Liming strategies for barley and canola production in no-tillage systems

by

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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ABSTRACT

The slow movement of lime in soil combined with no-tillage practices that restricts the incorporation of surface broadcast lime deeper into the soil has led to an increase in soil acid stratification with depth in soils under no-tillage over the long-term in the Western Cape Province of South Africa. A soil survey was conducted across the southern Cape and Swartland regions of the Western Cape Province to determine the extent and geographical spread of soil acidity and stratification (*Objective 1*). Soil samples were taken on long-term no-tillage fields at depth increments of 0 – 5, 5 – 15 and 15 – 30 cm. It was found that 19.3% of the soils surveyed in the Swartland had at least one depth increment with a pH_{KCl} lower than 5.0, which is, in general, below optimal for crop production. A field trial was also established in 2019 (Year 1) to investigate the effect of form, fineness and purity of lime as well as different degrees of incorporating lime into the soil, on soil chemical attributes (*Objective 2*) as well as on the growth and development of barley (Year 1) and canola (Year 2) (*Objective 3*). The field trial consisted of ten treatments which included a control treatment, 95% calcium carbonate equivalent (CCE) surface broadcast calcitic lime, 88% CCE surface broadcast lime, lime incorporated with either a disc plough, a chisel plough or a ripper, pelletised lime placed in-row (40 kg ha^{-1}), pelletised lime placed in-row and broadcast at 960 kg ha^{-1}, pelletised lime placed in-row and broadcast at 770 kg ha^{-1} and pelletised lime broadcast at 1000 kg ha^{-1}.

Minor differences in lime purity, type of tillage action (disc plough, chisel plough and ripper) used when incorporating lime as well as form and fineness of lime (pelletised micro-fine) led to an increase ($p \leq 0.05$) in pH_{KCl} up to a 30 cm depth, but did not show major crop responses within the first or second growing season after receiving 810 - 1000 kg ha^{-1} of lime on a sandy loam soil (pH_{KCL} of 5.05; SD ± 0.33 at 0 – 30 cm) that received a total of 558 mm of rainfall.

Broadcasting pelletised micro-fine lime at the recommended rate however, led to the greatest (0 - 5 cm depth) as well as the quickest increase in pH_{KCl}, up to a 30 cm depth three months after liming. Applying less than the recommended rate led to more effective neutralisation of soil acidity. Micro-fine pelletised lime however, did not lead to a greater crop growth and productivity within two growing seasons following liming compared to conventional class A lime.

There was however a trend for a one-off strategic tillage to result in greater crop biomass production. The positive response of crop growth to a one-off strategic tillage was most likely attributed to deeper redistribution of lime in the soil (15 – 30 cm depth), an increase in nutrient mineralisation and decrease in nutrient stratification, alleviation of soil physical limitations and reduced weed pressure.

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CHAPTER 1

INTRODUCTION

The adoption of conservation agriculture by farmers in South Africa and especially in the Western Cape has increased over the past 40 years (Smith et al., 2017; Findlater et al. 2019). This increase can be attributed to the benefits associated with implementing conservation agriculture principles, such as increased water use efficiency and soil organic carbon content, as well as overall improvement of soil quality and consequently higher profit margins (Thierfelder et al., 2014; Crookes et al., 2017). Following conservation agriculture entails implementing three farm management factors which include ensuring a permanent organic soil cover, incorporating crop diversity into the system (in the current context as crop rotations) and disturbing the soil to a minimum (FAO, 2014).

The latter entails that the disturbed area must be less than 15 cm wide or less than 25% of the total cropped area. Following conservation agriculture therefore inhibits the mixing of top and/or subsoil layers, contrary to conventional agricultural practices which involves primary and/or secondary soil tillage practices. Reviewing the current status of soils that have been subjected to long-term conservation agriculture (and thus no-tillage), it is evident that certain areas of concern need to be addressed.

Acid soils are treated with limestone (lime) [either calcitic lime ($CaCO_3$) or dolomitic lime ($CaMg(CO_3)_2$], which increases the pH of soil. When lime is applied in no-tillage systems, it is broadcast on the soil surface but is not mechanically incorporated into the soil with tillage practices. Because lime is immobile in soil [only moving 5 cm down the soil profile in a year in some cases (Caires et al., 2005; Miller, 2015)], surface application only allows for the top few centimetres of the soil profile to react with the lime (Whitten, 2000; Flower and Crabtree, 2011). Therefore, long-term no-tillage practices may result in severe contrasts between the top and subsoil pH values, with highly alkaline topsoils and very acid subsoils where the lime could not react (Barth et al., 2018). This pH stratification is often not picked up in soil tests, because the samples are usually only taken to a depth of 10 - 15 cm (Burns et al., 2017). Soil fertility parameters are often skewed towards the soil surface. The soil sampling procedure ultimately dilutes the stratification effect present between the top and subsoil layers and creates the impression that the soil pH is not far from optimum, whereas in actual fact there might be an acid subsoil present. Farmers will therefore be at risk of under-liming the soil, which will lead to further aggravation of subsoil acidity, which is a major growth limitation for most crops.

Barley (*Hordeum vulgare*) and canola (*Bassica napus*) are some of the most sensitive crops to acid soils in the dryland crop-rotation systems of the Western Cape; having an optimum pH_{KCl} of ≥ 5.5 (Foy, 1996; DAFF, 2016). Following wheat (*Triticum aestivum*), malting barley is the most important small-grain crop in South Africa (Burger et al., 2012), with an average annual commercial production of 345 080 tons on 131 960 hectares (Crop Estimates Committee, 2020). Furthermore, 89% of barley in South Africa is produced in the Western Cape Province under dryland conditions. Canola is also mainly produced in the Western Cape Province, and is a means by which a broadleaf crop can be integrated into the dryland crop rotation systems to assist with weed management. A total of 95 000 tons of canola was produced in 2019 over 74 000 hectares in South Africa (Crop Estimates Committee). Barley and canola have a deep root system, often with the only limitation for root growth being the depth of the soil profile. However, a soil pH_{KCl} of less than 5.5 will restrict further root growth and development, hindering the development of the plant as a whole (Foy, 1996; Samac and Tesfaye, 2003). The growth potential of barley and canola therefore decreases with increasing soil acidity beyond a pH_{KCl} of 5.5. This is largely because of an increase in aluminium (Al) availability in the soil as the pH decreases, causing Al toxicity in the plant. Toxic levels of Al stunts root growth of plants, leading to a decrease in nutrient and water uptake (Panda et al., 2009; Krstic et al., 2012). Further nutrient deficiencies often also occur because Al competes for the uptake of other nutrients amongst others calcium and magnesium (Barth et al., 2018).

Acid subsoils are a relevant issue to farmers in the Western Cape, as more than 60% of farmers follow conservation agriculture in the sense of incorporating crop rotations, having a permanent soil cover and disturbing the soil to a minimum, and more than 80% practise no-tillage (Smith et al., 2017). These farmers are thus prone to pH stratification or acid subsoils to some degree over the long-term for the reasons described above. Therefore, for effective production of barley and canola over the long-term under conservation agriculture or no-tillage systems, this issue of subsoil acidity must be addressed.

Previous research has shown that a one-off strategic tillage (once every four to eight years) has no significant effect on crop production and soil quality (Leygonie, 2016; Van Zyl, 2017; Conyers et al., 2019). Strategic tillage can thus be a suitable way of incorporating lime into the subsoil to reduce subsoil acidity without losing the benefits accumulated from practising conservation agriculture (Whitten et al., 2000). Strategic tillage however would not be suitable for farmers strictly following conservation agriculture and therefore excluding soil disturbance as an option. In such cases a fine lime can be considered as a potential solution. Fine lime may possibly move to the deeper soil layers than a coarser lime because of the ability of finer lime to move down via the macro-pores of the soil (Amaral et al., 2004). Also, a finer lime would react faster with soil acidity due to the increased surface area (Beegle, 2001), and then allow the excess alkalinity to leach further down the soil profile (Joris, 2013). A way in which fine lime can be applied is in the form of lime pellets, although not practiced on a large scale currently. Fine lime is pelletised with an organic binding agent and then applied with a conventional lime spreader, which allows for efficient application, especially in windy conditions. Pelletised lime can be applied on the soil surface followed by the planting process. If a tine no-till planter is used, the planting action will automatically integrate the lime a slightly deeper (ca. 5 to 8 cm) into the soil in the plant-row. Pelletised lime is more expensive than conventional lime due to the cost of pelletisation. However, in order to make it a more economically viable option, pelletised lime is often marketed so that less than the recommended lime rate is required. This argument is based on the fact that because the lime used in the pellets is much finer, it will supposedly be more reactive than typical class A agricultural lime. The effectiveness of applying less pelletised lime than the recommended lime rate in alleviating soil acidity is however under question. The occurrence and intensity of soil acidity and pH stratification in the grain producing areas of the Western Cape is currently unknown.

The aim of this research is therefore to determine liming strategies that are effective in alleviating subsoil acidity for barley and canola production under no-tillage, with the objectives of:

1. Determining the extent of soil acidity and pH stratification on long-term no-tillage soils across the Southern Cape and Swartland area.
2. Determining the effect of form, fineness and placement of lime with and without soil disturbance on soil chemical attributes.
3. Determining the effect of form, fineness and placement of lime with and without soil disturbance on barley and canola growth and development.

Layout of Thesis

This thesis consists of six chapters:

Chapter 1 (this chapter) is an introduction to the thesis and includes a background of the study, the problem identified which needs to be addressed, a possible rationale to the problem, the aim of the study as well as the objectives.

Chapter 2 consists of a literature review of the respective study field, including a background to soil acidity and the effects of soil acidity on crop production. This chapter also describes the characteristics of lime including different forms, fineness and purity and how these affect the movement of lime in soil. Furthermore, the effect of one-off soil tillage practises on no-till systems is discussed and its effect on lime movement and crop production. The two crops that are investigated (barley and canola) are also discussed in terms of their reaction to soil acidity and liming.

Chapter 3 consists of a soil survey that was conducted to determine the extent of soil acidity and pH stratification on long-term no-tillage soils across the Southern Cape and Swartland area. This chapter was published in the international journal *Land* (MDPI). This article is cited as follows: Liebenberg, A, Van der Nest, JRR, Hardie, AG, Labuschagne, J, Swanepoel, PA. **2020** Extent of soil acidity in no-tillage systems in the Western Cape province of South Africa. *Land*, 9, p361. (APPENDIX A).

The following contributions were made in the co-authoring of this chapter: methodology, validation, formal analysis, investigation, data curation, writing—original draft preparation.

Chapter 4 consist of a field trial conducted to determine the effect of form, fineness and placement of lime with and without soil disturbance on soil chemical attributes. The field trial was conducted over two growing seasons and included ten different liming treatments conducted on barley (2019) and canola (2020). This chapter was written as a stand-alone chapter with the intention of publishing it as a scientific article in a journal.

Chapter 5 is a continuation of Chapter 4 as the data was collected from the same trials however this chapter focuses on determining the effect of form, fineness and placement of lime with and without soil disturbance on barley growth and development. This chapter was written as a stand-alone chapter with the intention of publishing it as a scientific article in a journal.

Chapter 6 consists of the conclusions and recommendations drawn from all three of the objectives of the thesis and includes recommendations for future research.

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CHAPTER 2

LITERATURE REVIEW

2.1 Soil acidity

2.1.1 Definition, causes and factors affecting soil acidity

Acid soils are considered one of the most important growth limitations for crop production worldwide, with more than 30% of the world's total land area and more than 50% of potentially arable land being acid (Kochian et al., 2004).

Soil acidity, when expressed in pH, is defined as the concentration of hydrogen ions (H^+) in a soil solution (Li et al., 2019). Besides the hydrogen activity (pH) of soils, exchangeable acidity and acid saturation can also be used to quantify soil acidity and has been found to be a more accurate indicator especially in highly weathered soils (Bloem, 2002). There are two kinds of acidity in the soil, active acidity and reserve acidity (Beegle, 2001). Active acidity refers to the H^+ ions present in the soil solution, whereas reserve acidity comprises all acidity associated with solid phase surfaces in soil, and consists of exchangeable and non-exchangeable (residual) acidity. Exchangeable acidity refers to the H^+ and Al^{3+} ions on the cation exchange sites of clay and organic matter particles. Non-exchangeable acidity consists of more strongly bound acidity that cannot be easily displaced with a neutral salt solution (KCl), for example pH dependent charges on broken edges of clay minerals, and Al polymeric complexes bound to organic matter. Limestone (used in agriculture to alleviate soil acidity) requirements are determined from the exchangeable acidity of the soil.

Acid soils can originate from a number of or combination of factors that ultimately reduce the pH of the soil over time. Climate can play an important role in the acidification of soils. In high rainfall regions, basic cations (Ca, Mg, K, Na) which are responsible for the prevention of soil acidity by replacing H^+ ions on the cation exchange sites, are leached out of the soil profile and replaced by Al (Brady and Weil, 2016). Soils that derive from acid parent materials, which are thus low in basic cations, such as granite, tend to become acid more quickly (Fageria and Baligar, 2008; Agegnehu et al., 2019). Furthermore, the harvesting of crops, especially high yielding crops, that removed basic cations from the soil during growth, prevents the return of these cations to the soil, resulting in a lowering of the soil pH (Carver and Ownby, 1995). The excessive use of ammonium-based fertilisers is also considered a major cause of soil acidification in cultivated land through the process of nitrification (FAO, 2015). Nitrification results in the release of H^+ ions through the conversion of ammonium to nitrate, which then reduces the pH of the soil. Also, during the process of crop residue decomposition, H^+ ions are released which also contributes to soil acidity, however this effect is found to be insignificant over the short-term (Fageria and Baligar, 2008).

A decrease in soil pH alters the chemistry and thus availability of various nutrients to plants and changes the environment of the soil, which in turn has an effect on crop growth and development.

2.1.2 Effects of acid soils on crop production

There are three major factors that influence crop growth and development in acid soils, namely, soil microbiological effects, nutrient deficiencies and nutrient toxicities (Fageria and Baligar, 2003).

The effect of pH on soil microbial activity and functioning varies. For example, fungi is known to be suited to a wide pH spectrum whilst important soil bacteria such as *Rhizobium* and diazotropic bacteria are sensitive to low pH conditions, preferring more alkaline soils (Rousk et al., 2010). These bacteria for example play an important role in nitrogen fixation and suppressing pathogens, and thus contributing to the growth and development of crops (Baligar and Fageria, 1999). Soil acidity has been found to be the main factor influencing the distribution and nitrogen-fixing capability of *Rhizobium* (Watkin et al., 2000). Therefore, as soils become more acid, the distribution and efficiency of these bacteria in the soil are reduced (Frierer and Jackson, 2006) and therefore also their potential contribution to crop growth and development (Rousk et al., 2010).

Soil acidity can also lead to nutrient deficiencies. The solubility of nutrients change as the pH of the soil changes, therefore influencing the ability of a crop to absorb and utilise the nutrients (Fageria and Baligar, 2004). In the case of acid soils, essential nutrients such as P start to change to an insoluble form as the pH decreases causing deficiencies of this nutrient in the crop (Foy, 1991). Furthermore, nutrients such as Ca, Mg and K are displaced by acid cations and leach out of the soil profile leading to deficiencies of these nutrients and consequently inhibiting normal crop growth and development (Kunhikrishnan et al., 2016).

The most prominent factor affecting crop production in acid soils however, is related to the nutrient toxicity caused by heavy metals such as Fe, Mn but more especially Al (Kochian, 1995). Aluminum is one of the largest constituents that make up soil clay minerals and is thus in abundant supply (Taylor, 2011). When the pH of the soil decreases the Al species produced by the hydrolysis of Al^{3+} becomes more soluble (as shown in the reactions below) and is therefore taken up more readily by crops (Lindsay, 1979).

$Al^{3+} + 5H_2O \rightleftharpoons Al(OH)_5^{2-} + 5H^+$

$Al^{3+} + 4H_2O \rightleftharpoons Al(OH)_4^{1-} + 4H^+$

$Al^{3+} + 3H_2O \rightleftharpoons Al(OH)_3^{0} + 3H^+$

$Al^{3+} + 2H_2O \rightleftharpoons Al(OH)_2^{1+} + 2H^+$

$Al^{3+} + H_2O \rightleftharpoons Al(OH)^{2+} + H^+$

At a pH lower than 4.7, Al^{3+} is the most soluble ion followed by the $Al(OH)^{2+}$ and $Al(OH)_2^{1+}$ species at a pH of 4.7 - 6.5 (Bohn et al., 2001). The increased concentration of soluble Al that is taken up leads to toxicity in the crop, decreasing physiological productivity.

The most significant effect of Al toxicity on crop development is the inhibition of root growth (Krstic et al., 2012). Aluminum localises at the apex of roots where it inhibits cellular division and elongation, causing stunting of the roots (Figure 2.1) and thus reduces the growth and expansion of the primary and lateral roots (Kochian, 1995). This restriction of root system expansion reduces the ability of the crop to take up water and nutrients and therefore causes the crop to be more sensitive to drought stress and leads to nutrient deficiencies (Taylor, 2011).

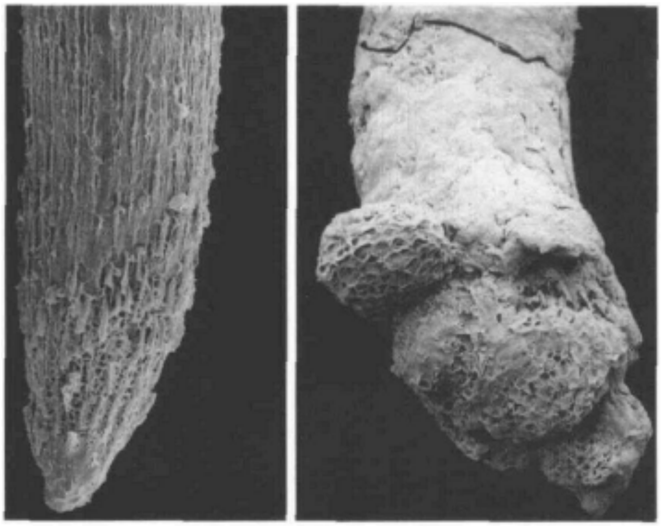

Figure 2.1. The root tip of a healthy (left) and deformed (right) wheat seedling as caused by Al toxicity (Taylor, 2011).

The amelioration of acid soils is therefore crucial for effective crop production. Limestone (lime) can serve as a neutralising agent for acid soils, raising the pH of the soil to a range that allows for optimum crop growth and development (Li et al., 2019).

2.2 Lime characteristics and sources

Agricultural lime which constitutes of either calcium carbonate (calcitic lime) or calcium magnesium carbonate (dolomitic lime) is used to neutralise soil acidity. Soil acidity alleviation through the use of lime is achieved by the release of a base (Ca or Mg) from the lime which replaces the H^+ ions that are attached to the soil clay or organic matter particles (Ritchey et al., 2016). Furthermore, the carbonate reacts to the hydrogen ions forming carbonic acid that is then converted into carbon dioxide and water as shown in the reaction below (in the case of calcitic lime):

$$\text{Clay-H}^+ + CaCO_3 \rightharpoonup \text{Clay-Ca}^{2+} + H_2CO_3 \rightharpoonup CO_2 + H_2O$$

Soils with high clay or organic matter content, and thus a high CEC, will require more Ca^+ ions for the neutralisation of acid due to its greater capacity to hold H^+ ions on the soil particles (Anderson et al., 2013). The more acid the soil is, the faster the reaction rate of the lime will be.

Agricultural lime is typically applied in a powder or pelletised form. Applying lime in a powder form presents the challenge of the fine liming material being blown away by wind during application with a typical lime spreader. A pelletised form is thus much easier to handle and allows for more efficient application and also allows making use of an even finer lime. However, the higher cost of lime pellets, due to the pelletisation process and the making use of a finer lime, relative to its benefits are in question.

Lime quality is expressed in terms of the fineness as well as the purity of the limestone (Wells and Dollarhide, 1995). The fineness of the lime has a direct correlation to the speed of the reaction with acidity because of the change in surface area for the reaction (Figure 2.2) (Beegle, 2001).

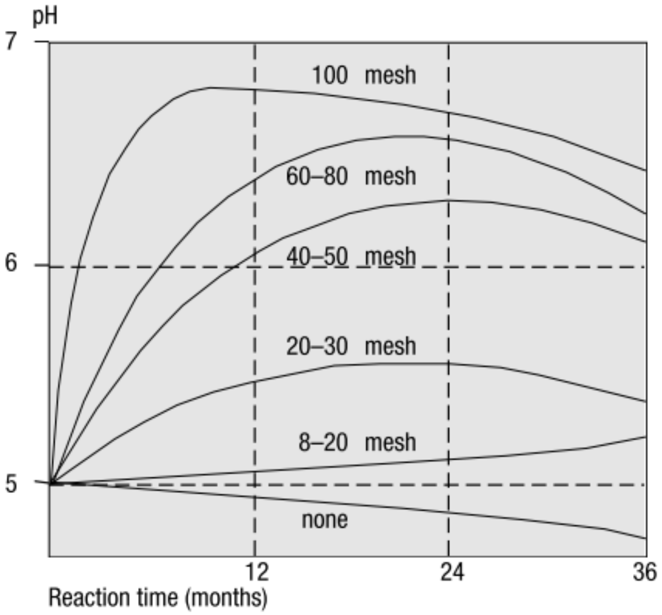

Figure 2.2. The effect of fineness on the speed of lime reaction (an increase in mesh number indicates smaller lime particles). (Beegle, 2001).

The fineness of agricultural lime is given as a percentage of the lime that passes through specific sieve sizes. A 10-mesh sieve for example allows the passing through of 2.00 mm particles, a 12-mesh sieve 1.70 mm particles, a 60 mesh sieve 0.25 mm particles and a 100 mesh sieve 0.15 mm particles. In South Africa, 100% of conventional agricultural lime must pass through a 12-mesh sieve and 50% must pass through a 60 mesh sieve according to Act 36 of 1947.

Lime particles finer than 0.25 mm (60 mesh) typically reach maximum reaction at 6 to 18 months after application and is completely soluble within three years, whereas particles with a size of 0.34 - 0.25 mm (40 - 60 mesh) reach maximum reaction after 12 to 18 months (Meyer, 1952; Beegle, 2001). Particles coarser than 0.30 mm (50 mesh) have been reported to be only half soluble after three years (Wells and Dollarhide, 1995). Particles coarser than 2.00 mm (10 mesh) has been shown to be ineffective for neutralising soil acidity (Ritchey et al., 2016).

The purity of lime is expressed as the calcium carbonate equivalent (CCE) of a given lime material and is a measure used to compare the mass of lime needed to neutralise hydrochloric acid, relative to that of pure calcium carbonate (100% CCE) (Peters et al., 1996). One molecule of $Ca(CO_3)$ is required to neutralise two H^+ ions (Zhang et al., 2004). The lower molecular mass of dolomitic lime [$CaMg(CO_3)_2$], means that it has a higher neutralising value per unit mass than calcitic lime [pure dolomitic lime has a CCE of 109% compared to the same mass of pure calcitic lime (100% CCE)] (Pagani and Mallarino, 2012). However, dolomitic lime is three times less soluble than calcitic lime and thus reacts slower (Rippy et al., 2007). The CCE is lowered by impurities such as clay and organic matter present in the lime source, and a minimum CCE of 70% is required for agricultural lime in South Africa according to Act 36 of 1947. The purity of the lime thus influences the application rate needed to neutralise a given amount of acidity.

There are many factors and combination of factors that determines soil acidity and lime requirement, which explains why there are different methods available to determine lime requirement. A method most widely used in the Western Cape Province is the Modified Eksteen Method, which takes into account the ratio between exchangeable acidity (H^+ in $cmol_ckg^{-1}$) and exchangeable Ca and Mg ($cmol_ckg^{-1}$), termed the R value (Eksteen, 1969). Fixed R values have previously been determined to achieve a desired soil pH and is substituted into the formula below:

$$X = \frac{(\mathrm{RxH}) - (\mathrm{Ca+Mg})}{R+1} \times F$$

Where:

X = Lime requirement

R = R value

H = Exchangeable acidity

Ca + Mg = Exchangeable calcium and magnesium

F = Field calibration factor. A factor of 4 is commonly used as this assumes that the soil has a CEC lower than 7 $cmol_ckg^{-1}$ and is low in organic matter.

The lime requirement is determined in ton of lime per hectare to neutralise soil to a pH_{CaCl2} of 5.5 up to a depth of 15 cm.

The effective neutralisation of soil acidity is not only determined by the application of the correct rate of lime. Other limitations such as the mobility of lime in the soil should also be considered when attempting to effectively correct the pH of soil to a relevant depth.

2.3 Soil pH stratification

2.3.1 Movement of surface applied lime

Literature highlights the extremely low mobility of lime in the soil (Miller, 2015; Caires et al., 2005; Caires et al., 2008; Godsey et al., 2007; Caires et al., 2008b; Conyers et al., 2003). The challenge with liming in no-tillage systems, is the limitation of being unable to incorporate lime into the soil, leaving one seemingly dependant on the ability of surface applied lime to move vertically into the soil profile. Miller (2015) found that 3 tons of surface applied lime (90% CCE) only moved 5 cm within a year of application on a loam soil receiving 489 mm of rainfall, and did not move into the 10 – 20 cm depth three years after application. Caires et al. (2005) found movement of 2, 4 and 6 t ha^{-1} of lime (84% CCE) at 0 - 5 cm and 5 - 10 cm one year after application on a loamy soil receiving 2067 mm of rainfall, however there was a greater change in pH in the 0 - 5 cm depth. After 2.5 years, there was significant change in pH at 10 - 20 cm depths. Surface applied lime was able to decrease Al toxicity to a depth of 1 cm a year after application and to a depth of 40 - 60 cm three years after application, this was however with a high application rate of 12 t ha^{-1} (Caires et al., 2008). In a trial by Godsey et al. (2007) on silty clay loam, 4.48 t ha^{-1} of lime only moved 7.5 cm after five years of applying the lime on the surface. Caires et al. (2008b) reported that not much lime moved past 5 - 7.5 cm even after three years from application of 3 t ha^{-1}. Furthermore, Conyers et al. (2003) found that it took between two to four years for 1.5 t ha^{-1} of surface applied lime to move to a depth of 10 cm.

With the majority of the acid neutralisation occurring only in the top few centimetres of the soil due to the shallow movement of lime, a stratification of pH will begin to develop over time between the top and subsoil, limiting the growth of crops.

2.3.2 Factors affecting movement of lime

There are a few factors influencing the vertical movement of surface applied lime in the soil. The first important factor to note is the pH of the topsoil. For excess alkalinity [as HCO_3^- or OH^- (Sumner, 1995)] to move further down the soil profile (> 10 cm), a pH of 5.5 [1 : 2.5 (0.01M $CaCl_2$)] is required in the topsoil, allowing the leaching of the carbonates to greater depths (Joris, 2013). Li et al. (2019) showed that by maintaining a pH_{CaCl2} of 5.5 [using super-fine lime (< 250 microns)] in the top 0 - 10 cm of the soil profile, lime could raise the pH at 10 - 20 cm depths and even allow for movement of lime down to 30 cm over an 18 year trial period. Azam et al. (2019) also achieved a greater pH_{CaCl2} throughout the top 30 cm of the soil profile compared to the control by maintaining a pH_{CaCl2} of 5.5 in the topsoil by recurring lime applications over a 23 year period. More so, Caires et al. (2008b) showed that liming on a site that has previously been limed (at a rate of 6 t ha^{-1}, seven years prior), therefore only having a slightly acid topsoil, significantly increased the pH to 10 cm within the first year and 60 cm within three years. This fact could have implications on soil management practises, motivating the maintenance of the topsoil (10 cm) to a pH_{CaCl2} of 5.5 in order to address subsoil acidity in no-tillage systems.

The effect of the pH of the topsoil on vertical lime movement also has an influence on the effect of lime application rates on the vertical movement of lime in the soil. A study by Flower and Crabtree (2011) in sand over sandy clay loam soil, showed a higher increase in pH of both the top 0 - 10 cm and bottom 10 - 20 cm of soil for 4 t ha^{-1} compared to 1 t ha^{-1} rates. Caires et al. (2005) also showed a more prominent increase in both the top and subsoil pH, 2.5 years after application of 6 t ha^{-1} of lime compared to 0, 2 or 4 t ha^{-1} rates. Increasing the lime rate will therefore provide enough alkalinity to neutralise the topsoil and then allow the excess alkalinity to leach to greater depths. Alkalinity will not move deeper if there is acidity present in the topsoil.

Soil type also affects the movement of surface applied lime down the soil profile. Lighter textured (sandy) soils with a lower buffering capacity will favour the downward movement of alkalinity over heavy textured (clayey) soils with a high organic matter content which is more resistant to pH change. This is shown in the trial by Godsey et al. (2007) where soils with a clay and organic matter content of between 24 - 32% and 2.3 - 3.1%, respectively, showed a movement of 7.5 cm or less within a year, even at a high rate of 8.4 t ha^{-1} of surface applied lime. Furthermore, Alleoni et al. (2010) also attributed the slower movement of surface applied lime to the high clay content (72%) of the soil compared to a lighter textured soil (30% clay) of a similar organic matter content, receiving the same treatment.

Another factor that should also be noted is the effect of rainfall on lime movement. In a trial conducted by De Oliveira and Pavan (1996) in a region receiving an average annual rainfall of 1500 mm, 5.5 t ha^{-1} of surface applied lime moved 40 cm in three years, despite the soil being high in clay and organic matter. Blevins et al. (1978) saw a vertical movement of lime to 30 cm in a region receiving 1100 mm of annual rainfall, only after applying three times the recommended rate.

Finally, the fineness of the lime also affects vertical movement and thus the amelioration of acidity lower down in the soil profile. Finer lime has a greater surface area for reaction and will lead to a quicker neutralisation of the topsoil compared to coarser lime particles that are more insoluble. This more efficient neutralisation of the topsoil acidity then allows for the movement of excess alkalinity into the subsoil. Whitten et al. (2001) showed that a fine lime was as effective as double the rate of a coarser lime in raising the topsoil pH over the same time period, and that there was a positive correlation between this increase of surface pH (0 - 10 cm), and the increase in subsoil pH (10 - 20 cm and 20 - 30 cm). Finer lime is also more prone to be leached down macropores in the soil by rainfall, assisting in its downward movement (Amaral et al., 2004).

It is however important to take into consideration that in practise, the application of very high rates of lime for example is not economically feasible and that soil texture and rainfall is beyond one's control. That being said, the cases mentioned above emphasises the effect of the different factors, but are not necessarily a reflection of common practise. The cases highlighted in section 2.3.1 seem to be a more accurate reflection of circumstances faced in common agricultural practise and thus the actual movement of lime in the soil.

In order to overcome the limitation of the poor mobility of lime in soil, the incorporation of surface applied lime is also considered as an option to assist in lime movement in order to address subsoil acidity. In the context of conservation agriculture this would be practised as a one-off tillage treatment every few years. The effectiveness of this 'strategic tillage' practise should be reviewed as well as its effect on the soil health and crop growth.

2.4 Incorporation of surface applied lime

2.4.1 Effects of a one-off strategic tillage on plant production and soil quality in no-tillage systems

When considering the incorporation of lime in no-tillage systems, its impact on crop production and soil quality is of great importance and requires reviewing to determine whether the advantages attained from long-term no-tillage will be lost after one-off tillage practise.

Various trials have shown the effect of one-off tillage on soil chemical properties. After 24 to 32 months of a one-off tillage with a mouldboard plough (Quincke et al., 2007), five years after one-off tillage with a chisel, disc or mouldboard plough (Wortmann et al., 2010) and one year after tillage with a disc, chisel or prickle disc (Crawford et al., 2014), it was reported that there was no significant effect on the loss of total soil organic carbon compared to no-tillage. Conversely, Stockfisch et al. (1999) reported a decrease in soil organic carbon at a 0 - 20 cm depth after tillage in a no-till system with a mouldboard plough.

It has also been reported that one-off tillage in no-tillage systems redistributes nutrients between the soil layers, therefore reducing stratification. Kettler et al. (2000) found a 20% decrease of organic C in the 0 - 7.5 cm depth and a 15% increase at a 7.5 - 15 cm depth as well as a decrease in N at the 0 - 0.75 cm depth but an increase at 7.5 - 15 cm, five years after tillage with a mouldboard plough. Similarly, Quincke et al. (2007) also noted a decrease in soil organic C in the top 0 - 2.5 and an increase in the 5 - 10 cm after one-off tillage with a mouldboard plough. Furthermore, Pierce et al. (1994) noted a reduction in soil organic C at 0 - 5 cm depth and an increase in the 5 - 10 and 10 - 15 cm depth seven years after one-off tillage with a mouldboard and disc plough and also reported a lower N content in the 0 - 5 cm compared to the no-till treatment but similar N content at the 5 - 20 cm depth four to five years after the one-off tillage.

In terms of soil physical properties, Quincke et al. (2007b) reported no effect of one-off disc, chisel or mouldboard tillage on soil aggregate stability and that water infiltration and sorptivity increased at one site but decreased at another after mouldboard tillage compared to no-tillage. In another trial by Wortmann et al. (2010), there was no effect five years following one-off tillage (chisel, disc or mouldboard plough) on soil bulk density or soil aggregate stability except that there were more macro-aggregates at one site in the 5 - 10 cm depth with mouldboard tillage compared to no-tillage. Furthermore, Liu et al. (2016) reported no effect of either a chisel or disc plough on bulk density or volumetric moisture content in the short-term (four to seven weeks after strategic tillage). Baan et al. (2009) also saw no effect of strategic tillage on aggregate stability whereas Conyers et al. (2019) however, found an initial decrease in wet aggregate stability which recovered within one to two years. Melland et al. (2016) and Dang et al. (2018) reported higher risk for soil erosion and nutrient runoff under high rainfall conditions for soils that were strategically-tilled compared to no-tillage soils.

Finally, Keller et al. (2000), Quincke et al. (2007b) , Baan et al. (2009) , Wortmann et al. (2010), (except at one site), Crawford et al. (2014), Liu et al. (2016), Dang et al. (2017) and Conyers et al. (2019) reported that one-off tillage in a no-tillage system had either no effect or resulted in an increase in grain yield.

2.4.2 Amelioration of sub-soil acidity with the incorporation of lime

One-off incorporation of surface applied lime is a tactic that could be considered by farmers wanting to address the issue of subsoil acidity in no-tillage systems as well as possibly benefiting from additional advantages such as weed control and reduction of nutrient stratification as well as soil compaction.

In a trial conducted by Conyers et al. (1996) that compared soil pH after direct-drilling, to the soil pH after tillage (off-set disc plough and a scarifier to a depth of 10 cm), a higher pH in the top 0 - 5 cm was found under direct-drilling, however at 5 - 10 cm depths there was a higher pH for the tillage treatments (after two or three cultivations). A similar trend can be found in trials by Conyers et al. (2003), Caires et al. (2006) and Caires et al. (2011) in which surface applied lime tended to raise the pH higher in the top 5 cm of soil and surface incorporated lime resulted in a higher pH in the 5 - 10 cm depths. Furthermore, 2.5 - 5 t ha^{-1} of lime incorporated to 10 cm depth in sandy soil was found to ameliorate subsoil acidity down to a depth of 30 cm in four to seven years (Whitten et al., 2000). Probert et al. (1998) found that seven years after applying 8 t ha^{-1} of lime incorporated with a rotary hoe to a depth of 10 cm, the pH increased to a depth of 10 - 20 cm. In a trial by Caires et al. (2006) in which 2.25 t ha^{-1} of lime was incorporated with a disc plough to a depth of 20 cm followed by 2.25 t ha^{-1} of lime incorporated to a depth of 10 cm with a disc harrow, acidity was neutralised to a depth of 20 cm after 23 months. However, acidity below 20 cm was not effectively addressed over the five-year trial period. Lime at a rate of 4.5 t ha^{-1} incorporated to a depth of 10 cm with a disc harrow was able to correct acidity at a depth of 10 - 20 cm and reduce acidity down to a depth of 60 cm after eight years (Caires et al., 2011). Tiritan et al. (2016) saw an improvement of pH, exchangeable acidity and reserve acidity to a depth of 30 cm after incorporating either rates of 2.7 or 5.4 t ha^{-1} of surface applied lime with a disc plough followed by two cultivations with a levelling harrow.

Conversely, Baan et al. (2009) reported no change in pH after one-off tillage with either a cultivator or disc plough at 7 - 8 cm depths without surface applied lime and Díaz-Zorita et al. (2004) also observed no difference in pH following strategic tillage compared to no-tillage.

Alternatively, to applying agricultural lime in a powder form on the soil surface or incorporating it into the soil, the pelletisation of fine lime has become another consideration for addressing soil acidity.

2.5 Pelletisation of lime

Pelletised lime is finely ground lime (< 100 mesh with 25 - 40% < 200 mesh) in a round pellet form, held together with a binding agent. Lime pellets are easier to handle than conventional agricultural lime as spreading is not affected by wind, leading to a more uniform application. Pelletised lime can also be broadcast or band-placed with fertiliser during planting. Once dissolved, the fine lime is expected to react rapidly with acidity due to its larger surface area. Pelletised lime is more expensive (+/- R 2500 per ton) than conventional agricultural lime (+/- R 170 – R 470 per ton) and is commonly marketed as more effective in neutralising soil acidity and thus less is required in order to make it an economically viable option.

Pelletised lime is claimed to be more effective in neutralising acidity because of the argument that recommended lime rate is based on the neutralising value of the lime, which is a combination of both the purity and fineness of the lime. Therefore finely ground lime in a pellet form should have a greater neutralising capacity and thus less is required compared to conventional agricultural lime. The contrasting argument is that chemically speaking, in order to neutralise two molecules of H^+ ions, one molecule of $Ca(CO_3)$ is required, and therefore pelletised lime of the same calcium carbonate equivalent cannot be more effective than conventional lime (Zhang et al., 2004).

2.5.1 Pellet binding agents

There are various binding agents that are used in the production of lime pellets. Lignosulfonates, bentonite clay, molasses and starches (brewex) are amongst the more common ones (Staton and Warncke, 2000). Lignosulfonates are the most widely used binding agent and usually comprise of 9% of the lime pellet. These binding agents are sulfonate salts made from lignin, originating as a by-product from the sulfite pulping process during paper-making (Tabil et al, 1997). Bentonite clay is an alumino-silicate that is composed of mostly montmorillonite (Clem and Doehler, 1961), while molasses are a by-product of the refining process of cane or beet sugar, whereas starches such as brewex are by-products from beer production (Veverka and Hinkle, 2002).

2.5.2 Broadcasting of pellets

Fine lime broadcast on the soil surface in a pelletised form could be expected to possibly move and react move effectively down and in the soil profile because of the smaller size of the particles compared to the coarser particles that makes up conventional agricultural limestone. In a trial by

Brown et al. (2008) lime pellets broadcast at a rate of 7 t ha^{-1} increased the pH of the soil significantly to a depth of 15 cm two years after application compared to the control treatment. The broadcast pellets in this study increased the pH by 1.9, 0.5 and 0.3 at 0 - 5, 5 - 10 and 10 - 15 cm, receptively. However, there was no significant difference found between the vertical movement of broadcast conventional lime and pelletised lime applied once-off at 1.1 t ha^{-1} in a trial by Godsey et al. (2007). The lime moved 5 - 7.5 cm over a five-year period for both the pelletised and conventional lime treatments at three different sites. In a trial by Higgins et al. (2012), in which dolomitic pelletised and conventional lime were compared at annual rates of 0, 175, 350 and 525 kg ha^{-1} for three years, no difference was found between the two lime materials in their ability to increase the soil pH. These trials thus suggest that the pelletised lime is not necessarily a more effective liming option. Furthermore, Snyder et al. (1996) reported that it would take between 568 - 795 kg ha^{-1} of broadcast lime pellets to have the same soil and soya bean yield response as 1 ton of conventional lime rather than the recommended rate of 286 kg ha^{-1}, which puts the ability of less pelletised lime needed to neutralise acidity in question.

2.5.3 Band-placed pellets

In a study conducted by Edwards et al. (2015) comparing the effectiveness of band-placed pelletised lime at lower than recommended lime rates (225 and 450 kg ha^{-1}) with broadcast and incorporated conventional lime (2.25 and 4.50 t ha^{-1}) to ameliorate soil acidity, 225 kg ha^{-1} of band-placed lime pellets did not increase the soil pH compared to the control, whilst 450 kg ha^{-1} had only a slightly higher pH than the control treatment. The broadcast and incorporated lime at both rates significantly increased the pH of the soil at the depth at which it was incorporated compared to the band-placed treatments. The pH was mostly raised for a small radius (~1.27 cm) around the pellets for the band-placed treatments and many of the pellets remained intact in the soil. The undissolved pellets could be due to them being concentrated too close in proximity to each other beneath the soil, preventing some to dissolve due to the alkaline environment created by the already-dissolved pellets. Stevens and Dunn (2000) conducted a study comparing incorporated conventional lime with band-placed followed by broadcast pelletised lime at fractions of normal recommended rate (less than 25% of the recommended rate). It was reported that neither treatments significantly increased soybean yield compared to the control treatments. Also, the conventional agricultural lime and the pellets achieved the same raise in pH when applied at the same rate, showing no favour to the pellets in neutralising soil acidity. Lentz et al. (2010) found that pelletised lime incorporated into the soil did not neutralise the acidity faster than incorporated conventional lime, and that the application of lower than recommended rates of pelletised lime did not neutralise the soil sufficiently. Moreover, Brown et al. (2008) reported no difference between the control treatment and 224 kg ha^{-1} (lower than recommended rate) of band-placed lime treatment in the change of the pH in the top 10 cm of the soil two years after lime application.

2.6 Crop response to soil acidity and liming

Crop production under conservation agriculture entails amongst other things, implementing crop diversity (in the current context of this study as crop rotations) into the system. In the dryland crop rotation system of the Western Cape Province (southern Cape and Swartland regions) both barley (*Hordeum vulgare*) and canola (*Brassica napus*) are incorporated. Barley is the second-most important small-grain crop in South Africa (Burger et al., 2016) of which 89% is produced under dryland conditions in the Western Cape Province (Mogala, 2017). Barley is mostly grown for the production of malt used in beer making, whilst a small portion that is less suitable for malt production is used as animal feed. Canola is also mainly produced in the Western Cape Province to produce products used for human consumption as well as for animal feed (DAFF, 2016). The production of these crops under conservation agriculture (with includes no-till practises) has farm management implications such as the inability to incorporate amendments such as lime into the soil. As mentioned before, due to the slow mobility of lime in soil and the lack of soil disturbance under no-tillage practises, long-term no-tillage leads to a stratification of pH down the soil profile (Barth et al., 2018). This stratification is usually in the form of an alkaline topsoil and an acid subsoil where the lime could not reach.

Soil acidity is a major growth limiting factor for most crops, but especially for barley and canola which are highly sensitive to low soil pH (Tang and Rengel, 2001; Angus, 2008). This growth limitation can be due to Mn toxicity or N, P, Mo, Ca, Mg and K deficiency (Foy, 1984; Samac and Tesfaye, 2003). The main growth limitation for crops in acid conditions however is due to the increase in toxic levels of soluble Al as the pH of the soil decreases (Kochian, 1995). High levels of these toxic Al species effect the root apex (root cap, meristem and elongating zone) of the barley and canola crop, by inhibiting the mechanisms of cellular elongation and division resulting in stunted root growth (Figure 2.3)

(Panda et al., 2009; Krstic et al., 2012). This subsequently results in reduced water and nutrient uptake and thus a decrease in crop quality and yield (Tang and Rengel, 2001; Samac and Tesfaye, 2003).

Barley and canola cultivars differ in their tolerance to Al toxicity (French, 2017). Tolerance mechanisms can be divided into external resistance mechanisms that exclude Al from the root apex, or internal tolerance mechanisms that allow the plant to tolerate the presence of Al within the root symplast tissue (Ryan et al., 2011). External mechanisms include amongst others the excretion of organic acids such as citrate, that chelate Al or the excretion of mucilage that binds Al, preventing it from entering the root tissue (Samac and Tesfaye, 2003). Internal mechanisms involve immobilizing or detoxifying the Al ions that have entered the root tissue (Taylor, 1995) by chelating the Al or storing it in sub-cellular compartments such as the vacuole (Wang et al., 2006). Tolerance of barley and canola cultivars to Al is however not sufficient in fully preventing the adverse effects of Al toxicity on crop growth and development. A reduction in the levels of soluble Al is required. Maintaining an ideal soil pH_{CaCl2} of ≥ 5.5 in the top 0 - 10 cm and ≥ 4.8 in the 20 - 30 cm (Gazey and Davies, 2009; Miller, 2020) of the soil is thus crucial for the success of barley and canola production, and is commonly achieved in practise by lime application.

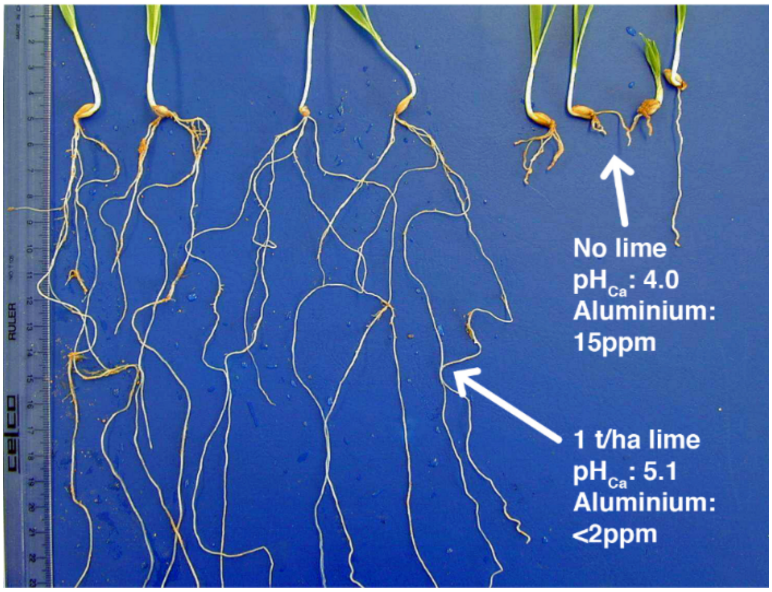

Figure 2.3. Barley seedlings grown in limed (left) and unlimed (right) acid subsurface soil (Gazey, 2018).

A growth and yield response from liming was reported for both barley (Dolling et al., 1991; Tang and Rengel, 2001; Tang et al., 2003; Liu et al., 2004) as well as for canola (Arshad et al., 1997; Gazey and Carmody, 2001; Scott et al., 2003; Li and Conyers, 2006; Arshad et al., 2012) grown in acid soil. The success of liming on barley and canola growth was mainly due to the alleviation of Al toxicity by increasing the soil pH and therefore causing the Al to convert back to an insoluble form. The lime that resulted in a positive barley and canola growth response in these trials varied from surface applied conventional agricultural lime (Tang and Rengel, 2001; Tang et al., 2003; Gazey and Carmody, 2001; Li and Conyers, 2006) to fine lime (as would also be found in pelletised lime) (Dolling et al., 1991; Liu et al., 2004; Scott et al., 2003). Furthermore, the lime in the trials by Arshad et al. (1997), Scott et al. (2003) and Arshad et al. (2012) were incorporated into the soil and the reports that barley growth and yield is not negatively affected by one-off strategic tillage (Dang et al., 2018) could indicate that incorporation of surface applied lime can be effective in alleviating soil acidity.

2.7 Summary

The effect of soil acidity on crop production is of global significance (Kochian et al., 2004). The challenge regarding the management of soil acidity under no-tillage systems is also pertinent (Barth et al., 2018). The inability to incorporate lime into the soil under no-tillage systems accompanied by the slow movement of lime in soil results in a stratified pH down the soil profile over the long-term (Flower and Crabtree, 2011). The adoption of no-tillage is motivated by increases in soil aggregate stability, water infiltration and water holding capacity (Findlater et al., 2019) which has direct and indirect positive influences on crop production. Therefore, strategies to effectively lime soils in no-tillage systems without compromising on the core principles of these systems is important. Crop response in pH stratified soils as well as the effective management of these soils is still not clear and requires further research.

Further investigation regarding the effect that lime characteristics, such as fineness, purity and form, has on its movement in the soil will promote the development of more effective liming methods that can address pH stratification experienced in long-term no-till systems. More specifically, there is a paucity of information on fineness of lime and its ability to move deeper into the soil and therefore be more effective in alleviating acidity lower in the soil profile. Purity of lime and its ability to neutralise soil acidity and move down the soil profile is another aspect that still needs more investigation. Furthermore, the effectiveness of fine lime in a pelletised form to alleviate soil acidity lower down the soil profile and whether less pelletised lime can be applied (as claimed by the industry) than the lime recommendation needs to be further investigated. Lastly, more knowledge is required regarding the effect of incorporating lime into the soil (as a one-off strategic tillage operation) and comparing the effectiveness of different incorporation methods (differing in depth of soil disturbance and degree of soil inversion). Measuring crop growth in response to different fineness, purity, and forms of lime as well as its response to lime incorporation is also knowledge that can be expanded on.

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CHAPTER 3

DETERMINING THE EXTENT OF SOIL ACIDITY AND PH STRATIFICATION ON LONG-TERM NO-TILLAGE SOILS ACROSS THE SOUTHERN CAPE AND SWARTLAND AREA

3.1. Introduction

Conservation agriculture (CA) is an effective strategy to improve the efficiency of production of crops (Smith et al., 2017; Findlater et al., 2019). No-tillage is an important part of CA, along with crop rotation and the maintenance of an organic soil cover. No-tillage entails disturbing less than 25% of the total cropped area or implementing soil disturbances that are less than 25 cm wide (FAO, 2014).

In the Western Cape Province of South Africa, more than 80% of farmers have converted to no-tillage systems (Smith et al., 2017). The implications of implementing no-tillage is that soil amendments, such as limestone (lime), cannot be mixed into the soil with tillage actions, as in the case of conventional agriculture. As soil has not been disturbed through tillage for several decades in this region, soil layers are expected to form with more nutrients skewed towards the soil surface, as well as pH stratification with increasing soil depth due to the relatively slow movement of lime (Barth et al., 2018). Surface broadcast lime has been found to take up to a year to move only 5 cm down the soil profile of a loam soil that received 489 mm of rainfall (Miller, 2015) or five years to move 7.5 cm in a silty clay loam soil that received a mean annual rainfall of 739 mm over the five years (Godsey et al., 2007). In a study by Conyers et al. (2003) it was found that it took between two and four years for 1.5 t ha^{-1} of surface-applied lime to move to a depth of 10 cm in a clay loam soil that received 570 mm of rainfall. Acidity will thus only be neutralised to the depth that lime is able to move.

The southern Cape and Swartland regions of the Western Cape Province produce a large proportion of the country's wheat (*Triticum aestivum*) (> 50%), barley (*Hordeum vulgare*) (89%), and canola (*Brassica napus*) (100%) under dryland conditions (USDA, 2015; Mogala, 2017; De Kock, 2018). Wheat, barley, and canola are sensitive crops to acid soil conditions (Tang et al., 2003; Angus et al., 2008). Soil acidification results in decreased solubility or displacement of crop nutrients such as P, Ca, Mg, and K (Foy and Atkinson, 1991; Kunhikrishnan et al., 2016). More importantly, however, is that as the pH_{KCl} of the soil decreases below 4.5, heavy metals such as Al become more soluble (Kochian, 1995). Toxic levels of Al causes, inter alia, stunting of crop roots (Krstic et al., 2012), thus limiting the uptake of water and nutrients and consequently crop growth and production. It also results in the displacement and subsequent leaching of essential basic cations from cation exchange sites. Soil acidity may be detrimental to microbial activity in soil, such as *Rhizobium* that are important for nitrogen fixation (Fageria and Baligar, 1999; Rousk et al., 2010) as well as bacteria that break down complex carbon structures and mineralise other nutrients (Robson and Abbott, 1989; Kunito et al., 2016). Acid soil conditions are thus limiting for crop growth as well as soil biology. Failing to address acidity within the soil profile will have a negative influence on sustainability of crop production systems.

Currently little is known regarding the extent to which the soils in southern Cape and Swartland regions are acid, or the extent of the occurrence of soil pH stratification. A lack of knowledge regarding the state of soils in these production regions with regards to soil acidity restricts addressing this crop-growth limitation. Therefore, a soil-sampling survey was conducted, taking soil samples at 0 – 5, 5 – 15 and 15 – 30 cm depths from fields that have been under no-tillage for at least eight years. The soil samples were taken at three depth increments with the purpose of identifying the change in soil acidity with depth, while identifying whether there is an association with other soil attributes and explanatory variables. Explanatory variables included region, soil texture, rainfall, and years since last liming. The final objective was thus to determine the extent and geographical spread of soil acidity and pH stratification throughout the southern Cape and Swartland production regions in the Western Cape Province of South Africa, as well as possible causes thereof.

3.2. Materials and Methods

3.2.1. Description of Climate, Soil Types, and Land Use of the Survey Sites

For the purpose of the survey, the Western Cape Province was separated into two regions according to differences in rainfall distribution and soil type, namely the southern Cape and Swartland regions (Figure 3.1). Both regions have a Mediterranean-type climate. The timing of rainfall differs between the two regions, with the majority (about 80%) of the rainfall in the Swartland occurring from April to October, and the majority of the rainfall in the southern Cape (roughly 60% in the eastern districts and 75% in the western districts) occurring from April to October. The areas surrounding the following towns within the southern Cape region were sampled: Albertinia, Riversdale, Heidelberg, Witsand, Swellendam, Riviersonderend, Bredasdorp, Napier, Caledon, and Greyton. The annual mean rainfall for these areas ranged from 300 – 550 mm annually and the mean temperature is 17 – 18°C for all these areas. The areas surrounding the following towns were sampled in the Swartland: Malmesbury, Riebeek Kasteel, Gouda, Moorreesburg, Koringberg, Piketberg, and Porterville. The annual mean rainfall for these areas ranges from 300 – 600 mm and mean temperatures are 18 – 19°C.

The soils in both regions are classified as soils with minimal development, usually shallow and on hard or weathering rock, with or without intermittent diverse soils (Western Cape Department of Agriculture, 2020). The soils in the Swartland are also red and yellow, massive or weak structured soils, with low-to-medium base status (Western Cape Department of Agriculture, 2020).

In terms of land use, similar crops are cultivated in both regions, due to both regions having Mediterranean-type climates. Both regions are mostly under dryland wheat, barley, oats, canola, and lupine (*Lupinus* spp.) production. Various forage crops are incorporated into crop rotation systems to support livestock production. The preferred forage crops by southern Cape farmers generally include lucerne (*Medicago sativa*), whereas the Swartland farmers tend to cultivate annual *Medicago* spp. (mostly *M. trancatula* and *M. polymorpha*).

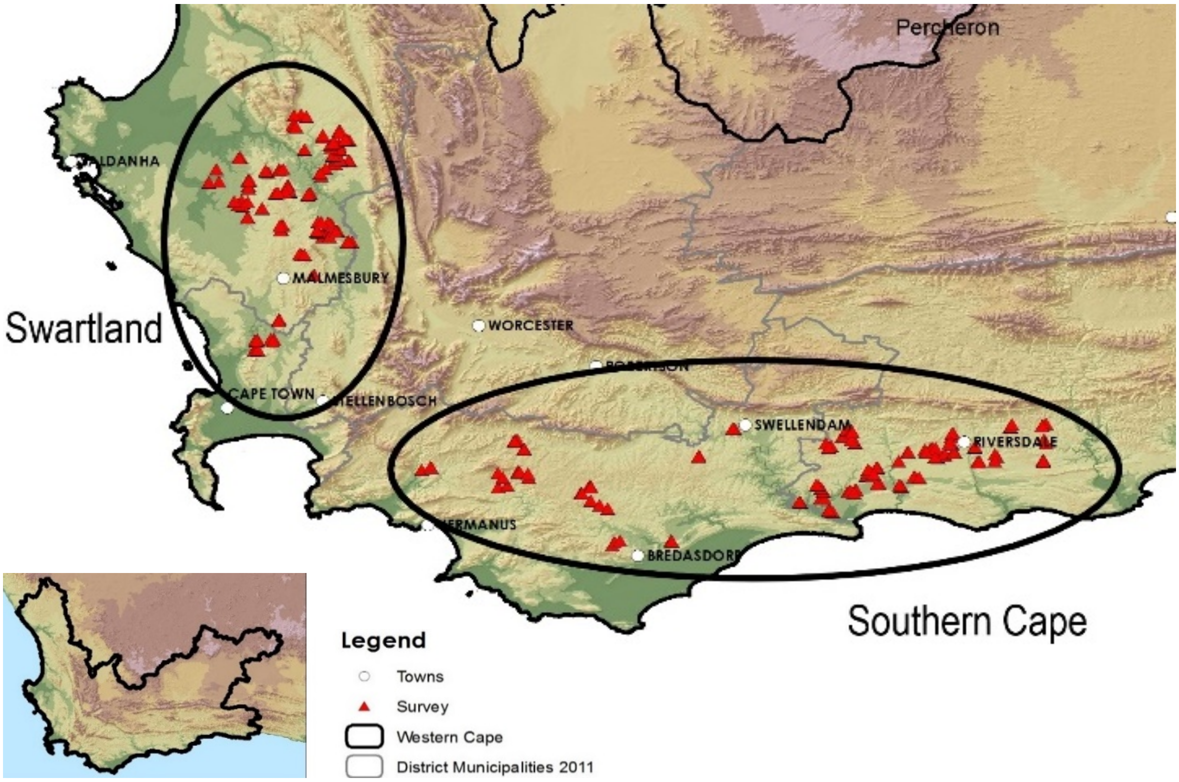

Figure 3.1. A map indicating the surveyed area, which included the southern Cape and Swartland regions of the Western Cape Province of South Africa.

3.2.2. Sampling and Analyses

The survey was conducted by means of soil samples accompanied by questionnaires (APPENDIX B) relating to system management and liming history. The questionnaires were completed by each farmer who participated in the survey to obtain information regarding liming methods, liming history, and the crop history of the fields that were sampled.

For a respective field to be surveyed, the following criteria had to be met: (i) The field had to be managed under no-tillage for at least eight years prior to sampling for the survey; (ii) no liming should have been done on the respective fields in the current year of surveying (2019); (iii) the crop rotation system used by the farmer had to include either wheat, barley, or canola. Two hundred and fifty three fields were sampled across the Western Cape Province. At each field, six soil cores (4 cm diameter) were taken at depths of 0 – 5, 5 – 15, and 15 – 30 cm and composited per depth increment. Soil analyses included exchangeable base cations (K, Ca, Mg, Na), soil pH_{KCl}, exchangeable acidity, and electrical resistance according to the methods described by Non-Affiliated Soil Analysis Work Committee (1990). Chemical analyses of pH were done in a 1:2.5 soil: KCl solution, and of exchangeable acidity and base cations with a potassium chloride and citric acid solution, respectively (Non-Affiliated Soil Analysis Work Committee, 1990). The standard procedures of Non-Affiliated Soil Analysis Work Committee (1990) were used for the determination of cation-exchange capacity (CEC; ammonium acetate). Electrical resistance was determined by the method described by the United States Salinity Laboratory Staff (1954). These soil chemical attributes were analysed at the three respective depths in order to determine the presence of nutrient or acidic stratification between the depth increments as well as to identify possible reasons for why acidity could be present in the soil.

In 15 of the fields where canola was planted in 2019, leaf samples were taken at physiological maturity to investigate relationships between soil nutrients, and nutrient uptake by crops. Leaf samples were taken of the youngest mature leaves shortly before flowering. Canola was chosen as the crop to analyse, since its requirement for various nutrients is higher than the other crops in the rotation systems. Calcium deficiencies are sometimes observed in the region on canola, but not for other crops (Personal communication, G.A. Agenbag, 2018). Therefore, if soil conditions are deteriorating due to acidification, canola would be the most likely crop in the system to show deficiencies first. The Ca concentrations in the leaves of the canola could thus be a further indication of the acid status of the soil.

3.2.3. Data Analyses

Descriptive statistics including mean, maximum, minimum, median, and standard deviation were calculated for samples for both the Swartland and southern Cape combined, as well as separately for the two regions. We used the standard deviation as an indicator of the variability of soil properties. Groups of correlated variables were defined by using a factor analysis to reduce the number of variables and to detect structure in the relationships between soil chemical properties. Latent variables for each group of soil chemical properties were created by normalising (varimax rotation) and averaging variables from each factor for which the eigenvalues of the correlation matrix were one or greater.

Analysis of variance for acid soil response variables and factor loadings were performed with mixed models incorporating the Kenward–Roger degrees-of-freedom method (Kenward and Roger, 2009). This method adjusts the estimator in computation of the Satterthwaite-type correction of the covariance matrix to account for heteroscedasticity. Soil depth was specified as the fixed effect and field as the replicated random effect. A Bonferroni post-hoc test was performed to compare soil parameter means across depths. Subsequently, fields with soil pH_{KCl} values lower than 5.5, the optimal threshold for most crops, were identified and separated into a subset for further analyses, and analysed using the Kenward-Roger method as described above. STATISTICA software version 13 was used to conduct the statistical analyses (TIBCO Software, 2020).

3.3. Results and Discussion

Figure 3.2 shows the distribution of soil pH_{KCl} for samples from the Swartland and southern Cape regions of South Africa, as well as individually for each region. Farmers aim for a soil pH_{KCl} of 5.5, so a pH_{KCl} distribution where the majority of observations are around 5.5 is to be expected. More samples from the Swartland region had a pH_{KCl} lower than 5.0 than the southern Cape region.

The pH_{KCl} stratification trend observed in both areas (Table 3.1) showed a decrease (from 0 – 5 to 5 – 15 cm) followed by an increase (from 5 – 15 to 15 – 30 cm) in pH_{KCl} with increasing depth.

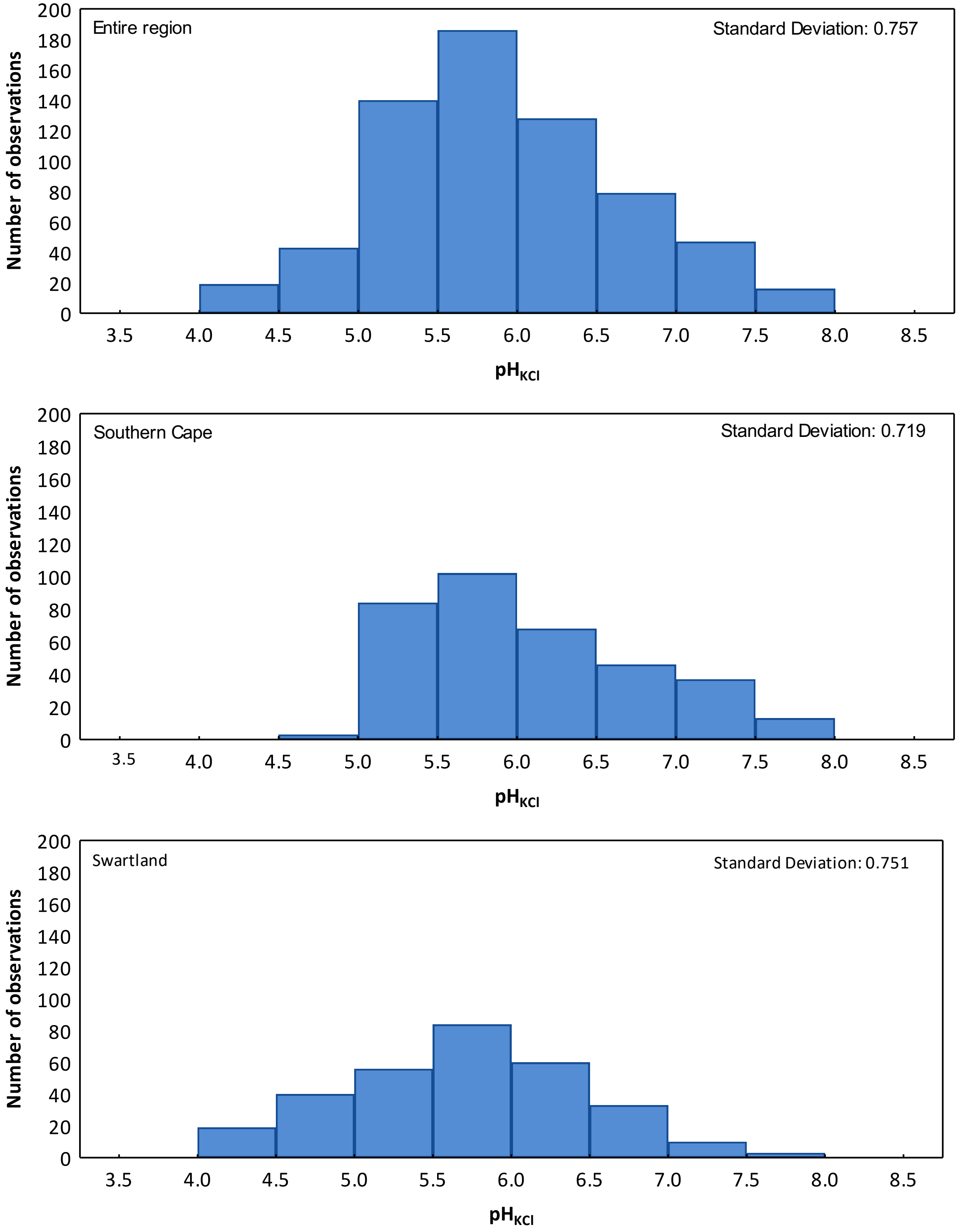

Figure 3.2. The mean soil pH_{KCl} distribution for all samples (top) as well for the southern Cape (middle) and the Swartland (bottom) regions separately.

Table 3.1. Descriptive statistics of soil chemical attributes between three depths (0 – 5, 5 – 15 and 15 – 30 cm) for soils sampled in the southern Cape and Swartland regions. SD = standard deviation.

	n			Mean		Median		Minimum		Maximum		SD	
	Southern Cape	**Swart-Land**	**Depth (cm)**	**Southern Cape**	**Swart-Land**	**Southern Cape**	**Swart-Land**	**Southern Cape**	**Swart-Land**	**Southern Cape**	**Swart-Land**	**Southern Cape**	**Swart-Land**
pH_{KCl}	118	99	0 – 5	6.2	6.0	6.2	6.1	4.8	4.5	7.5	7.4	0.64	0.69
	115	106	5 – 15	6.0	5.5	5.9	5.6	5.0	4.2	7.7	7.6	0.70	0.73
	115	100	15 – 30	6.2	5.8	5.8	5.7	5.1	4.1	7.9	7.9	0.87	0.76
Ca (mg kg $^{-1}$)	118	99	0 – 5	2514	1728	1761	1390	430	344	12.898	10.134	2193	1473
	115	106	5 – 15	1857	985	1127	763	366	116	9634	8562	1818	1007
	115	100	15 – 30	1818	658	889	545	326	106	11.644	3798	2339	550
Mg (mg kg $^{-1}$)	118	99	0 – 5	241	255	206	218	46	53	679	888	116	150
	115	106	5 – 15	201	141	173	119	41	18	481	408	99	81
	115	100	15 – 30	247	148	190	124	60	17	1463	720	182	107
Exchangeable Acidity ($cmol_c$ kg^{-1})	118	99	0 – 5	0.13	0.18	0	0	0	0	1.30	1.39	0.33	0.40
	115	106	5 – 15	0.19	0.39	0	0	0	0	1.22	1.54	0.35	0.46
	115	100	15 – 30	0.12	0.24	0	0	0	0	1.00	1.12	0.28	0.36
Acid saturation (%)	118	99	0 – 5	1.49	2.64	0	0	0	0	15.53	23.00	3.78	5.88
	115	106	5 – 15	2.72	8.17	0	0	0	0	17.44	44.16	5.07	10.38
	115	100	15 – 30	2.00	6.51	0	0	0	0	16.63	44.65	4.56	10.71

The increase in soil pH_{KCl} from the 5 – 15 to the 15 – 30 cm depth could be due to the 15 – 30 cm depth increment having the natural pH_{KCl} of that specific soil, which is related to base status of the parent material (Grieve, 1999). The differential depth effect between the southern Cape and Swartland could possibly be due to the acid saturation component of the effective cation exchange capacity (ECEC) of the Swartland soils being higher than that of the southern Cape soils. The parent material and physical attributes, such as texture, of the soils that differ between the Swartland and southern Cape regions may further account for the differences in pH_{KCl} and exchangeable acidity, since ECEC depends highly on the texture of a soil (Fooladmand, 2008). Soils containing more clay or organic matter will have a greater ECEC. These soils will thus have a greater capacity to hold basic cations leading to a greater buffering capacity against pH change compared to sandy soils with a lower ECEC (Nathan, 2020). It was, however, found that soil texture had no effect ($p > 0.05$) on pH_{KCl} and exchangeable acidity (Table 3.3). This result may be due to a disproportionate number of samples being from a sandy-loam texture class (Table 3.4).

Stratification could possibly be attributed to the higher ($p \leq 0.05$) concentrations of basic cations found in the 15 – 30 cm depth increment compared to the 5 – 15 cm depth increment (Table 3.3). Basic cations can be leached downward through the soil profile and accumulate in the subsoil on top of impervious layers that prevent the complete loss of these cations. Clay particles tend to accumulate deeper in the soil profile, and the higher ECEC of these particles is able to hold more basic cations and therefore have a greater resistance to change in pH compared to the sandy soil in the shallow depth increments (Jacobsen, 1997; Sumner and Miller, 1996).

It is clear that the degree of pH stratification in the Swartland is more severe than in the southern Cape. A higher degree ($p \leq 0.05$) of pH stratification was observed between the three respective soil depths of the Swartland soils, especially between the 0 – 5 and 5 – 15 cm depths (Tables 3.1 and 3.3). Despite the abrupt change of pH_{KCl} from the topsoil to the subsoil, the subsoil pH_{KCl} was not lower than the optimal pH_{KCl} for most crops. According to the South African fertiliser guidelines, the optimal pH_{KCl} for wheat is 5.0, and for barley and canola 5.5 (FERTASA, 2016). Other sources report an optimal pH_{CaCl2} of 5.5 for most crops (Gazey and Davies, 2009; Miller, 2020), which is equivalent to an approximate pH_{KCl} of 5.2 (Van Lierop, 1981).

Table 3.2. Principal component extraction using factor analysis. Varimax-normalised factor loadings for soil chemical properties across the Western Cape crop production region in South Africa are presented, along with the eigenvalue, total variance, and cumulative variance. Boldfaced values indicate the highest loading of each soil attribute, therefore forming part of a particular factor.

Soil Chemical Properties	Factor 1	Factor 2	Factor 3	Factor 4
pH$_{KCl}$	0.465	0.073	**0.747**	0.060
Electrical resistance (Ohm)	−0.021	**−0.628**	−0.183	−0.498
Electrical conductivity (mS m^{-1})	−0.036	**0.787**	0.072	0.433
Exchangeable acidity (cmol$_c$ kg^{-1})	−0.110	−0.057	**−0.941**	−0.056
Ca (mg kg^{-1})	**0.919**	−0.070	0.165	0.225
Mg (mg kg^{-1})	**0.690**	0.543	0.172	−0.101
Na (mg kg^{-1})	0.052	**0.829**	0.0531	−0.160
K (mg kg^{-1})	0.194	0.072	0.154	**0.766**
P (mg kg^{-1})	0.131	0.009	0.009	**0.719**
Effective cation exchange capacity (cmol$_c$ kg^{-1})	**0.944**	0.042	0.151	0.212
Acid saturation (%)	−0.126	−0.172	**−0.916**	−0.146
Eigenvalue	5.302	2.072	1.632	1.426
Total variance (%)	40.8	15.9	12.6	10.7
Cumulative variance (%)	40.8	56.7	69.3	80.2

Table 3.3. ANOVA F statistics and *P*-values for the fixed effects in the mixed models of soil of depths (0 – 5, 5 – 15, and 15 – 30 cm), region (Swartland vs. southern Cape), annual rainfall, soil texture, and years since previous liming. ECEC = Effective cation exchange capacity.

Factor	**Factor 1**		**Factor 2**		**Factor 3**		**Factor 4**	
Variables	Ca, Mg, ECEC		Electrical Resistance, Conductivity, Na		pH$_{KCl}$, Exchangeable Acidity, Acid Saturation		K, P	
	F	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Depth	14.25	< 0.001	16.21	< 0.001	12.06	< 0.001	306.59	< 0.001
Region	18.85	< 0.001	0.01	0.938	12.62	0.001	8.24	0.004
Rainfall	3.32	0.001	0.39	0.924	6.33	< 0.001	3.43	0.001
Texture	2.37	0.070	12.84	< 0.001	1.71	0.166	0.57	0.636
Years since liming	0.92	0.500	0.73	0.667	0.98	0.451	1.69	0.103

Table 3.4. Percentage of soil samples per texture class.

Texture	Percentage of Samples		
	All Samples	Southern Cape	Swartland
Sandy loam	89.13	92.55	85.20
Sand	9.04	7.45	10.86
Sandy clay loam	1.68	0	3.62
Clay	0.15	0	0.32

The mean pH_{KCl} of all three soil depths in the southern Cape was suitable to produce wheat, barley, and canola. A slight pH_{KCl} stratification was observed between the three soil depths of the soils sampled in the southern Cape, with the highest pH_{KCl} in the region being 7.9 and the lowest being 4.8 (Table 3.1). The mean pH_{KCl} of all three of the respective soil depths in the southern Cape were also optimal for wheat, barley, and canola production.

The trend observed for exchangeable acidity was as expected, when compared to the trend of pH_{KCl} over increasing depth. In both regions the 5 – 15 cm depth increment had higher ($p \leq 0.05$) amounts of exchangeable acidity than the 0 – 5 and 15 – 30 cm depth increments (Tables 3.1 and 3.3). It is as expected that the depth increment with the lowest pH_{KCl} also has the highest amount of exchangeable acidity. The mean exchangeable acidity in the 5 – 15 and 15 – 30 cm depth increments in the Swartland was more than double the amount in the same depth increments of the southern Cape. The maximum values of exchangeable acidity in the Swartland were higher in all three depth increments than the corresponding values of the southern Cape region. The difference in exchangeable acidity between the two regions may be ascribed to the higher ($p \leq 0.05$) amounts of Ca in the southern Cape soils than the Swartland soils (Tables 3.1 and 3.3). This corresponds to findings that showed that increases ($p \leq 0.05$) in the Ca content of soils correspond with decreases in the exchangeable acidity, specifically the Al component (Whitten et al., 2000). The relationship between high concentrations of Ca and lower amounts of exchangeable acidity in the soil may help to identify soils in other regions that are similarly managed, that may develop exchangeable acidity problems over time. This could especially be the case if the soils naturally contain low concentrations of Ca.

A clear difference ($p \leq 0.05$) in acid saturation for both regions was observed (Tables 3.1 and 3.3). The acid saturation for all three depths in the Swartland were higher ($p \leq 0.050$) than the corresponding depths in the southern Cape (Table 3.3). The mean acid-saturation percentages of both the 5 – 15 and the 15 – 30 cm depths in the Swartland were over three times the values of the corresponding depths in the southern Cape (Table 3.1). The mean value for the 5 – 15 cm soil depth in the Swartland was also above the 8% threshold given by (Dang et al., 2015), which is unfavourable for wheat production. The maximum acid saturation for all three depths of the Swartland soils were higher than the corresponding values in the southern Cape. The maximum acid saturation for all three depths in the Swartland were also above the 8% threshold value given for wheat. Furthermore, barley and canola are less tolerant to soil acidity than wheat, and therefore these acid saturation values in the Swartland may be even more restricting to these crops than to wheat (Foy, 1996; DAFF, 2016; DAFF, 2016b).

The mean Ca concentrations in the Swartland soils (Table 3.1) were low for crop production in the top 0 – 15 cm of the soil profile and very low at the 15 – 30 cm depth when compared to the relative concentrations for crop production (Table 3.5). Furthermore, the minimum and maximum Ca concentrations reported in these soils were very low and very high respectively for crop production. The mean Mg concentration throughout the 0 – 30 cm of the soil profile in the Swartland soils were suitable for crop production. The minimum Mg concentrations ranged from low (0 – 5 cm depth) to very low (5 – 15 cm and 15 – 30 cm depth), while the maximum Mg concentrations reported were relatively high throughout the 0 – 30 cm.

The mean Ca concentration in the 0 – 15 cm soil depth in the southern Cape soils was suitable for crop production in general (Table 3.5). However, the minimum Ca concentrations reported for the southern Cape soils were too low for crop production whilst the maximum concentrations ranged from high (15 – 30 cm depth) to very high (0 – 5 and 5 – 15 cm depth). The mean Mg concentrations in the southern Cape soils were suitable for crop production throughout the soil profile (0 – 30 cm). The minimum Mg concentrations were low at all three depth intervals and the maximum concentrations were high (0 – 5 and 5 – 15 cm depth) to very high (15 – 30 cm depth).

Both Ca and Mg are important macronutrients for plant growth and development, however different crops have varying requirements. Canola, for example, has twice the demand for Ca than wheat (Norton, 2013). Furthermore, well-structured soils generally have more than twice as much Ca than Mg (Botta, 2015). Both Ca and Mg play an important role in soil aggregate stability (Magdoff, 1993) and Ca helps maintain a nutrient balance within the soil (Parnes, 2013). Furthermore, Ca is essential for maintaining the structural integrity and expansion of cell walls and lipid membranes (Schlecht et al., 2006). Calcium plays an important role in osmoregulation and internal signaling within the plant cells. Magnesium on the other hand forms part of the chlorophyll molecule and is thus essential in the photosynthetic processes within plants (Magdoff, 1993). Magnesium also plays a role in the metabolism and movement of sugar in plants, which is essential for their growth and development.

Table 3.5. Ca (mg kg^{-1}) and Mg (mg kg^{-1}) concentrations in the soil for crop production (Hazelton and Murphy, 2007).

	Ca (mg kg^{-1})	**Mg (mg kg^{-1})**
Very low	< 400	< 36
Low	400 – 1000	36 – 120
Moderate	1000 – 2000	120 – 360
High	2000 – 4000	360 – 960
Very high	> 4000	> 960

The availability of nutrients such as Ca and Mg to plants is influenced by the soil pH. As the soil pH decreases, the H^+ and Al^{3+} that become more soluble under these pH conditions displace basic cations such as Ca and Mg from the cation exchange sites on the soil particles, leading to the basic cations being leached down the soil profile where they are not available for plant uptake (Kunhikrishnan, 2016).

The mean Ca concentration of the southern Cape soils was higher ($p \leq 0.05$) for all three depth increments than the Ca concentrations of the Swartland soils, with the mean concentration in the 15 – 30 cm depth increment being nearly three times that of the Swartland soils (Tables 3.1 and 3.3). The higher ($p \leq 0.05$) Ca concentrations reported in the southern Cape soil compared to the Swartland soils could be attributed to the soil parent material of the southern Cape being of a more calcareous nature (White and Holland, 2018). Soils with a higher pH_{KCl} are expected to generally have a greater Ca concentration (Norton, 2013), which could also explain the higher ($p \leq 0.05$) Ca concentration in the southern Cape soils compared to the Swartland soils, which had a lower mean pH_{KCl} (Table 3.1). Although the criteria for sampling a field in the survey included no lime applications in the last year prior to sampling, relatively recent lime applications (one to three years before sampling) could potentially explain the high Ca concentrations reported in the maximum values of both the Swartland and southern Cape Ca concentrations (Espinoza et al., 2006). It was however found that there was no relationship ($p > 0.05$) between Ca and Mg concentrations in the soil and the number of years since the previous lime application was done (Table 3.3). The mean Mg concentrations did not show the same trend as Ca. The Swartland soils had higher ($p \leq 0.05$) concentrations of Mg in the 0 – 5 cm depth increment and the southern Cape soils had higher concentrations in the 5 – 15 as well as the 15 – 30 cm depth increment (Table 3.3). The addition of dolomitic lime on soils already high in Mg concentration could explain the high Mg concentrations reported in the maximum values of both regions' soils. Sandy textured soils with a low ECEC are more vulnerable to low Ca and Mg concentrations due to greater risk of being leached down the soil profile and could form part of the soils that were reported as having minimum Ca and Mg concentrations in both regions (Magdoff, 1993). It was found that texture did not influence ($p \geq 0.05$) Ca and Mg concentrations in the soils (Table 3.3). As stated earlier, this result may be due to the disproportionate number of samples being in the same texture class and therefore an inaccurate correlation between soil texture and Ca and Mg concentrations could have been obtained (Table 3.4).

It was found that rainfall only influenced ($p \leq 0.05$) Factor 1 (concentrations of both Ca and Mg as well as the CEC of soils) as such that increased rainfall was associated with increased loadings of Factor 1 (results not shown). Although higher annual rainfall could result in leaching of Ca and Mg, higher rainfall can be associated with a higher CEC of soils as a result of a higher content of soil organic matter (Magdoff, 1993; Schlecht, 2006). Rainfall did not influence ($p > 0.05$) Factor 3, which is linked to soil acidity aspects.

3.3.1 Subset data from fields with $pH_{KCl} \leq 5.0$ at any depth increment

Of the total number of samples taken at all three depths across the survey, 19.3% of the samples from the Swartland had a $pH_{KCl} \leq 5.0$ and 6.2% ≤ 4.5 (Figure 3.3, Table 3.6). For the soils where at least one depth increment had a $pH_{KCl} \leq 5.0$, the 5 – 15 cm depth had a pH_{KCl} that was lower ($p \leq 0.05$) than the 0 – 5 depth increment (Figure 3.3) and the exchangeable acidity (Table 3.7) was higher ($p \leq 0.05$) than that of the 0 – 5 cm depth increment (Table 3.3). The pH_{KCl} and acidity of the 0 – 5 and the 15 – 30 cm depth increments were more similar than the 0 –5 and 5 – 15 cm depth increments. The change in pH_{KCl} from the 0 – 5 to the 5 – 15 cm depth increment is severe enough for the rooting depth to become limited, due to the 5 – 15 cm depth increment being below the threshold pH_{KCl} values for most crops (FERTASA, 2016).

Table 3.6. Percentage of samples per depth for each region with $pH_{KCl} \leq 5.0$.

Depth (cm)	Southern Cape (%)	Swartland (%)
0 – 5	0.00	11.11
5 – 15	1.74	29.25
15 – 30	0.87	17.00
Total	0.86	19.30

Figure 3.3 showed that for the soils where at least one of the depth increments had $pH_{KCl} \leq 5.0$, there was a decrease ($p \leq 0.05$) in pH_{KCl} from the 0 – 5 to the 5 – 15 cm depth increment. The 15 – 30 cm depth increment did not, however, differ ($p \leq 0.05$) from the 0 – 5 cm depth increment. Soil

pH_{KCl} of below 5.0 is a growth limitation for barley, wheat, and canola (FERTASA, 2016). The stratification shown in Figure 3.3 indicates that the change in soil pH_{KCl} is severe enough in these soils to possibly become a growth limitation to barley, wheat, and canola. The acid soil layer in a soil profile becomes a limitation for plant growth, ultimately decreasing the effective rooting depth. A decrease in the effective depth that roots can grow in a soil profile could impact crop production. In the study by (Hirzel and Matus, 2013), it was reported that grain yield, plant height, and number of stems per meter of wheat were affected by the depth of the soil profile. In this study, grain yield was up to 37% higher in deep soils compared to shallow soils. Furthermore, there are various reports (Busscher et al., 2001; McDonald, 2006; Christopher et al., 2008; Whitmore and Whalley, 2009) stating that increases in effective soil depth for root growth improved the productivity and yield of maize (*Zea mays* L.), wheat, and barley. The positive effect of soil depth on crop productivity could be attributed to the increased ability of roots to take up nutrients and water at greater soil depths (Richards, 2008). Whereas in shallow root systems, nutrients such as N can leach beyond the shallow root zone and be lost from the system (Thorup-Kristensen, 2006). The concentrations of Ca and Mg in the 0 – 5 cm depth increment were higher ($p \leq 0.05$) than in both the 5 – 15 and 15 – 30 cm depth increments (Table 3.7). Stratification of nutrients such as Ca and Mg with increasing soil depth can be expected in long-term no-tillage soils (Dang et al., 2015; Ismail et al., 1994; Rahman et al., 2008).

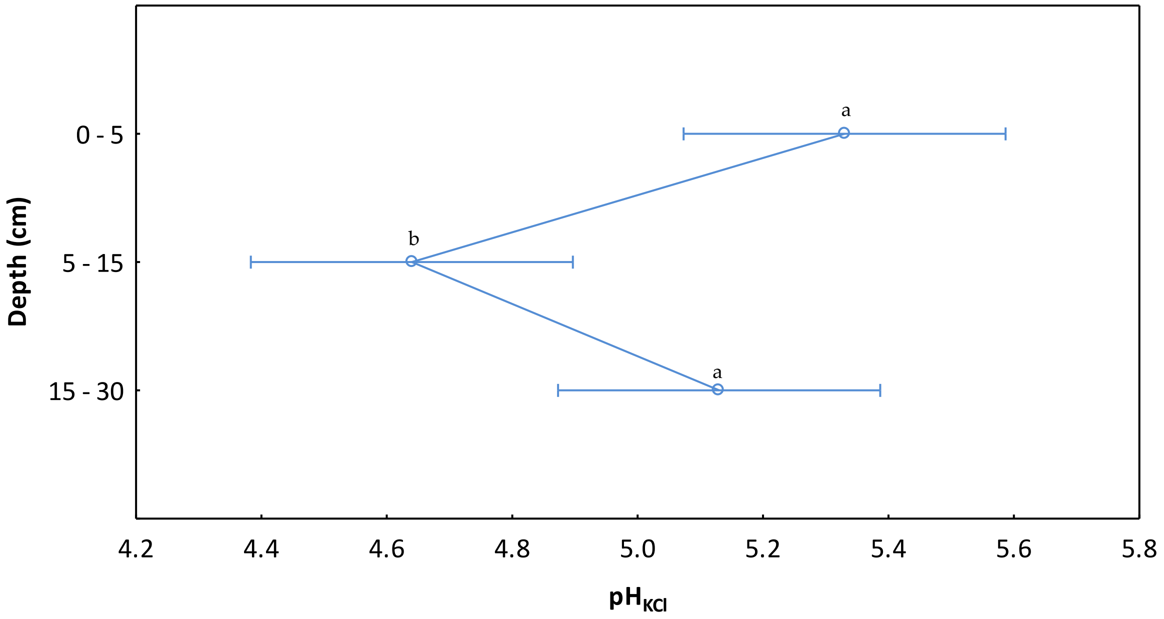

Figure 3.3. Stratification of pH_{KCl} between 0 – 5, 5 – 15, and 15 – 30 cm soil depth of soils with at least one depth increment with $pH_{KCl} \leq 5.0$. No common superscript letter indicates a significant ($p \leq 0.05$) difference.

Table 3.7. F-and *p* values of pH_{KCl}, Ca (mg kg^{-1}), Mg (mg kg^{-1}), exchangeable acidity (cmolc kg^{-1}), and acid saturation (%).

	F Value	*p* Value
pH_{KCl}	7.76	< 0.001
Ca (mg kg^{-1})	13.58	< 0.001
Mg (mg kg^{-1})	6.88	< 0.001
Exchangeable acidity (cmolc kg^{-1})	3.59	0.040
Acid saturation (%)	6.13	0.040

Figures 3.4 and 3.5 indicate that the base status of the topsoil (0 – 5 cm) is higher ($p \leq 0.05$) than that of the deeper depth (5 – 15 and 15 – 30 cm) increments (Table 3.8). Figures 3.4 and 3.5 indicate that the exchangeable acidity component of the effective cation exchange capacity (ECEC) of the 5 – 15 cm depth increment is much higher than the acidity component of the above or below depth increments. These trends in base status and exchangeable acidity correspond with Table 3.1, which indicates that the pH_{KCl} of the 5 – 15 cm depth increment was the lowest of the three sampling depths, since low pH_{KCl} corresponds with high levels of exchangeable acidity.

Table 3.8. Mean values of various soil measurements for the three depth increments. No common superscript letter indicates a significant ($p \leq 0.05$) difference.

Soil Depth (cm)	Exchangeable Ca (mg kg^{-1})	Exchangeable Mg (mg kg^{-1})	Exchangeable Acidity (cmol kg^{-1})
0 – 5	1039^{a}	188^{a}	0.68^{ab}
5 – 15	535^{b}	103^{b}	0.95^{a}
15 – 30	417^{b}	149^{b}	0.56^{b}

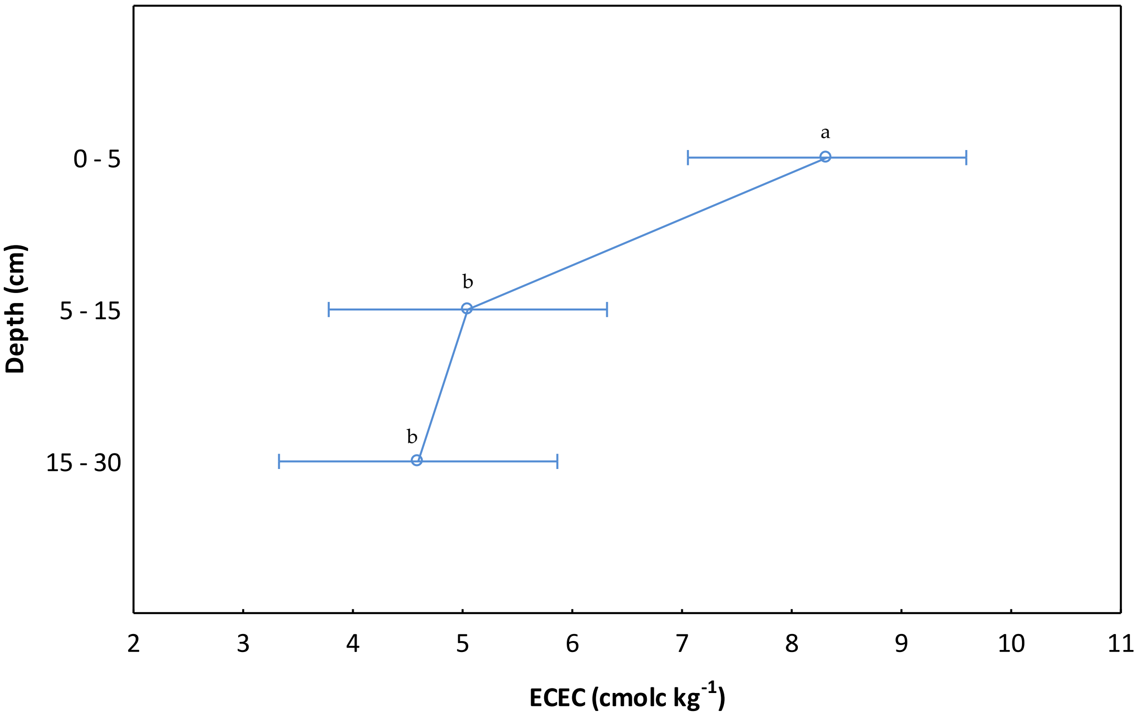

Figure 3.4. ECEC between 0 – 5, 5 – 15, and 15 – 30 cm soil depths of soils where at least one depth increment had pH_{KCl} ≤ 5.0. ECEC = Effective cation exchange capacity. No common superscript letter indicates a significant ($p \leq 0.05$) difference.

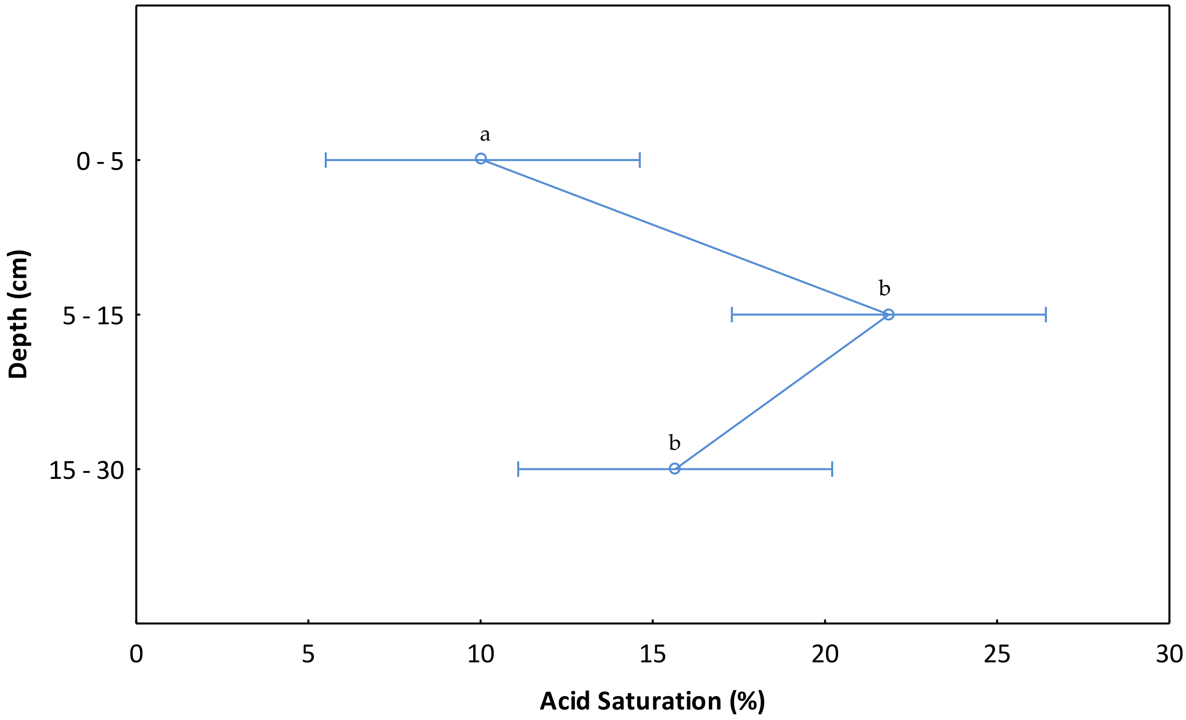

Figure 3.5. Stratification of acid saturation between 0 – 5, 5 – 15, and 15 – 30 cm soil depths of soils where at least one depth increment had pH_{KCl} ≤ 5.0. No common superscript letter indicates a significant ($p \leq 0.05$) difference.

3.3.2. Canola Leaf Nutrient Content

Table 3.9 shows that of the 15 fields included in the survey where canola was cultivated, the leaf samples averaged above both the Canadian, South African, and USA threshold values for all the nutrients measured (FERTASA, 2016; Canola Council of Canada, 2017; Campbell, 2000) Some individual samples did, however, contain suboptimal amounts of B, even though the mean value is above the threshold values of the Canadian and USA standards, whilst also being within the range for the South African standard. It is standard practice for farmers who cultivate canola to apply leaf sprays in the growing season to apply B. The results from the leaf analyses that were done for this survey support this practice that farmers are already implementing.

Table 3.9. Sample means of analysed canola leaf nutrients in comparison with the Canadian, USA, and South African (RSA) threshold values for each nutrient. *n* = 15; standard deviation is indicated in parenthesis.

	N (%)	**P (%)**	**S (%)**	**Ca (%)**	**Mg (%)**	**K (%)**	**Fe (mg kg^{-1})**	**Cu (mg kg^{-1})**	**Mn (mg kg^{-1})**	**Zn (mg kg^{-1})**	**B (mg kg^{-1})**
Sample mean	**5.46 (0.62)**	**0.53 (0.11)**	**0.83 (0.10)**	**4.28 (1.24)**	**0.86 (0.38)**	**4.10 (2.10)**	**250.99 (185.28)**	**6.76 (5.55)**	**74.02 (27.94)**	**33.45 (6.58)**	**30.28 (12.71)**
Canadian threshold	2.40	0.24	0.24	0.49	0.19	1.40	19.00	2.60	14.00	14.00	29.00
USA threshold	3.60	0.37	0.47	1.60	0.10	2.15	82.00	4.00	20.00	28.00	20.00
RSA threshold	3.50	0.3 – 0.6	0.50	1.4 – 3.0	0.2 – 0.6	2.20	50 – 300	3 – 5	30 – 200	20.00	20 – 50

3.3.3. Recommendations

Incorporating a one-off strategic tillage every few years in which surface-broadcast lime is incorporated into the soil profile could be a possible solution to the pH_{KCl} stratification (with an acid subsoil) that occurs in these long-term no-tillage soils. One-off strategic tillage in no-tillage systems has been found to be effective in alleviating nutrient stratification in the soil (Kettler et al., 2000; Quincke et al., 2007). One-off tillage can thus be considered to redistribute the higher Ca and Mg concentrations that occur near the soil surface in both the Swartland and southern Cape soils. Furthermore, research done by (Quincke et al., 2007b, Baan et al., 2009; Crawford et al., 2015; Leygonie, 2016; Liu et al., 2016; Van Zyl, 2017; Dang et al., 2018; Conyers et al., 2019) has shown that conducting a one-off tillage in soils that have been under no-tillage has no significant negative impact on soil physical and chemical attributes or on grain yield. It was reported by (Whitten et al., 2000; Caires et al., 2006; Caires et al., 2011; Tiritan et al., 2016) that incorporating lime into the soil (at varying depths, methods, and rates) was successful in alleviating subsoil acidity.

The relatively low Ca concentrations of the soils sampled in both the Swartland and southern Cape regions could be addressed through the addition of soil amendments such as gypsum [$Ca(SO_4)$] or lime (Norton, 2013). The application of gypsum can be considered on the soils with a suitable pH_{KCl} for crop production but a low concentration of Ca. Gypsum which constitutes of about 22% Ca will allow for an increase in the Ca concentration of the soil without increasing the soil pH_{KCl} (due to its lack of carbonates), however it is more commonly used on sodic soils.

In the case of an acid soil, the addition of lime can be used to rectify soil acidity whilst addressing low Ca concentrations in the soil. Furthermore, in acid soils where the Mg concentration is low, as in the case of the minimum values reported for the Mg concentrations of both the Swartland and southern Cape soils, the application of dolomitic lime may be considered. The addition of dolomitic lime will enable soil acidity to be addressed as well as increasing the Ca and Mg concentrations in the soil.

3.4. Conclusions

Although the mean pH_{KCl} across the entire surveyed area (Swartland and southern Cape) was of little concern in terms of crop production, a relatively large portion (19.3%) of soils (specifically in the Swartland) had at least one depth increment with $pH_{KCl} \leq 5.0$, which is below the optimal values for barley, wheat, and canola production. Furthermore, a change ($p \leq 0.05$) in soil acidity was observed over increasing depth, indicating stratification of acidity. It was also found that soil depth, annual rainfall of the region as well as the region itself, had an influence ($p \leq 0.05$) on Ca, Mg, pH, exchangeable acidity, and the acid saturation of the soil. The mean acid saturation in the 5 – 15 cm depth increment in the Swartland was above the 8% threshold value for wheat production. Due to barley and canola being less tolerant to soil acidity than wheat, however, these acid-saturation values may be more restricting to the production of these crops.

Of the fields that contained at least one depth increment with pH ≤ 5, higher amounts ($p \leq 0.05$) of acidity were found in the 5 – 15 cm depth increment, where lime evidently was not able to neutralise acidity in no-tillage systems. Therefore, crop yield is expected to be negatively affected by acid soil conditions on 19.3% of Swartland soils. The significant stratification of soil acidity and Ca and Mg observed between soil layers needs to be addressed. Strategic one-off tillage may address the stratification of both soil acidity and nutrients, such as Ca and Mg, and could therefore be considered as a viable option to incorporate into the management of no-tillage production systems.

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CHAPTER 4

DETERMINING THE EFFECT OF FORM, FINENESS AND PLACEMENT OF LIME, WITH AND WITHOUT SOIL DISTURBANCE ON SOIL CHEMICAL ATTRIBUTES

4.1 Introduction

Ground agricultural limestone (lime) is very immobile in soil. In some cases, lime can take a year or longer to move only about five centimetres down the soil profile (Caires et al., 2005; Miller, 2015). In conventional agriculture, the poor mobility of lime is overcome by incorporating the lime into the soil via tillage action after surface broadcasting of the lime. Tillage thereby assists the vertical distribution of lime in the soil profile. With the introduction of conservation agriculture, of which minimum soil disturbance (i.e. no-tillage) is one of the principles, lime is no longer incorporated into the soil. The immobile nature of lime in no-tillage soils may thus lead to a soil profile with a vertically stratified pH consisting of an alkaline topsoil and an acid subsoil where the lime was not able to react (Flower and Crabtree, 2011; Barth et al., 2018). The acidic subsoil becomes a growth limitation for crops. The high concentrations of soluble Al in acidic soils causes Al toxicity in plants and leads to root stunting (Krstic et al., 2012). The severity of pH stratification will increase over time, especially for farmers who have been practising no-tillage over the long-term. More than 80% of grain farmers in the Western Cape Province of South Africa have implemented no-tillage (Smith et al., 2017). These farmers are thus likely to be faced with the challenge of pH stratification to some degree of severity depending on factors such as the period of no-tillage. There is therefore motivation to investigate strategies that allow for more effective liming in no-tillage systems to address pH stratification.

There are various characteristics of lime that might influence vertical movement of lime in soil, namely, its fineness, form and purity. A finer lime (with a greater surface area for reaction) may be more mobile in the soil due to its ability to react faster with acidity (Beegle, 2001). A faster reaction between the lime and the soil acidity will allow the alkaline front to continue moving deeper in the soil profile (Whitten et al., 2001; Li et al., 2019). In South Africa, conventional Class A lime should consist of particles smaller than 1.7 mm and 50% smaller than 0.25 mm in accordance with Act 36 of 1947. Fine lime would generally be considered to consist of 90% of the particles smaller than 0.25 mm and 80% smaller than 0.106 mm (FERTASA, 2019). Due to the practical implications of applying fine lime, such as non-uniform application or significant losses during windy conditions, the application of fine lime in a pelletised form has been proposed as a strategy to overcome these challenges.

During planting with a no-tillage seed-drill, seeds and fertiliser are channelled from tanks to furrow-openers that place seed and fertiliser in the row. Lime in a pelletised form provides the option of being placed in-row together with the fertiliser. In-row placement of lime would not be possible in the powder form of conventional agricultural lime as this would lead to the blockage of the pipes that carry the lime from the fertiliser tanks. In-row placement will automatically place the lime in a deeper position (5 - 8 cm) in the soil, depending on the working depth of the openers used to place fertiliser (and lime) in the row.

Lime purity could also influence its movement in the soil. The purity of lime is expressed as its calcium carbonate equivalent (CCE), which is a measure that compares the ability of a lime to neutralise acidity relative to that of pure calcium carbonate (100% CCE). Lime with a greater purity (i.e. a higher CCE) should thus have a greater capacity to neutralise acidity. The effective neutralisation of the soil acidity will therefore allow the continuation of lime movement deeper down the soil profile.

Previous research has shown that implementing a one-off strategic-tillage operation in no-tillage systems every few years has no effect on soil quality or yield of grain crops (Leygonie, 2016; Van Zyl, 2017; Conyers et al., 2019). The fact that a one-off tillage does not negatively affect crop production therefore allows the option of making use of strategic tillage to incorporate lime into the soil profile in order to assist its movement to deeper layers. Furthermore, different tillage actions will incorporate the lime in different manners. The difference in working depth and degree of soil inversion between different implements will influence the distribution of the lime in the soil. Implements differing in working depth and degree to which it inverts the soil should therefore be compared to determine which action would assist the movement of lime in the soil the greatest.

The aim of this study was to determine how form, fineness and purity of lime affect its movement in the soil with or without different soil disturbance actions.

4.2 Materials and Methods

4.2.1 Description of trial site

A trial was conducted over the 2019 (Year 1) and 2020 (Year 2) growing seasons on a farm approximately eight kilometers southeast of the town of Caledon in the southern Cape region of South Africa (34°17'33.162"S 19°31'28.133"E; 358 m) (Figure 4.1). The trial site was selected according to its management history (under no-tillage for at least seven years and did not received lime the previous year) as well as the soil pH (a soil profile with clear pH stratification between the top and subsoil layers, with a subsoil pH_{KCl} of below 5.0). The soil profile on the trial site was shallow and had a sandy loam texture.

Figure 4.1. A map of the Western Cape, indicating the location of the trial site near the town of Caledon.

4.2.2 Climate

The long-term average annual rainfall at the trial site is 545 mm. The long-term average monthly rainfall and temperature compared to the average monthly temperature and rainfall of 2019 and 2020 is shown in Figure 4.2.

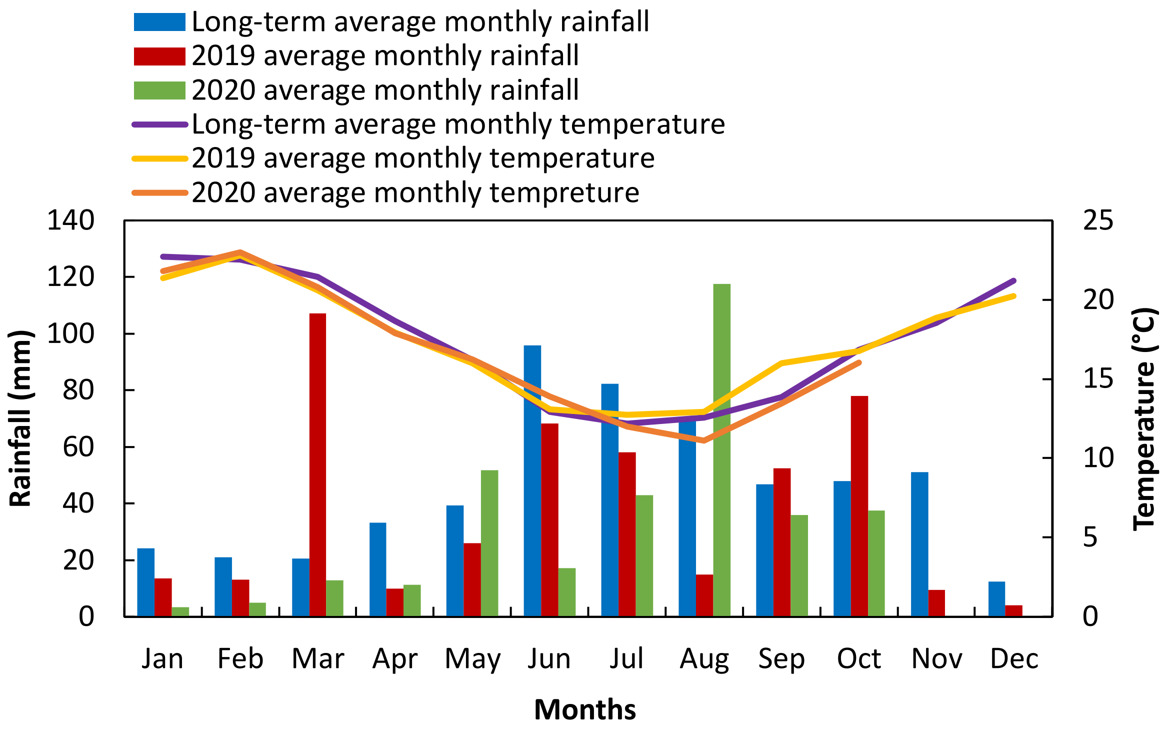

Figure 4.2. The average monthly rainfall and temperature of 2019 and 2020 and the long-term average monthly rainfall and temperature of the trial site area.

4.2.3 Experimental design and treatments

The trial was laid out in a randomised block design consisting of ten treatments (Table 4.1) repeated in four blocks. The treatments were conducted on 4.5 x 20 m plots with 2 m buffer zones between plots. The treatments differed in terms of the form, fineness and purity of the lime (APPENDIX C) as well as the type or lack of soil disturbance and placement of the lime relative to the soil surface. Barley (cv. Hessekwa) was established in Year 1 using a seed-drill with tine openers (Equalizer tine planter) over all the treatments at a 300 mm row spacing.

Table 4.1. Description of the trial treatments, the application or placement method of the lime as well as the form, purity and rate at which lime was applied in each treatment.

	Treatment description	Application or placement method	Lime form	Lime purity	Lime rate (kg ha^{-1})
1	**Control**	-	-	-	-
2	**95% CCE calcitic lime**	Broadcast	Class A	95% CCE	1000
3	**88% CCE calcitic lime**	Broadcast	Class A	88% CCE	1000
4	**Disc plough**	Broadcast followed by incorporation with a disc plough (10 – 15 cm deep with soil inversion)	Class A	88% CCE	1000
5	**Chisel plough**	Broadcast followed by incorporation with a chisel plough (20 – 25 cm deep with no soil inversion)	Class A	88% CCE	1000
6	**Ripper**	Broadcast followed by incorporation with a ripper (30 cm deep with no soil inversion)	Class A	88% CCE	1000
7	**Pelletised lime placed in-row (no broadcasting)**	In-row placement during crop establishment	Micro-fine Pelletised	93% CCE	40
8	**Pelletised lime broadcast at 960 kg ha^{-1} and in-row placement**	Broadcast followed by in-row placement during crop establishment	Micro-fine Pelletised	93% CCE	Broadcast: 960 In-row: 40
9	**Pelletised lime broadcast at 770 kg ha^{-1} and in-row placement**	Broadcast followed by in-row placement during crop establishment	Micro-fine Pelletised	93% CCE	Broadcast: 770 In-row: 40
10	**Pelletised lime broadcast (no pellets placed in-row)**	Broadcast followed by crop establishment	Micro-fine Pelletised	93% CCE	1000

In general, the fertiliser tank on a seed-drill in which the lime pellets are mixed has limited space, and thus a limited rate of only 40 kg ha^{-1} was applied for in-row lime placement. The treatment with 960 kg ha^{-1} pellets broadcasted was done therefore to make up the remaining lime requirement in order to achieve 1000 kg ha^{-1}, whereas the 770 kg ha^{-1} broadcast pellets was to test whether less lime [19% less than the recommended rate (Jones and Mallarino, 2018)] can be applied when making use of pelletised micro-fine lime as frequently suggested by the industry. Micro-fine lime pellets bound with a molasses binding agent was used. The micro-fine (90% < 53 um) lime used in the pellets was made from a different lime source (93% CCE) than the two Class A limes (95 and 88% CCE) used in the trial. The 95% Class A lime was only surface broadcast, while the 88% CCE Class A was surface broadcast, and mixed in with various ploughs (Table 4.1).

The trial replicated the incorporation of crop rotations in a production system, in which canola (a broad-leaf crop) is a fitting crop to be planted after barley. Therefore, in Year 2 canola (cv. Diamond) was planted directly over the field trial site, repeating none of the liming or soil disturbance treatments.

4.2.4 Crop management

Representative soil samples comprising of five sub-samples were taken at 0 - 5, 5 - 15 and 15 - 30 cm depths in each plot in the form of soil cores (4 cm diameter) in order to determine soil pH and fertility status for lime and fertiliser recommendations. An average lime requirement of 1000 kg ha^{-1} was determined in 2019 using the Modified Eksteen method (Eksteen, 1969), which aims at raising the pH to a depth of 15 cm (in this case to a target pH_{KCl} of 5.5) making use of the information acquired from the soil sample analyses. All the lime (conventional lime and pelletised lime) broadcasting was done by hand and took place before planting on 29 April 2019. The soil disturbance treatments were done on 29 - 30 April 2019. Crop establishment (barley) took place on 15 May 2019.

During barley planting 16 kg ha^{-1} N, 16 kg ha^{-1} P and 4 kg ha^{-1} S was applied and 60 kg ha^{-1} N and 8 kg ha^{-1} S was top-dressed four weeks after emergence on 24 June 2019. Herbicides in the form of a selective broadleaf herbicide (Buctril MPCA) as well as a Metribuzin herbicide was sprayed during the course of the growing season for weed control using a sprayer attached to a quadbike.

In Year 2 canola was planted directly over the field trial site in May 2020 and plots were then marked out and paths between plots established using GPS markers taken at the end of the previous season. The canola was established with a seed-drill with tine openers with a 270 mm row spacing. The trial site was fertilised with 71 kg ha^{-1} N, 5 kg ha^{-1} P and 12 kg ha^{-1} K prior to planting. At planting 9 kg ha^{-1} N, 12 kg ha^{-1} P and 3 kg ha^{-1} K was applied in-row and a top-dress consisting of 50 kg ha^{-1} N, 5 kg ha^{-1} P, 15 kg ha^{-1} K and 12 kg ha^{-1} S was applied 90 days after planting.

Weeds were controlled with Clethodim for the control of annual grasses as well as a foliar fungicide containing Prothioconazole and Tebuconazole. Boron foliar spray was also applied during the course of the season.

4.2.5 Data collection

The effect of treatments on the soil chemical attributes in both years was monitored by means of soil tests. Composite soil samples were taken on three different occasions during the first season, namely before planting, 90 days after crop emergence (3 months after liming) and after crop harvest (6 months after liming) and then once during the second season (1 year after liming). Each composite soil sample in every plot comprised of five sub-samples per depth and were taken in the form of soil cores (4 cm diameter) at 0 - 5, 5 - 15 and 15 - 30 cm depths. In the row and between row soil samples (5 sub-samples per depth for both in-row and between the row) were taken for all treatments where lime was placed in-row during crop establishment and analysed separately.

The following soil chemical attributes were analysed using the methods prescribed by the Non-affiliated Soil Analysis Work Committee (1990): Exchangeable cations (K, Ca, Mg, Na), Extractable P, Soil pH_{KCl}, exchangeable acidity and electrical resistance.

4.2.6 Statistical analysis

Linear mixed models were used to test for treatment effects, incorporating the restricted maximum likelihood (REML) procedure and type III decomposition. The fixed models contained treatment and depth, as well as their interaction or treatment and sampling date, as well as their interaction. The random model contained three terms, namely block, block x treatment and block sampling date/depth. The random model therefore compensates for repeated measures or equicorrelation between sampling depths. Residuals were normally distributed and had homogenous variances. Post-hoc tests were conducted to determine differences between treatments at a 5% level of significance. Calcium was the only parameter that showed pre-treatment effects between plots due for lime/tillage treatments and therefore an Analysis of Covariance (ANCOVA) was conducted to eliminate the pre-treatment effects. STATISTICA software version 13 was used to conduct the statistical analyses (TIBCO, 2018).

4.3 Results

Treatment effects on the 0 – 5 cm soil layer over time

A treatment effect ($p \leq 0.05$) was observed over time for all the chemical attributes measured at the 0 – 5 cm depth (Table 4.2). Treatments generally resulted in an increase in pH_{KCl}, although it did not always differ ($p > 0.05$) from the pre-treatment pH_{KCl} (Figure 4.3). The control treatment did not have an effect ($p > 0.05$) on pH_{KCl}. There was also no difference in pH_{KCl} between the treatments one year after liming. The mean change in pH_{KCl} across all treatments at the 0 – 5 cm depth was 0.43 (Figure 4.4).

The treatment where pelletised lime was only placed in-row at a rate of 40 kg ha^{-1}, with no additional surface broadcasting, did however result in the smallest ($p \leq 0.05$) change in pH_{KCl} (Figure 4.4) at the 0 – 5 cm depth (together with the control) and did not reach the target pH_{KCl} of 5.5 a year after liming (Figure 4.3). Surface broadcasting pelletised lime (with no in-row placement) at the recommended lime rate (1000 kg ha^{-1}) showed the greatest ($p \leq 0.05$) as well as the quickest ($p \leq 0.05$) increase (three months after liming) in soil pH_{KCl} at the 0 - 5 cm depth (Figure 4.3 and 4.4).

Furthermore, the effect of placing pelletised lime in-row led to a higher ($p \leq 0.05$) pH_{KCl} at the 0 – 5 cm depth in the rows than between the rows (Figure 4.5). The pH_{KCl} was 1.3 units higher ($p \leq 0.05$) in-row than between rows.

The treatments varied in their effect on exchangeable acidity and acid saturation. The 95% CCE calcitic lime showed a decrease ($p \leq 0.05$) in both the exchangeable acidity and the acid saturation one year after liming (Figure 4.6 and 4.7). The 88% CCE calcitic lime did not decrease ($p > 0.05$) the exchangeable acidity or the acid saturation at the 0 – 5 cm depth one year after liming (Figure 4.6 and 4.7). In the treatments in which surface broadcast Class A lime was incorporated with a disc plough, chisel plough or a ripper, the exchangeable acidity and acid saturation in the 0 – 5 cm depth remained similar ($p > 0.05$) to the pre-treatment exchangeable acidity and acid saturation one year after liming.

Table 4.2. The mixed model results for soil chemical attributes measured at the 0 – 5 cm depth in response to liming treatments and time.

Factor	**Depth (cm)**	**pH_{KCl}**		**Exchangeable acidity (cmolc kg^{-1})**		**Acid saturation (%)**		**Ca* (mg kg^{-1})**		**ECEC (cmolc kg^{-1})**	
		F	**p**	**F**	**p**	**F**	**p**	**F**	**p**	**F**	**p**
Date	**0 - 5**	17.35	< 0.001	13.84	0.001	9.28	0.004	17.79	< 0.001	8.30	0.006
Treatment	**0 - 5**	2.89	0.016	2.94	0.014	2.65	0.024	5.31	< 0.001	2.96	0.014
Date*Treatment	**0 - 5**	3.92	< 0.001	2.15	0.005	2.24	0.003	1.79	0.018	1.88	0.016

*Analysis of covariance (ANCOVA) was only performed on parameters when pre-treatment effects were significant ($p \leq 0.05$). The covariate for the 0 – 5 cm layer, F = 11.80 and p = 0.002.

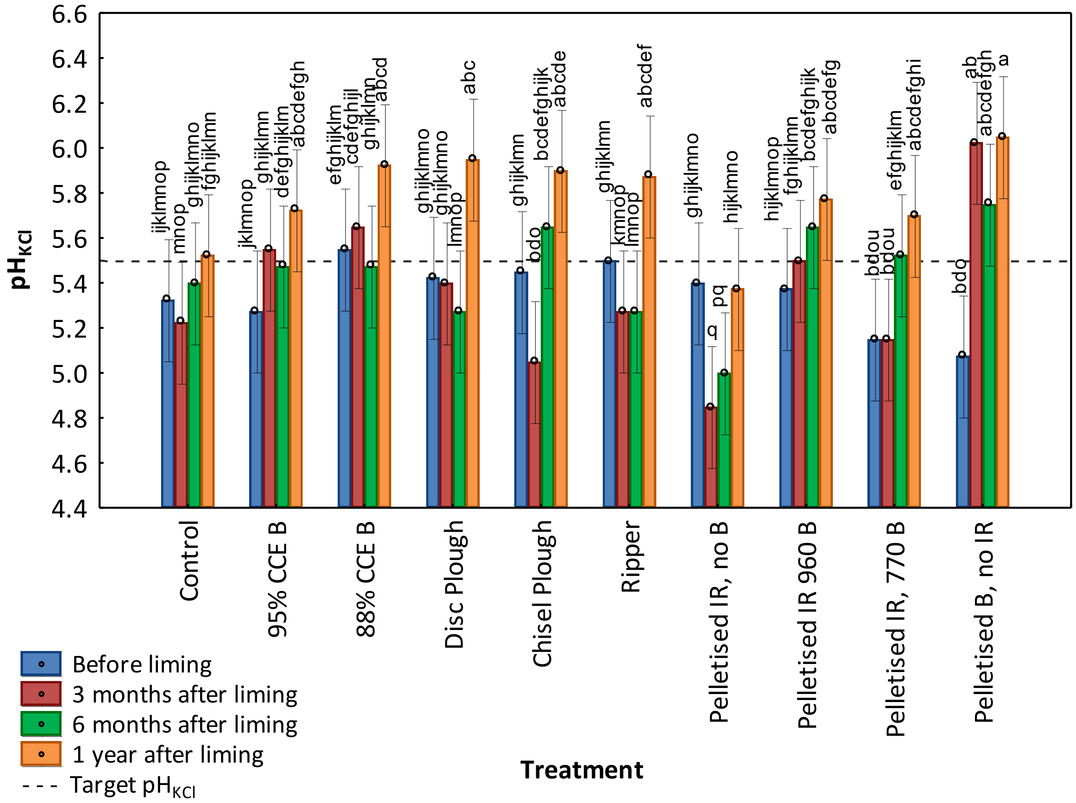

Figure 4.3. The pH$_{KCl}$ and target pH$_{KCl}$ of all the treatments at the 0 – 5 cm depth measured over the duration of the trial. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

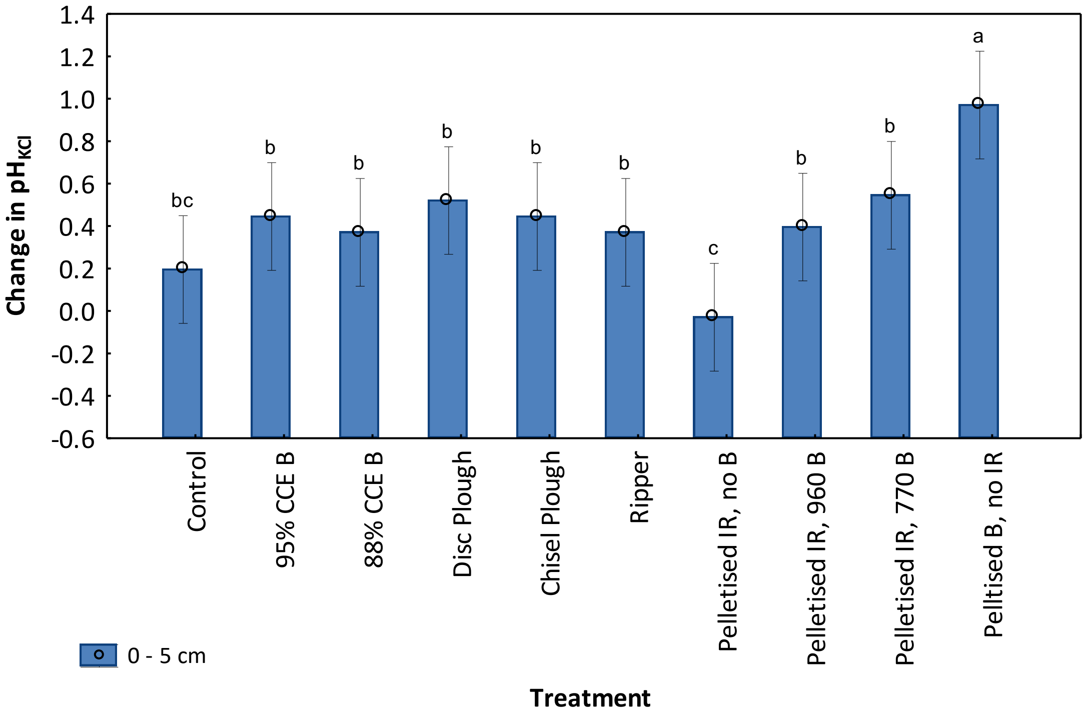

Figure 4.4. The change in pH$_{KCl}$ over time (one year) between treatments at 0 – 5 depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

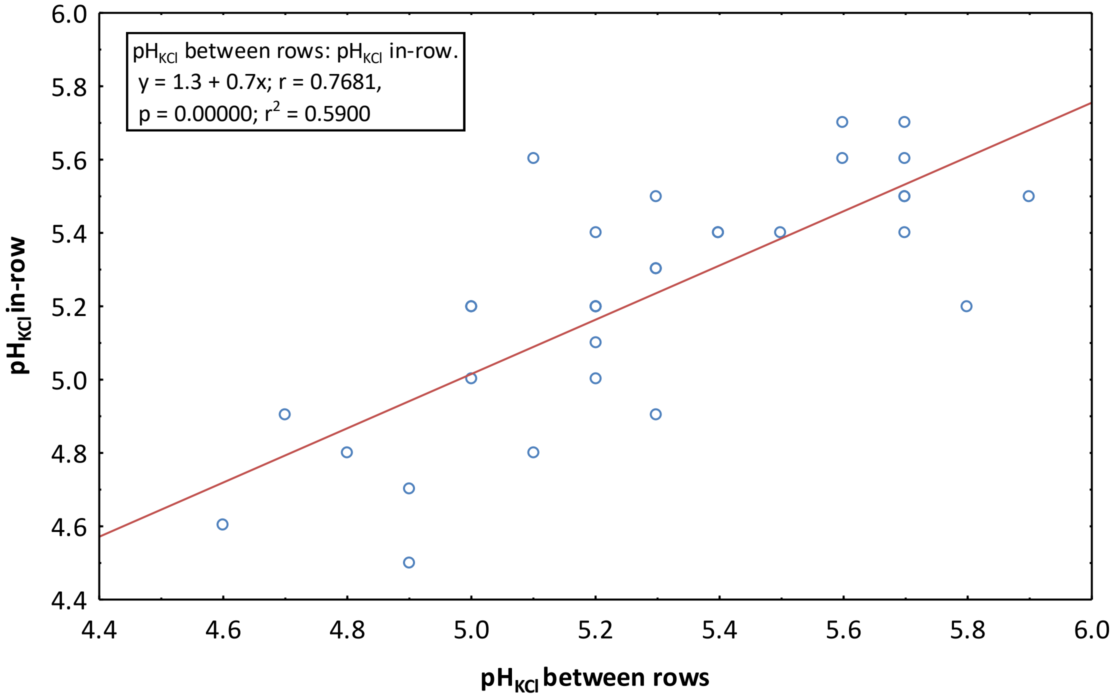

Figure 4.5. The pH$_{KCl}$ in the row and between rows at the 0 – 5 cm depth of all the treatments that placed pelletised lime in-row.

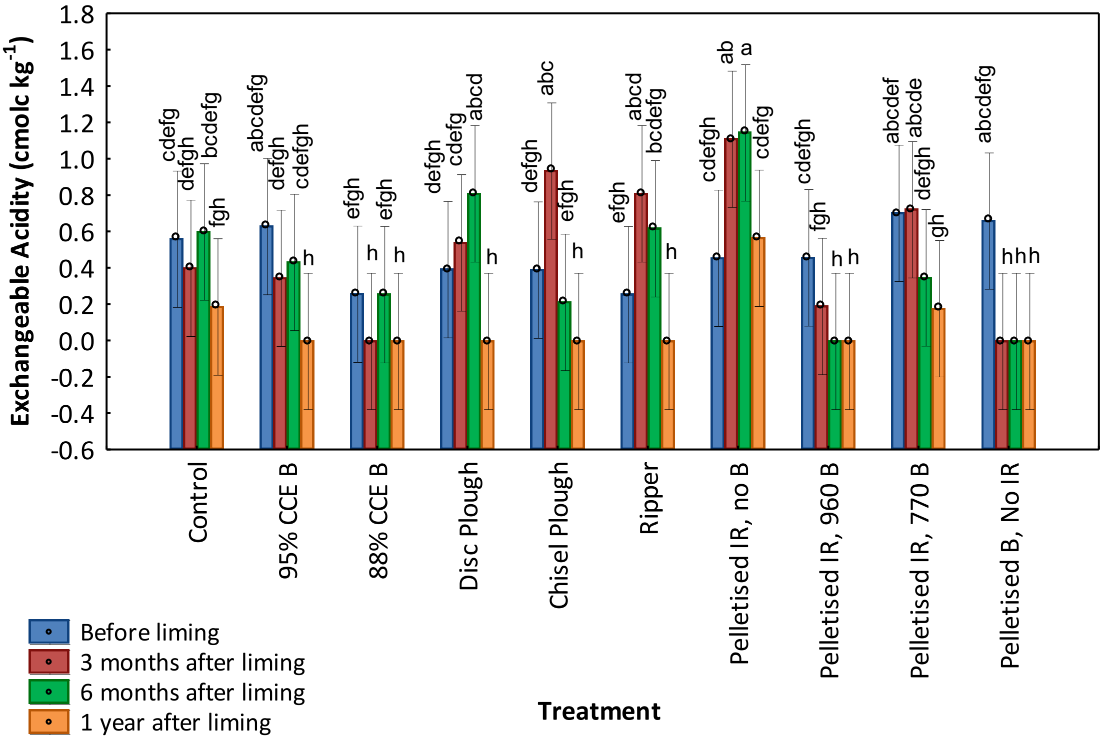

Figure 4.6. The exchangeable acidity (cmolc kg^{-1}) of all the treatments at the 0 – 5 cm depth measured over the duration of the trial. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

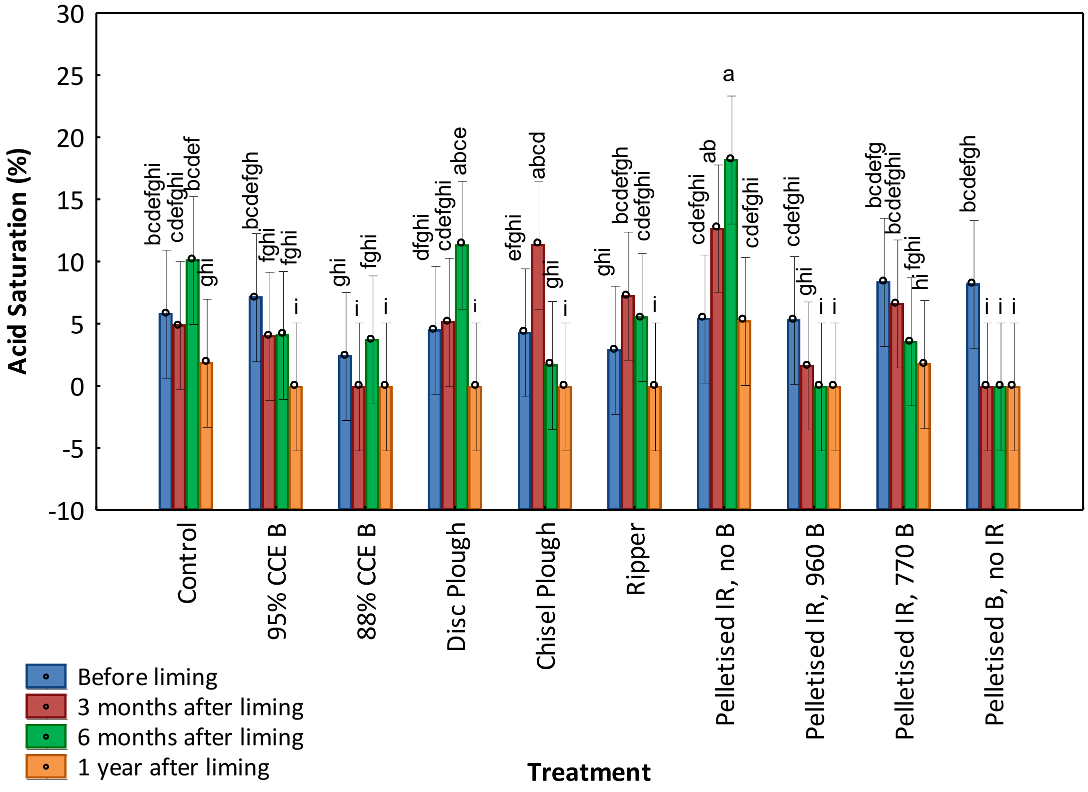

Figure 4.7. The acid saturation (%) of all the treatments at the 0 – 5 cm depth measured over the duration of the trial. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

All three tillage treatments led to an increase ($p \leq 0.05$) in exchangeable acidity 3 to 6 months after lime application and the disc and chisel plough also first showed an increase ($p \leq 0.05$) in acid saturation in the 0 – 5 cm depth (Figure 4.6 and 4.7). All three tillage treatments did eventually however end with no exchangeable acidity and acid saturation, respectively.

Both the treatment that only placed pellets in-row (40 kg ha^{-1}) and the treatment that broadcast pellets at 960 kg ha^{-1} with in-row placement also did not differ ($p > 0.05$) to the pre-treatment exchangeable acidity and acid saturation one year after liming. The treatment where 770 kg ha^{-1} pellets was broadcast with in-row placement decreased ($p \leq 0.05$) exchangeable acidity and acid saturation one year after liming. The treatment where pellets were surface broadcast at the recommended rate lead to the quickest ($p \leq 0.05$) decrease in both exchangeable acidity and acid saturation compared to all the other treatments (Figure 4.6 and 4.7).

The treatments in which 95% and 88% CCE Class A lime were broadcast, the disc plough and ripper treatment as well as the treatment in which lime pellets were broadcast (at the recommended rate) increased ($p \leq 0.05$) the Ca concentration at the 0 – 5 cm depth one year after liming (Figure 4.8). The 95% and 88% CCE broadcast lime treatment as well as the pelletised micro-fine lime broadcast at the recommended rate ended with the highest ($p \le 0.05$) Ca and change in Ca concentration one year after liming at the 0 – 5 cm depth (Figure 4.8 and 4.9). There was no difference ($p > 0.05$) in Ca concentration one year after liming for the treatment that only placed lime pellets in-row (at 40 kg ha^{-1}), broadcast pellets at 960 kg ha^{-1} and 770 kg ha^{-1} with in-row placement and the treatment where lime was incorporated with a chisel plough (Figure 4.8).

Lime incorporated with a chisel plough, lime pellets only placed in-row (at 40 kg ha^{-1}) as well as lime pellets place in-row and broadcast at 960 and 770 kg ha^{-1} had a similar ($p > 0.05$) ECEC at the 0 – 5 cm depth one year after liming (Figure 4.10). The rest of the treatments increased ($p \le 0.05$) the ECEC at the 0 – 5 cm depth. The 95% and 88% CCE broadcast lime treatment and the pelletised lime broadcast at the recommended rate ended with the highest ($p \le 0.05$) ECEC at the 0 – 5 cm depth (Figure 4.10).

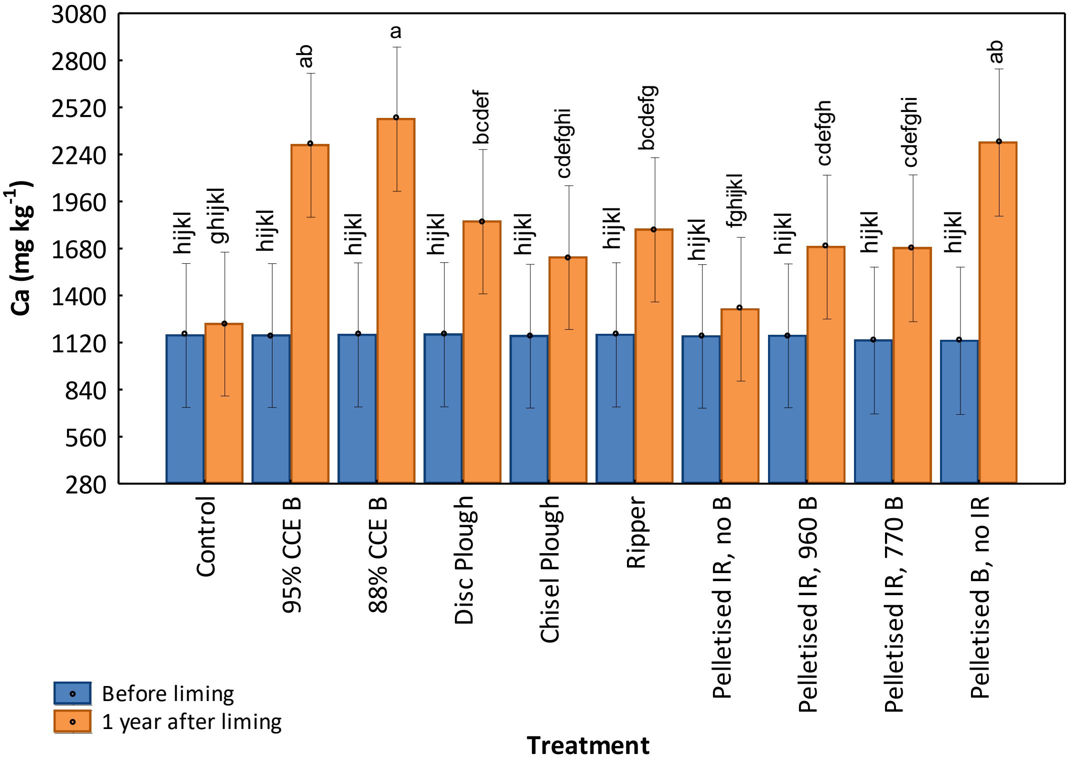

Figure 4.8. The Ca (mg kg^{-1}) concentration for all the treatments at the 0 – 5 cm depth before and one year after liming. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

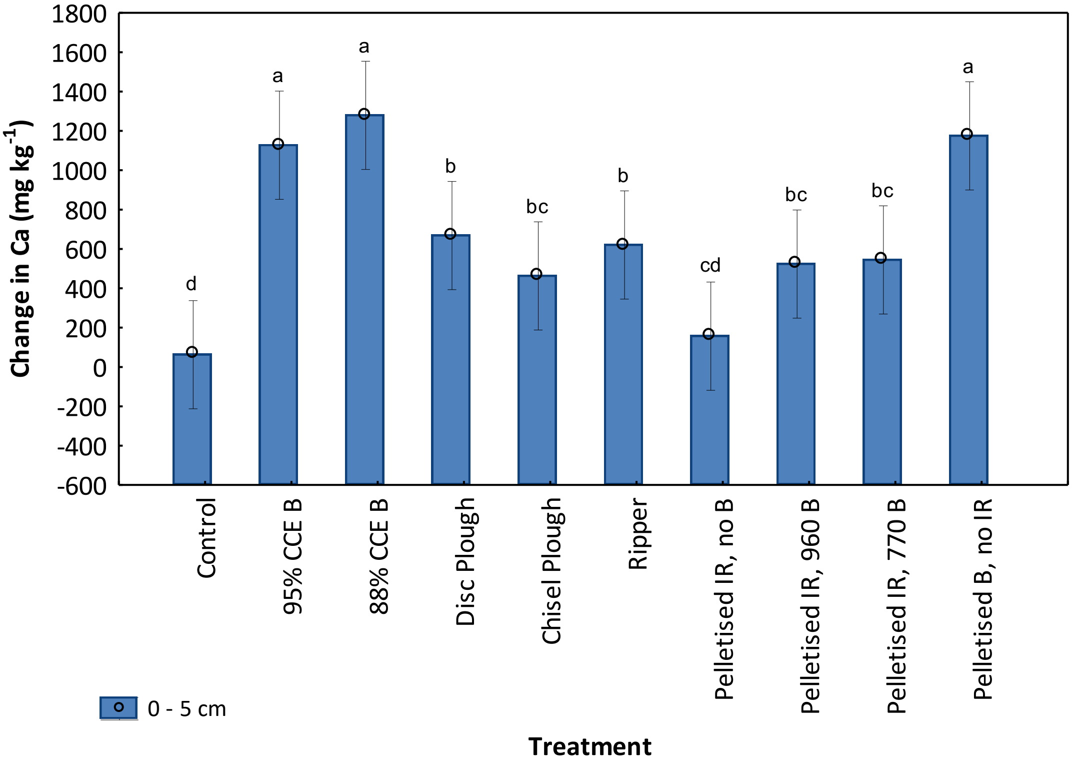

Figure 4.9. The change in Ca (mg kg^{-1}) over time (one year) between treatments at 0 – 5 depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

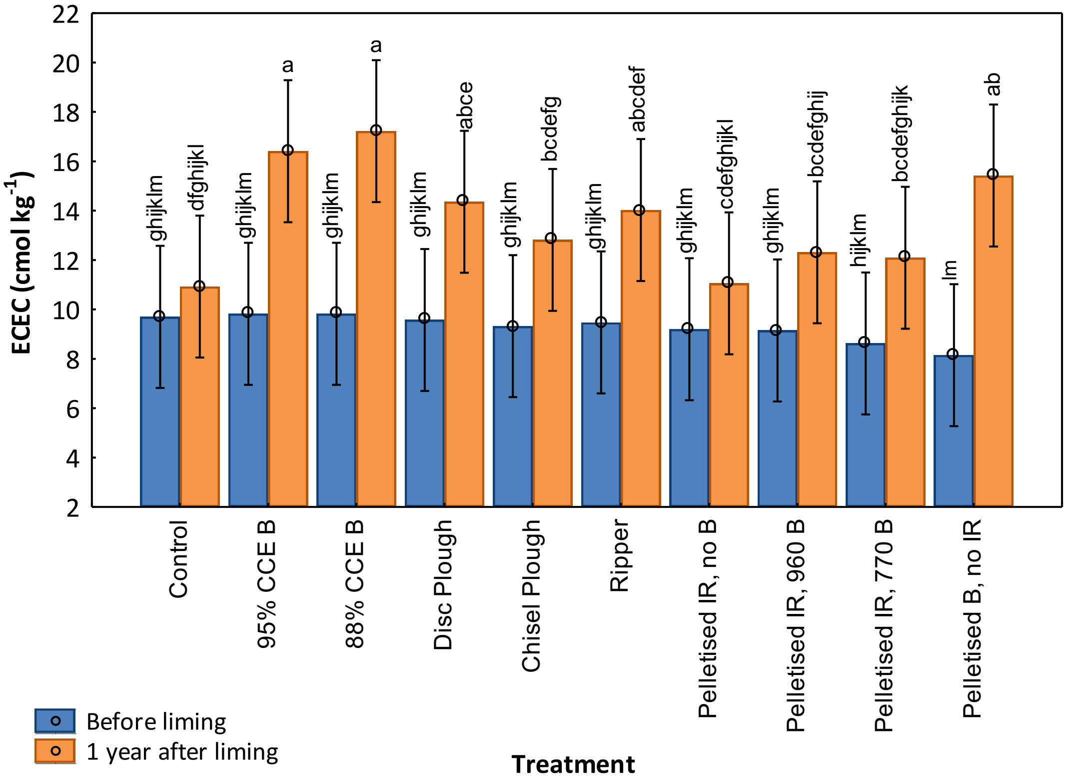

Figure 4.10. The ECEC (cmol kg^{-1}) for all the treatments at the 0 – 5 cm depth before and one year after liming. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

Treatment effects on the 5 – 15 and 15 – 30 cm soil layers over time

There was no difference ($p > 0.05$) between the treatments for all the chemical attributes measured at the 5 – 15 and 15 – 30 cm depth over the duration of the trial (Table 4.3). The chemical attributes measured did however differ ($p \leq 0.05$) over time within each treatment.

All treatments increased ($p \leq 0.05$) the pH_{KCl} at both the 5 – 15 and 15 – 30 cm one year after liming (Figure 4.11 and 4.12). There was no difference in the change in pH_{KCl} between treatments at these depths and the mean change in pH_{KCl} at the 5 – 15 and 15 – 30 cm depth was 0.36 and 0.40 respectively (Figure 4.13). Although the soil varied at the trial site in terms of the starting pH_{KCl} at each depth increment, none of the treatments were able to reach the target pH_{KCl} at the 5 – 15 cm depth one year after liming.

The treatment in which pelletised micro-fine lime was broadcast at the recommended rate did however lead to the quickest ($p \leq 0.05$) increase (three months after liming) in pH_{KCl} at the 5 – 15 cm depth (Figure 4.11). The treatment in which pelletised micro-fine lime was broadcast at the recommended along with 95% CCE lime broadcast and lime incorporated with a disc plough rate lead to the quickest ($p \leq 0.05$) increase (three months after liming) in pH at the 15 – 30 cm depth (Figure 4.12).

Furthermore, all pelletised micro-fine lime placed in-row once again lead to a higher ($p \leq 0.05$) pH_{KCl} in the row than between the rows at both the 5 – 15 and 15 – 30 cm depths (Figure 4.14 and 4.15). The pH_{KCl} was 0.5 and 2.3 units higher ($p \leq 0.05$) in the rows at the 5 – 15 and 15 – 30 cm depths respectively.

Table 4.3. The mixed model results for soil chemical attributes measured at the 5 – 15 and 15 – 30 cm depth in response to liming treatments and time.

Factor	Depth (cm)	pH$_{KCl}$		Exchangeable acidity (cmolc kg^{-1})		Acid saturation (%)		Ca* (mg kg^{-1})		ECEC (cmolc kg^{-1})	
		F	**p**	**F**	**p**	**F**	**p**	**F**	**p**	**F**	**p**
Date	**5 - 15**	33.68	< 0.001	18.46	< 0.001	8.74	0.005	25.86	< 0.001	14.39	0.001
	15 - 30	37.68	< 0.001	24.01	< 0.001	27.60	< 0.001	14.12	< 0.001	7.87	0.007
Treatment	**5 – 15**	1.29	0.289	0.79	0.627	1.46	0.213	0.99	0.453	2.12	0.063
	15 - 30	0.75	0.665	0.99	0.472	1.09	0.404	0.99	0.452	2.08	0.068
Date*Treatment	**5 – 15**	1.06	0.401	0.80	0.741	0.76	0.789	0.58	0.947	0.70	0.852
	15 - 30	1.05	0.418	1.14	0.321	1.25	0.224	1.21	0.243	1.00	0.474

*Analysis of covariance (ANCOVA) was performed on Ca as pre-treatment effects were significant ($p \leq 0.05$). The covariate for the 5 – 15 cm layer, $F = 17.95$ and $p < 0.001$ and for the 15 – 30 cm layer, $F = 11.95$ and $p = 0.010$.

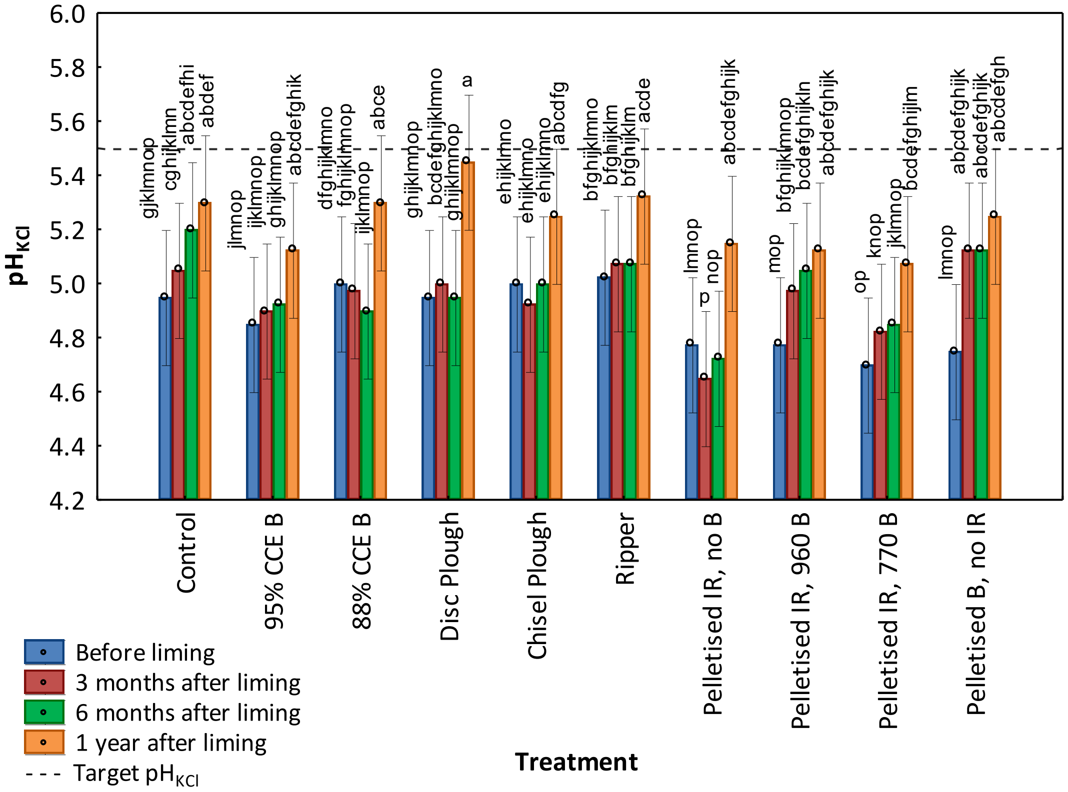

Figure 4.11. The pH$_{KCl}$ and target pH$_{KCl}$ of the treatments over time at the 5 – 15 cm depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

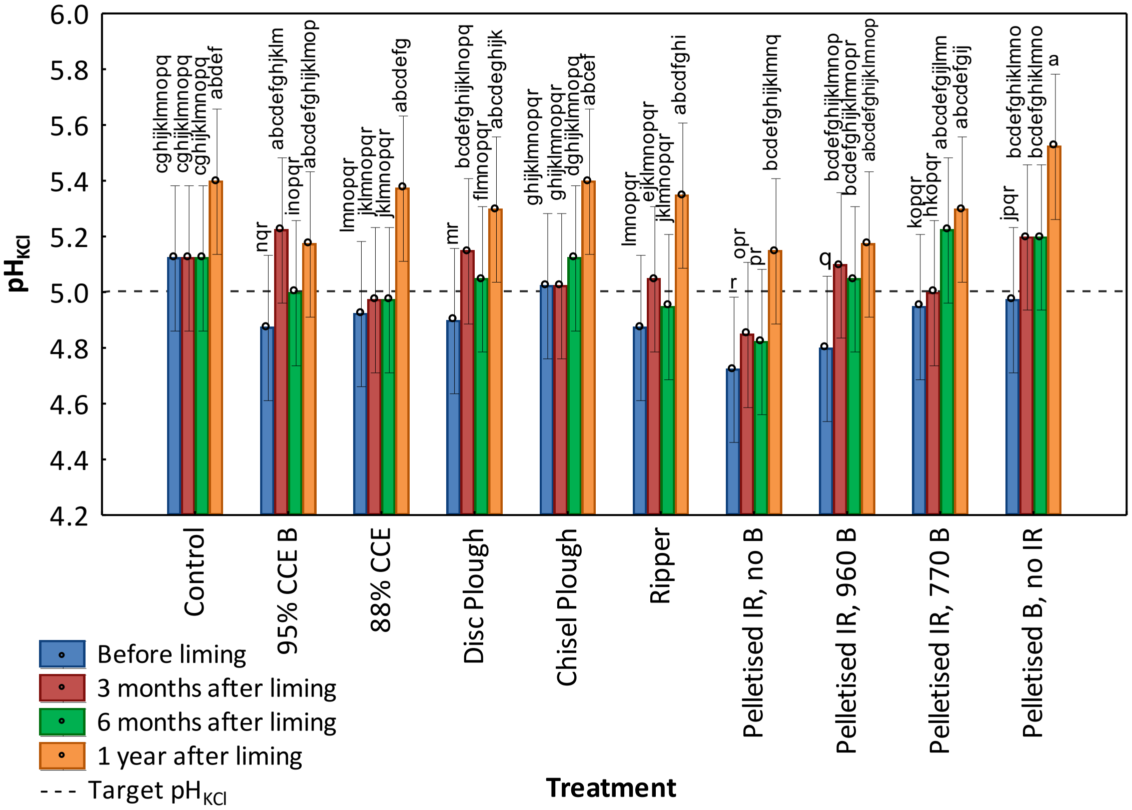

Figure 4.12. The pH$_{KCl}$ and target pH$_{KCl}$ of the treatments over time at the 15 - 30 cm depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

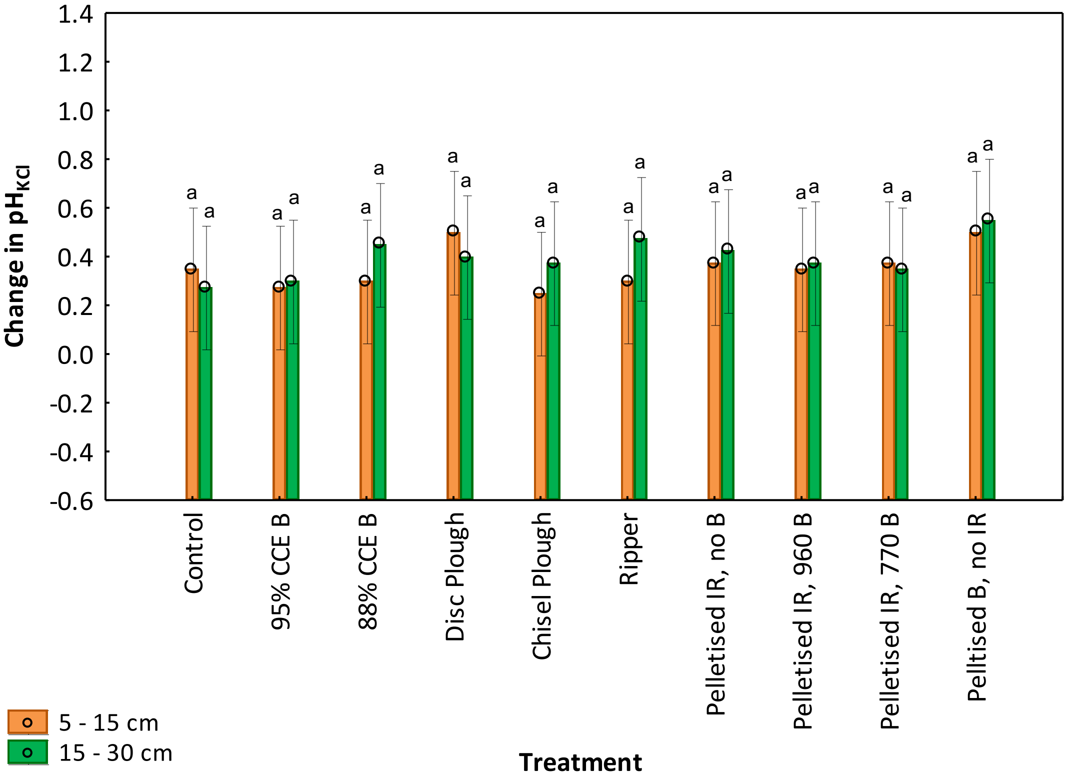

Figure 4.13. The change in pH_{KCl} over time (one year) between treatments at the 5 - 15 and 15 – 30 cm depths. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

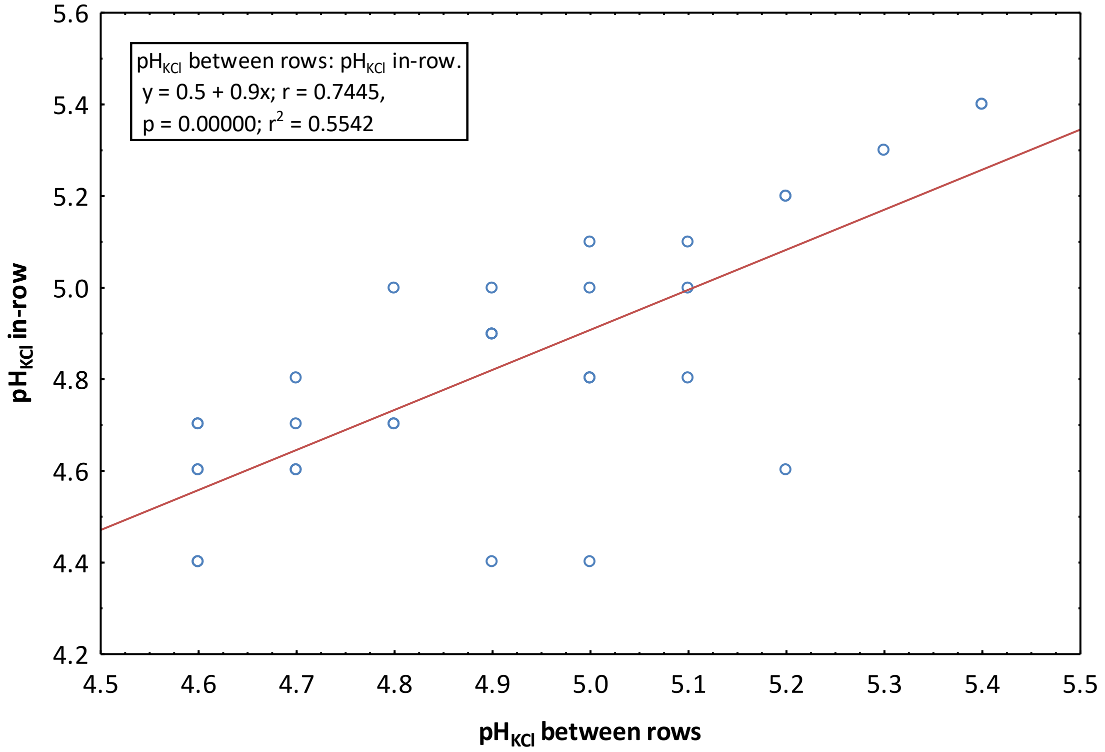

Figure 4.14. The pH_{KCl} in the row and between rows at the 5 - 15 cm depth of all the treatments that placed pelletised lime in-row.

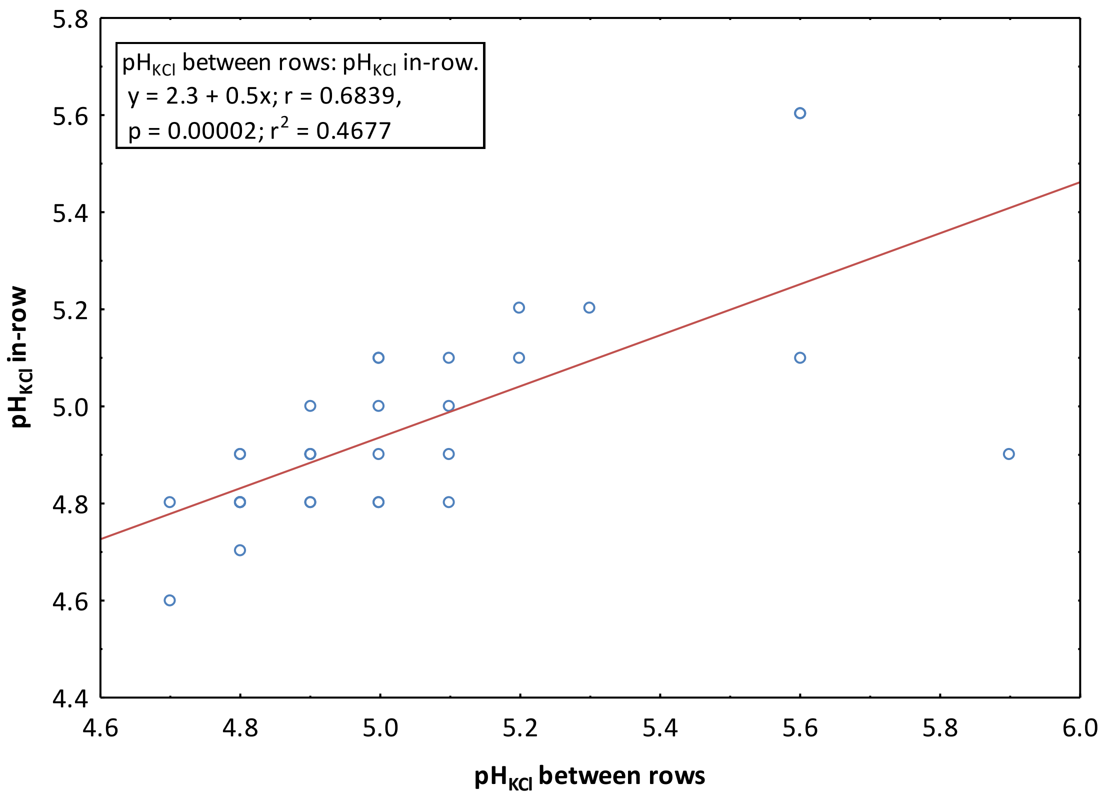

Figure 4.15. The pH_{KCl} in the row and between rows at the 5 - 15 cm depth of all the treatments that placed pelletised lime in-row.

All the treatments ended with a similar ($p > 0.05$) concentration of exchangeable acidity to the pre-treatment exchangeable acidity at both the 5 - 15 and 15 - 30 cm depths (Figure 4.16 and 4.17).

The acid saturation for each treatment was also similar ($p > 0.05$) one year after liming at both the 5 - 15 and 15 - 30 cm depths (Figure 4.18 and 4.19) except for the treatment in which pelletised micro-fine lime was surface broadcast at the recommended lime rate at the 15 - 30 cm depth (Figure 4.19). Broadcast pelletised lime at the recommended rate had a lower ($p \leq 0.05$) acid saturation at the 15 – 30 cm depth one year after liming (Figure 4.19).

The change in Ca concentration over time was variable in the different treatments at both the 5 – 15 and 15 – 30 cm depths. At the 5 – 15 cm depth, the Ca concentration either increased ($p \leq 0.05$) or remained the same ($p > 0.05$) one year after liming (Figure 4.20). The treatments where surface broadcast Class A lime was incorporated with a chisel plough, pelletised lime placed in-row and broadcast at 770 kg ha^{-1}, and pelletised lime broadcast at the recommended rate increased ($p \leq 0.05$) the Ca concentration at the 15 – 30 cm depth (Figure 4.21).

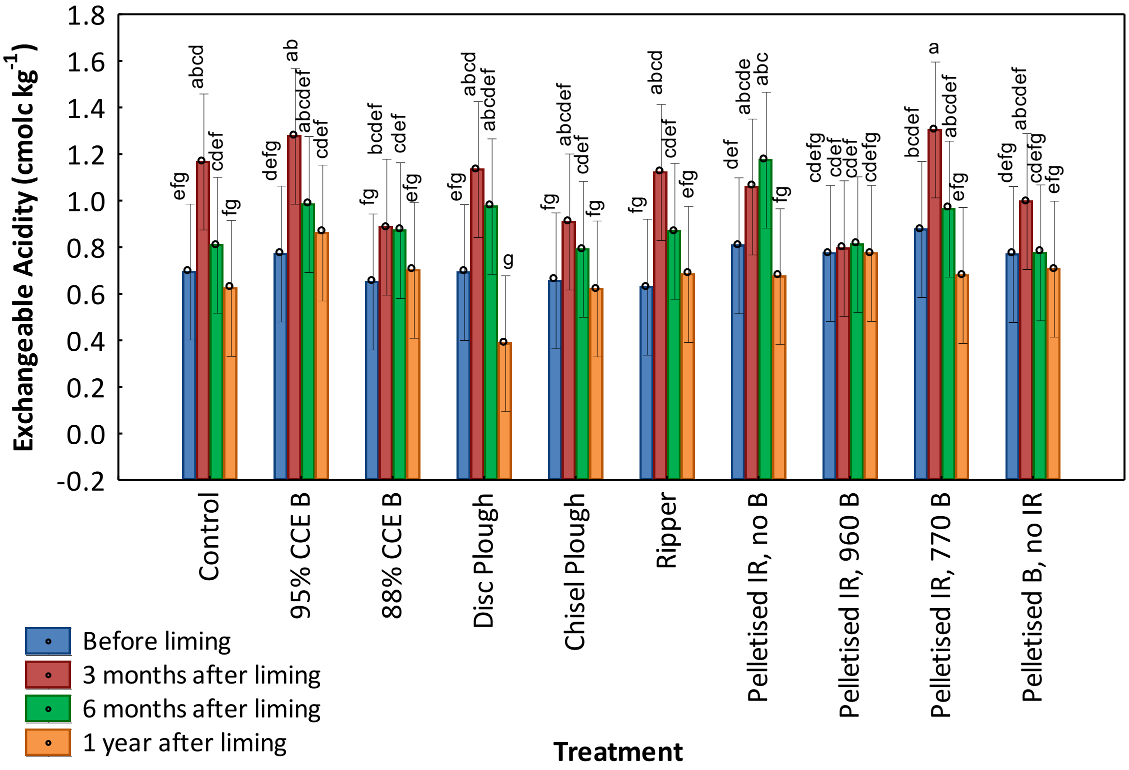

Figure 4.16. The exchangeable acidity (cmolc kg^{-1}) of the treatments over time at the 5 – 15 cm depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

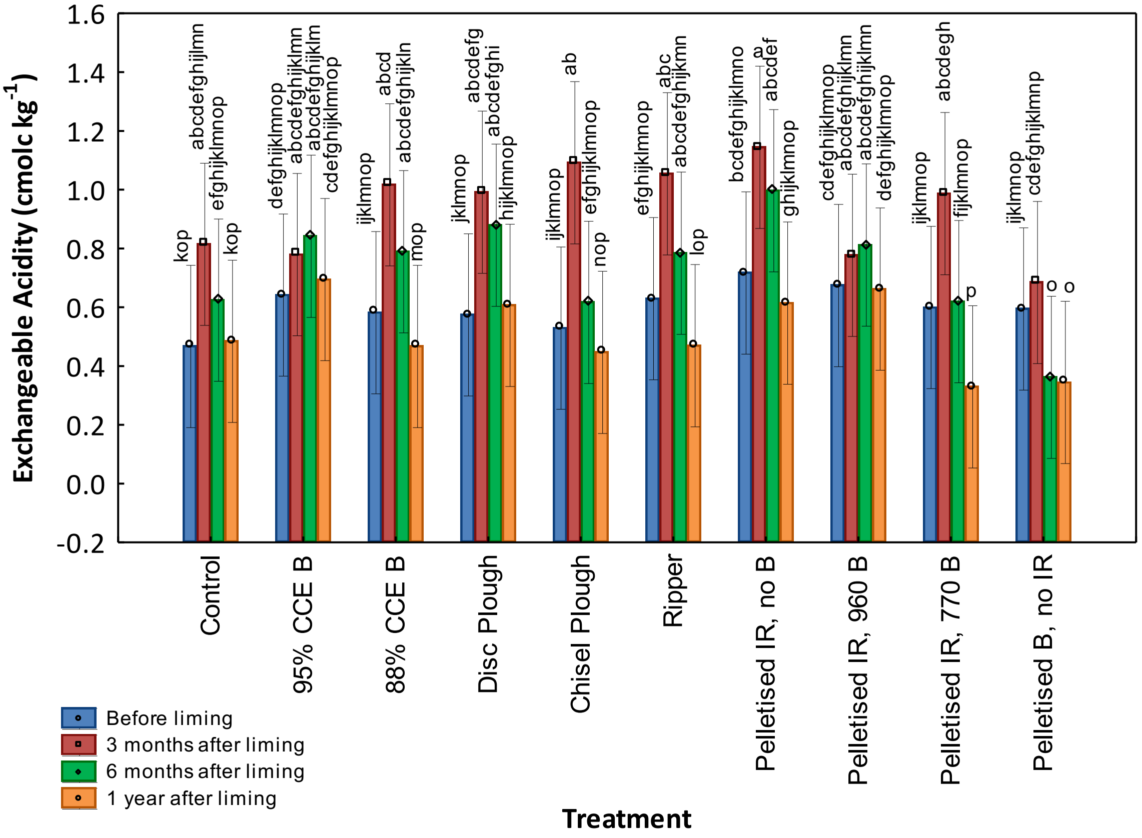

Figure 4.17. The exchangeable acidity (cmolc kg^{-1}) of the treatments over time at the 15 – 30 cm depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

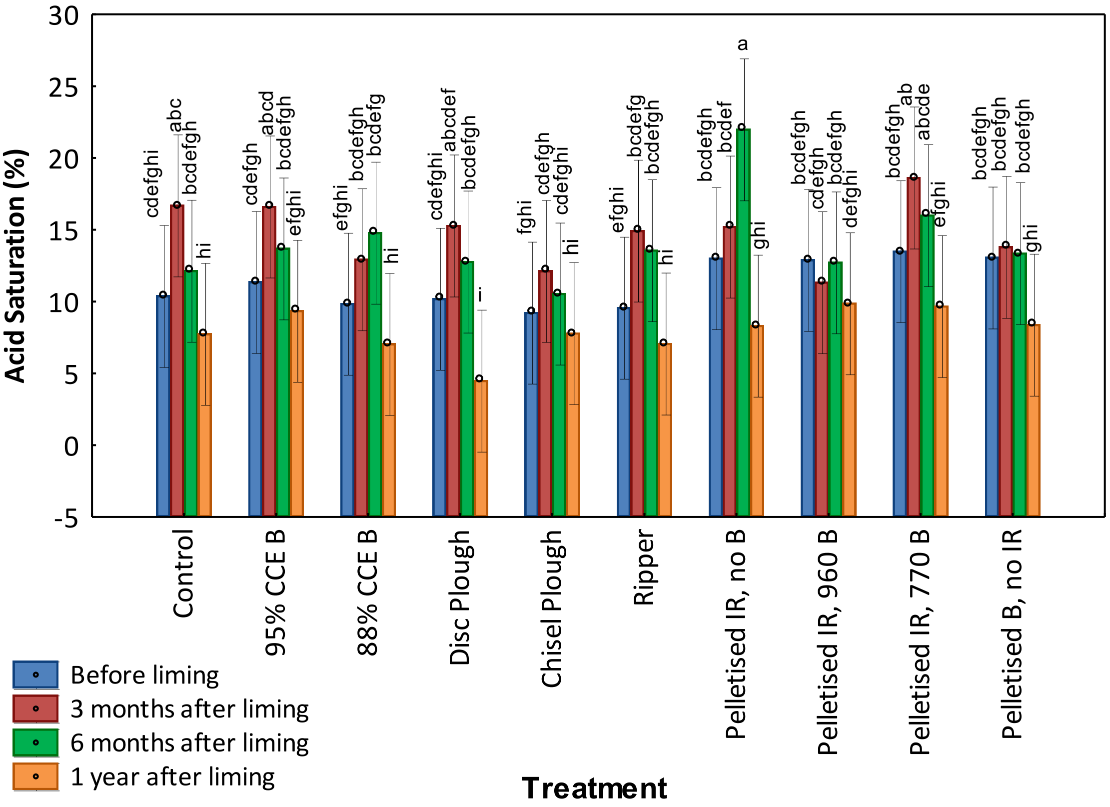

Figure 4.18. The acid saturation (%) of the treatments over time at the 5 – 15 cm depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

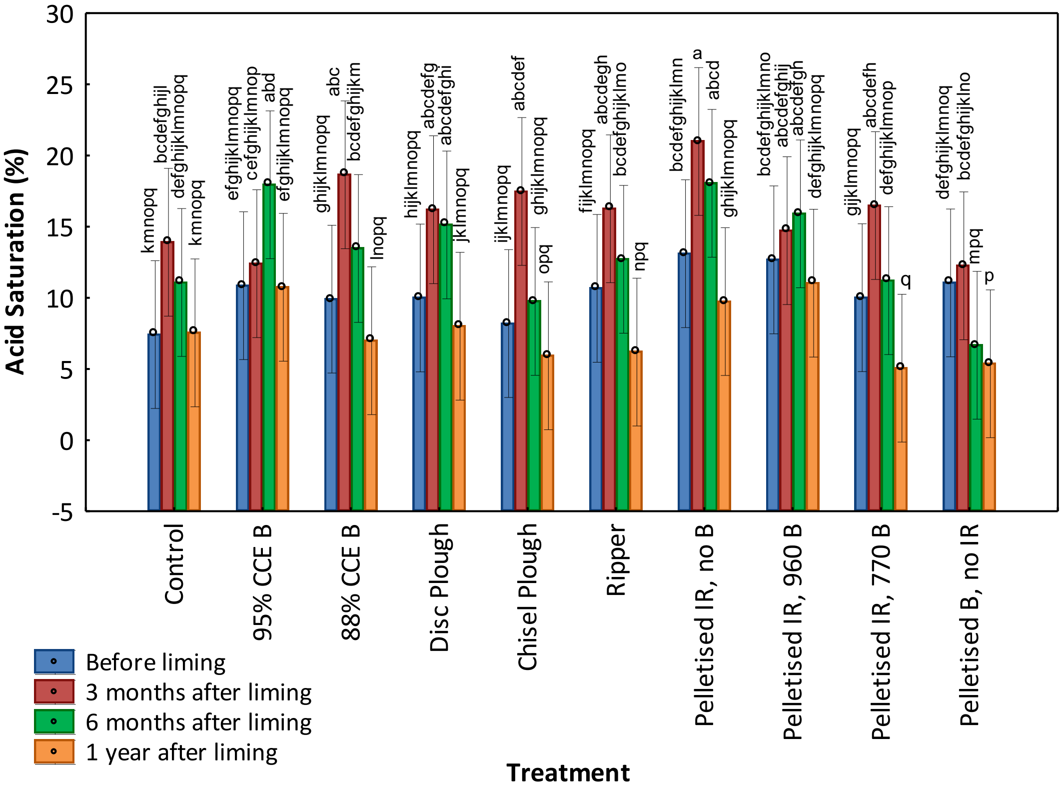

Figure 4.19. The acid saturation (%) of the treatments over time at the 15 – 30 cm depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

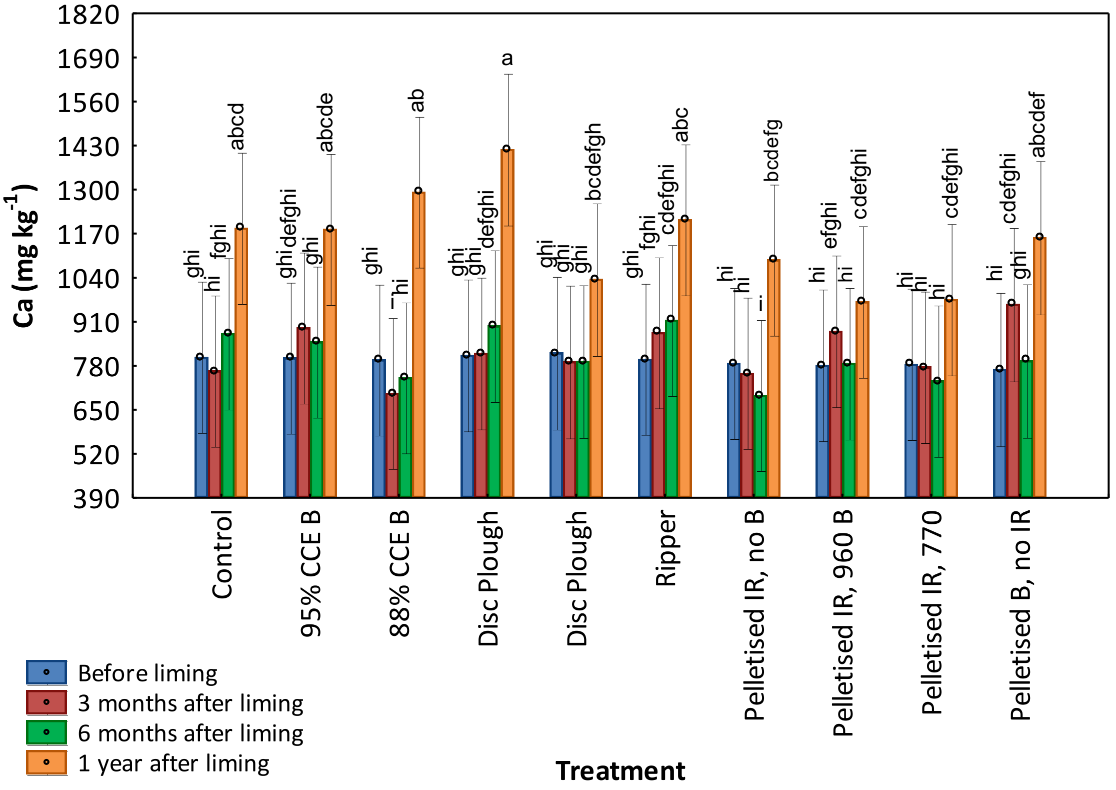

Figure 4.20. The Ca (mg kg^{-1}) concentration of the treatments over time at the 5 – 15 cm depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

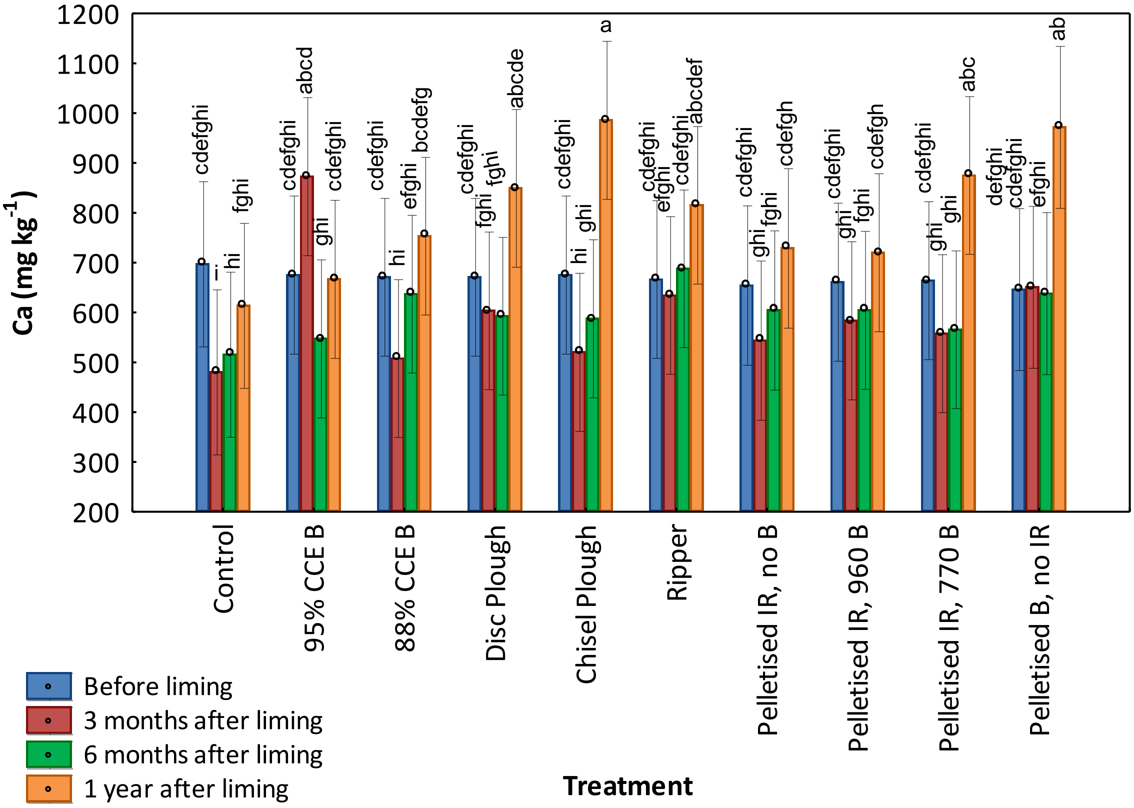

Figure 4.21. The Ca (mg kg^{-1}) concentration of the treatments over time at the 15 – 30 cm depth. Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

The ECEC increased for all the treatments at the 5 – 15 cm depth except the pelletised lime placed in-row and broadcasted at 770 kg ha^{-1} which ended the same as before liming (results not shown). The ECEC at the 15 – 30 cm depth either increased ($p \leq 0.05$) or remained the same ($p > 0.05$) for the different treatments one year after liming (results not shown).

4.4 Discussion

Treatment effects on the 0 - 5 cm soil layer over time

Considering that the starting pH$_{KCl}$ of 5.35 at the 0 – 5 cm depth was not far from the target pH$_{KCl}$, the fact that all treatments reached the target pH$_{KCl}$ does not necessarily reflect the effectiveness of the treatments to favour lime movement and acid neutralisation at the 0 – 5 cm depth only one year after liming.

When assessing the effect of lime purity on movement and acid neutralisation, both the treatments where 95% and 88% CCE Class A calcitic lime was surface broadcast equally increased ($p \leq 0.05$) the soil pH$_{KCl}$ at the 0 – 5 cm depth layer one year after lime application (Figure 4.4). It is thus evident that within both these treatments lime was able to neutralise acidity at the 0 – 5 cm depth increment within a year of liming and that the 95% CCE lime did not lead to greater neutralisation than the 88% CCE lime, despite being more pure in nature. These two treatments represent the conventional practise of applying Class A lime in no-till systems, and it could therefore be reported that these are effective practises to increase soil pH$_{KCl}$ at a 0 – 5 cm depth a year after lime application.

Furthermore, although the 95% CCE lime decreased ($p \leq 0.05$) both exchangeable acidity and acid saturation whilst the 88% CCE did not, the soil onto which the 88% CCE lime was broadcast had a lower exchangeable acidity and acid saturation before liming. A lower exchangeable acidity and acid saturation would thus mean that the 88% CCE lime did not have to decrease acidity by as much, consequently not leading to significant decreases of these parameters as with the 95% CCE lime. Both these treatments had no exchangeable acidity and acid saturation respectively one year after liming and it would therefore be unlikely that the slight difference in purity between the two lime sources had an effect on their ability to decrease exchangeable acidity and acid saturation.

The neutralisation of acidity by surface broadcast lime to a 5 cm depth below the soil surface a year after liming was also reported by both Miller (2015) and Caires et al. (2005). In the study by Miller (2015), 3 t ha^{-1} of lime (90% CCE) was surface broadcast on loam soil receiving 489 mm of rainfall. Caires et al. (2005) surface broadcast 2, 4 and 6 t ha^{-1} of lime (84% CCE) on loamy soil receiving 2067 mm of rain. Despite the slight difference in lime purity (90 and 84% CCE respectively) in these trials, lime was able to neutralise acidity to a 5 cm depth in both trials. The 100% and 88% CCE broadcast lime treatments were applied at lower rates of 1 t ha^{-1} but were still however able to neutralise acidity at the 0 - 5 cm depth within the same time period as the trials mentioned above. The neutralisation of acidity by the 95% and 88% CCE lime at the 0 – 5 cm depth after one year despite the lower rates could be attributed to the sandy loam texture of the soil at the trial site. The lower clay content, compared to what was reported by Caires et al. (2005), and thus lower buffering capacity of the soil at the trial site could allow for easier downward movement of the lime. The effect of texture on lime movement can be supported by both Godsey et al. (2007) and Alleoni et al. (2010) who attributed the slower movement of surface broadcast lime to the clay content in the soil, despite the higher lime application rates in their trials.

A high stone fraction in the 0 – 5 cm depth of the trial site could further account for the successful neutralisation of soil acidity by the 95% and 88% CCE Class A lime at a lower lime rate, as the higher the stone content, the less acid soil is needed to be neutralised (less lime is needed). Also, the Eksteen method of determining lime requirement assumes that the lime used has a 70% CCE, and therefore making use of even more pure lime would also result in higher than expected acid neutralisation.

Lime of a purer nature (and thus higher CCE) is expected to neutralise acidity more effectively per unit mass compared to a lime with a lower CCE (Mullins et al., 2009). However, the fact that 95% CCE broadcast lime did not increase ($p > 0.05$) soil pH_{KCl} more effectively at the 0 – 5 cm depth compared to the less pure 88% CCE lime, could lead to the assumption that slight differences in lime purity (i.e. 7% in this case) will not have an effect on soil pH or lime movement at a 0 – 5 cm soil depth.

The fact that the broadcast 95% and 88% CCE Class A lime treatments (as well as the pelletised 93% CCE micro-fine lime broadcast at the recommended rate) ended with the highest ($p \leq 0.05$) Ca and change in Ca concentration at the 0 – 5 cm depth (Figure 4.8 and 4.9) could have soil management implications. In terms of Ca fertilisation, broadcasting lime in its conventional powder form or in a pelletised form at the recommend rate could thus be considered an effective strategy for increasing the Ca concentration in the 0 – 5 cm depth. It is however important to note that the Ca concentration in the 0 – 5 cm depth only increased one year after surface broadcasting the lime, therefore Ca fertilisation should be done in advance in order to give the lime time to move down the soil profile.

In terms of the effect of soil disturbance actions on lime movement and acid neutralisation, all three the treatments in which surface broadcast lime was incorporated into the soil with the respective tillage actions (disc plough, chisel plough and ripper) were able to increase ($p \leq 0.05$) the soil pH_{KCl} at the 0 – 5 cm depth one year after liming (Figure 4.3). Depth of soil disturbance and degree of soil inversion by the different ploughs therefore had no effect ($p > 0.05$) on soil pH_{KCl} or speed of increase of pH_{KCl} at the 0 – 5 cm depth.

After incorporating lime into the soil at depths greater than 5 cm, it has been reported that the pH was lower at the 0 – 5 cm depth than when lime was surface broadcast, and thus lime incorporation did not favour the increase in pH at the 0 – 5 cm depth (Conyers et al., 1996; Conyers et al., 2003; Caires et al., 2006; Caires et al. 2011). In the trial however, the pH_{KCl} for all three tillage treatments was not less ($p > 0.05$) than the 95 and 88% CCE Class A surface broadcast lime treatments in the 0 – 5 cm depth. The tillage treatments in this trial were thus equally as effective in increasing the soil pH_{KCl} at the 0 – 5 cm depth compared to surface broadcast lime.

These findings could encourage the use of a one-off strategic tillage every few years in a no-till systems in which lime is incorporated as it will be able to address soil acidity at a 0 – 5 cm depth as well as result in additional benefits such as weed control and loosening of compacted soil layers.

Assessing the effect of the form and fineness of lime on movement and acid neutralisation, the treatments where pelletised micro-fine lime was applied differed in their effects over time and between treatments on the soil pH_{KCl} in the 0 – 5 cm depth (Figure 4.4). It is often suggested by the industry that low application rates of pelletised micro-fine lime can be applied on the basis that due to its fineness, it is more effective in neutralising soil acidity per unit mass (Stevens and Dunn, 2007). The small change in pH_{KCl} by the treatment where lime was only band-placed in-row (40 kg ha^{-1}) with no additional surface broadcasting (Figure 4.5) negates these suggestions and correlates with previous findings in literature. Brown et al. (2008) reported no difference in the change in pH in the top 10 cm of the soil between the control treatment and 224 kg ha^{-1} of in-row placed lime even two years after lime application. Furthermore, Edwards et al. (2015) found that 225 kg ha^{-1} of in-row placed lime pellets did not increase the soil pH compared to the control, whilst 450 kg ha^{-1} only had a slightly higher pH than the control treatment. An application rate of 40 kg ha^{-1} of in-row placed pellets would thus be considered too low for the amelioration of soil acidity given the low change in pH and the lack thereof at even higher application rate in the studies by Brown et al. (2008) and Edwards et al. (2015). Chemically speaking, in order to neutralise two molecules of H^+ ions, one molecule of $Ca(CO_3)$ is required, and therefore pelletised lime of the same calcium carbonate equivalent cannot be more effective than conventional lime (Zhang et al., 2004). In-row placement of pellets that remained undissolved in the soil as well as placement of pellets placed below the 0 – 5 cm depth increment could further contribute to the small change in pH_{KCl} in the 0 – 5 cm depth (Staton and Warncke, 2000; Edwards et al., 2015).

The pH_{KCl} also decreased ($p \leq 0.05$) at the 0 – 5 cm depth up to six months after liming where lime pellets were only paced in-row at 40 kg ha^{-1}, most probably due to the fact that the majority of lime pellets were placed in-row at a depth of 5 – 8 cm and therefore not neutralising acidity in the 0 – 5 cm depth as effectively. The treatment did however result in an increase ($p \leq 0.05$) in pH_{KCl} one year after liming.

When comparing the treatments where pelletised lime was applied in-row and broadcast at 770 kg ha^{-1} (19% less than the recommended rate) and where pelletised lime was applied in-row and broadcast at 960 kg ha^{-1}, there was no difference ($p > 0.05$) in the increase in pH_{KCl} or change in pH_{KCl} at the 0 – 5 cm depth (Figure 4.4 and 4.5). Furthermore, in-row placement with 770 kg ha^{-1} broadcast lime showed a quicker increase ($p \leq 0.05$) in pH_{KCl} (6 months after liming). Therefore, one could assume that broadcasting 19% less lime pellets than the recommended rate will not compromise on increasing the soil pH_{KCl} at the 0 – 5 cm depth of the soil profile, which is in line with a study by Jones and Mallarino (2018).

The higher ($p \leq 0.05$) pH_{KCl} at the 0 – 5 cm depth in the rows than between the rows (Figure 4.6) for all the treatments that placed lime pellets in-row, is similar to findings in literature. Edwards et al. (2015) also reported a higher pH in the row (a radius of about 1.27 cm around where the pellets were placed) than between rows, after in-row placement of pelletised lime. There is thus an uneven distribution of lime across the field and this higher pH in the rows could be disadvantageous for crop root development in the current year. The higher pH in the rows may also affect crops planted in subsequent years as planting will not occur exactly on the same row, and thus the crops of the following years will not benefit from the higher pH. However on the other hand, over time planting rows with in-row lime placement will be more evenly spread out across fields, which would be more beneficial for crop growth and could thus be considered as a long-term approach. Further research regarding the long-term build up and maintenance of soil pH is still required in this aspect.

Surface broadcasting pelletised lime (with no in-row placement) at the recommended lime rate (1000 kg ha^{-1}) showed the greatest ($p \leq 0.05$) as well as the quickest ($p \leq 0.05$) increase (three months after liming) in soil pH_{KCl} at the 0 - 5 cm depth (Figure 4.4 and 4.5). Fine pelletised lime was thus able to neutralise acidity at the 0 – 5 cm depth within three months after lime application which is even quicker than reports by Beegle (2001) who reported fine lime to react within 6 – 18 months.

Some literature suggests that broadcasting fine pelletised lime is not more effective than conventional lime. Godsey et al. (2007) reported no difference in the vertical movement on pelletised and conventional lime applied at 1.1 t ha^{-1}. In trials by Snyder et al. (1996) and Higgins et al. (2012), it was reported that broadcasting lime pellets at rates much lower than what is recommended did not significantly increase or differ to conventional lime in their effect on in soil pH. Snyder et al. (1996) did however report that a slightly lower rate (568 - 795 kg ha^{-1}) of fine pelletised lime could have the same effect on soil pH as 1000 kg ha^{-1} of conventional lime.

On the contrary, however, Whitten et al. (2001) reported that fine lime was double as effective in raising soil pH as coarse lime over the same period. The quick movement of the lime and neutralisation of acidity by broadcast pelletised lime was also evident in the trial and could be attributed to the increased surface area of the fine lime (Beegle, 2001), resulting in a quicker reaction with soil acidity, allowing the excess alkalinity to move further down the soil profile (Joris, 2013).

The quick reaction of fine pelletised lime is an extremely valuable characteristic as it means that acid soils can be addressed within a much shorter period compared to conventional lime and therefore crop growth does not have to be limited by the delay (one year) in acid neutralisation after lime application.

Seeing as though pelletised lime is only more effective than conventional lime when applied at the recommended rates, the economic viability thereof has to be questioned (Zhang et al., 2004; Staton and Warncke, 2000). A local pelletised fine lime product for example costs around R2500 per ton compared to locally sourced conventional agricultural lime of approximately R170 to R470 per ton. A consideration could be to incorporate a combination of pelletised and conventional lime into the liming strategy. Conventional lime application could be followed by yearly applications of pelletised lime at low rates to maintain the soil pH to an optimal level. Higgens et al. (2012) reported the successful maintenance of soil pH up to a depth of 15 cm for three years following yearly applications of pelletised lime at rates of 175, 350 and 525 kg ha^{-1}.

The maintenance of soil pH following annual applications of surface broadcast pelletised lime at low rates during fallow seasons or before planting could thus be an effective strategy to ensure optimal soil pH levels and whilst still being financially viable at low rates. Furthermore, maintaining a higher soil pH in the topsoil could additionally allow lime to leach deeper into the soil profile which will be crucial in soils with a higher clay content. Further research is however required in this regard.

Treatment effects on the 5 – 15 and 15 – 30 cm soil layers over time

The similarity ($p > 0.05$) in chemical attributes between treatments at the 5 – 15 and 15 – 30 cm depth therefore indicates that neither lime purity (95% vs 88% CCE), type of soil disturbance (disc plough, chisel plough or ripper) or form of lime (pelletised) leads to differences ($p \leq 0.05$) in neutralising soil acidity at both the 5 – 15 and 15 – 30 cm depths.

The failure to reach the target pH_{KCl} at the 5 – 15 cm depth by any treatment one year after liming, highlights the slow movement and reactivity of lime in the soil and the ineffectiveness of the tillage treatments to mix lime in the soil. The starting pH_{KCl} at the 15 – 30 cm depth was not far from the target pH_{KCl}, most probably due to the natural pH of the soil parent material, and therefore the pH_{KCl} did not have to raise by much to reach the target and therefore is not necessarily an indication of deep lime movement one year after liming.

The findings reported in this trial is contrary to some literature which suggests that incorporating surface applied lime leads to greater increases in pH at a 5 – 30 cm depth than surface broadcast lime. The similarity in the increase in pH at a depth of 5 – 15 or 15 – 30 cm between surface broadcast lime and incorporated lime could potentially be attributed to spread of lime over a greater volume of soil when incorporated and therefore less acidity is neutralised. Incorporating lime over a greater volume of soil at a rate of only 1 t ha^{-1} may be too little to increase the soil pH more at depths of 5 – 15 and 15 – 30 cm than when surface broadcasting lime (Whitten et al., 2000; Conyers et al., 2003; Caires et al., 2006; Caires et al., 2011). It might have to be considered to incorporate a higher lime rate, taking into account the increased volume of soil the lime is going to be spread across (depending on the depth on incorporation). Another point to consider is that the results reported in the literature are after a longer time period (two to eight years), giving lime a greater time to move in the soil and react with acidity, whereas this trial reported the change in pH_{KCl} after one year.

Finally, the soils at the 5 – 15 and 15 – 30 cm depth at the trial site were not extremely acid, and therefore the amount of acidity that could be neutralised was limited. This could thus suggest that, given the conditions of the soil at the trial site, the effectivity of incorporated lime to neutralise acidity at greater depth is not necessarily poor.

Furthermore, irregularities in the depth of incorporation caused by the large stone fraction at the trial site which, could otherwise have resulted in lime not being incorporated into the 15 – 30 cm depth increment for example, thus leading to lower than expected pH.

It was however evident that pelletised lime broadcast at the recommended rate lead to the quickest ($p \leq 0.05$) (three months after liming) neutralisation of soil acidity at the 5 – 15 depth (Figure 4.12). The 88% CCE lime broadcast, lime incorporated with a disc plough, pelletised lime placed in-row and broadcast at 960 kg ha^{-1} and pelletised lime broadcast the recommended rate lead to the quickest increase (3 months after liming) in pH$_{KCl}$ at the 15 - 30 cm depth (Figure 4.13). The quick increase in pH$_{KCl}$ at both the 5 – 15 and 15 – 30 cm depth by pelletised lime broadcast at the recommended rate could motivate the use of this strategy not only to address acidity at the 0 – 5 cm depth but also to address subsoil acidity (5 – 15 and 15 – 30 cm) within a shorter time period.

It was therefore evident that lime was able to move down to both these depth increments in all the treatments within the period of a year after lime application. These findings are contrary to some literature that reports a much longer time period for lime to move to such depths, especially surface applied lime (Conyers et al., 2003; Godsey et al., 2007; Caires et al., 2008; Miller, 2015). This quicker vertical movement of lime could be attributed to the light- textured (sandy loam) soil at the trial site, as well as a high stone fraction (leading to less soil acidity needing to be neutralised), which would favour the downward movement of lime more than a heavily texture soil with a smaller percentage of stones (Godsey et al., 2007; Alleoni et al., 2010).

The higher ($p \leq 0.05$) pH$_{KCl}$ in the row than between the rows at both the 5 – 15 and 15 – 30 cm depths for the treatments that placed pellets in-row (Figures 12 and 13) which was also found at the 0 – 5 cm depth, could present similar complications of highly concentrated lime in the rows. High concentrations of lime in the row as well as uneven distribution of lime across the field due to the changing of row positions each year could be a limitation to crop growth. The higher pH$_{KCl}$ in the row at the 15 – 30 cm depth compared to the shallower 5 – 15 cm depth could be attributed a higher natural pH deeper in the soil profile due to higher clay contents and thus having greater buffering capacity against change in pH (Nathan, 2020) as well as the natural base status of the soil parent materials (Grieve, 1999).

4.5 Conclusion

Slight differences in lime purity, type of tillage action (disc plough, chisel plough and ripper) used when incorporating lime as well as form and fineness of lime (pelletised micro-fine) will all lead to an increase ($p \leq 0.05$) in pH_{KCl} up to a 30 cm depth one year after receiving 810 - 1000 kg ha^{-1} of lime on a sandy loam soil that received a total of 558 mm of rainfall.

The pH_{KCl} can be raised by 0.43 at a 0 – 5 cm depth and by 0.36 and 0.40 at a 5 – 15 cm and 15 – 30 cm depth respectively, one year after liming, regardless of the purity, form, fineness of lime and degree of incorporation.

Broadcasting pelletised fine lime at the recommended rate however, leads to the greatest as well as the quickest ($p \leq 0.05$) (3 months after liming) decrease ($p \leq 0.05$) in soil acidity at a 0 – 5 cm depth as well as the quickest ($p \leq 0.05$) (3 months after liming) increase in pH_{KCl} at a 5 - 15 cm depth and amongst the quickest (3 months after liming) increase in pH_{KCl} at the 15 – 30 cm depth. Applying less than the recommended rate (in-row or in-row and broadcast) will not lead to more effective neutralisation of soil acidity.

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CHAPTER 5

DETERMINING THE EFFECT OF FORM, FINENESS AND PLACEMENT OF LIME WITH AND WITHOUT SOIL DISTURBANCE ON BARLEY AND CANOLA GROWTH AND DEVELOPMENT

5.1 Introduction

The adoption of conservation agriculture by farmers in the Western Cape has increased exponentially over the past 40 years (Smith et al., 2017; Findlater et al., 2019). More than 60% of farmers in the Western Cape have adopted crop rotation, maintenance of an organic soil cover as well as no-tillage. More than 80% of farmers have converted to no-tillage (Smith et al., 2017). Implementing all or some of the principles by which conservation agriculture is defined, leads to benefits such as an increase in soil organic carbon content, increased soil water-holding capacity, improved soil structure and microbial activity (Thierfelder et al., 2014). These benefits are reflected by increases in crop yields as well as a greater overall capacity of crops to tolerate dry conditions.

Long-term implementation of conservation agriculture practices has, however, started to reveal some challenges. No-tillage restricts the mixing of soil amendments such as agricultural limestone (lime), which is used to rectify soil acidity, between the various soil layers. The lack of mixing lime with tillage may result in the development of pH stratification down the soil profile (Flower and Crabtree 2011). The stratification of pH down the soil profile, in the form of an alkaline topsoil followed by more acid soil layers, tends to become more severe over the long-term due to the poor mobility of lime in soil (Barth et al., 2018). The consequence of a soil profile with acid soil layers is reduced crop growth or impaired development (Fageria and Baligar, 2003). Reduced crop growth and development under acid soil conditions can largely be attributed to the increased solubility of heavy metals such as Al (Kochian, 1995). Toxic levels of Al in the soil leads to the stunting of crop roots (Krstic et al., 2012). Crops with stunted roots are hindered in their ability to effectively take up nutrients and water, which in turn reduces its growth and development (Panda et al., 2009).

Crops in the dryland rotation system in the Western Cape Province of South Africa such as, amongst others barley (*Hordeum vulgare*) and canola (*Brassica napus*) are particularly sensitive to acid soil conditions (Tang and Rengel, 2001; Angus, 2008). The optimum soil pH_{KCl} for barley and canola is more than 5.5. A lower pH leads to a significant decrease in crop growth and development (Foy, 1996; DAFF, 2016). Malting barley is the second-most produced small-grain crop in South Africa [345

080 ton produced on 131 960 hectares (Crop Estimates Committee, 2020)], of which 89% is produced in the Western Cape Province (Mogala, 2017). Canola in South Africa is also exclusively produced in the Western Cape Province (DAFF, 2016) with an annual production of 95 000 tons in 2019 (Crop Estimates Committee, 2020). Due to the significant adoption of no-tillage in the Western Cape Province and the high production of barley and canola in this area, it is important to rectify the problem of soil acidity for these production systems.

Previous research has shown that one-off strategic tillage every few years has no negative effect on soil quality and yield of grain crops (Leygonie, 2016; Van Zyl, 2017; Conyers et al., 2019). The fact that there is no or limited long-term negative impact of strategic tillage on soil quality and crop yield opens the possibility of making use of strategic tillage to incorporate lime deeper into the soil profile. Tillage implements differ however in their working depth and degree to which they invert the soil which will influence the distribution of lime in the soil. It should therefore be investigated as to which tillage action will assist the greatest in the movement of lime in the soil.

Furthermore, the vertical movement of lime in the soil could also potentially be influenced by the characteristics of lime, such as its fineness, form and purity. In South Africa, conventional class A agricultural lime should consist of particles smaller than 1.7 mm and 50% smaller than 0.25 mm in accordance with Act 36 of 1947. A finer lime [90% of particles smaller than 0.25 mm of which 80% is smaller than 0.106 mm (FERTASA, 2019)] could be more mobile in the soil because of its greater surface area for reaction and should therefore react faster with acidity (Beegle, 2001). Once the surrounding acidity has been neutralised the lime will be enabled to move deeper down the soil profile (Whitten et al., 2001; Li et al., 2019). Furthermore, a finer lime will be more prone to leaching via macropores in the soil, assisting further in its downward movement (Amarel et al., 2004). Applying fine lime in a powder form such as conventional class A agricultural lime could however present challenges such as non-uniform application and losses when applied in windy conditions. For this reason, applying micro-fine lime in a pelletised form is a good strategy to overcome these challenges.

Lime in a pelletised form can be placed in-furrows created by openers of a seed-drill. The furrow-opener is connected by pipes to tanks that contain seeds and fertiliser. This action will automatically place the lime 5 - 8 cm beneath the soil surface (depending on the working depth of the furrow-openers). The placement of the pelletised lime below the soil surface could assist in the movement of lime to lower soil depths.

Lime purity could also be influential in the vertical movement of lime in the soil. Lime purity is expressed as calcium carbonate equivalent (CCE), which is a measure that compares the acid neutralising capacity of the lime relative to pure calcium carbonate (100% CCE). A purer lime will have a higher CCE and should thus have a greater capacity to neutralise acidity. Effective neutralisation of acidity should then enable the lime to continue to move deeper down the soil profile.

The aim of this study was to determine effects of form, fineness and purity of lime on its movement in the soil with or without different soil disturbance actions and the consequent effect on the growth and development of barley and canola grown in a dryland rotation system.

5.2 Materials and Methods

5.2.1 Description of trial site

The trial site was located near the town of Caledon in the southern Cape region of South Africa (34°17'33.162"S 19°31'28.133"E; 358 m) (Figure 5.1). The trial was conducted over two growing seasons (2019 and 2020). Most of the region is used to produce wheat (*Triticum aestivum*), barley, oats (*Avena sativa*) and canola, along with various forage crops, under dryland conditions. The criteria for the trial site was that it should be under no-tillage for at least seven years, it must not have received lime in the past year and there must be clear pH stratification between the top and subsoil layers, with a subsoil pH_{KCl} of less than 5.0 (Table 5.1). The soil profile was shallow and consisted of soil with a sandy-loam texture.

Figure 5.1. A map of the Western Cape Province, indicating the location of the trial site near the town of Caledon, Western Cape Province, South Africa.

Table 5.1. The soil pH_{KCl} of the trial site at three respective depths before the start of the trial.

Soil depth (cm)	pH_{KCl}	Standard deviation
0 – 5	5.35	0.27
5 – 15	4.88	0.25
15 – 30	4.92	0.24

5.2.2 Climate

The long-term average annual rainfall at the trial site is 545 mm. The long-term average monthly rainfall and temperature compared to the average monthly temperature and rainfall of 2019 and 2020 is shown in Figure 5.2.

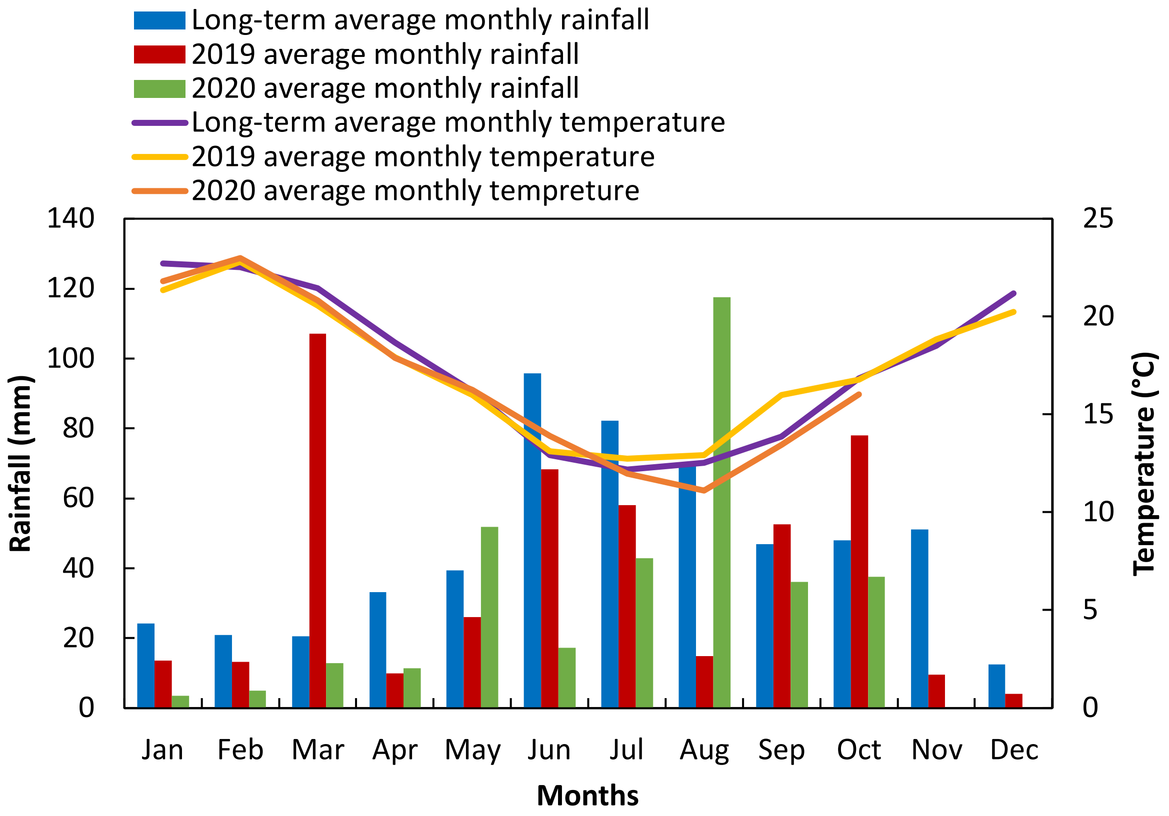

Figure 5.2. The average monthly rainfall and temperature of 2019 and 2020 and the long-term average monthly rainfall and temperature of the trial site area. (The data of 2020 was only reported to the end of October).

5.2.3 Experimental design and treatments

Ten treatments (Table 5.2), replicated in four blocks, consisting of 4.5 x 20 m plots, were laid out in a randomised block design. Buffer zones of 2 m were established in between plots. The treatments were distinguished from one another by the form, fineness and purity of the lime applied (APPENDIX C), as well as the method of soil disturbance, or lack thereof (no-tillage). The barley cultivar Hessekwa was established in 2019 using an Equalizer seed-drill with tine openers (Equalizer AG (Pty.) Ltd., Brackenfell, South Africa) at a 300 mm row spacing.

Table 5.2. Description of the trial treatments, the application or placement method of the lime as well as the form, purity and rate at which lime was applied in each treatment. CCE = calcium carbonate equivalent.

	Treatment description	Application or placement method	Lime form	Lime purity	Lime rate (kg ha^{-1})
1	**Control (no lime)**	-	-	-	-
2	**95% CCE calcitic lime**	Broadcast	Class A	95% CCE	1000
3	**88% CCE calcitic lime**	Broadcast	Class A	88% CCE	1000
4	**Disc plough**	Broadcast followed by incorporation with a disc plough (10 – 15 cm deep with soil inversion)	Class A	88% CCE	1000
5	**Chisel plough**	Broadcast followed by incorporation with a chisel plough (20 – 30 cm deep with no soil inversion)	Class A	88% CCE	1000
6	**Ripper**	Broadcast followed by incorporation with a ripper (30 cm deep with no soil inversion)	Class A	88% CCE	1000
7	**Pelletised lime placed in-row (no broadcasting)**	In-row placement during crop establishment	Micro-fine Pelletised	93% CCE	40
8	**Pelletised lime broadcast at 960 kg ha^{-1} and in-row placement**	Broadcast followed by in-row placement during crop establishment	Micro-fine Pelletised	93% CCE	Broadcast: 960 In-row: 40
9	**Pelletised lime broadcast at 770 kg ha^{-1} and in-row placement**	Broadcast followed by in-row placement during crop establishment	Micro-fine Pelletised	93% CCE	Broadcast: 770 In-row: 40
10	**Pelletised lime broadcast (no pellets placed in-row)**	Broadcast followed by crop establishment	Micro-fine Pelletised	93% CCE	1000

A limited rate of 40 kg ha^{-1} was applied for in-row lime placement due to restrictions in the size of the fertiliser tanks on a seed-drill. The treatment where 960 kg ha^{-1} of lime pellets were broadcast was therefore to make up the remaining lime requirement to achieve 1000 kg ha^{-1}. Broadcasting only 770 kg ha^{-1} of lime pellets [19% less than the recommended rate (Jones and Mallarino, 2018)] was to evaluate whether less lime can be applied when making use of pelletised micro-fine lime as frequently suggested by the industry. Lime pellets bound with a molasses binding agent was used.

The trial was conducted in-line with conservation agriculture production systems that incorporate crop rotations, in which canola (a broad leaf crop) is a fitting crop to be planted after barley. Therefore, in 2020 canola (cv. Diamond) was planted directly over the field trial site with a seed-drill and without application of lime or soil tillage. The effect of the treatments applied in 2019 on crop growth and development was therefore monitored for two production seasons after being conducted.

5.2.4 Soil and crop management

Soil pH and fertility status was determined by taking representative soil samples comprising of five sub-samples taken at 0 - 5, 5 - 15 and 15 - 30 cm depths in each plot in the form of soil cores (4 cm diameter). The analysis of these soil samples was used to determine lime and fertiliser requirements. The lime requirement was determined at 1000 kg ha^{-1} in 2019 to reach a pH$_{KCl}$ of 5.5, using the Modified Eksteen method (Eksteen, 1969). All the lime (class A and pelletised lime) broadcasting was done by hand and took place before planting on 29 April 2019. The soil disturbance treatments were done on 29 - 30 April 2019. Crop establishment (barley) took place on 15 May 2019.

The soil was fertilised in 2019 by applying 16 kg ha^{-1} N, 16 kg ha^{-1} P and 4 kg ha^{-1} S during planting and top-dressing 60 kg ha^{-1} N and 8 kg ha^{-1} S four weeks after emergence on 24 June 2019. Weed management was conducted with the use of a selective broadleaf herbicide (Buctril MPCA) as well as a Metribuzin herbicide during the growing season.

In Year 2 canola was planted directly over the field trial site in May 2020 and plots were then marked out and paths between plots established using GPS markers taken at the end of the previous season. The canola was established with a seed-drill with tine openers with a 270 mm row spacing. The trial site was fertilised with 71 kg ha^{-1} N, 5 kg ha^{-1} P and 12 kg ha^{-1} K prior to planting. At planting 9 kg ha^{-1} N, 12 kg ha^{-1} P and 3 kg ha^{-1} K was applied in-row and a top-dress consisting of 50 kg ha^{-1} N, 5 kg ha^{-1} P, 15 kg ha^{-1} K and 12 kg ha^{-1} S was applied 90 days after planting.

Weeds were controlled with Clethodim for the control of annual grasses as well as a foliar fungicide containing Prothioconazole and Tebuconazole. Boron foliar spray was also applied during the course of the season.

5.2.5 Data collection

Root biomass (kg ha^{-1}) was determined 30 days after emergence in Year 1 by complete removal of 10 random plants from each plot and then cutting each at ground level, washing, oven-drying at 60°C for 72 hours and weighing the below-ground plant parts. Plant above-ground biomass (kg ha^{-1}) and leaf area index (LAI) were determined 30, 60 and 90 days after emergence in Year 1. Plant above-ground biomass was determined by removing 10 random plants per plot and then oven-drying them at 60°C for 72 hours and weighing them. Leaf area index (LAI) was determined by removing the leaves of the 10 random above-ground plant samples and putting them through a Li-Cor LI 3100C area meter. Plant above-ground biomass (kg ha^{-1}) was also determined at physiological maturity (150 days after emergence) by removing five one-meter strips of above-ground plant biomass at random in each plot followed by oven-drying at 60°C for 72 hours and weighing.

The barley plant population (m^{-2}) was determined four weeks after emergence (24 May) in 2019. This was done by determining the average number of plants established in five randomly distributed one-meter strips in each plot. The number of ear-bearing tillers as well as the number of spikelets and seeds per ear were also determined at physiological maturity from five randomly selected one-meter strips.

The plots were harvested at the end of the season with a Hege 140 plot combine (1.5 m). Thousand kernel mass (g) was determined using a Numigral seed counter machine and the grain yield (kg ha^{-1}) was also determined once the grain was cleaned and weighed.

The quality parameters that were measured included the nitrogen content (%) and hectoliter mass (kg hL^{-1}), which were determined using near infrared reflectance spectroscopy grain analyser (model IM 9500, Perten Instruments, Waltham, USA). Kernel plumpness (%) (> 2.5

mm) and screenings (%) (< 2.2 mm) were also determined using a Sortimat sieve machine (Sortimat, Stockholm, Sweden).

In Year 2, canola above-ground biomass (kg ha^{-1}) was determined at 60, 90 and 150 (physiological maturity) days after emergence by the selection of five random plants per plot and following the same procedure as in Year 1. Canola plant population (m^{-2}) was determined 30 days after emergence similarly as in Year 1. LAI was also determined at 60 and 90 days after emergence following the same procedure as in Year 1. The number of branches per canola plant was also determined at physiological maturity.

Plots were harvested at the end of the growing season and the grain was cleaned and weighed in order to determine grain yield (kg ha^{-1}). Thousand kernel mass (g) was determined using a canola seed counting paddle.

The quality parameter that was measure was the seed oil content (%) of the canola, which was done with an infrared reflectance spectroscopy grain analyser.

5.2.6 Statistical analyses

Analysis of variance for crop production variables were performed using the Kenward-Roger degree-of-freedom approximation methodology for mixed models (Kenward et al., 1997). This method adjusts the estimates in such models using restricted maximum likelihood (REML) procedure, similar to what the Satterthwaite-type correction does in fixed effects, to account for heteroscedasticity. Treatment was specified as the fixed effect and block as replicated random effect. Least Significant Difference (LSD) post-hoc tests for multiple comparisons were performed to compare crop parameter means. The correlation between biomass at 150 days after establishment and soil pH at various depths were estimated using Spearman's rank correlation analysis. Only pH$_{KCl}$ at the 15 – 30 cm soil depth increment had a significant correlation with biomass, and correlations for shallower depths are not shown. STATISTICA software version 13 was used to conduct the statistical analyses (TIBCO, 2018).

5.3 Results and discussion

Year 1 (barley)

5.3.1 Plant parameters

Barley plant population was not affected ($p > 0.05$) by the treatments in Year 1 (Table 5.3). An optimal plant population for barley in the dryland production regions of the southern Cape is between 130 - 170 plants m^{-2} (ARC, 2019). A low plant population was recorded across all the treatments in Year 1. The plant populations were all below the optimal range, but were not below 50 plants m^{-2}, which is considered the threshold after which yield is significantly affected (GRDC, 2018).

Table 5.3. The mean (± standard deviation; SD) and p-value for plant population (m^{-2}), root biomass (kg ha^{-1}), above-ground biomass (kg ha^{-1}) and leaf area index for all the treatments measured in Year 1 (barley). DAE = Days after emergence, LAI = Leaf area index.

	Mean ± SD	**p**
Plant population (m^{-2})	100.9 ± 12.4	0.266
Root biomass 30 DAE (kg ha^{-1})	55.3 ± 22.6	0.603
Above-ground biomass 30 DAE (kg ha^{-1})	110.8 ± 26.1	0.776
Above-ground biomass 60 DAE (kg ha^{-1})	686.4 ± 255.0	0.453
Above-ground biomass 90 DAE (kg ha^{-1})	4122.0 ± 1059.8	0.601
LAI 30 DAE	0.3 ± 0.1	0.564
LAI 60 DAE	1.5 ± 0.6	0.516
LAI 90 DAE	4.1 ± 1.3	0.423

The below optimal plant populations recorded could be attributed to the high amount of weed pressure experienced in some plots from what seemed to be herbicide resistant ryegrass (*Lolium* spp.) and wild oats (*Avena fatua*) at the trial site.

The barley root biomass at 30 days after emergence showed no difference ($p > 0.05$) between treatments (Table 5.3). Neither above-ground biomass nor leaf area index of barley at 30, 60 and 90 days after emergence showed any effect ($p > 0.05$) from the treatments (Table 5.3). A treatment effect ($p \leq 0.05$) was however observed for the above-ground biomass of barley at 150 days after emergence (Figure 5.3). The treatments in which surface broadcast lime was incorporated with a disc plough, a chisel plough or a ripper had amongst the highest above-ground biomass at 150 days after emergence. The control, the 95% CCE lime treatment and the pelletised lime broadcast at 960 kg ha^{-1} with in-row placement treatment had amongst the lowest, however not always significantly, biomass at 150 days after crop emergence. The rest of the treatments were similar ($p > 0.05$) to the treatments with the lowest biomasses.

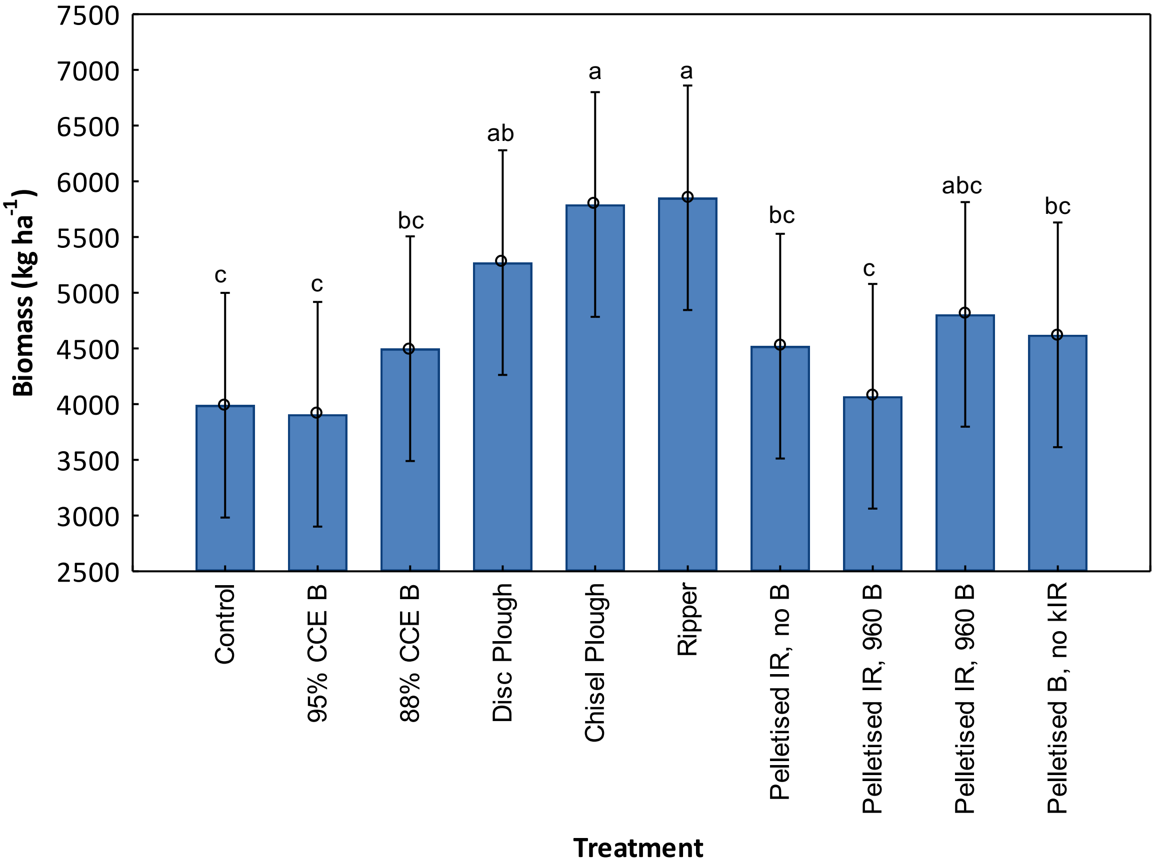

Figure 5.3. The mean above-ground biomass (kg ha^{-1}) of all the treatments at 150 days after emergence for barley (Year 1). Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement. P = 0.005, standard deviation = 1098.3.

When referring to the results in Chapter 4 of the current study, the pH_{KCl} of the tillage treatments deeper down the soil profile at a 15 – 30 cm depth was not higher ($p > 0.05$) than the other treatments. There was however a correlation ($p < 0.05$) between pH_{KCl} at a 15 – 30 cm depth and biomass at 150 days (Figure 5.4). The correlation between pH_{KCl} at a 15 – 30 cm depth and biomass at 150 days indicates the effect the tillage treatments have on lime redistribution to greater depths and thereby promoting crop growth and development.

Due to the slow reactivity and movement of lime in soil however (Caires et al., 2005; Miller, 2015), and the fact that the correlation between pH_{KCl} and biomass was only 0.41, it is unlikely that the higher above-ground biomass of the treatments in which lime was incorporated with a chisel plough, a disc plough or a ripper at 150 days was completely due to the treatment effects on lime redistribution within the first year of lime application. Tang et al. (2003) also reported significant increases (compared to an unlimed control) in above-ground biomass of barley at physiological maturity, however this was one year after lime was surface broadcast.

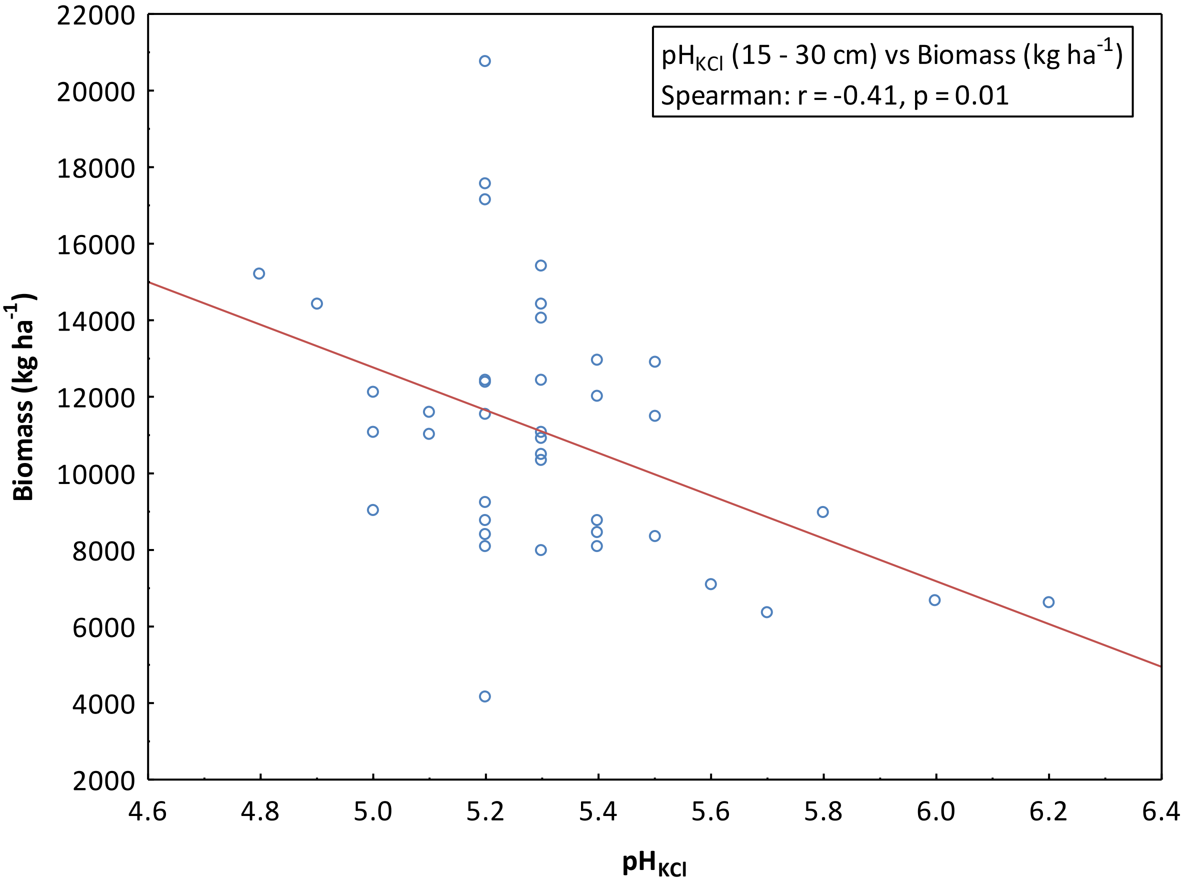

Figure 5.4. The correlation between biomass (kg ha^{-1}) at 150 days and pH_{KCl} at a 15 – 30 cm depth.

Therefore, there is a low probability that the barley biomass at 150 days was entirely influenced by liming the same year of lime application. This fact has implications on the management of lime application, as soil acidity will therefore have to be addressed in advance or a suitable pH will have to be maintained or else crop growth may be hindered until lime is given time to neutralise soil acidity.

The higher above-ground biomass production by physiological maturity (150 days after emergence) could have further be attributed to tillage effects such as an increase in nutrient mineralization and reduction of nutrient stratification (Quincke et al., 2007), alleviation of soil physical limitations (Hamza and Anderson, 2005), as well as more effective weed control (Crawford et al., 2014) of the tillage treatments. The reduced weed pressure in the plots in which the soil was more severely disturbed (by the chisel plough, disc plough or the ripper) was most likely the big contributing factor which could have promoted greater crop growth and development, leading to a higher above-ground biomass. Kettler et al. (2000), McLean et al. (2012), Crawford et al. (2014), Liu et al. (2016) and Dang et al. (2017) found that a one-off strategic tillage in a no-tillage system lead to a significant reduction in weeds including ryegrass (*Lolium* spp.) of which there was a high density of in some of the trial plots in Year 1.

A one-off strategic tillage in which lime is incorporated into the soil could thus be an effective means to promote crop growth and development, especially in the period shortly after lime application, through weed control as well as by increasing nutrient mineralization and reducing nutrient stratification and soil physical limitations. Implementing a one-off strategic tillage into systems that incorporates crop rotations could lead to even more effective weed control (MacLaren et al., 2020). Long-term no-tillage has led to an increased use of herbicides to control weeds, which have led to herbicide resistant weeds (Dang et al., 2015). A one-off tillage could thus result in a reduction in herbicide use by burying weed seeds to depths that will not allow for weed emergence (McGillion and Storrie, 2006).

There was no difference ($p > 0.05$) in terms of the effect the type of tillage action (chisel plough, disc plough or ripper) had on above-ground barley biomass production at 150 days. It can then be assumed that the type of tillage action in this study had the same effect on nutrient mineralization and reduction in stratification, alleviation of soil physical limitations and effectiveness of weed control. Liu et al. (2016), Dang et al. (2017) and Van Zyl (2017) reported no difference in tillage action in terms of weed control.

The number of spikelets per ear and the number of seeds per ear also showed no treatment effect ($p > 0.05$) in Year 1 (Table 5.4).

A treatment effect was however observed in the number of ear-bearing tillers (Figure 5.5). The broadcast lime incorporated with a ripper had the highest number of ear-bearing tillers although not significantly compared to the chisel or disc plough treatments. The control and the pelletised lime broadcast at 960 kg ha^{-1} with in-row placement treatment were among the treatments with the lowest number of ear-bearing tillers although only significantly if compared to chisel and ripper.

Table 5.4. The mean (± standard deviation; SD) and p value for the number of spikelets per ear and the number of seeds per ear measured for all the treatments for barley (Year 1).

	Mean ± SD	p
Number of spikelets per ear	17.8 ± 1.6	0.098
Number of seeds per ear	16.3 ± 1.6	0.100

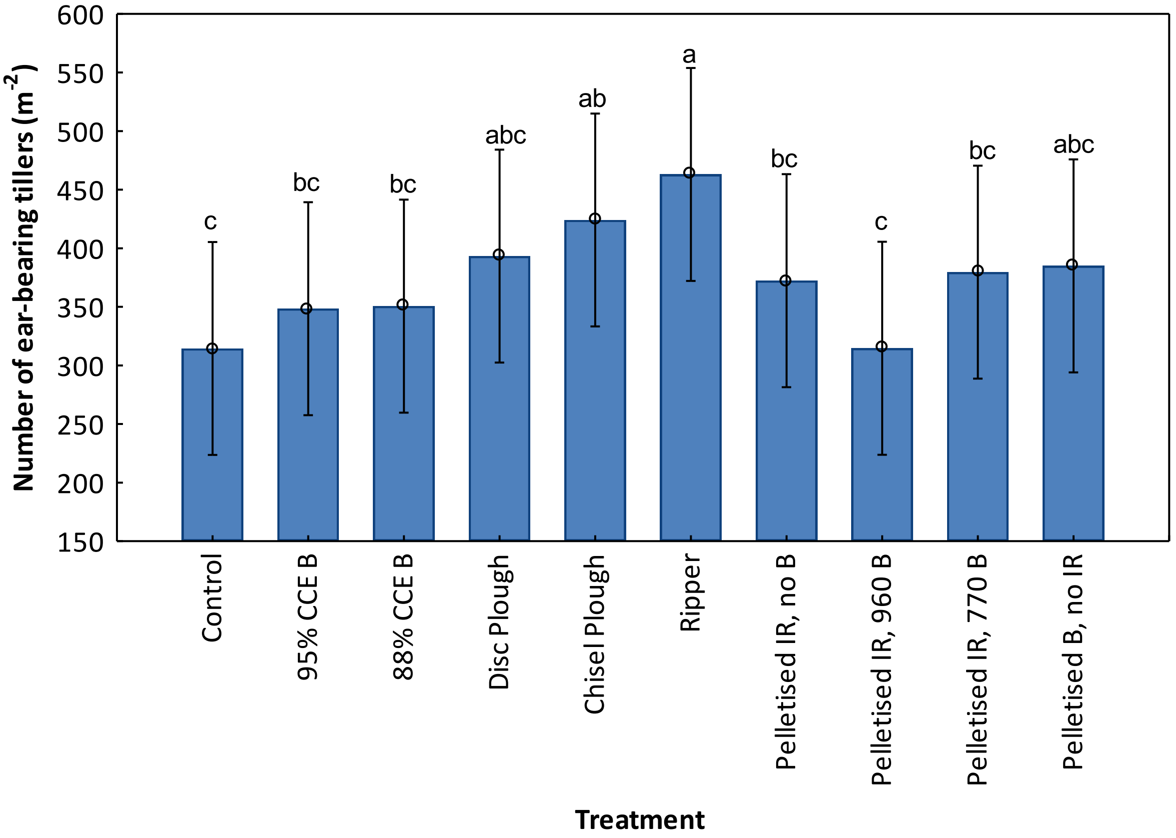

Figure 5.5. The mean number of ear-bearing tillers (m^{-2}) of all the treatments measured for barley (Year 1). Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement. P = 0.025, standard deviation = 89.8.

There was also a treatment effect ($p \leq 0.05$) observed for thousand kernel mass (Figure 5.6). The ripper treatment once again had the highest thousand kernel mass with the chisel plough and disc plough treatments having a similar thousand kernel mass. The 95% CCE lime broadcast treatment was one of the treatments with the lowest thousand kernel mass.

The higher number of ear-bearing tillers and thousand kernel mass for the chisel plough, disc plough and ripper treatments could once again be attributed to the effect that the tillage action had on crop growth rather than its effect on lime redistribution within the first year of lime application.

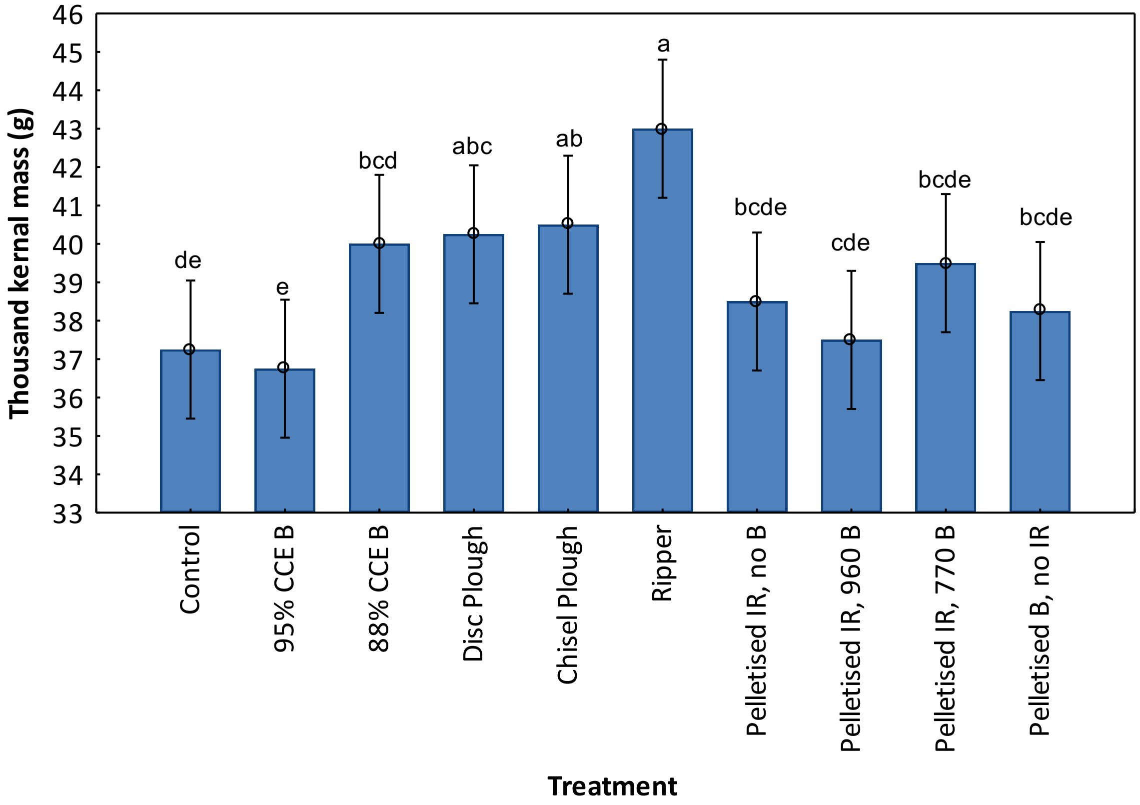

Figure 5.6. The mean thousand kernel mass (g) of all the treatments measured for barley (Year 1). Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement. P > 0.001, standard deviation = 2.4.

An increase in crop productivity due to reduced weed density for example following a one-off strategic tillage has been reported by Dang et al. (2017), regardless of which tillage action was used. All three of the tillage treatments did however not significantly (p > 0.05) affect crop productivity in terms of grain yield, which is similar to results from Baan et al. (2009), Wortmann et al. (2010), Lopez-Garrido et al. (2011), Liu et al. (2016) and Van Zyl (2017). Although grain yield showed no treatment effect (p > 0.05) in Year 1, the tillage treatments showed an inclination towards a higher yield (Figure 5.7). Kettler et al. (2000) and Díaz-Zorita et al. (2004) reported an increase in grain yield following a one-off strategic tillage, linking it to the reduction in weed density. Besides weed control, the effect of the tillage actions on increased nutrient mineralization, reduced nutrient stratification and alleviation of soil physical limitations could have further accounted for the trend of the tillage treatments to be inclined towards a higher yield. Conversely, Díaz-Zorita et al. (2004) reported a decrease in grain yield two years following a one-off strategic tillage.

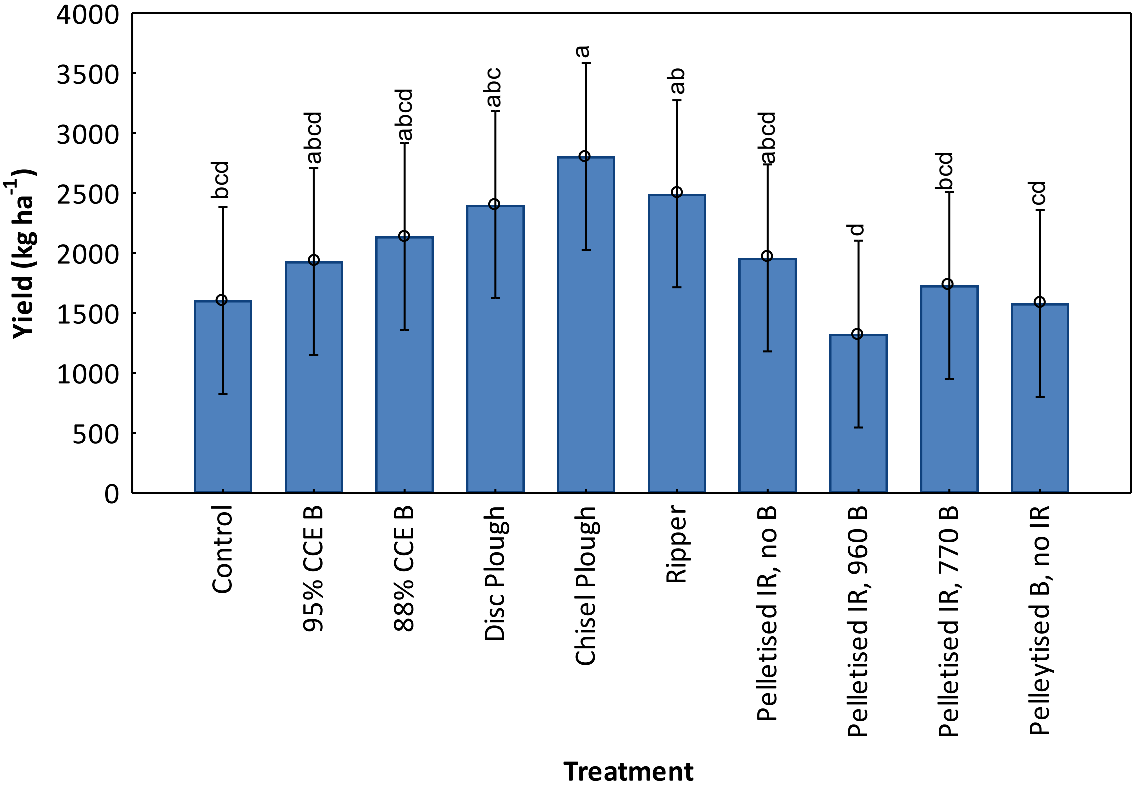

Figure 5.7. The mean yield (kg ha^{-1}) of all the treatments for barley (Year 1). Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement. P = 0.052, standard deviation = 805.1.

A low grain yield was recorded across all the treatments (between 1324 and 2805 kg ha^{-1}) compared to the average grain yield of the region for the five years prior to the trial, as well as the average grain yield of a barley line evaluation trial conducted in 2019 by AB-InBev and SABBI (2019) in the same region. The average grain yield of the five years prior to the study of barley (cv. Hessekwa) for the region was 4830 kg ha^{-1} (ARC, 2019), and the average grain yield for the line evaluation trial of the same barley cultivar in the region in 2019 was 5501 kg ha^{-1} (AB-InBev and SABBI, 2019).

The slow reactivity and movement of lime could have partially be accounted for the low grain yield as the soil would remain at a sub-optimal pH for crop growth while the lime is still reacting and moving down the soil profile within the first year after lime application. Tang et al. (2003) reported a 25% increase in barley yield compared to the control only a year after lime was surface applied. In the same study it was found that re-liming a previously limed soil increased the barley yield by over 50% a year after re-liming, indicating the positive effect of maintaining the soil pH at optimal levels and not only liming the soil once it is acid. Furthermore, Arshad et al. (1999) reported significant increases in barley yield only three and four years after lime was incorporated into the soil, once again highlighting the delayed benefits of liming on crop yield.

The low grain yield could also possibly be attributed to the high weed pressure experienced in some plots (GRDC, 2018). Furthermore, sub-optimal growing conditions during the season could also have led to the lower yield. Rainfall was below the long-term average and was poorly distributed (Figure 5.2) across the season. There was also a high spike in temperature during the critical flowering stage of the barley.

5.3.2 Quality Parameters

No difference ($p > 0.05$) was observed in the grain nitrogen content between the treatments in Year 1 (Table 5.5). The nitrogen content across all the treatments were ideal to produce high-quality malt, falling in the 1.7 – 2.1% range for which a premium is paid for malting barley grain (AB-InBev, 2019). The average grain nitrogen content for the region is 1.85% (ARC, 2019) of which all except one treatment in the trial (1.83%) had higher ($p \leq 0.05$) nitrogen contents.

Table 5.5. The means (± standard deviation; SD) and p values of the quality parameters measured for all the treatments for barley (Year 1). B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement.

	Mean ± SD	**p**
Nitrogen content (%)	2.0 ± 0.1	0.257
Plump kernels (%)	85.8 ± 6.3	0.163
Screenings (%)	0.7 ± 1.4	0.225

Hectoliter mass was also affected ($p \leq 0.05$) by the treatments in Year 1 (Figure 5.8). The surface broadcast lime incorporated with a disc plough had of the highest hectoliter masses but only differed from the pelletised lime broadcast at 960 kg ha^{-1} with in-row placement treatment and the pelletised lime broadcast with no in-row placement.

Top grade malting barley should have a hectoliter mass of no less than 65 kg hL^{-1} (NSW, 2010). Despite there being differences ($p \leq 0.05$) in hectoliter mass between the treatments, all of the treatments had a hectoliter mass of above 65 kg hL^{-1}.

The percentage of pump kernels and screenings did not differ ($p > 0.05$) between the treatments (Table 5.5). The percentage of plump kernels is indicative of the grade of the grain as plump kernels contain more starch which in turn will produce more beer from a given weight of malt (MacLeod, 2013). Malting barley is required to have a minimum plumpness of 70% and have maximum screenings of 5% (AB-InBev, 2019). The average grain plumpness for the Caledon region for the past 5 years was 95.63% (ARC, 2019) and in the line evaluation trial of the region by AB-InBev and SABBI (2019) a plumpness of 85.0% and screenings of 2.4% were recorded. All the treatments had a plumpness of between 98.5 and 100% with maximum screenings of 2%, which is indicative of high-grade grain for malt production.

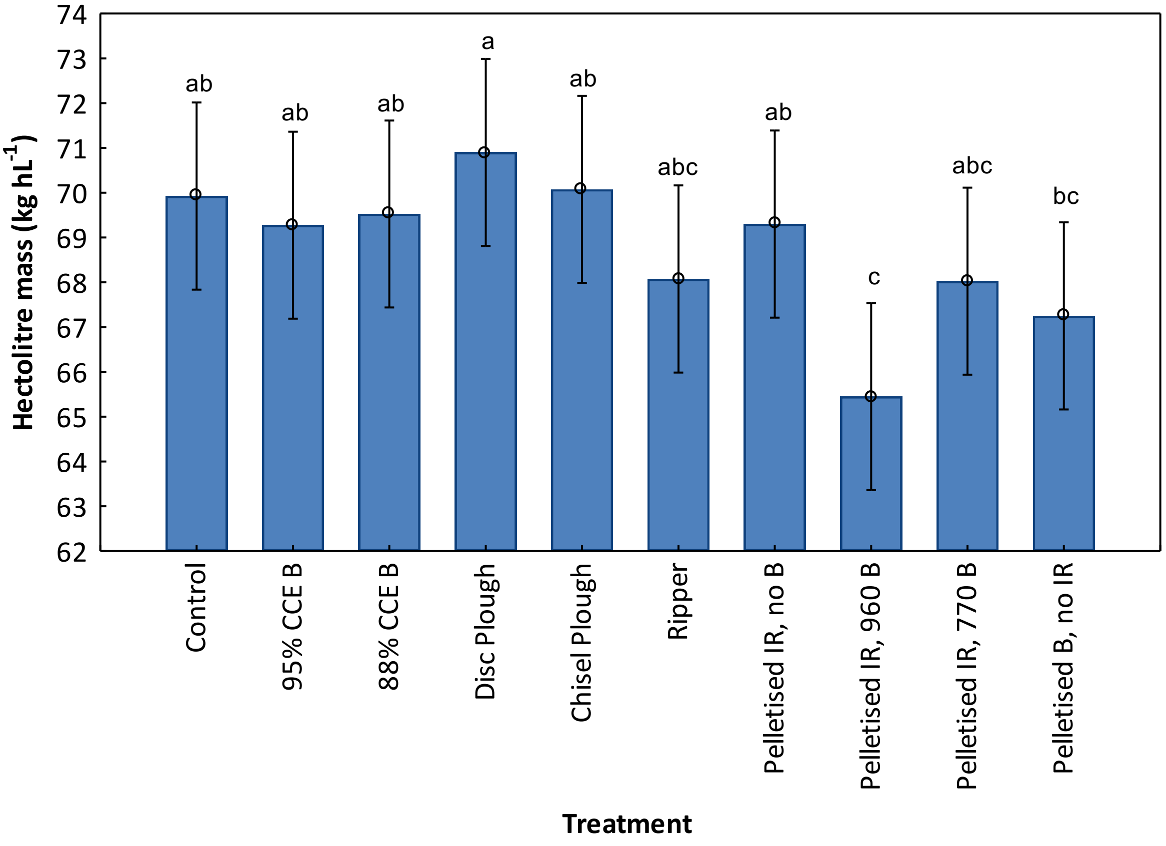

Figure 5.8. The mean hectoliter mass (kg hL^{-1}) of all the treatments measured for barley (Year 1). Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement. P = 0.035, standard deviation = 2.4.

Year 2 (canola)

5.3.3 Plant parameters

There was no treatment effect ($p > 0.05$) in Year 2 for canola biomass (60, 90 and 150 DAE) or leaf area index (60 and 90 DAE) (Table 5.6). The tillage treatments therefore resulted in a higher ($p \leq 0.05$) biomass at physiological maturity in Year 1 due to the reduced weed pressure but not in Year 2. These findings are in line with studies by Dang et al. (2017), Conyers et al. (2019) and Van Zyl (2017) who also reported positive effects of strategic tillage on dry matter production due to weed control within the first year after tillage, but no positive effects in the subsequent years.

Table 5.6. The mean (± standard deviation; SD) and p value for above-ground biomass (kg ha^{-1}) and leaf area index for all the treatments measured in 2 (canola). DAE = Days after emergence, LAI = Leaf area index.

	Mean ± SD	**p**
Above-ground biomass 60 DAE (kg ha^{-1})	3069.5 ± 717.0	0.254
Above-ground biomass 90 DAE (kg ha^{-1})	7961.7 ± 2647.0	0.443
Above-ground biomass 150 DAE (kg ha^{-1})	11007.4 ± 3401.6	0.240
LAI 60 DAE	2.6 ± 0.7	0.062
LAI 90 DAE	1.4 ± 0.6	0.338

A treatment effect ($p \leq 0.05$) on plant population was however observed in Year 2, following the establishment of canola (Figure 5.9). Both the treatments where lime pellets were placed in-row and broadcast (at a rate of 770 and 960 kg ha^{-1}) had amongst the lowest plant populations. The local target plant population for canola in South Africa is between 50 and 90 plants m^{-2} (DAFF, 2010), but Bucat and Seymour (2019) reported no negative response when plant population is as low as 20 plants m^{-2}. A plant population of less than 20 plants m^{-2} increases the risk of higher weed pressure, which ultimately reduces growth and development (GRDC, 2017).

Lime pellets placed in-row leads to a concentration of lime where the planting rows were the previous year, and thus the uneven distribution of lime in these plots could have negatively affected the emergence of the canola in Year 2.

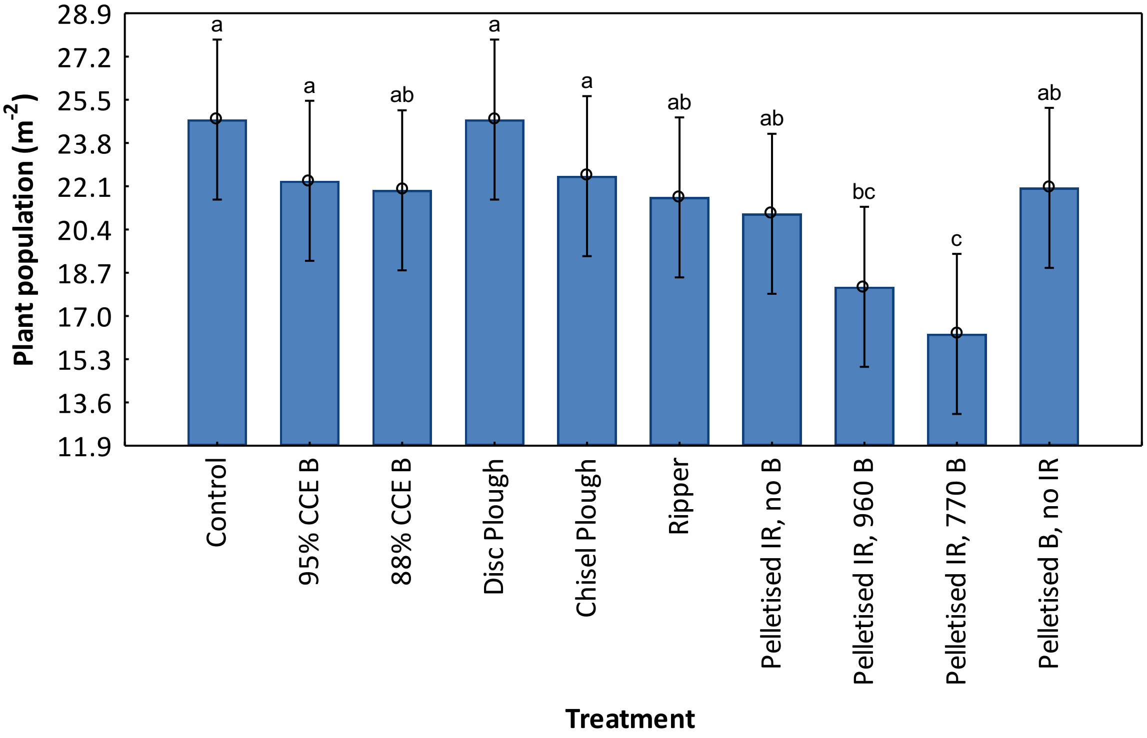

Figure 5.9. The mean plant population (m^{-2}) for all the treatments measured for canola (Year 2). Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement. P = 0.006, standard deviation = 3.7.

A difference ($p \leq 0.05$) in treatments were observed in the number of branches per plant in Year 2 (Figure 5.10). The treatment in which surface broadcast lime was in incorporated with a ripper produced the greatest ($p \leq 0.05$) number of branches. A higher number of branches is usually associated with greater spaces in between plants (lower plant density) and thus crops try to compensate for yield losses by producing more side branches (DAFF, 2010). In this case, however, the ripper treatment did not have a lower plant population compared to the other treatments.

The greater potential for root growth and expansion created by the breaking up of the soil as well as more effective weed control (and thus fewer plants per m^{-2} in total) by the ripper could have led to the development of larger canola plants with more side branches.

There was no difference ($p > 0.05$) in leaf Ca and Mg concentrations between treatments in Year 2 (Table 5.7). Furthermore, all treatments had a Ca and Mg concentration that was higher than the threshold values for production standards of the USA, Canada and South Africa (Campbell, 2000; Canola Council of Canada and 2017; FERTASA, 2016).

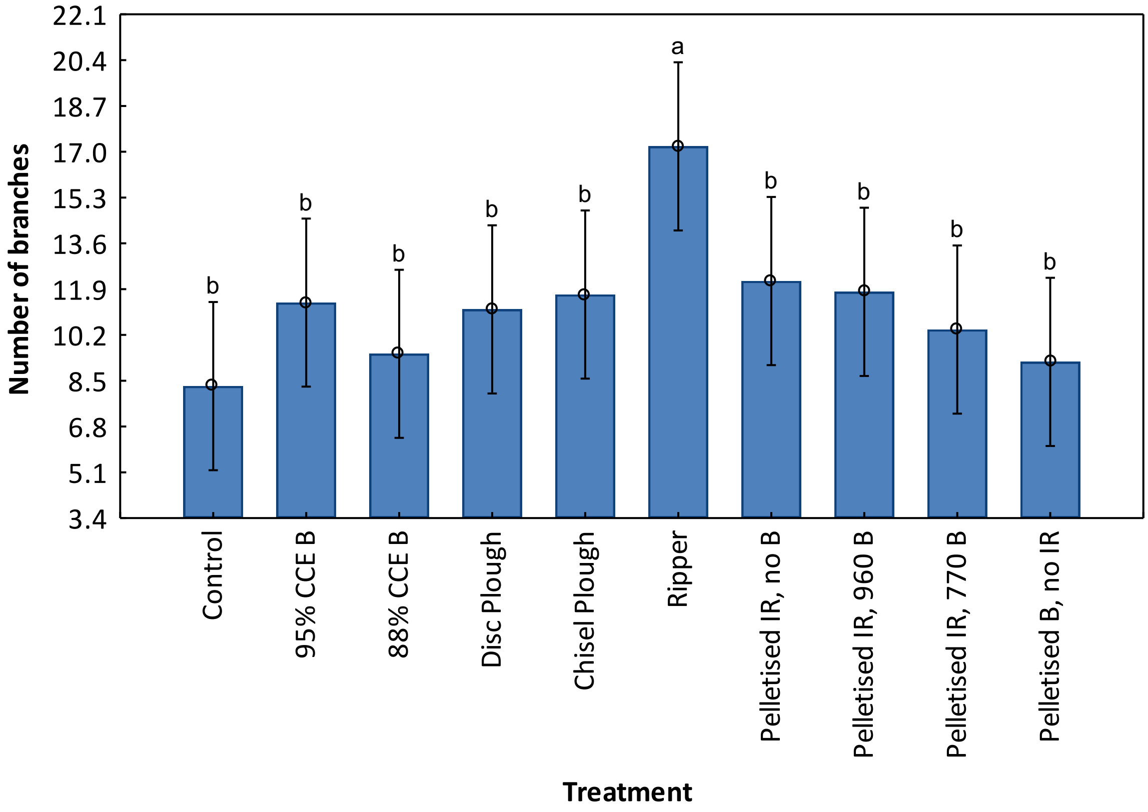

Figure 5.10. The mean number of branches for all the treatments measured for canola (Year 2). Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement. P = 0.029, standard deviation = 3.6.

Table 5.7. The mean (± standard deviation; SD) and p value of leaf Ca content (%), leaf Mg content (%), thousand kernel mass (g) and grain yield (kg ha^{-1}) measured for all the treatments in of canola (Year 2).

	Mean ± SD	**p**
Leaf Ca content (%)	4.1 ± 0.7	0.264
Leaf Mg content (%)	0.3 ± 0.1	0.521
Thousand kernel mass (g)	41.6 ± 3.6	0.164
Grain yield (kg ha^{-1})	2263.8 ± 381.7	0.569

No treatment effect was observed in terms of thousand kernel mass between treatments in Year 2 (Table 5.7).

There was no treatment effect ($p > 0.05$) on grain yield in Year 2 (Table 5.7). The average grain yield for canola in the local area is between 1.3 – 1.8 t ha^{-1} depending on climatic conditions (Human, 2020). Both Arshad et al. (1997) and Scott et al. (2003) reported a significant increase in canola yield 1 and 3 years after lime application respectively, which could be due to the fact that the lime was able to neutralise soil acidity at a greater depth over time. In the trial however, the control also showed high yields and thus the crop growth was most likely not a response to lime a year after application, rather, the high yields recorded in Year 2 could be attributed to highly favourable climatic conditions.

5.3.4 Quality parameters

A difference ($p \leq 0.05$) was observed in seed oil content between treatments (Figure 5.11). The ripper treatment had amongst the lowest seed oil content. Oil content is generally related to genetic or climatic conditions and not to seed size for example (Edwards et al., 2015). The larger ($p \leq 0.05$) number of side branches by the ripper treatment could however have contributed to more seeds per plant, but of lower quality (oil content). All the treatments showed adequate seed oil content which should be around 30 – 49% (Flipova et al., 2017).

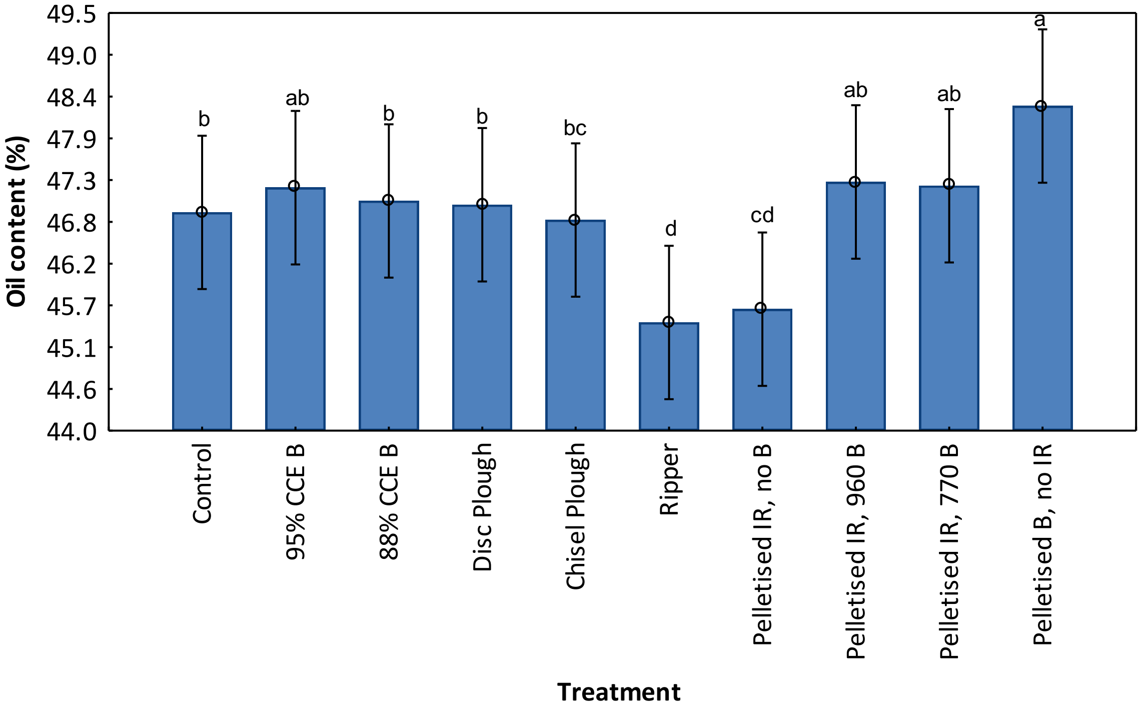

Figure 5.11. The oil content (%) of all the treatments measured for canola (Year 2). Common letters indicate no significant difference. B = Broadcast, CCE = Calcium carbonate equivalent, IR = In-row placement. P = 0.004, standard deviation = 1.2.

5.4 Conclusion

The slow movement and reactivity of lime in soil is evident, and it is unlikely to see major crop responses from lime within the first or even second year of liming 810 - 1000 kg ha^{-1} of lime on a sandy loam soil that received a total of 558 mm of rainfall. Regardless of the fineness, form or purity of lime applied, or the degree to which lime is incorporated into the soil, the application of lime will not result in significant crop responses within two years of lime application. There is however an inclination towards a trend for a one-off strategic tillage to result in greater crop growth and productivity, especially with the same year of tillage, even before lime is able to show major crop responses. The positive response of crop growth to a one-off strategic tillage is most likely attributed to deeper redistribution of lime in the soil (15 – 30 cm depth), an increase in nutrient mineralisation and decrease in nutrient stratification, alleviation of soil physical limitations and reduced weed pressure. Furthermore, micro-fine pelletised lime applied in-row, surface broadcast or both, does not lead to a greater crop growth and productivity within two years following liming compared to conventional surface broadcast class A lime.

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CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Soil acidity and especially the stratification of soil acidity with increasing depth has become a challenge to producers, especially in the Western Cape Province of South Africa, where no-tillage has been used over a long term (> 20 years). The slow movement of lime in soil combined with the lack of incorporating lime deeper into the soil with soil disturbing actions, as in conventional practises, has ultimately lead to the intensification of acid stratification with depth over time (Flower and Crabtree, 2011; Barth et al., 2018).

A soil survey was conducted (*Objective 1*) in order to determine the extent of soil acidity and pH stratification on long-term no-tillage soils across the Western Cape Province (southern Cape and Swartland area). From the data of the survey, a greater understanding of the true state of the soils in terms of soil acidity and stratification in these production systems was acquired.

Furthermore, a field trial consisting of ten treatments was set up in order to determine the effect of lime characteristics and incorporation of lime with tillage actions on lime movement and acid neutralisation. The form, fineness and placement of lime was evaluated as well as the effect of soil disturbance on soil chemical attributes (*Objective 2*) and crop growth and development (*Objective 3*).

Objective 1: Determining the extent of soil acidity and pH stratification on long-term no-tillage soils across the southern Cape and Swartland area

Despite the fact that the mean overall pH_{KCl} across the entire surveyed area was optimal for the production of wheat, barley and canola, there was a however large portion of soils in the Swartland that were too acid for the optimal production of these crops (Liebenberg et al., 2020). A total of 19.3% of the Swartland soils that were sampled had a pH_{KCl} of less than 5.0, which is below the optimal pH for wheat, barley and canola production. The majority of the acidity in these Swartland soils were found in the 5 – 15 cm depth increment where surface applied lime was most likely not able to reach (due to the slow movement of surface applied lime), confirming the presence of acid stratification in long-term no-till soils.

The less acid soils in the southern Cape could be attributed to more calcareous parent materials (Grieve, 1991) and higher clay contents in these soils, therefore having a greater buffering capacity against pH change (Nathan, 2020). Although many parts of the southern Cape were surveyed, the area is characterised by soil and landscape heterogeneity, and some areas that were not surveyed could possibly have led to a distortion of the overall state of the soils in the southern Cape. Soils more inland, closer to the mountain ranges running parallel to the coast, were not well-represented in the survey. These soils typically have parent materials with a lower natural pH or a sandier soil texture with a lower buffering capacity. Investigating these soils could potentially reveal soils with a similar state of acidity as found in the Swartland area.

Despite the clear findings of acidity or lack thereof in soils sampled across the survey, it is important to note that for accurate management of soil acidity in these areas, respective fields should be analysed and managed individually and not according to deductions made from the survey which covered a widespread area.

Objective 2: Determining the effect of form, fineness and placement of lime with and without soil disturbance on soil chemical attributes

The pH_{KCl} of a sandy loam soil receiving 810 - 1000 kg ha^{-1} of lime and a total of 558 mm of rainfall, can be raised by 0.43 pH_{KCl} units at a 0 – 5 cm depth and by 0.36 and 0.40 at a 5 – 15 cm and 15 – 30 cm depth respectively, one year after liming, regardless of the purity, form, fineness of lime and degree of incorporation. Although the control treatment where no lime was applied also lead to an increase in pH_{KCl}, more research is required to confirm these results.

Broadcasting pelletised micro-fine lime at the recommended rate however, increased pH_{KCl} three months after liming to a 30 cm depth. Broadcasting pelletised fine lime at the recommended rate therefore, leads to the greatest as well as the quickest ($p \leq 0.05$) decrease ($p \leq 0.05$) in soil acidity at a 0 – 5 cm depth as well as the quickest ($p \leq 0.05$) increase in pH_{KCl} at a 5 - 15 cm depth and amongst the quickest (three months after liming) increase in pH_{KCl} at the 15 – 30 cm depth. Applying less than the recommended rate (in-row or in-row and broadcast) will not lead to more effective neutralisation of soil, despite recommendations sometimes made in industry regarding the application of lime pellets that fine lime may have a more effective neutralisation capacity.

Objective 3: Determining the effect of form, fineness and placement of lime with and without soil disturbance on barley and canola growth and development

It is unlikely to see crop (barley and canola) responses from lime within the first or even second year after liming 810 - 1000 kg ha^{-1} of lime on a sandy loam soil that received a total of 558 mm of rainfall, despite the increase in pH$_{KCl}$ from different forms, purity, fineness and incorporations of lime.

A one-off strategic tillage does however show an inclination towards greater crop growth and productivity, especially within the same year of tillage regardless of the limited lime movement and reactivity in that time period. One-off tillage can result in deeper redistribution of lime in the soil (15 – 30 cm depth), increase nutrient mineralisation and decrease nutrient stratification, alleviate of soil physical limitations as well as reduced weed pressure, which is most likely why there was a positive crop response following tillage.

Furthermore, micro-fine pelletised lime applied in-row, surface broadcast or both, does not lead to a greater crop growth and productivity within two years following liming compared to conventional surface broadcast class A lime.

6.1 General conclusion

Soil acidity and stratification in long-term no-tillage systems in the Western Cape Province is evident. Increasing the soil pH$_{KCl}$ can be achieved similarly using conventional class A lime (with a Calcium carbonate equivalent of 88 – 95%), micro-fine pelletised lime broadcast or placed in-row and broadcast or incorporating surface broadcast lime with different tillage actions (disc plough, chisel plough or ripper). Only placing pelletised lime in-row at the low rate of 40 kg ha^{-1} will result in the smallest change in pH$_{KCl}$ at a 0 – 5 cm depth. Surface broadcasting micro-fine lime at the recommended rate will lead to the quickest (three months after liming) and greatest change in pH$_{KCL}$ up to a depth of 30 cm, however, a greater crop response will not necessarily be evident.

Incorporating a one-of strategic tillage with either a disc plough, chisel plough or ripper tillage can result in deeper redistribution of lime in the soil (15 – 30 cm depth) and promote nutrient mineralisation, decrease nutrient stratification, alleviate soil physical limitations and reduce weed pressure, which will in turn promote crop growth and development.

6.2 Recommendations for future research

Combining the application of conventional and pelletised lime could be further investigated. The application of the two lime forms could be investigated by combining in-row placement of lime pellets with surface broadcasting of conventional lime (instead of pelletised lime) or the broadcasting of both conventional and low annual rates of pelletised lime. The quick and effective neutralisation effects of fine pelletised lime is evident, however not at low rates and therefore the combination of conventional and pelletised lime could allow for the benefits of pelletised lime, whilst still applying sufficient amounts of lime. Due to the effectiveness of applying pelletised lime at the recommended rate, an investigation regarding the economic feasibility could also be conducted.

The combination of applying both lime and gypsum in order to address soil acidity and acid stratification could also be a topic of more in depth future research.

Researching strategies regarding the building up and maintaining of soil pH by various practises such as annual in-row placements of lime to spread the in-row lime application across field over time could also be valuable. Furthermore, longer trial periods (more than two years) could be conducted in the future, as liming is usually done every four years and it would thus be relevant to attain knowledge of the movement and acid neutralisation of lime three and four years after liming.

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APPENDIX A

Liebenberg, A, Van der Nest, JRR, Hardie, AG, Labuschagne, J, Swanepoel, PA. **2020** Extent of soil acidity in no-tillage systems in the Western Cape province of South Africa. *Land*, 9, p361.

APPENDIX B

Letter of Consent

STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Dear participant *(Afrikaans onder)*

Ruan van der Nest and Adriaan Liebenberg are MSc students at the Stellenbosch University. We are busy with a survey about soil acidity and liming methods on farms that are under minimum tillage and we would like to invite you to take part in a survey, the results of which will contribute to a research project in order to complete MSc degrees. The aim of this survey is to get an idea of how widespread soil acidity is across the Southern Cape and Swartland areas. The questionnaire which forms part of the survey will be used to determine possible correlations between liming methods and tillage practises.Your participation is entirely voluntary and you are free to decline to participate. If you say no, this will not affect you negatively in any way whatsoever. You are also free to withdraw from the study at any point, even if you do agree to take part.

The information from the soil samples and response to the survey will form part of the above mentioned students MSc thesis, scientific articles and popular articles, which may possibly be published. All information will be kept anonymous and at no stage will an individual's questionnaire be made available to any other party. All information from the questionnaire will be published in a processed form only.

If you have any questions or concerns about the research, please feel free to contact the researcher (JR van der Nest, 0793523853 or 19009976@sun.ac.za) and/or the Supervisor, Dr Pieter Swanepoel (pieterswanepoel@sun.ac.za)

Adriaan Liebenberg en Ruan van der Nest is MSc studente aan die Universiteit Stellenbosch wat 'n opname doen oor grondsuurheid en bekalkingsmetodes op plase wat minimumbewerking toepas. Die doel van hierdie opname is om 'n geografiese beeld van die verspreiding van ondergrondse suurheid deur die Suid-Kaap en Swartland, te vorm. Die vraelys vorm deel van die opname om moontlike korrelasies tussen bekalkingsmetodes en bewerkingspraktyke te kan identifiseer.

Deelname aan hierdie opname is vrywillig en indien u besluit om deel te neem aan hierdie opname, kan u enige tyd besluit om te onttrek van die opname. Indien u besluit om sekere vrae in die vraelys oop te laat, behou ons die reg om die inligting wat u wel verskaf, te gebruik.

Inligting vanuit die vraelys, asook resultate van grondontledings sal deel vorm van die betrokke studente se MSc tesisse, wetenskaplike artikels en populêre artikels wat moontlik gepubliseer gaan word. Alle inligting gaan anoniem hanteer word en op geen stadium gaan individuele vraelyste se inligting bekend gemaak word nie, alle inligting wat vanaf vraelyste ingewin sal word, sal slegs in 'n verwerkte vorm gepubliseer word.

As U enige vra het oor die navorsing, kontak of Ruan van der Nest (0793523853 of 19009976@sun.ac.za) en/of die studieleir, Dr Pieter Swanepoel pieterswanepoel@sun.ac.za

RIGHTS OF RESEARCH PARTICIPANTS:

You have the right to decline answering any questions and you can exit the survey at any time without giving a reason. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research participant, contact Mrs Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

DECLARATION OF CONSENT BY THE PARTICIPANT

As the participant I confirm that:

- I have read the above information and it is written in a language that I am comfortable with.
- I have had a chance to ask questions and all my questions have been answered.
- All issues related to privacy, and the confidentiality and use of the information I provide, have been explained.

By signing below, I ________________________________ agree to take part in this research study, as conducted by ____

____ ______________________

Signature of Participant **Date**

AFDELING A: ALGEMENE BESTUUR OP PLAAS

1. Hoe word u kalkbehoefte vir toediening bepaal, met grondmonsters of vasgestelde hoeveelheid as deel van stelsels?

Grondmonsters ☐
Vasgestelde hoeveelheid/ onderhoud ☐

1.1. Indien grondmonsters geneem word:

Tot op watter diepte? ________________________________

1.2. Indien vasgestelde hoeveelheid:

Watter peil kalk is toegedien? __________________________

2. Word Albrecht-beginsels gevolg om kalkbehoefte te bepaal?

Ja ☐

Nee ☐

Ek is nie vertroud met die Albrecht-stelsel nie ☐

3. Watter kalkbron word gebruik?

Kalsities ☐

Dolomities ☐

Volgens behoefte ☐

4. Watter vorm van kalk is toegedien?

Klas A (gewone kalk) ☐

Gehidreerde kalk ☐

Korrels ☐

Ander: ______________________

5. Beskryf asseblief die implement wat gebruik word om kalk toe te dien:

____

____

____

____

6. Wanneer word kalk toegedien?

Na-oes ☐ Voor plant ☐ Tydens plant ☐

7. Word kalk volgens presisieboerdery toegedien (GPS in veld)?

Ja ☐ Nee ☐

8. Word kalsium (Ca) bemesting ook toegedien?

Ja ☐
Nee ☐
Volgens behoefte ☐

Bron indien bekend: _________________________

**Let wel: KAN is 3% Ca*

9. Wanneer word kalsium bemesting toegedien?

Na-oes ☐ Voor plant ☐ Tydens plant ☐

AFDELING B: KAMP-SPESIFIEKE INLIGTING

Vul asseblief inligting oor die vier kampe waar grondmonsters geneem word in:

Kamp nommer			
Gewasrotasie wat in die spesifieke kamp gevolg word			
Watter gewas gaan in die huidige seisoen geplant word?			
Hoeveel kalsium bemesting is toegedien tydens die laaste toediening?			
Watter bron van kalsium word toegedien?			
Notas oor die spesifieke kamp wat noemenswaardig kan wees			

APPENDIX C

		Mesh size (% volume under)					%	
Name	**CCE**	**325**	**200**	**100**	**60**	**40**	**Ca**	**Mg**
Vredendal - Class A	95	20	28	45	64	79	39	0.45
Bredasdorp - Class A	88	19	23	42	68	89	34	0.39
Reacti-cal - Micro-powder	93	94	98	99	100	100	37	0.77
Reacti-cal - Granules	93	94	98	99	100	100	37	0.77