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Effects of long-term (42 years) tillage sequence on soil chemical characteristics in a dryland farming system

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Abbreviations: CEC = cation exchange capacity; CP = conventional ploughing; MB = mouldboard; NT = no-till; SOC = soil organic carbon; ST = shallow tine-tillage; TT = tine-tillage

Abstract

No-tillage can improve soil quality but can also increase the stratification of soil chemical parameters. Nutrient uptake by crops might be limited when nutrients are stratified, especially in semi-arid or Mediterranean regions. To reduce stratification, infrequent tillage could be considered. However, there is a paucity of information on the effects of long-term infrequent tillage on the stratification of soil chemical parameters. This study aimed to assess the effects of long-term infrequent tillage on the stratification of selected soil chemical parameters to a depth of 300 mm. The research was conducted on a long-term (42 years) research site at Langgewens Research Farm in South Africa. Seven tillage treatments were investigated: continuous mouldboard ploughing to a depth of 200 mm, tine-tillage to 150 mm, shallow tine-tillage to 75 mm, no-tillage, shallow tine-tillage every second year in rotation with no-tillage, shallow tine-tillage every third year in rotation with no-tillage and shallow tine-tillage every fourth year in rotation with no-tillage. Tillage treatments had differential effects on the distribution of soil chemical parameters. The mouldboard plough prevented stratification of most soil chemical parameters, such as soil acidity, soil organic carbon (SOC), extractable P, exchangeable Ca and Mg and cation exchange capacity (CEC). However, mouldboard ploughing also led to significantly lower SOC stocks and extractable P stocks. The SOC stocks and extractable P stocks of the no-tillage treatment were not significantly different from those of the infrequent tillage treatments. Overall, the infrequent tillage treatments were no better ($P > 0.05$) than the no-tillage treatment as infrequent tillage could not effectively ameliorate the stratification of most soil chemical parameters and did not increase the stocks and stratification ratios of SOC and extractable P.

Keywords: *Infrequent tillage, tillage sequence, no-tillage, nutrient stratification.*

1. Introduction

Soil tillage is described as the mechanical manipulation of soil for crop production (Busari et al., 2015). The development and use of tractors and tillage implements such as the mouldboard and disc ploughs have facilitated the increased frequency and depth of soil disturbance through tillage (Hobbs et al., 2008; Kassam et al., 2009). Soil tillage significantly affects various soil characteristics, *inter alia*, soil water holding capacity, infiltration rate (Das et al., 2018), soil temperature (Kladivko, 2001) and bulk density (Swanepoel et al., 2017). Tillage can be an effective method of controlling weeds and preparing a suitable environment for plant growth (Lal et al., 2007). However, increased tillage intensity or frequency has been identified as a major contributor to soil degradation (Dendooven et al., 2012; Hobbs et al., 2008; Lal, 2001; Swanepoel et al., 2015) as it leads to more soil erosion, compaction, soil organic carbon (SOC) depletion and decreased soil microbial activities (Derpsch, 2004; Swanepoel et al., 2015).

To combat the constraints that arise from frequent tillage, no-tillage (NT) has been promoted as an alternative method to establish crops, while also enhancing soil quality (Busari et al., 2015; Haarhoff et al., 2020; Swanepoel et al., 2015; Wezel et al., 2014). One outcome of these NT practices is an increased frequency of nutrient stratification (Franzluebbers, 2002a, 2002b), whereby some nutrients become concentrated in the top few centimetres of the soil (Kirkegaard et al., 2014; Moreno et al., 2006). This stratification can have beneficial effects. For example, stratification of SOC may enhance the soil surface characteristics, such as soil aggregation and improved soil aeration, leading to more effective water infiltration (Franzluebbers, 2002a; Franzluebbers et al., 2007; Grove et al., 2007; Zhao et al., 2015). Nutrient stratification can, however, become a problem if the topsoil dries out. Immobile nutrients such as phosphorus may become adsorbed to the soil particles (Shen et al., 2011) and unavailable for uptake by crops. Crop growth and productivity may, therefore, be severely reduced. To mitigate the negative impacts of NT arising from nutrient stratification, some farmers may resort to strategic tillage, which is one-off tillage of a field under no-tillage (Dang et al., 2018; Kirkegaard et al., 2014). Alternatively, infrequent tillage practices might be considered as an option to ameliorate the nutrient stratification problem.

In contrast to strategic tillage, infrequent tillage refers to specific tillage sequences (or tillage rotations) that are planned to occur periodically. For example, tillage is conducted after one year (or growing season) of no-tillage, or after two, or three years of no-tillage. To date, most studies on nutrient stratification have reported on one-off tillage applications in no-tillage soils (Dang et al., 2018; Kirkegaard et al., 2014; Leygonie, 2016), but little is published on the effects of infrequent tillage. Only long-term studies can shed light on the impacts of infrequent tillage on soil characteristics. This study was conducted within a 42-year-old long-term tillage trial and aimed to determine the effect of tillage and infrequent tillage on the distribution of key soil chemical parameters within the top 300 mm soil profile.

2. Material and methods

2.1 Site description

The research was conducted at Langgewens Research Farm (33°17ˈ0.78ˈˈ S, 18°42ˈ28.09ˈˈ E) of the Western Cape Department of Agriculture, in the Swartland region of South Africa. The Swartland region has a Mediterranean-type climate. The Köppen-Geiger climate classification is Csa (warm temperate climate with hot, dry summer). Langgewens receives an average long-term (55 years) annual rainfall of 395 mm (standard deviation = 101.1 mm), of which approximately 80% falls between April and September.

The trial site had a 300 mm shallow lithic soil, locally known as a Glenrosa-soil form (Soil Classification Working group, 1991) or internationally, as Haplic Cambisols (Fey, 2010; IUSS Working Group WRB, 2015) The soil at the trial site has a 14.7% clay content (excluding the gravel and stone content), whilst the gravel and stone content in the A horizon is about 45% (Maali and Agenbag 2003).

2.2 Trial history and current treatments

The long-term tillage trial was started in 1976. The trial was laid out in a randomised block design with four replicated blocks. Each block had 14 plots and each plot measured 50 m x 6 m. The blocks were separated by a buffer zone of 9 m, and plots were separated by a 1 m buffer zone. The tillage treatments included conventional ploughing (CP), tine tillage (TT) and no-tillage (NT) (Agenbag, 2012; Agenbag and Maree, 1989). Conventional ploughing included primary tillage with a mouldboard plough to a depth of 200 mm in April or after the first autumn rains, followed by secondary tillage with a one-way disc plough at 120 mm depth and seeding with a seed-drill in May. The primary tillage for the TT treatment was done by a chisel plough to a depth of 150 mm, followed by a field cultivator at a depth of 100 mm and seeding with a seed drill. The NT treatment did not have any primary tillage. Herbicides were applied in the NT plots before seeding with a seed-drill fitted with tine furrow openers (Agenbag and Maree, 1989).

Increased production costs and soil deterioration forced farmers in the Western Cape to shift from conventional mouldboard and disc ploughing to shallow tine- and no-tillage methods (Agenbag and Maree, 1991; Swanepoel et al., 2016). The cropping system and tillage treatments on the research site were, therefore, changed to meet the needs of the local farming community. In 1990 the long-term trial was split into continuous wheat (*Triticum aestivum*) production and a four-year rotation system where wheat was rotated with lupins (*Lupinus* spp.) and canola (*Brassica napus*). Four-year crop rotation sequences used were continuous wheat (WWWW) and wheat/lupin/wheat/canola (WLWC) (Maali and Agenbag 2006; Agenbag 2012). The tillage treatments were changed to include minimum-tillage treatments, but the CP, TT and NT treatments in the continuous wheat system were still applied on the same plots as before (Agenbag, 2012). From 1990, the tillage treatments included: (i) a modified conventional ploughing treatment, herewith referred to as the mouldboard (MB) treatment. Unlike the conventional ploughing treatment mentioned earlier, the MB treatment involved ploughing with a chisel plough to a depth of 150 mm after the first autumn rains, followed by a mouldboard plough at a depth of 200 mm and field cultivator at a depth of 50 mm before planting time. (ii) The TT treatment continued as described previously. (iii) The shallow tine-tillage (ST) involved primary tillage with a chisel plough (75 mm) after the first autumn rains, followed by a non-selective herbicide before seeding. (iv) The NT treatment relied on chemical weed control as described previously. (v) ST every second year in rotation with NT, (ST-NT). (vii) ST every third year in rotation with NT, (ST-NT-NT). (vii) ST every fourth year in rotation with NT, (ST-NT-NT-NT).

In 2018, the ST-NT treatment sequence received the ST treatment whilst the ST-NT-NT and ST-NT-NT-NT treatment sequences both received the NT treatment.

The underlined treatment in the sequence indicates the tillage treatment conducted in 2018.

In November 1999, all plots were cultivated to a depth of 75 mm to incorporate calcitic lime (2000 kg ha^{-1}) into the soil (Maali and Agenbag, 2003). Lime was also applied by broadcasting (no incorporation through tillage) in 2001, 2005 and 2016 at a rate of 2000 kg ha^{-1} (Agenbag, 2012). In 2016, an additional 2000 kg dolomitic lime ha^{-1} was applied. Although the tillage treatments were maintained, in some years, additional experiments with different aims and fertiliser requirements have been conducted within this trial site. Fertilisation applications ranged between 60 and 140 kg N ha^{-1} per year, depending on the aims of the trials being conducted. 70 kg N ha^{-1} and 14.5 kg P ha^{-1} were applied along with 1.75 kg ha^{-1} S in 2017, in accordance with soil test results.

2.3 Soil sample collection

Six soil cores (Ø 45 mm) were collected per plot in April 2018 at depths of 0 - 50, 50 - 100, 100 - 150 and 150 - 300 mm. The soil cores were combined to form a single sample per depth for each plot. Standard procedures for soil analysis, set out by the Non-Affiliated Soil Analysis Work Committee (1990) were used for the analysis of pH_{KCl}, exchangeable acidity, organic carbon (Walkley–Black method), exchangeable Ca, Mg, K and Na (citric acid extraction), cation exchange capacity (CEC), extractable P (citric acid extraction) and S (calcium phosphate extraction), Cu (di-ammonium EDTA), Mn (di-ammonium EDTA), Zn (di-ammonium EDTA) and B (hot water method).

The SOC stock was calculated by summing the nutrient values in the four sampling depths (0 – 50, 50 – 100, 100 – 150 and 150 – 300 mm). The nutrient stratification ratios were calculated for the SOC stock, K and P, by dividing the soil properties at 0 - 50 mm by those at 150 – 300 mm (Franzluebbers, 2002a). Unlike Wuest, (2009) and Ellert and Bettany, (1995), we did the soil analysis by considering the soil linear depth instead of equivalent soil mass because we were interested in the distribution of nutrients down the soil profile.

2.4 Data analysis

The Variance Estimation, Precision and Comparison (VEPEC) package of STATISTICA^{TM} software version 13.5.0.17 (TIBCO Software Inc.) was used to analyse the data using the Restricted Maximum Likelihood (REML) procedure, with the assumption of compound symmetry or equicorrelation between depth measures. Tillage sequence, sampling depth and their interactions were specified as fixed effects in order to take the repeated measures into account. Block was specified as a random effect whilst sampling depth was regarded as the time factor for the repeated measures. All parameters were subjected to a test of normality using the normal probability plots of raw residuals. Where the F-test was significant, the mean separation was performed using Fisher’s least significance difference (LSD) test at a 5% significance level. Data that did not meet the assumptions of an analysis of variance were log-transformed, and back-transformed data are presented in figures. Tillage sequence was specified as the fixed effect and block as the random effect for SOC stock and nutrient stratification ratios.

3. Results

3.1 Effect of tillage on soil chemical characteristics

A significant interaction between tillage sequence and sampling depth was apparent for the distribution of most of the soil nutrients (Table 1). For nutrients where no interaction ($P > 0.05$) was recorded, the soil depth effect was significant in all cases, except for Cu and Mn. Tillage effects were significant ($P < 0.05$) only for Cu.

3.2 Soil pH_{KCl}

The MB treatment resulted in a similar ($P > 0.05$) pH_{KCl} across all the soil depths from 0 – 300 mm (Figure 1). Apart from the MB treatments, the ST treatment resulted in more stratification ($P < 0.05$) than the other treatments as the 50 – 100 mm depth layer had a higher pH_{KCl} than that of the other treatments at the corresponding depth. The TT treatment did not lead to the effective mixing of layers and pH_{KCl} was as stratified as the NT treatment ($P > 0.05$). The infrequent tillage treatments (ST-tillage rotations with NT) did not effectively diminish pH_{KCl} stratification. Exchangeable acidity reflected similar treatment responses to pH_{KCl} and therefore results are not shown.

INSERT TABLE 1 HERE

INSERT FIGURE 1 HERE

3.3 Soil organic carbon (SOC)

Compared to other tillage treatments, the MB treatment resulted in a relatively uniform ($P > 0.05$) distribution of SOC in the soil profile from 0 – 300 mm (Figure 2). The TT treatment led to reduced stratification as the bottom three depths (50 – 300 mm) had similar SOC values. Significant SOC stratification across all the sampling depths (0 – 300 mm) was evident in the NT and ST-NT treatments, whilst the ST treatment and the infrequent tillage treatments ST-NT-NT and ST-NT-NT-NT led to reduced SOC stratification as at least two sampling depths were not different ($P > 0.05$) from each other.

INSERT FIGURE 2 HERE

3.3.1 Soil organic carbon stock (0 – 300 mm depth)

The MB treatment resulted in the lowest ($P < 0.05$) SOC stock at less than 2.0 kg m^{-3} (Figure 3). Although the SOC stocks increased with a reduction in tillage intensity, there was no difference ($P > 0.05$) between the SOC stocks in the TT, ST, NT, ST-NT and ST-NT-NT-NT treatments. The ST-NT-NT treatment had the highest SOC stocks (> 3.0 kg m^{-3}) but did not differ from that of ST, NT, ST-NT and ST-NT-NT-NT treatments.

INSERT FIGURE 3 HERE

3.3.2 Soil organic carbon stratification ratio

The SOC stratification ratio was lowest ($P < 0.05$) in the MB treatment and highest in the NT treatment. The stratification ratios for the MB and NT treatments were 1.1 and 3.8, respectively (Table 2). There was no difference in the SOC stratification ratio of the TT, ST, ST-NT-NT and ST-NT-NT-NT treatments. Furthermore, the TT treatment did not differ ($P > 0.05$) from the NT and ST-NT treatments. Except for the MB treatment, all other treatments had stratification ratios greater than 2.

INSERT TABLE 2 HERE

3.4 Extractable phosphorus (P)

Relative to the NT treatment, the infrequent tillage treatments (ST-NT and ST-NT-NT-NT) did not affect ($P > 0.05$) P stratification. All treatments had a similar distribution of P and the two middle depths (50 –100 and 100 - 150 mm) were not different ($P > 0.05$) from each other (Figure 4). In the ST-NT-NT treatment, the two lowest sampling depths had similar P content. Extractable P was stratified from the 0 to 300 mm depth in the TT treatment. Extractable P was relatively uniformly distributed in the 0 – 100 mm and also in the 50 – 150 mm depth in the MB treatment. However, the extractable P in 0 – 50 mm depth differed from the 100 – 150 mm depth.

INSERT FIGURE 4 HERE

3.4.1 Extractable phosphorus stock (0 – 300 mm depth)

The extractable phosphorus stock was lowest ($P < 0.05$) in the MB treatment but was not different ($P > 0.05$) from the ST and ST-NT treatments (Table 2). Both the ST and ST-NT treatments did not differ ($P > 0.05$) from the TT, ST-NT-NT and ST-NT-NT-NT treatments. The NT treatment had the highest ($P < 0.05$) extractable phosphorus stock.

3.4.2 Extractable phosphorus stratification ratio

The extractable P stratification ratio was highest in the TT treatment but did not differ ($P > 0.05$) from the ST, NT, ST-NT, ST-NT-NT and ST-NT-NT-NT treatments (Table 2). The TT, NT and ST-NT-NT treatments had ratios slightly greater than 2.0. The ST treatment did not differ ($P > 0.05$) from the MB treatment, which had the lowest P stratification ratio of 1.3.

3.5 Exchangeable potassium (K)

The distribution of exchangeable K was affected by the sampling depth and differed with depth. The highest ($P < 0.05$) K content was in the 0 – 50 mm depth followed by the 50 – 100, 100 – 150 and 150 – 300 mm depths, respectively (results not shown).

3.5.1 Exchangeable potassium stock (0 – 300 mm depth)

There was no difference ($P > 0.05$) in the total amount of exchangeable potassium across all tillage treatments. Nonetheless, the MB treatment had the lowest total K content (432 mg kg^{-1}) and the highest was in the ST-NT-NT-NT treatment with 534 mg kg^{-1}. The NT treatment had a total K content of 518 mg kg^{-1} (results not shown).

3.5.2 Exchangeable potassium stratification ratio

The exchangeable potassium stratification ratio did not differ ($P > 0.05$) across all tillage treatments. The lowest P stratification ratio was however in the MB treatment (2.3) and the highest was in the TT treatment (>3). In general, the K stratification ratios ranged between 2.3 and 3.1 (results not shown).

3.6 Exchangeable calcium (Ca)

The MB treatment resulted in a uniform ($P > 0.05$) distribution of Ca across all the soil depths. The TT treatment was, however, not effective in reducing Ca stratification as it led to a relatively similar distribution pattern to the NT as well as the infrequent tillage treatments (Figure 5). The treatments had a higher ($P < 0.05$) Ca content in the top 50 mm, whilst the lower three sampling depths (50 – 300 mm), were relatively similar ($P > 0.05$) to each other.

INSERT FIGURE 5 HERE

3.7 Exchangeable magnesium (Mg)

In the MB treatment, there was no difference ($P > 0.05$) in the distribution of Mg across all depths. The NT treatment was not effective in preventing Mg stratification as the top two sampling depths were different from each other (Figure 6). The infrequent tillage treatment ST-NT-NT-NT had no differences ($P > 0.05$) in Mg content in the lower three depths (50 – 300 mm). The TT treatment led to a similar Mg distribution pattern as the infrequent tillage treatment ST-NT-NT, with at least two of the lower three sampling depths not different ($P > 0.05$) from each other. The distribution of Mg in the ST and ST-NT treatments was similar. The two middle sampling depths (50 – 150 mm) did not differ ($P > 0.05$) from each other.

INSERT FIGURE 6 HERE

3.8 Exchangeable sodium (Na)

The highest ($P < 0.05$) soil Na content was in the 0 – 50 and 50 – 100 mm depths, which did not differ significantly from each other. The Na content in the 100 – 150 mm depth was lower ($P > 0.05$) than that in the 0 – 100 mm depths but was higher than that in the 150 – 300 mm depth (results not shown).

3.9 Cation exchange capacity (CEC)

The CEC differed ($P < 0.05$) across soil depths in the ST and ST-NT-NT treatment (Figure 7) and were thus not effective in reducing the CEC stratification. Stratification was evident in the NT treatment as the top two sampling depths (0 – 100 mm) were different from each other. The infrequent tillage treatment ST-NT-NT-NT led to reduced CEC stratification as the bottom three depths (50 – 300 mm) were relatively similar to each other ($P > 0.05$). The MB treatment was effective in the mixing of soil and had a uniform ($P > 0.05$) CEC down the soil profile (0 – 300 mm).

INSERT FIGURE 7 HERE

3.10 Extractable sulphur (S)

Although the S content decreased ($P < 0.05$) with depth, it did not differ in the 0 – 50 and 50 – 100 mm depths. The 100 – 150 mm depth had more ($P < 0.05$) S than the 150 – 300 mm depth, which had the lowest S content (Table 3).

INSERT TABLE 3 HERE

3.11 Trace elements: extractable Cu, Mn, Zn and B

There were no differences ($P > 0.05$) in soil extractable Cu content in the MB, TT, ST, NT and ST-NT-NT-NT treatments (Table 2). Furthermore, the Cu content of the tillage treatments TT, ST, NT and ST-NT-NT-NT were also similar ($P > 0.05$) to that of the ST-NT-NT treatment. The ST-NT treatment had the lowest ($P < 0.05$) Cu content but did not differ ($P < 0.05$) from the Cu content of the ST, NT and ST-NT-NT treatments.

The soil extractable Mn content was not affected by any treatment (Table 3). The Mn content ranged between 71.1 and 79.4 mg kg^{-1}.

In the NT treatment, Zn was stratified across all sampling depths (Figure 8). The MB treatment did not show any significant Zn stratification. The tillage treatments ST-NT, ST-NT-NT and ST-NT-NT-NT slightly reduced Zn stratification as the top 0 – 50 and 50 – 100 mm depths did not differ from each other. The ST treatment led to a relatively uniform distribution of Zn in the top three sampling depths (0 – 150 mm). The TT treatment was not as effective as the ST treatment and led to a uniform Zn content in the 50 – 100 and 100 – 150 mm depths.

INSERT FIGURE 8 HERE

The sampling depth affected ($P < 0.05$) soil extractable B content. The 0 – 50 mm depth had the highest ($P < 0.05$) B content. At depths of 50 – 100 and 100 – 150 mm B content was not significantly different and likewise for depths of 100 – 150 mm and 150 – 300 mm (Table 3).

4. Discussion

4.1 Effects of continuous tillage with a mouldboard plough

Tillage and tillage rotations over the long-term (42 years) had differential effects on the distribution of the soil chemical parameters. The MB treatment was generally most effective in preventing stratification of most soil chemical parameters, such as soil acidity, SOC, exchangeable Ca and Mg, and the CEC. The mouldboard caused soil inversion which may aid in the distribution of nutrients (Conyers et al., 2003; Derpsch, 2004; Zhao et al., 2015). However, the soil inversion probably promoted the breakdown of SOC and led to a reduction in extractable P. The SOC stocks were lowest in the MB treatment (Figure 3). Some studies also found that continuous ploughing with the mouldboard can lead to the reduction of the SOC stocks (Chen et al., 2009; Dendooven et al., 2012; Zhao et al., 2015). The soil mixing effect of the MB encourages increased aeration of the soil, leading to increased C decomposition and depletion of SOC (Omonode et al., 2007). Similar to the findings by Dendooven et al. (2012), Plaza-Bonilla et al. (2013) and Zhao et al. (2015), we noted that the SOC stock generally increased as the level of soil disturbance was reduced. Furthermore, since soil stores more C than the atmosphere (Ellert and Bettany, 1995), the emission of C from the soil to the atmosphere as a result of conventional tillage with the MB plough can contribute to increased global warming and climate change (Abdalla et al., 2013; Rutkowska et al., 2018). A study conducted by Carbonell-Bojollo et al., (2019) in Spain showed that soils under conventional tillage emitted 67% more C than soils under conservation tillage.

4.2 Effects of tillage on soil nutrient stratification

The NT treatment which does not involve any primary tillage generally resulted in more stratification compared to the TT and MB treatments. Such stratification was more pronounced for SOC stocks compared to other soil chemical parameters. Soil organic C was most stratified in the NT treatment, in agreement with several other studies (Blanco-Canqui and Ruis, 2018; Franzluebbers, 2002a; Moreno et al., 2006). Stratification in NT systems could be due to the accumulation of plant materials (Deng et al., 2016; Moreno et al., 2006) and fertilisers or manure (Matsuura et al., 2018) on the top surface coupled with lack of soil disturbance. The stratification of SOC can be good as it leads to the localised build-up of soil organic matter and improves soil aggregation, reduces bulk density and enhances porosity and water infiltration (Blanco-Canqui and Wortmann, 2020; Xu et al., 2018). Nonetheless, Blanco-Canqui and Wortmann (2020) also highlighted the benefits of one-off tillage as it buries the C-enriched top layer, thereby bringing up the low-SOC layer to the surface which may improve the properties of the low-C layer. We noted that the degree of stratification was slightly reduced by the introduction of an ST treatment in an NT system, such as the infrequent treatment ST-NT-NT-NT. When compared to the NT treatment, the infrequent tillage treatment ST-NT-NT-NT managed to slightly reduce stratification of SOC, exchangeable Mg, CEC and Zn. We assume that the relative mobility of the exchangeable Mg in the soil might have contributed to its distribution as affected by the tillage treatments. The degree of nutrient stratification seemed to generally increase, but not for all chemical parameters, as the tillage depth and soil mixing capability of the tillage treatment was reduced.

4.3 Effects of tillage on soil pH and exchangeable acidity

Interestingly, none of the tillage treatments, except for the MB treatment, could prevent stratification of soil pH, exchangeable acidity and extractable phosphorus. We suspect that the low soil pH_{KCl} could have been caused by the continuous application of nitrogen fertilisers (Barak et al., 1997; Godsey et al., 2007) during the last four decades. Previous reports by Maali and Agenbag, (2003) and Agenbag, (2012) suggest that the research site had an ongoing problem of low soil pH as several lime applications of 2000 kg ha^{-1} in 1999, 2001 and 2005 did not ameliorate the low soil pH. A further 4000 kg ha^{-1} of lime was broadcast in 2016 but the tillage treatments were not able to distribute this down the soil profile. Our findings on pH stratification are comparable to the findings by Conyers et al. (2003) who found that the low mobility of lime and subsequent low rainfall could only enable the amelioration of soil pH in the top 0 - 50 mm. Different results were obtained in high rainfall areas as stated by Caires et al. (2008, 2015). In their study, lime was able to move down the soil profile to a depth of 600 mm in NT soils, but only in an area that received an annual rainfall of at least 1000 mm. It is important to note that there was a severe drought at the trial site from 2015 to 2017 which could have affected the overall distribution of soil chemical parameters down the soil profile. Nonetheless, the low soil pH_{KCl} (<5) within the research site is not ideal for the production of wheat, canola, barley and legumes in the Swartland region as the crops require a pH_{KCl} of at least 5.0, and ideally 5.5 (Fertlizer Society of South Africa 2007). Both the soil pH and exchangeable acidity had a similar distribution pattern.

4.4 Effects of tillage on the extractable phosphorus stocks

The dry topsoil and subsequent low soil pH could have caused adsorption of the immobile phosphorus to the soil surface such that the tillage treatments could not prevent its stratification. Our results on extractable P stratification were in agreement with the findings by Garcia et al. (2007) and Smith et al. (2017) who found that the MB plough was the only treatment that was able to prevent the stratification of P. Furthermore, Smith et al. (2017) found that a disc plough could not ameliorate the P stratification problem on their trial site. Ywih et al. (2014) stated that in acidic soil the extractable P is bound and unavailable for uptake by plants. In our study, the soil pH_{KCl} in the 50 – 300 mm depth was generally below 4.6 and could have affected the movement and distribution of the extractable phosphorus. Also, the annual rainfall in the years after the lime application was below the long term annual of 395 mm, therefore the topsoil could have been dry and led to the adsorption of the extractable P (Shen et al., 2011). Other factors such as low soil organic matter content (Ywih et al., 2014) could have also negatively affected the availability (Yang et al., 2019) and distribution of the extractable phosphorus. The soils at Langgewens Research Farm and surrounding areas have an inherently low soil organic matter content, which is typical of most soils of the Mediterranean region (Da Gama et al., 2019; Hernanz et al., 2002; Romanyà et al., 2010) and this may be attributed to the hot dry summers that stimulate decomposition of soil organic carbon (Costantini, 2015)

The extractable P stocks were also lowest in the MB treatment but there was no distinct pattern set out by the tillage treatments. Except for the ST and ST-NT treatments, all other tillage treatments resulted in higher extractable P stocks in the root zone when compared to the MB treatment. Franzluebbers and Hons, (1996), Motta et al., (2002) and Grove et al., (2007) found similar results and reported that the

NT treatment led to greater extractable P stocks than the MB treatment. The low extractable P stocks in the MB treatments could be indicative of the negative impact of the MB, such as the potential shortage of P for the crops.

4.5 Effects of tillage on soil nutrient stratification ratios

To counter the effects of different environmental conditions, nutrient stratification ratios are used as standards for comparing soil nutrients. Soil nutrient stratification ratios greater than 2 were generally described as reliable indicators of soil quality (Franzluebbers, 2002a, 2002b; Moreno et al., 2006; Tan et al., 2015; Xu et al., 2018; Zhao et al., 2015). In our study, the SOC stratification ratios (0-50:150-300) for all tillage treatments were greater than 2, except for the MB treatment which had a stratification ratio of 1.1. The NT treatment had the highest stratification ratio of 3.8. The SOC stratification ratios from this study show that minimising soil disturbance can lead to improved soil quality. Conversely, the stratification ratio of extractable P was less than 2 for the MB (1.4), ST (1.7), <u>ST</u>-NT (1.9) and ST-NT-<u>NT</u>-NT treatments (1.9). The TT treatment had the highest extractable P stratification ratio of 2.2. The relatively low stratification ratios of extractable P could be suggestive of a need to either increase P fertilisation on the research site, or increase soil pH, or both. Nonetheless, during this study, there was no evidence of P deficiency in crops.

Exchangeable K was highest in the 0 – 50 mm depth and decreased with depth but there was no difference in the exchangeable K stocks across all tillage treatments. Our results concerning the distribution of exchangeable K were similar to the results by Motta et al., (2002). Leaving crop residues on the soil surface could have contributed to the higher amount of exchangeable K on the soil surface (Motta et al., 2002). The stratification ratio of the exchangeable K was greater than 2 for all tillage treatments and that could be indicative of soil of good quality in terms of potassium content (Tan et al., 2015; Xu et al., 2018; Zhao et al., 2015).

Extractable S was generally higher in the top 0 – 100 mm depth and decreased with depth. Sulphur is a mobile nutrient and was similar in the 0 – 50 mm and 50 – 100 mm depth. Exchangeable Na had a similar distribution trend as extractable sulphur. however, exchangeable Na is not part of plant nutrition but is vital for soil health as it can lead to either soil salinity (Bennett et al., 2009; Gorji et al., 2017) or sodicity (Filho et al., 2020; Swanepoel and Tshuma, 2017). The soils at the research site did not have any salinity or sodicity problems.

4.6 Effects of tillage on extractable trace elements

The extractable trace elements, Cu, Mn, Zn and B, had varying responses to tillage. Mn was not affected by any treatments and will not be discussed, whilst Cu was affected by tillage sequence and was highest in the MB treatment than in the NT treatment. The soil Cu results are similar to those reported by Franzluebbers and Hons, (1996) but contradict the results by Shiwakoti et al. (2019b) who found that tillage systems did not affect the concentration of Cu in the soil. Our results also show that the infrequent tillage ST-NT-NT and ST-NT-NT-NT could result in increased Cu concentration. Zn was affected by the interaction of tillage sequence and sampling depth. In general, the top 0 - 100 mm had more extractable Zn than the lower 100 – 300 mm depth and the NT treatment had clearer stratification than all other treatments. This agrees with the report by Motta et al. (2002) and Shiwakoti et al. (2019) who stated that the relative immobility of Zn in the soil could contribute to its stratification. Extractable B was affected by sampling depth and generally decreased with depth. An earlier report by Sherrell and Toxopeus (1978) showed that B, normally considered a mobile nutrient, can become immobile and stratified if the topsoil is dry. We suspect that the weather conditions before this investigation, such as the drought, could have affected the overall distribution of the soil chemical parameters such as pH and P or other nutrients. Future research will clarify the effects of long-term tillage and infrequent tillage on crop productivity and quality.

5 Conclusions

Overall, this long-term study showed that the infrequent tillage treatments only slightly reduced the stratification of some soil chemical parameters compared to the other treatments employed. However, we suggest that the MB treatment is not the best option in reducing the stratification of soil chemical parameters as it led to the depletion of SOC stocks and extractable P stocks. When compared to the NT treatment, the infrequent tillage treatments, especially the ST-NT-NT-NT, slightly reduced the stratification of SOC, exchangeable Mg, CEC and Zn. Furthermore, the same infrequent tillage treatment had a SOC stratification ratio greater than 2, meaning that it could be considered as an option for reducing SOC stratification. The infrequent treatments, could not, however, ameliorate the stratification of some key soil chemical parameters such as pH, exchangeable acidity and extractable P. This variation in the ability to reduce the stratification of soil chemical parameters by the infrequent tillage could be attributed to the specifics of the ST treatment which was set to cultivate to 75 mm and could not facilitate the redistribution of all soil chemical parameters down the soil profile. It is worth investigating whether the stratification could be reduced by using the TT treatment instead of the ST treatment in the infrequent tillage treatments.

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Table 1: Soil nutrients, as affected by the tillage sequence, sampling depth and by the tillage sequence x depth interactions at the Langgewens long-term tillage trial in 2018; Significant treatments (P < 0.05) are highlighted in bold.

Soil nutrient	**Tillage sequence**		**Sampling depth**		**Tillage sequence** x **depth interaction**	
	F-value	**P-value**	**F-value**	**P-value**	**F-value**	**P-value**
pH_{KCl}	1.384	0.274	102.965	**< 0.001**	5.206	**< 0.001**
Exchangeable acidity	3.297	**0.023**	18.388	**< 0.001**	2.084	**0.009**
Log(Soil organic C)	6.471	**0.001**	164.477	**< 0.001**	5.217	**< 0.001**
Exchangeable Ca	1.962	0.125	131.730	**< 0.001**	5.135	**< 0.001**
Log(Exchangeable Mg)	2.043	0.112	119.539	**< 0.001**	5.063	**< 0.001**
Log(Exchangeable K)	1.767	0.163	366.656	**< 0.001**	1.259	0.221
Log(Exchangeable Na)	1.025	0.441	39.856	**< 0.001**	1.576	0.071
Log(Cation exchange capacity)	2.515	0.060	176.975	**< 0.001**	7.022	**< 0.001**
Extractable P	2.946	**0.035**	73.077	**< 0.001**	3.171	**< 0.001**
Log(Extractable S)	0.407	0.865	31.334	**< 0.001**	0.447	0.975
Log(Extractable Cu)	3.632	**0.015**	0.731	0.559	0.173	0.999
Extractable Mn	2.117	0.102	0.356	0.786	0.198	0.999
Extractable Zn	1.792	0.157	99.704	**< 0.001**	2.044	**0.010**
Log(Extractable B)	2.056	0.110	50.659	**< 0.001**	1.109	0.347

Table 2: The soil quality parameters as influenced by tillage sequence at Langgewens long-term tillage trial in 2018. Values are the mean + SE. Different superscript letters within each row indicate the tillage sequence with a significant difference ($P < 0.05$). Stratification ratio (0-50 mm value/ 150-300 mm value); SOC = Soil organic carbon; P = Phosphorus stocks; MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. ST-NT^{2} = ST-NT-NT; ST-NT^{3} = ST-NT-NT-NT; The underlined treatment in the sequence indicates the treatment for 2018.

Soil parameter	Tillage sequences						
	MB	TT	ST	NT	ST-NT	ST-NT^{2}	ST-NT^{3}
SOC stratification ratio	1.12 ± 0.07^{c}	2.99 ± 0.29^{ab}	2.51 ± 0.18^{b}	3.86 ± 0.41^{a}	3.46 ± 0.48^{a}	2.56 ± 0.33^{b}	3.03 ± 0.30^{ab}
Extractable P (mg kg^{-1})	228 ± 7.07^{c}	285 ± 23.3^{ab}	248 ± 8.45^{bc}	295 ± 11.1^{a}	263 ± 8.75^{abc}	281 ± 12.5^{ab}	279 ± 8.80^{ab}
Soil P stratification ratio	1.36 ± 0.08^{b}	2.18 ± 0.29^{a}	1.74 ± 0.13^{ab}	2.02 ± 0.15^{a}	1.86 ± 0.05^{a}	2.09 ± 0.17^{a}	1.95 ± 0.14^{a}
Extractable Cu (mg kg^{-1})	0.77 ± 0.07^{a}	0.65 ± 0.04^{ab}	0.61 ± 0.05^{abc}	0.61 ± 0.05^{abc}	0.35 ± 0.01^{c}	0.45 ± 0.04^{bc}	0.71 ± 0.05^{ab}

Table 3: The distribution of soil nutrients S, Mn and B from 0 – 300 mm as influenced by sampling depth at Langgewens long-term tillage trial in 2018. Values are the mean + SE. Different superscript letters within each row indicate the sampling depth (0 – 50, 50 – 100, 100 – 150 and 150 – 300 mm) with a significant difference ($P < 0.05$).

Nutrient	Sampling depth (mm)			
	0 – 50	50 - 100	100 - 150	150 - 300
Sulphur	27.8 ± 1.8^{a}	27.9 ± 1.8^{a}	20.1 ± 1.2^{b}	12.2 ± 0.7^{c}
Manganese	77.5 ± 7.3^{a}	75.6 ± 8.0^{a}	79.4 ± 9.1^{a}	71.1 ± 8.2^{a}
Boron	0.30 ± 0.01^{a}	0.21 ± 0.01^{b}	0.18 ± 0.01^{bc}	0.17 ± 0.01^{c}

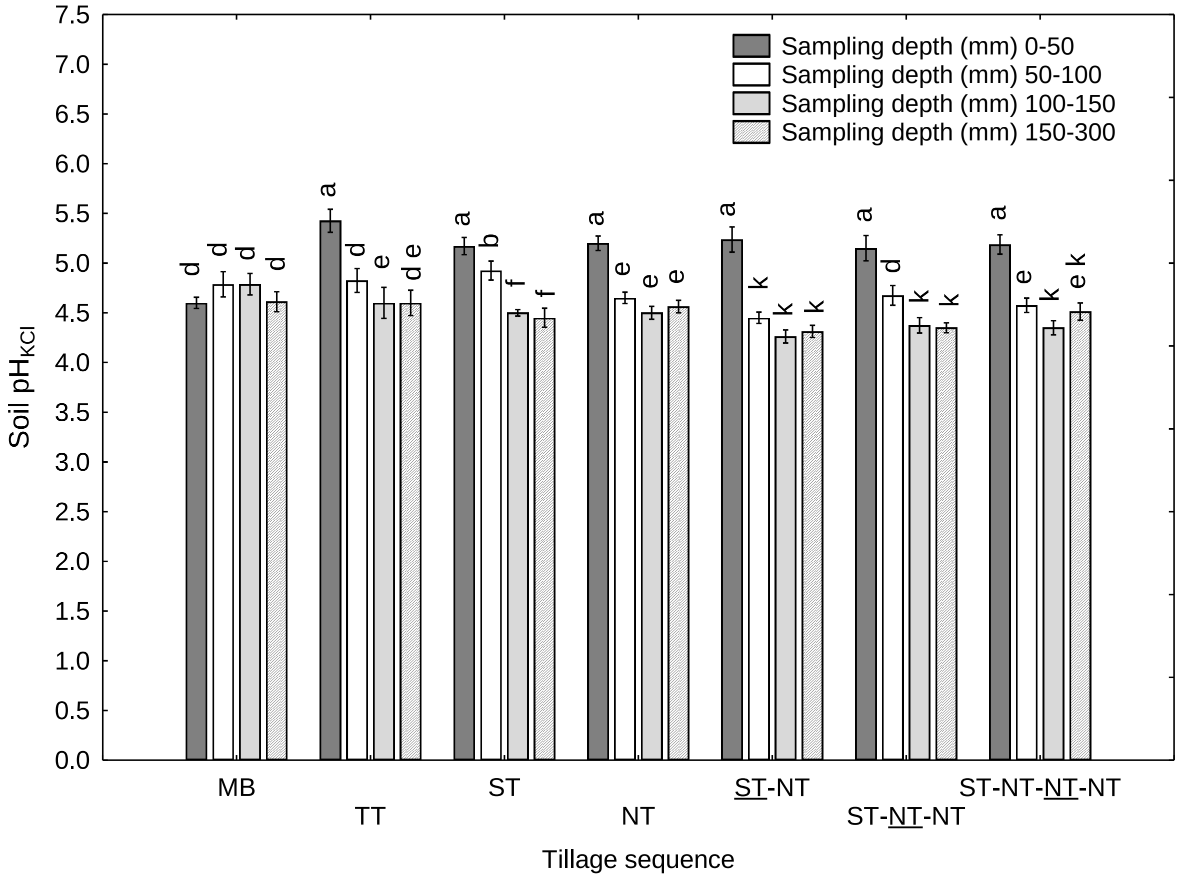

Figure 1: The distribution of soil pH_{KCl} from 0 – 300 mm as influenced by tillage sequence and sampling depth at Langgewens long-term tillage trial in 2018. Different letters on top of the bars denote a significant difference ($P < 0.05$). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the treatment for 2018.

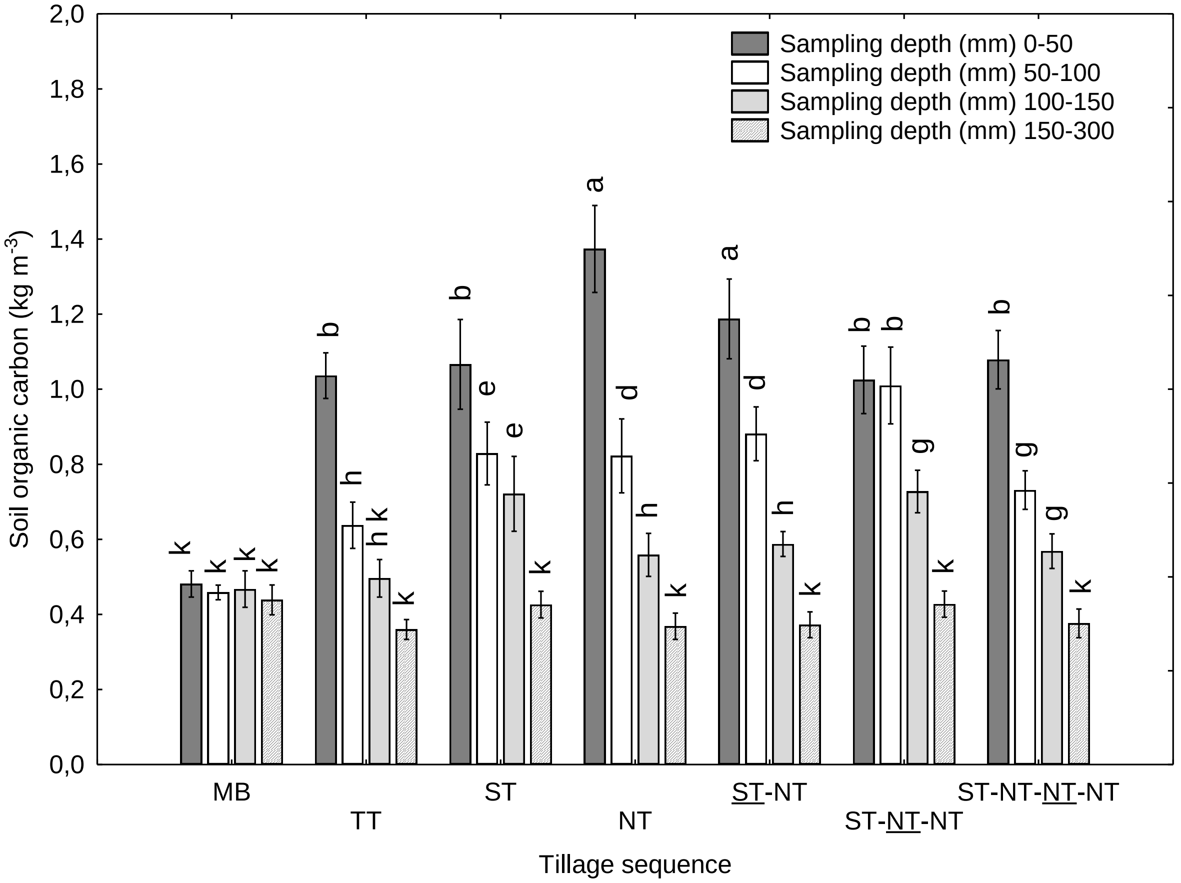

Figure 2: The distribution of soil organic carbon (kg m^{-3}) from 0 – 300 mm as influenced by the interactions between tillage sequence and sampling depth at Langgewens long-term tillage trial in 2018. Different letters on top of the bars denote a significant difference ($P < 0.05$). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the treatment for 2018.

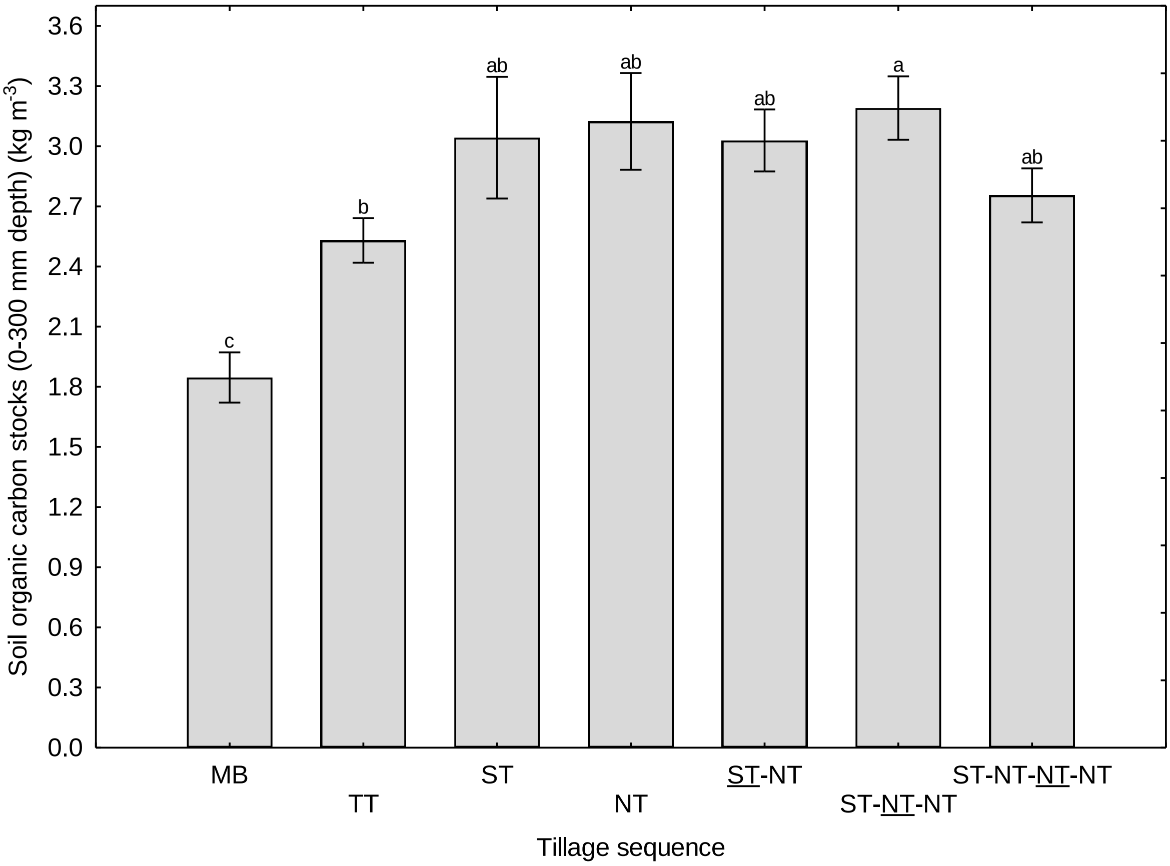

Figure 3: The soil organic carbon stocks (kg m^{-3}) in the 0 – 300 mm depth as influenced by tillage sequence at Langgewens long-term tillage trial in 2018. Different letters on top of the bars denote a significant difference ($P < 0.05$). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the treatment for 2018.

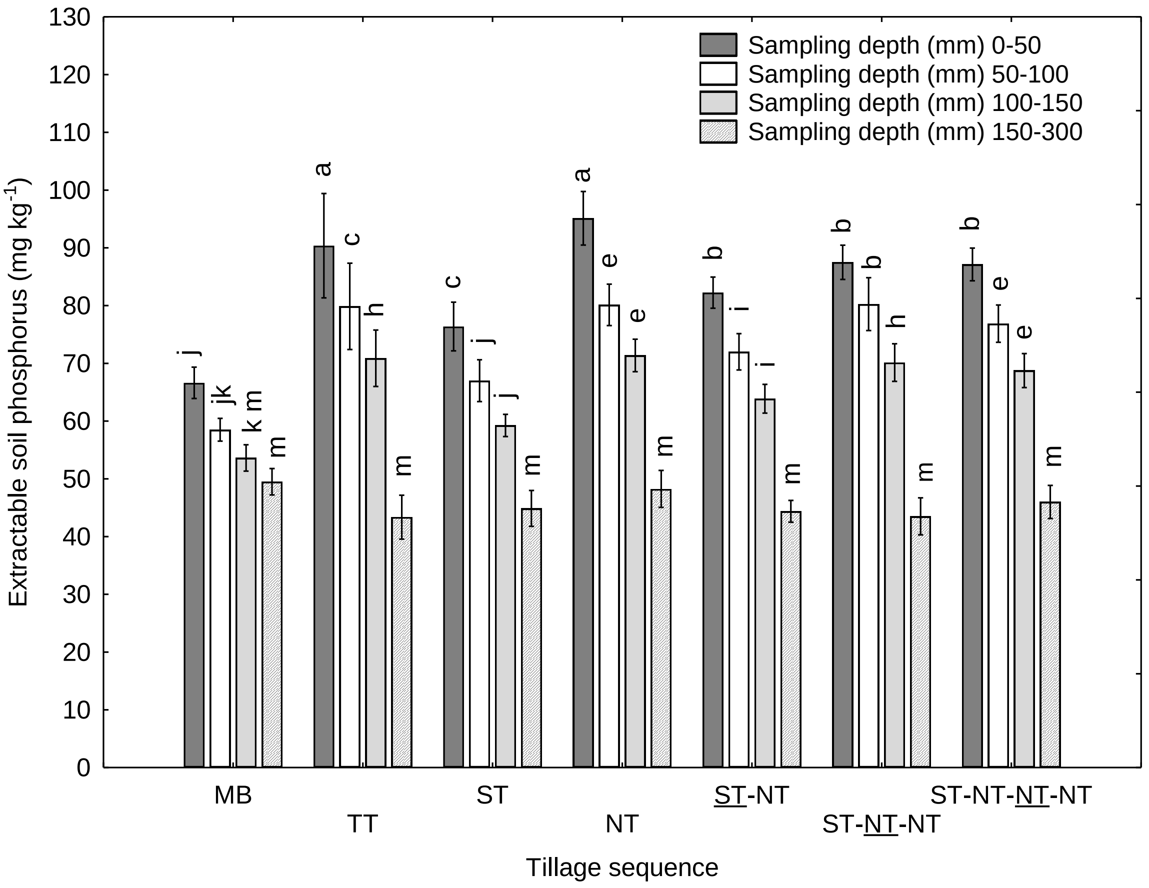

Figure 4: The distribution of soil P (mg kg^{-1}) from 0 – 300 mm as influenced by the interactions between tillage sequence and sampling depth at Langgewens long-term tillage trial in 2018. Different letters on top of the bars denote a significant difference (P < 0.05). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the treatment for 2018.

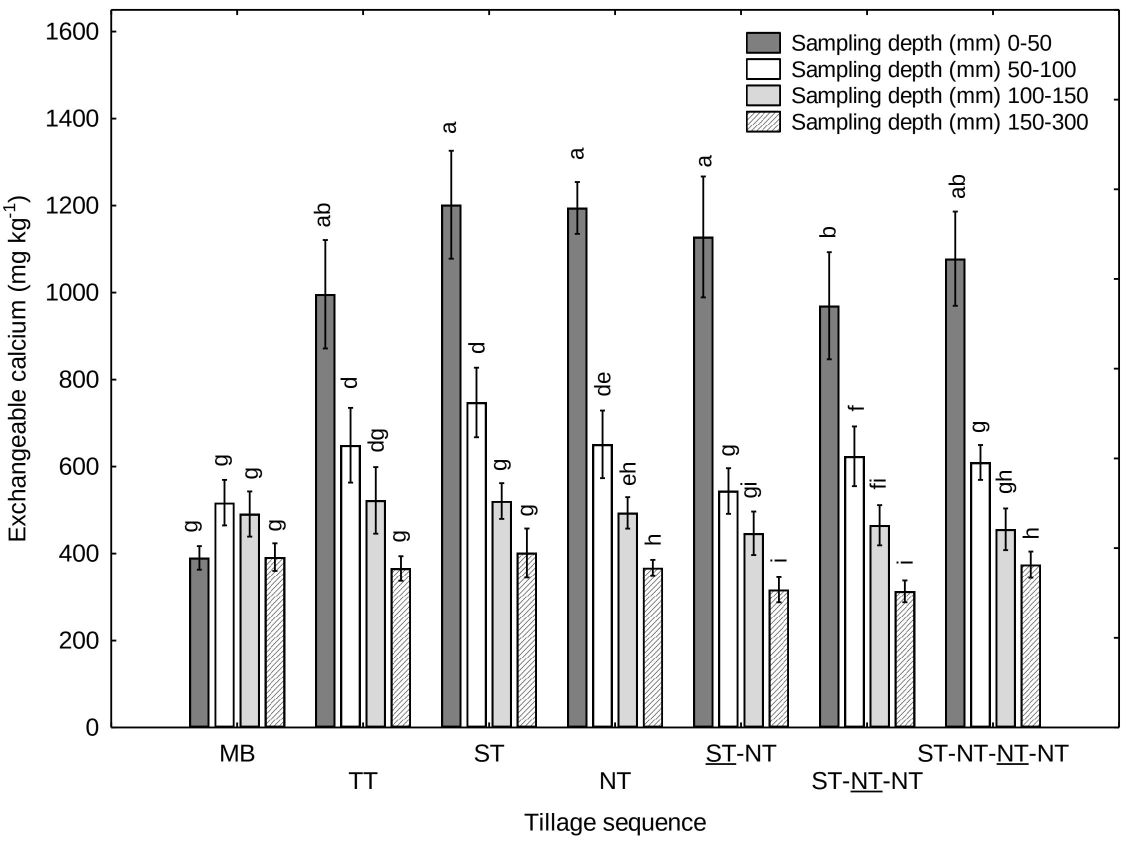

Figure 5: The distribution of soil Ca (mg kg^{-1}) from 0 – 300 mm as influenced by tillage sequence and sampling depth at Langgewens long-term tillage trial in 2018. Different letters on top of the bars denote a significant difference ($P < 0.05$). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the treatment for 2018.

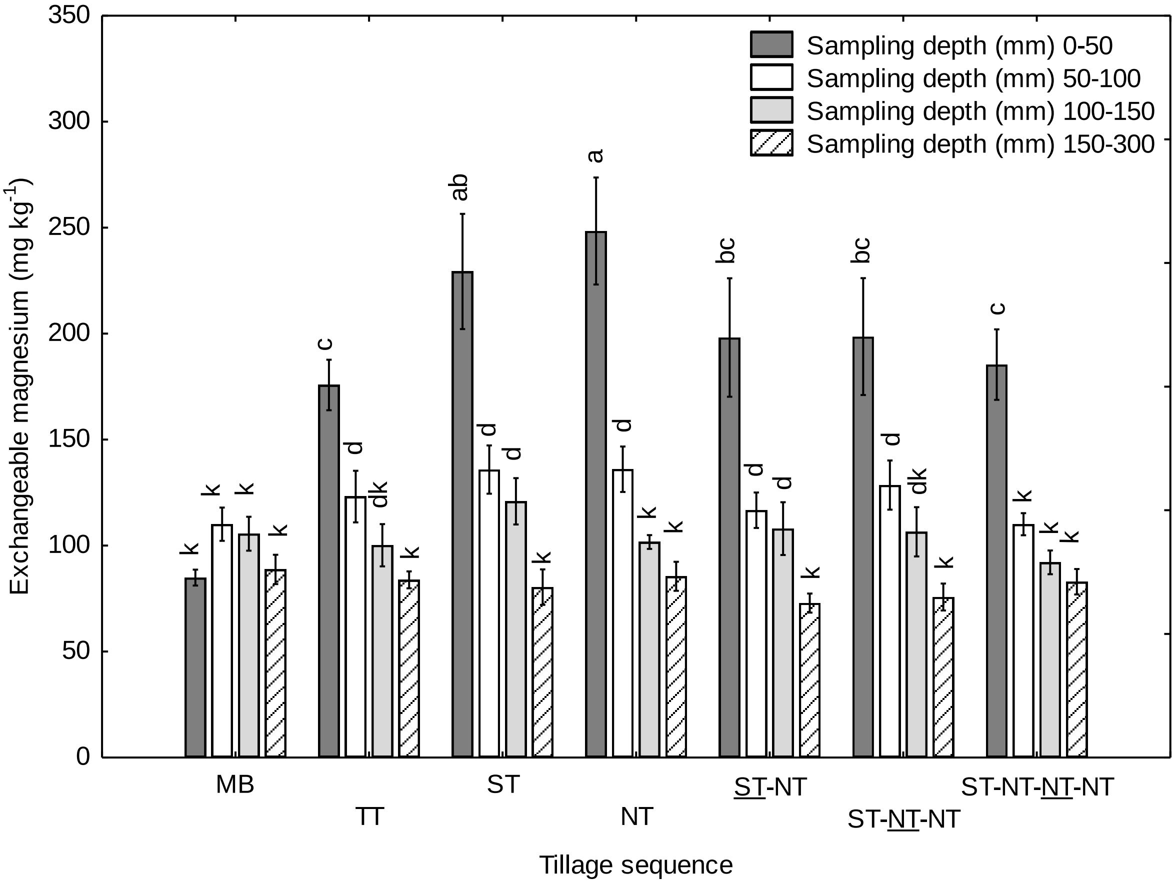

Figure 6: The distribution of soil Mg (mg kg^{-1}) from 0 – 300 mm as influenced by tillage sequence and sampling depth at Langgewens long-term tillage trial in 2018. Different letters on top of the bars denote a significant difference ($P < 0.05$). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the treatment for 2018.

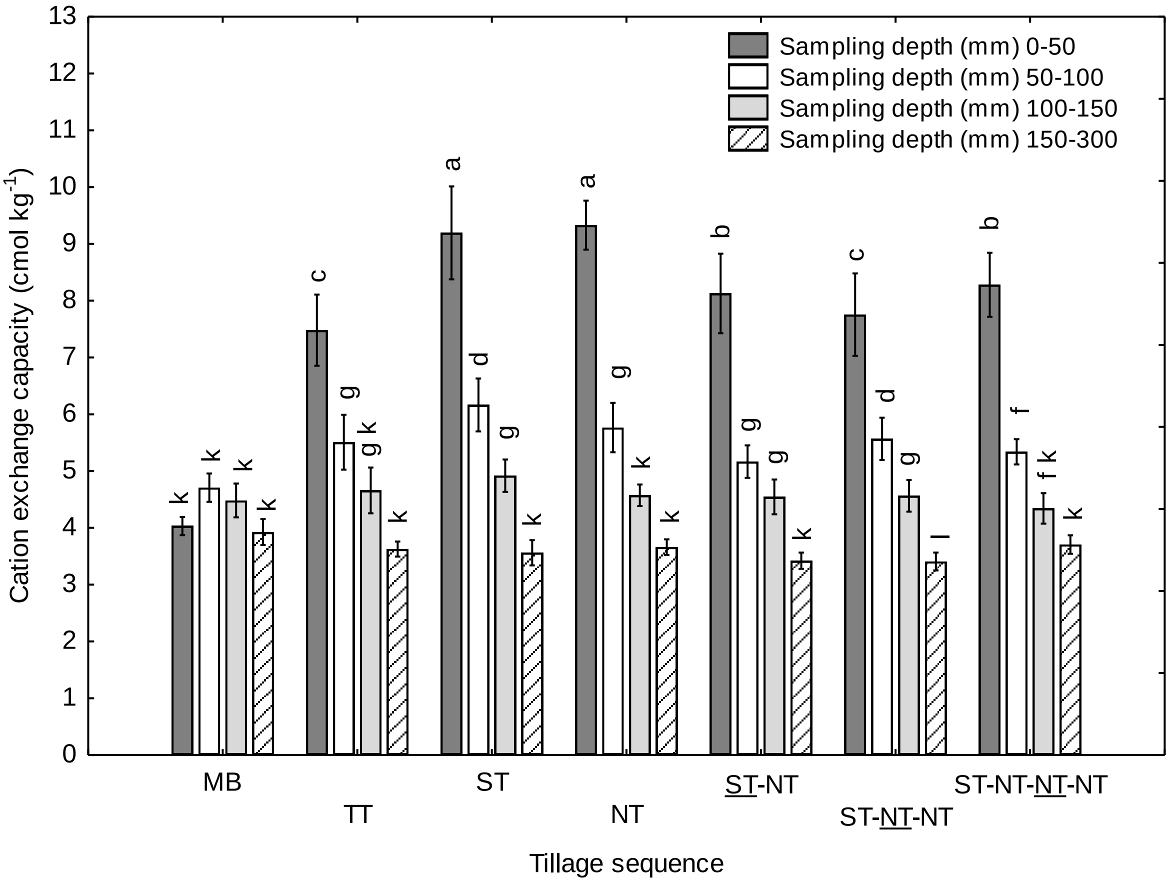

Figure 7: The soil cation exchange capacity (mg kg^{-1}) from 0 – 300 mm as influenced by the interactions between tillage sequence and sampling depth at Langgewens long-term tillage trial in 2018. Different letters on top of the bars denote a significant difference ($P < 0.05$). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the treatment for 2018.

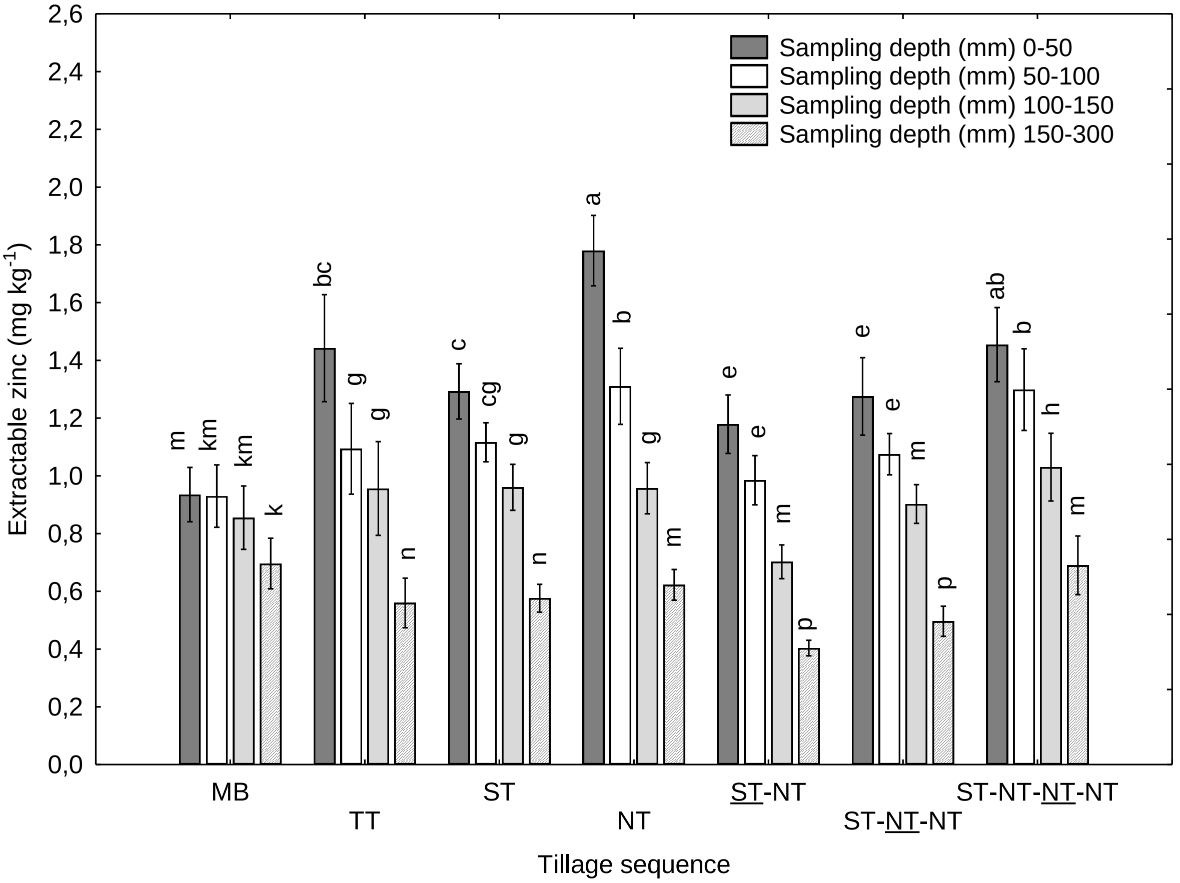

Figure 8: The distribution of soil Zn (mg kg^{-1}) from 0 – 300 mm as influenced by tillage sequence and sampling depth at Langgewens long-term tillage trial in 2018. Different letters on top of the bars denote a significant difference (P < 0.05). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The <u>underlined</u> treatment in the sequence indicates the treatment for 2018.