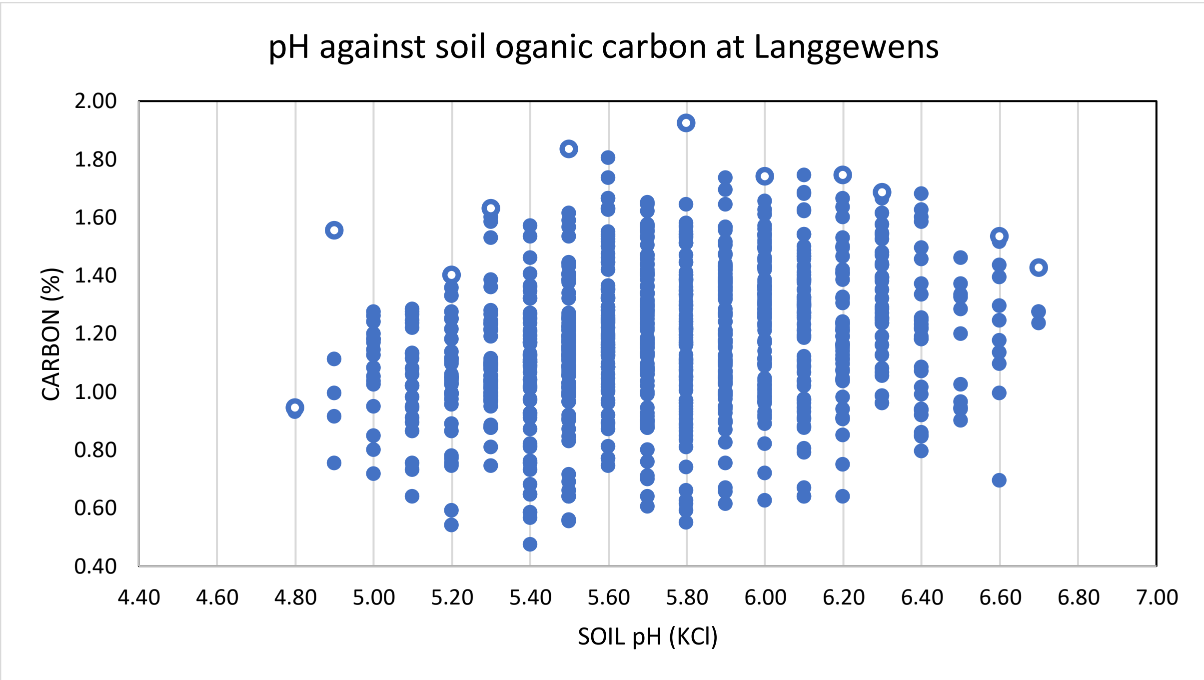

Figure A 26: Boundary line analysis of pH (KCl) against soil organic carbon (%) at Langgewens from 2002 to 2020

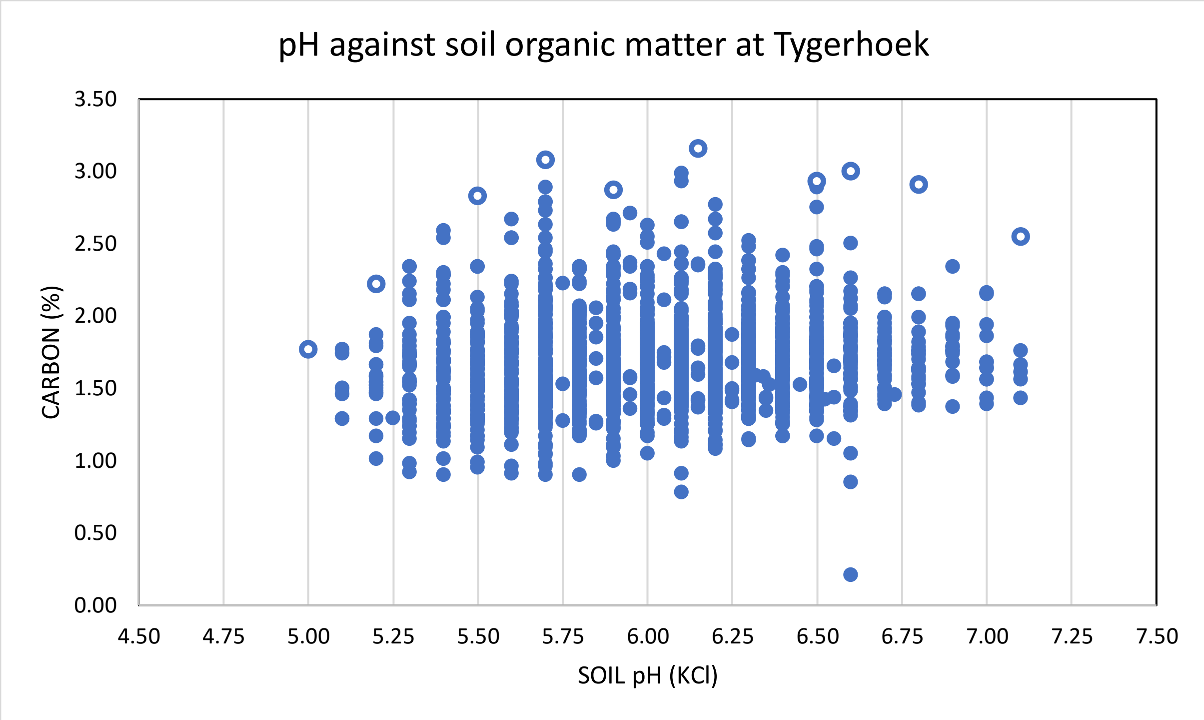

Figure A 27: Boundary line analysis of pH (KCl) against soil organic carbon (%) at Tygerhoek from 2002 to 2020

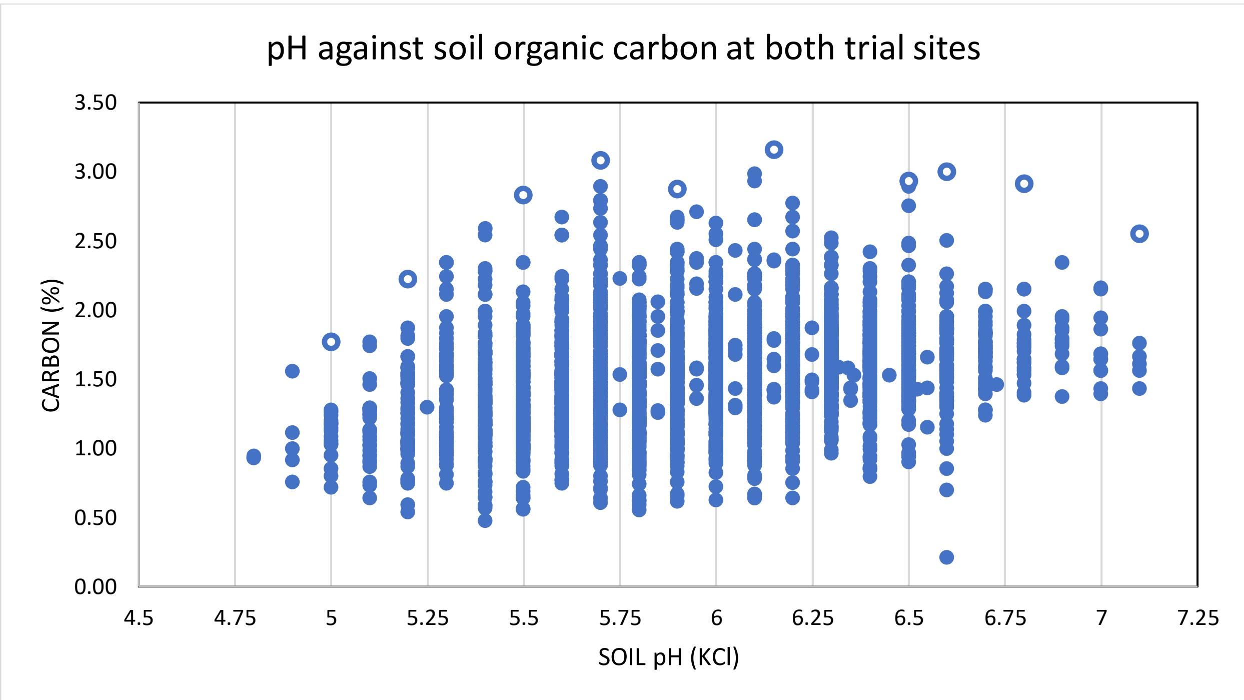

Figure A 28: Boundary line analysis of pH (KCl) against soil organic carbon (%) at both Langgewens and Tygerhoek from 2002 to 2020

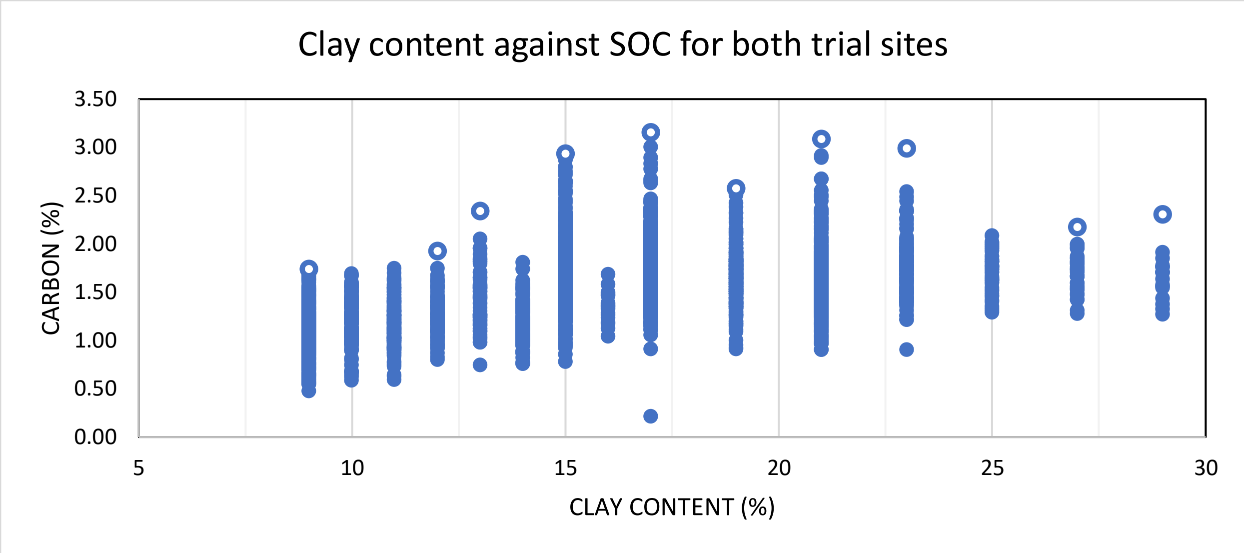

Figure A 29: Boundary line analysis of clay content (%) against soil organic carbon (%) at both Langgewens and Tygerhoek from 2002 to 2020

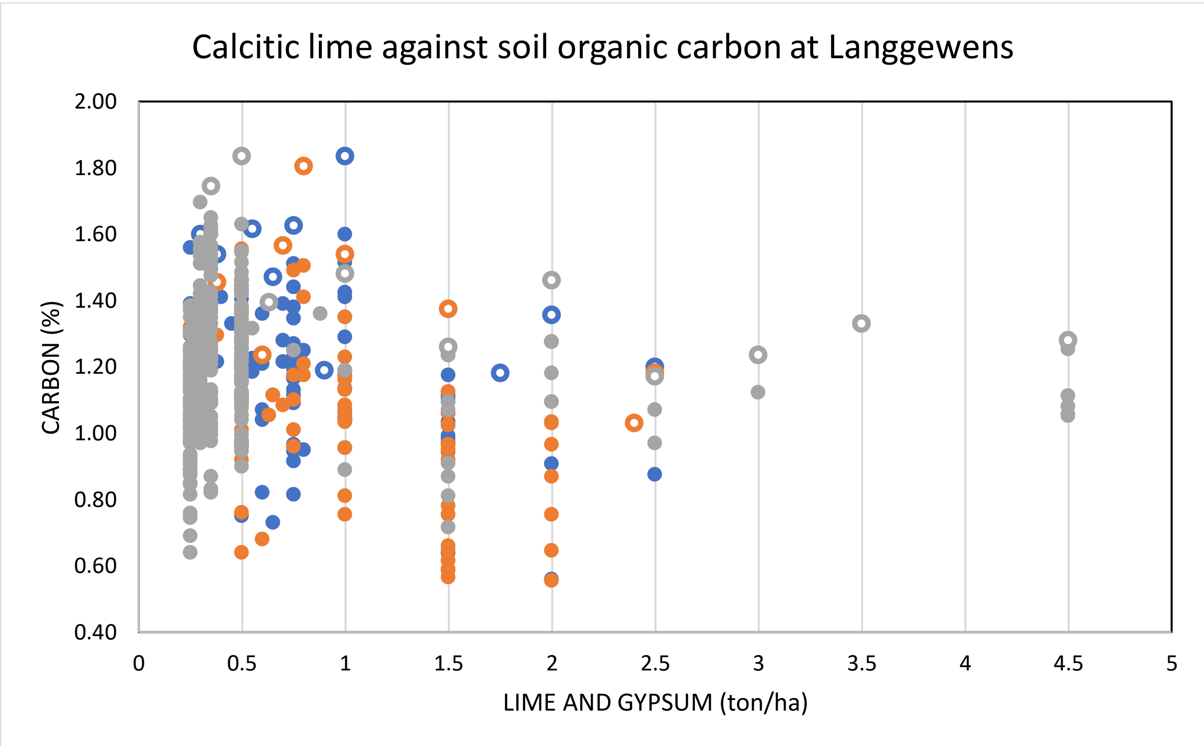

Figure A 30: Boundary line analysis of calcitic and dolomitic lime, and gypsum (kg ha^{-1}) against soil organic carbon (%) at Langgewens from 2002 to 2020