COMPARISON OF SOIL PHOSPHORUS FRACTIONS AFTER 37 YEARS OF WHEAT PRODUCTION MANAGEMENT PRACTICES IN A SEMI-ARID CLIMATE

by

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DECLARATION

I, **Khanyisile Ncoyi**, hereby declare that all the work included in this dissertation is my own work; that none of the work included in this dissertation is a copy of the work of any other current or former candidate in this module or any other similar module; and that all sources that were consulted and used for completing this dissertation have been properly and completely acknowledged according to generally accepted principles of referencing.

Signature:……………………………………………….

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ABSTRACT

Wheat production management practices are essential for optimum crop growth and the attainment of higher yields. However, these management practices have an impact on the sustainability of soil fertility and productivity. Therefore, it was important to investigate the impact of these residue management options on some soil fertility indicators such as phosphorus (P) fractions under a semi-arid climate. The aim of the study was to evaluate the influence of wheat residue management practices on soil P fractions in a long-term trial near Bethlehem in the Eastern Free State. The trial was established in 1979 and consisted of two methods of straw disposal (burned and unburned), three primary tillage methods (no-tillage, stubble mulch and ploughing) and two methods of weed control (chemical and mechanical). Representative soil samples were collected in 2016 at various soil depth intervals of 0-50, 50-100, 100-150 and 150-250 mm and analysed for soil P fractions. A sequential extraction procedure was used to differentiate between labile (0.5 M $NaHCO_3$ extractable), moderately labile (0.1 M NaOH extractable), stable (1 M HCl extractable) and residual (concentrated HCl) fractions. Except for the residual P fraction, the total P (Pt) of the other fractions was separated into inorganic (Pi) and organic (Po) P.

The straw disposal methods had variable influence on soil P fractions. Burning of wheat residues increased the labile Pi and hence Pt fractions when compared to the unburned residues across all four soil layers. However, the unburned plots had a slightly higher labile Po fraction than the burned plots except in the deepest soil layer (150-250 mm). In the moderately labile P fraction, burned residues resulted in a slightly higher Pi, Po and Pt compared to the unburned residues, except in the 0-50 mm (Pi) and 50-100 mm (Pi, Po and Pt) soil layers. Furthermore, burning of wheat residues increased the stable Pi, Po and Pt fractions when the unburned residues served as a reference. Conversely, the unburned plots had a slightly higher residual Pt fraction in the 0-50 and 50-100 mm soil layers.

The tillage methods had a larger influence on soil P fractions than either straw disposal or weed control methods. No-tilled plots had higher labile Pi and Pt fractions, followed by stubble mulched plots and then by ploughed plots to a soil depth of 250 mm. On the other hand, ploughing increased the labile Po fraction followed by stubble mulch and then by no-tilled plots in all four soil layers. The no-tilled plots had higher moderately labile Pi and Pt, and residual Pt contents than either the stubble mulched or ploughed plots, particularly in the 0-50 mm soil layer.

The chemical weeding method enhanced the labile and stable P fractions more than the mechanical weeding method to a soil depth of 250 mm. However, a reverse pattern was noted that the mechanical weeded plots had a slightly higher moderately labile Po, Pt and residual Pt. The combination of the no-tillage with chemical weeding had a significantly higher labile Pi than either stubble mulch or plough combined with mechanical weeding to a depth of 250 mm. No-tillage combined with either burning of wheat residues or chemical weeding increased the stable Pi fraction, particularly in the 50-150 mm soil layer. Burning of wheat residues combined with chemical weeding resulted to a higher moderately labile Pi compared to burned wheat residues combined with mechanical weeding in all four soil layers. Similarly, chemical weeding combined with burning of wheat residues enhanced the stable Pi fraction compared to mechanical weeding combined with burning of residues.

Keywords: Phosphorus fractions, straw disposal, tillage method, weed control, wheat residues.

PREFACE

This dissertation consists of six chapters. Chapter one contains the background, problem statement, justification and the objectives of the study. Chapter two consists of a literature review of other studies relevant to the one. Chapter three describes the materials and methods used in the study. Chapter four separately presents the findings of soil P fractions from different wheat management practices, whilst chapter five is the discussion of the findings and a comparison with the findings of previously conducted studies. Chapter six contains the general summary, recommendations for further studies and conclusion.

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DEDICATION

This work is dedicated to the Ncoyi family at large. You were a constant source of support which made me to go this far. Thank you for believing in me.

CHAPTER ONE

RATIONALE, OBJECTIVES AND HYPOTHESES

1.1 Rationale

The escalating human population has triggered intensive crop production across the globe. As a result, several soil fertility problems which are reflected in crop yield have been a matter of high concern in both commercial and small-scale farming systems. The relief that was brought by the green revolution in food security is now overshadowed by new challenges related to soil degradation and water scarcity (Stubbs et al., 2008). In South Africa, the increasing rate of soil degradation has been a major challenge, hindering crop growth and threatening agricultural sustainability; indeed, some researchers had termed it “alarming” (Chinedu, 2015). In arid and semi-arid regions such as the Free State Province, organic matter loss resulted in a decline in soil fertility (Loke et al., 2013). In addition, bulky crop harvest leads to large nutrient exports from the soil ecosystem (Chesworth, 2007; Aher et al., 2015). Furthermore, losses through ammonia volatilization, nitrate leaching, and soil erosion also contribute to a decline in soil fertility (Mokwenye et al., 1997).

Therefore, in order to obtain and maintain optimum soil fertility and to ensure food security, it is necessary to replenish the lost nutrients. The available approaches to the replenishment of soil nutrients encompass the application of organic material and chemical fertilizer (Mtambanengwe et al., 2007). The use of organic materials as a source of nutrients was a common practice by farmers in ancient times, as they had a limited understanding of chemistry (Singh et al., 2015). However, in the mid-1980’s, chemical fertilizers were introduced worldwide. In South Africa, about 2 million tons of fertilizers are supplied by fertilizer industries into the local market annually (FSSA, 2007). Recent studies indicate that the use of chemical fertilizers has become a challenge in most developing countries, due to increasing fertilizer costs with low revenue (Loke et al., 2014). As a result, most subsistence farmers in rural areas of KwaZulu-Natal Province use an organic material as an alternative to chemical fertilizer (Mbatha, 2008).

Although chemical fertilizers enhance crop yield and labour efficiency, their continuous use results in a depletion of soil organic matter, which may induce soil erosion and water quality deterioration (Lal, 2015). Moreover, application of fertilizers can also contribute to heavy metal deposition, salinization, and acidification (Kotzé, 2004; Aher et al., 2015). Long-term investigations suggest that there is a limit in which chemical fertilizers can sustain crop productivity on intensively cultivated soil (Soremi et al., 2017). Furthermore, the production process of chemical fertilizer releases greenhouse gasses into the atmosphere, which contributes to global warming (Vanlauwe et al., 2002).

Henceforth, other alternative approaches have been initiated to enhance soil fertility sustainably with little detrimental impact on the environment. In recent years, conservational practices combined with the application of organic material have received substantial attention from agriculturists, environmentalists, and consumers. The emerging evidence reveals that conservational agriculture (CA) is the only potential management practice to enhance soil productivity, reduce soil degradation, and improve nutrient cycling in agroecosystems (Loke et al., 2014; Murphy et al., 2016). This is an agronomic system that practices minimum mechanical soil disturbance, crop rotation and permanent soil cover (Kassam and Friedrich, 2011; Piccoli et al., 2016).

The recycling of crop residues is one of the CA pillars and has been identified as a primary source of soil organic matter and essential plant nutrients (Du Preez et al., 2001). For this reason, several studies have identified crop residues to be an effective tool to increase crop yield in southern parts of Africa (Malawi, Zambia, Zimbabwe, and South Africa) and in many other parts of the world (Andersson and D'Souza, 2014; Pittelkow et al., 2015). This is because it releases a wide range of nutrients in an unbalanced manner, during and after the process of residue decomposition (Chesworth, 2007).

The available residue management practices include retention of crop residue at or near the soil surface, residue incorporation into the soil surface and removal or burning of residues after harvesting (Kotzé and Du Preez, 2007). Various tillage systems such as conservational tillage (no-tillage, minimal tillage, and stubble mulch tillage) and conventional tillage (mouldboard and disc plough) can be joined together with residue management practices (Wiltshire and Du Preez, 1993; Loke et al., 2012). According to Hu et al. (2016), the retention of crop residues under conservational tillage increases soil water content by improving water infiltration and decreasing water loss by reducing evaporation. This encourages the accumulation of organic matter at or near the soil surface, thereby enhancing the concentration of nutrients; especially immobile nutrients (Kotzé and Du Preez, 2008). However, during dry periods, nutrient transport and absorption by the plant can be severely hampered by reduced soil water content, since nutrient availability greatly depends on soil water content (Loke et al., 2014).

Alternatively, conventional tillage is used to incorporate crop residues into the soil surface. Historically, soil tillage has been a traditional practice used to prepare a seedbed, alleviate soil compaction, control weeds, improve soil aeration, root growth and water infiltration (Kouwenhaven et al., 2002). In sub-Saharan Africa, mouldboard ploughing is identified to be more effective in weed control, since it kills weeds and buries the seeds deeper to prevent germination (Renton and Flower, 2015). On the contrary, intensive and frequent conventional tillage often leads to elevated soil erosion by reducing soil organic matter and aggregate stability, which will result in a decline in soil productivity (Raiesi and Kabiri, 2016). Correspondingly, Kotzé and Du Preez (2007) and Loke et al. (2012) postulated that soils are highly prone to a loss of organic matter when conventional mouldboard ploughing is used frequently in a cropping system, especially in arid and semi-arid regions. It is therefore necessary to adhere to management practices that will protect and conserve soil organic matter.

In spite of all the benefits of retaining crop residues, some farmers traditionally remove residues from the field for others uses, giving rise to a large export of nutrients from the soil system (Ventrella et al., 2016). Alternatively, burning of straw has become a universal phenomenon to control weeds, pathogens, diseases; and ease tillage and seeding operation; especially in areas where cereals are traditionally planted (Mu et al., 2016). Interestingly, Du Preez et al. (2001) reported that burning of residue under conservational tillage gives rise to accumulation of P, K and Zn in the top 50 mm of soil. Several studies concluded that burning of crop residues significantly increase crop yields (Ventrella et al., 2016). Furthermore, burning of straw quickly releases nutrients in an available form and are natural liming material (Loke et al., 2012). By contrast, burning reduces soil organic matter content and hence soil organic carbon and carbon substrates for soil microbes. In addition, it also leads to air pollution through emission of greenhouse gasses. As a result, it has been prohibited in many countries across the globe (Loke et al., 2014).

Although CA has been recommended to be a panacea for problems that threaten sustainable agriculture, its adoption rate has been lagging behind in Africa, including South Africa (Derpsch and Friedrich, 2009; Kassam and Friedrich, 2011). The major barrier to the adoption of CA in sub-Saharan Africa (mainly South Africa, Zambia, and Ghana) is a lack of capacity to control weeds (Giller et al., 2009). In agricultural soils, weed infestation commonly occurs and is the major biological constraint to crop production. This leads to significant yield losses in any cropping system worldwide (Scherner et al., 2016). Weeds compete with the crop for water, nutrients, and sunlight; thereby interfere with essential plant functions and suppress crop growth and development (Jabran et al., 2015).

In Africa, weed management suffers from the limited use of herbicides, chemical fertilizers and the lack of available labourers for weeding (Mhlanga et al., 2016). Emerging farmers in rural districts commonly use hands and hand hoeing to control weeds. On the other hand, farmers in most developed countries rely more on the use of herbicides for weed control. There is limited information on how weed control methods influence soil fertility, especially in arid and semi-arid regions. Nevertheless, Kotzé and Du Preez (2007; 2008) reported that the use of herbicides leads to more soil organic matter and accumulation of nutrients to a depth of 100 mm, when mechanical weeding is used as a reference.

Based on the literature, various production management practices have a direct or indirect impact on soil fertility indicators. It is against this backdrop that several authors found it necessary to establish a detailed investigation to evaluate soil fertility indicators such as P, since it is the most limiting nutrient in crop production in South Africa and many parts of the world (Van Averbeke and Yaganatha, 2003; Wang and Zhang, 2012; Soremi et al., 2017). In addition, extensive investigations have been conducted on the effect of conservation practices on N, and therefore detailed studies are needed on other nutrients such as P, about which there is limited information (Loke et al., 2013). Furthermore, the benefit of CA still needs to be illustrated under local conditions. After all, Liebig's law states that "the nutrient least available is the first factor that restricts crop growth and yield formation" (Loke et al., 2014). As a matter of fact, crops such as millet (*Pennisetum glaucum*) do not respond well to N fertilizer when P is severely deficient in soil (Knewtson et al., 2008).

Soil P has a complicated chemistry by virtue of it reacting with soil constituents. Inorganic P can react with Fe and Al in acidic soils, and Ca in alkaline soils and form discrete phosphate compounds. On the other hand, organic P (Po) can occur in various forms that have different resistance to microbial degradation (Zhang and Kovar, 2000). This chemical reaction with the soil constituents leads to P existing in different fractions in soil, which differ in their biological availability and solubility. Previous studies demonstrate that P fractions and distribution are directly and indirectly influenced by different production management practices such as tillage system, straw disposal, and weed control. Therefore, it is essential to evaluate and quantify the changes and distribution that occur in different P fractions as influenced by such practices.

The fractionation of P allows for an understanding of the relationships and interactions of different P fractions in soils and the numerous factors that influence P availability, which is essential for P management. There is a gap in the available information regarding the change of P fractions in response to different production management practices, particularly in arid and semi-arid regions where there is a high potential for soil organic matter loss. In agriculture, long-term experiments provide means to evaluate the sustainability and viability of production management systems. This is because time is an essential factor in both organic and inorganic P transformations to plant available forms. The effects of soil tillage, weed control and straw disposal methods on P fractions and their distribution are poorly known in most soils. Through P fractionation, the interactions of the P fractions can then assist in the evaluation of P fractions that act as a source of plant available P (Costa, 2016).

1.2 Objectives

The general aim of this study was to evaluate the change and the distribution of P fractions in an Avalon soil subject to a range of long-term wheat production management practices in the eastern Free State, South Africa.

Specific objectives were therefore to:

- Evaluate the effect of different straw disposal methods on soil P fractions and their stratification in soil under wheat production after 37 years in a semi-arid climate.
- Evaluate the effects of different tillage systems on soil P fractions and their stratification in soil under wheat production after 37 years in a semi-arid climate.
- Determine the effect of weed control methods on soil P fractions and their stratification in soil under wheat production after 37 years in a semi-arid climate.
- Evaluate the interaction effects of straw disposal methods, tillage systems and weed control methods on soil P fractions and their stratification in soil under wheat production after 37 years in a semi-arid climate.

1.3 Hypotheses

- Different methods of straw disposal methods, tillage system and weeding methods applied to wheat production will have a significant effect on soil P fractions and their stratification.
- The interactions of various straw disposal methods, tillage systems and weed control methods will affect soil P fractions and their stratification in soil.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Phosphorus is one of the essential nutrients for optimum crop growth and development (Jalali and Jalali, 2016). Among macro-nutrients, it is regarded as the most deficient nutrient in South African soils and in many parts of the world (Wang and Zhang, 2012). Therefore, to obtain and maintain optimum crop production, supplemental P is necessary. Organic material and chemical fertilizers are the primary sources in replenishing crop nutrients in the soil (Gaind and Singh, 2015). However, the added P is subjected to several physical, chemical, and biological processes with soil constituents. This allows P to exist in various fractions in the soil which vary in their availability for crop uptake (Soremi et al., 2017).

These fractions are categorized into inorganic and organic P fractions that buffer P in the soil solution. According to Conyers and Moody (2009), P in the soil solution is readily available (labile) for crop uptake, followed by the moderately labile P fraction, and then the less active fractions (stable and residual P fractions). Although it is a slow process, the less available P fractions are converted into more available forms to replenish P in the soil solution (Wang and Zhang, 2012). Several researchers indicated that the change in the quantity and distribution of P fractions is influenced by various crop production practices (Seehusen et al., 2016). Traditionally, conventional tillage has been a common cultivation practice to prepare a seedbed, aerate soil, and control weeds (Van der Watt and Van Rooyen, 1995). Although conventional tillage is beneficial in the agricultural industry, its continuous use has detrimental effects on soil structure and fertility (Wiltshire and Du Preez, 1993; Kotzé and Du Preez, 2007; Raiesi and Kabiri, 2016).

Therefore, alternative management practices that enhance soil fertility sustainably with little detrimental effects on the environment have received much attention in recent years. Based on the literature, CA has been considered to be the only promising management strategy. Conservational agriculture improves soil structure, water infiltration, conservation of soil water, and soil organic matter (Murphy et al., 2016). Alternative to conventional tillage, conservational tillage has been adopted rapidly by farmers in developed countries. On the contrary, the adoption rate in developing countries, such as South Africa, has been lagging (Derpsch and Friedrich, 2009).

Conservational tillage involves reduced tillage that maintains a minimum of 30% residues on the soil surface (Stubbs et al., 2008). Several researchers indicate that conservational tillage minimizes soil degradation and ultimately soil erosion, whilst enhancing soil water and organic matter contents and concentration of nutrients such as P, K, Ca, Mg as well as micronutrients (Loke et al., 2014; Shao et al., 2016). In addition, it encourages microbial diversity and activity (Kotzé and Du Preez, 2007) which are key drivers of crop residue decomposition, mineralization and immobilization of nutrients such as N and P (Turkington et al., 2009).

The retention of crop residues after harvest is a prerequisite for the successful implementation of CA. In the past, it was ascertained that crop residues are beneficial in recycling nutrients in the soil system by increasing organic matter content (Du Preez et al., 2001). Interestingly, several studies indicated that retention of crop residues significantly enhances crop growth and development across the globe (Pittelkow et al., 2015). The residue management practices include *interalia* surface retention, incorporation into the soil, and straw burning (Singh and Sidhu, 2013). According to Du Preez et al. (2001) and Loke et al. (2013), surface retention of residues increases the concentration of nutrients such as P, in the top soil which elevates their availability for crop uptake. Similarly, burning of residues escalates the accumulation of P, K, Mg, Na and micronutrients (Loke et al., 2013; 2014).

Usually, these crop residue management practices are beneficial in recycling nutrients and improving soil physical and biological properties. Contrary to this, Seehusen et al. (2016) reported that surface retention of residues or stubble mulch, decreases soil temperature and increase the infestations of weeds and diseases. On the other hand, incorporation of crop residues promotes nutrient immobilization which results in restricted nutrient availability to crops (Loke et al., 2014). In addition, burning of crop residues encourages nutrient volatilization and emission of greenhouse gasses that contribute to global warming (Li et al., 2016).

In many African countries, the adoption rate of CA is slow even though it is beneficial in crop production (Kassam and Friedrich, 2011). According to Giller et al. (2009) one of the major challenges that hinder the acceptance is weed infestation that severely affects crop yield. As a result, various weed control methods have been studied and applied across the globe. The most commonly used approaches are the use of herbicides (chemical) and machinery or hand weeding (mechanical) to control weeds (Gopinath et al., 2009; Elkoca et al., 2010). These approaches significantly reduce weeds, which results in higher crop yields over a wide range of cropping systems. However, long-term use of herbicides leads to resistance in weeds that reduce the effectiveness of herbicides in controlling weeds (Pieterse, 2013). Although these weed control methods have been proven to be effective, there is limited information on long-term influences on soil fertility; especially on P fractions. Nevertheless, Kotzé and Du Preez (2008) demonstrated that chemical weeding results in an increased nutrient content such as N, P and K in the top soil in compared to mechanical weeding.

2.2 Management practices relating to crop residues

In Africa, wheat (*Triticum aestivum*) production constitutes less than 2% of the total wheat grown in the world. Approximately 80% of this wheat, namely 5 million metric tons grown in the world is produced in South Africa and Ethiopia (Jordaan, 2008). Wheat is the most important grain crop in South Africa after maize (*Zea mays*) (Meyer and Kirsten, 2010). The three leading provinces in wheat production are Western Cape, followed by Free State and then Northern Cape with 6.8, 5.5 and 2.8 million tons, respectively (DAFF, 2010). In 2010, approximately 217 million hectares were harvested for wheat globally (FAO, 2012).

From an agricultural perspective, crop residues are primarily derived from plant leaves, stalks and root tissues that remain after harvest. Among the major crops, maize, wheat, sorghum (*Sorghum bicolor*) and rice (*Oryza sativa*) produce large amounts of residues (Turmel et al., 2015) under intensified cropping systems. Singh and Sidhu (2013) reported that over 500 million tons of crop residues are produced annually in many parts of the world. As a result, a range of crop residue management practices have been studied and applied across the globe. At first, crop residues were often mistakenly regarded as “agriculture waste” or something of little or no value (Blanco-Canqui and Lal, 2009). Consequently, farmers traditionally remove crop residues from the field or allow an *in situ* grazing of livestock in the field; especially in areas where cereal crops are commonly grown (Turmel et al., 2015).

In the last decades, crop residues were identified as a great source for the synthesis of organic matter and hence the recycling of plant nutrients in agricultural soils. Approximately 25% of N, 25% of P, 75% of K and 50% of S remain in the vegetative parts of cereal crops (Singh and Singh, 2001). In wheat for example, 25-30% of N and P, 70-75% of K, and 35-50% of S are retained in the residues (Singh and Sidhu, 2013), thus making them an essential source of nutrients. These nutrients are released into the soil system during the microbial decomposition of residues. According to Loke et al. (2012) nutrients such as P, Cu, Fe, Mn and Zn are released into the soil system during and after residue decomposition. The microbial community in soil is the major driver of the breaking down of crop residues into simpler bio-molecules (De Kok-Mercado, 2015). In return, microbes receive their food and energy from the residues which stimulate their activity and diversity (Kotzé and Du Preez, 2007; Piccoli et al., 2016).

The ratio of C mass to the mass of other elements such as N or P in a substrate determines the rate of decomposition, and whether a nutrient will be immobilized or mineralized. A C:P ratio greater than 300:1 promotes P immobilization while a C:P ratio less than 100:1 encourages P mineralization (Shafqat et al., 2009). Likewise, Loke et al. (2013) postulated that during decomposition of crop residues, large amounts of nutrients might become immobilized and that soil pH may drop, which induces P deficiency and micronutrient toxicity.

In many parts of the world, various crop residue management practices have been developed and applied in a wide range of cropping systems. Research demonstrated that crop residue management directly or indirectly influences soil fertility, which reflects on crop yields after several years (Kotzé and Du Preez, 2008). The quality of crop residues, the health status of the previous crop, edaphic factors together with relevant practices, determines the influence of residues in the soil system (Ventrella et al., 2016). Proper management of crop residues has been identified as an essential tool for sustainable crop production; especially in arid and semi-arid regions where there is water scarcity.

In both commercial and subsistence farming, residue management involves retention of residues at or near the soil surface, incorporation into the soil and removal or burning of residues after harvesting (Kotzé and Du Preez, 2007), while stubble mulch is also a good option (Singh and Sidhu, 2013). The practice of retaining crop residues on a field is one of the CA principles and it has significantly increased yields in a wide range of cropping systems. In soil, nutrients such as P have a very low mobility that limits their diffusion towards plant roots during water and nutrient absorption. Interestingly, retention of residues at or near the soil surface enhances the concentration of nutrients, including P in the topsoil (Loke et al., 2014). Correspondingly, Du Preez et al. (2001) reported that retention of crop residues resulted in the accumulation of nutrients such as K in the top 150 mm of soil. By contrast, surface accumulation of nutrients combined with conservational tillage can limit nutrient uptake by crops during dry periods in the growing season (Loke et al., 2014).

According to Mubarak et al. (2007) the absorption of nutrients by crops is more greatly enhanced under crop residue retention than application of chemical fertilizer alone. In addition, organic matter derived from residues escalates micronutrient availability by providing a chelating agent, which reduces nutrient fixation by binding or coating Fe- and Al-oxides (Kotzé and Du Preez, 2007; Loke et al., 2013). Apart from chemical and biological benefits, retention of residues improves soil structure and aggregate stability. This leads to improved water infiltration and reduced surface runoff, hence more water storage in soil and less erosion (Aher et al., 2017). In developing countries of Africa, residue retention under conservational tillage improves soil quality and productivity. However, a substantial accumulation of residues on the soil surface results in a decrease in soil temperature. Moreover, crop residues enhance P and N immobilization and together with waterlogging hinders optimum crop performance (Loke et al., 2014).

It is against this backdrop that most farmers often prefer incorporation of crop residues into the soil. Conventional practices such as mouldboard ploughing are used to incorporate residues into the soil. This practice exposes a large surface area of crop residues to the microbial community that are responsible for residue decomposition. An investigation by Turkington et al. (2009) demonstrated that the decomposition rate of residues was rapid when incorporated in the soil compared to soil surface retention. *In situ* incorporation of residues is a common practice by farmers in an attempt to reduce the substantial accumulation of residues, which interfere with tillage and seeding operations for the succeeding crops (Singh and Singh, 2001).

Although *in situ* incorporation of residues is beneficial in recycling nutrients it also requires an investment of energy and time. Furthermore, the incorporation of crop residues often lead to microbial immobilization of N and P; as a result, crops grown just after residue incorporation commonly suffer from N and P deficiencies (Singh and Sidhu, 2013). It has been suggested that a period of 10-20 days after incorporation is enough to avoid N deficiency, due to immobilization in a wheat cropping system. The incorporation of residues and fertilizer increases the direct contact with soil colloids. This escalates the potential of nutrient fixation which reduces nutrient availability for plants.

South Africa is characterized by a variety of climates; however, it is classified as a semi-arid country (SA Yearbook, 2016). In semi-arid conditions, nutrient availability can be limited severely due to reduced soil water resulting from evaporation that exceeds precipitation. Thus, in the agricultural industry, practices that conserve water and improve soil fertility sustainably are of high importance. According to Raza et al. (2014) stubble mulch is one of the promising key interventions in this regard. This practice chiefly uses plant straw, dry grass, and crop residue to cover the soil surface (Liang et al., 2007). Stubble mulch conserves soil water by minimizing evaporation, reducing soil temperature, preventing diffusion of water vapour by absorbing it into mulch, and reducing the wind speed gradient at the soil-atmosphere interface (Raza et al., 2014). A study by Myburgh (2013) demonstrated that wheat straw mulches which consisted of 4 t ha^{-1}, 8 t ha^{-1} and 12 t ha^{-1}, respectively, reduced water losses due to evaporation in relation to straw mulch thickness.

The cover of the soil surface with stubble mulch eliminates surface crusting by protecting soil aggregates from the direct impact of raindrops (Liang et al., 2007), and reduces surface runoff and erosion. Apart from the physical influence on soil, during the process of residue decomposition, it adds a fair amount of nutrients into the soil system and encourages microbial activity (Loke et al., 2013). Similarly, Myburgh (2013) postulated that when wheat straw mulch decays, nutrients such as K are released into the soil system. In addition, straw mulch is also used to control weeds (Mitra and Mandal, 2011), by reducing the light penetration that promotes weed growth (Brar et al., 2014). On the contrary, stubble mulch induces a microclimatic condition that has a negative impact on crop yield (Myburgh, 2013). Furthermore, residue mulch encourages disease and pest infestations, nutrient immobilization and stratification of immobile nutrients near the soil surface (Loke et al., 2012). Stubble mulch may hamper sowing and plant establishment and increase overwintering of fungal diseases in cereals that survive on the stubble mulch or even on the weed (Seehusen et al., 2016).

In spite of the benefits, farmers in several developing countries completely remove residue for use as biofuel, fodder, building material, and as animal feed (Turmel et al., 2015). This leads to a large nutrient export from agroecosystems (Loke et al., 2014). In South Africa and other countries such as China, United Kingdom, Spain, and India, maize and wheat residues are used for modern bioenergy production (Batidzirai et al., 2016). Alternatively, burning is also practised as one of the crop residue management practices (Loke et al., 2012).

The burning of crop residues is proven to be beneficial in controlling weeds and pests such as aphids, pathogens, and diseases; however, it has two major effects on soil (Butterworth, 1985). Firstly, burning of crop residue has deleterious effects on organisms that are living at or near the soil surface due to elevated temperatures. Secondly, burning of residues has direct and indirect effects on soil fauna by reducing soil organic matter. In 1997, burning of crop residues in China was prohibited because it posed threats to human health and air quality (Li et al., 2016). Similarly, in 1992 the European Community prohibited the burning of straw due to its deleterious effect on the environment (Loke et al., 2014). Furthermore, large quantities of C, N, and S are lost to the atmosphere during and after crop residue burning (Loke et al., 2012). These elements are emitted in the form of CO, CO_2, CH_4, N_2O, NH_3, NO_x, and SO_2 (Li et al., 2016). Likewise, Wiltshire and Du Preez (1993) reported that burning of straw reduced organic matter, organic C, and C substrates in soil that led to a decrease in microbial biomass in the upper 250 mm.

The above findings notwithstanding, several authors reported that burning of crop residues resulted in a significant yield increase in the long-run (Ventrella et al., 2016). According to Loke et al, (2014) mentioned that burning of wheat straw increased the concentration of K, Ca, Mg and Na; as well as their solubility. Burning practices add plant residue ashes directly to the soil, which are an important source of P and micronutrients (Loke et al., 2012). The comparison made by Singh and Rengel (2007) between burning and surface retention of straw, indicated that nutrients are released more rapidly in available forms and as a result succeeding crops can benefit early in the growing season. However, soluble nutrients are susceptible to leaching and erosion, and as a result, large amounts may be lost from the soil system (Menzies and Gillman, 2003). However, leaching of nutrients could also be influenced by soil texture and hence by the amount of percolating water.

Based on the existing literature, various crop residue management practices have an influence on physical, chemical and biological soil properties. These residue management practices directly or indirectly influence the availability of P in soils. However, there is a gap in the available information of how various crop residue management practices affect different P fractions in soils; particularly in arid and semi-arid areas. Therefore, it is essential to evaluate and to quantify changes in P fractions, if any, in response to different crop residue management practices. Phosphorus fractions differ in their availability for crop uptake. Furthermore, information on the response of either total P or extractable P is not enough to evaluate soil fertility; as Mortvedt et al. (1999) reported that total P had little relationship to the P available for crop uptake.

2.3 Conventional and conservational tillage systems

Historically, soil tillage has been a traditional practice in both small- and large-scale farming system to preparing a seedbed, controlling weeds and aerating the soil. Thus, tillage can be described as the mechanical manipulation of soil for a specific purpose. For cropping, various tillage systems are applied, however, they can be categorized as either conventional or conservational. A conventional tillage system is an operation that is performed in preparing a seedbed for a given crop grown in a given geographical area (Van der Watt and Van Rooyen, 1995) with the use of mouldboard and/or disc plough (Wiltshire and Du Preez, 1993; Loke et al., 2012). On the other hand, in a conservational tillage system there is minimum mechanical soil disturbance, which involves direct planting of seeds with a special planter to maintain a minimum of 30% of residues on the soil surface (Stubbs et al., 2008).

Conventional tillage has a significant influence on crop performance and hence productivity. During the past three decades, technological advancement has led to more intensive soil tillage. For example, weed infestation can be influenced by tillage methods such as ploughing, disc ploughing and harrowing, which can also affect crop production (Lehozcky et al., 2013). Similarly, Seehusen et al. (2016) reported that optimum crop emergence that results in high yields of good quality can be obtained through loosening the soil and controlling weeds by means of conventional tillage. However, conventional tillage has an impact on the vertical distribution of weed seeds which promotes the survival and growth of weed seedlings (Mohler, 1993). The use of a mouldboard plough has been found to be more effective in controlling weed by killing weeds and burying the seeds in deeper soil layers to prevent germination (Renton and Flower, 2015).

The rate of residue decomposition is increased by incorporating the residues through conventional tillage, which plays a significant role in maintaining a balance in C:N and C:P ratios (Shafqat et al., 2009). In alkaline soils of arid and semi-arid regions, volatilization of ammonium-based fertilizers is often reported. The agricultural industry is the largest source of atmospheric NH_3, through livestock waste and N fertilizers applied on fields (Hayashi et al., 2009). Similarly, Mupambwa et al. (2017) reported that poultry manure contains higher concentrations of NH_4 and therefore is highly susceptible to volatilization losses when applied directly on the field.

Interestingly, the incorporation of residues and/or N-based fertilizers through conventional tillage to a depth of 150 mm, result in negligible NH_3 volatilization losses (Hayashi et al., 2009). Soil factors such as texture, water content, pH and CEC have an influence on the volatilization losses (Fenilli et al., 2007). Conventional tillage systems result in a less acidic soil surface compared to conservational tillage systems (Kotzé and Du Preez, 2008). This implies that there are reduced chances of P precipitation as secondary minerals (Fe- and Al-P) under conventional tillage compared to conservational tillage. Subsoil compaction instigated by heavy farm machinery can be loosened by conventional tillage (Kouwenhaven et al., 2002).

In spite of such benefits, intensive and continuous soil tillage often leads to detrimental effects on soil fertility, which therefore threatens agricultural sustainability. Primarily, conventional tillage is energy- and labour-intensive, and it is regarded as a significant contributor to CO_2 emissions (Shrestha et al., 2008; Seehusen et al., 2016). In arid and semi-arid regions, conventional tillage escalates oxidation of soil organic matter and hence results in soil degradation and a decline in soil fertility (Wiltshire and Du Preez, 1993). Similarly, Kotzé and Du Preez (2007) postulated that soils of semi-arid regions are highly prone to loss of organic matter when conventional mouldboard plough is frequently used. Furthermore, intensive conventional tillage often results in soil erosion due to a loss of soil structure and aggregate stability in the surface layer (Raiesi and Kabiri, 2016).

In soil, nutrient availability and transport to plant roots greatly depends on soil water content (Loke et al., 2014). A study by Myburg (2013) showed that a shallow tillage of 60 mm did not conserve water or improve the yield of grapevine compared to no-tilled soils. Moreover, the tilled layers dry out more rapidly than the no-tilled layers of similar depth, but the layers below the tillage depth remain wetter than the corresponding layers of no-tilled soil. The rapid loss of water and organic matter from the top soil under conventional tillage can restrict nutrient uptake by plants during a dry period, resulting in poor yields (Loke et al., 2014). A conventional tillage system mixes crop residue or fertilizer with soil colloids, thereby increasing their potential for nutrient fixation, and would thus reduce the availability and absorption by crops.

Water scarcity has become an urgent global problem that threatens the development of sustainable agriculture and long-term food security. The change in climatic conditions in South Africa and possibly many parts of the world has a severe impact on agricultural production. Efforts to conserve soil water and to reduce organic matter losses have been investigated and applied across the globe. In recent years, conservation tillage has received paramount attention as an alternative to conventional tillage. No-till is one of conservation agriculture's pillars and it involves zero and/or minimum soil disturbance. The soil is undisturbed from harvesting to planting and the only disturbance is during narrow seedbed preparation for seed and fertilizer placement (Renton and Flower, 2015). Minimum or reduced tillage makes use of implements such as a disc, chisel, and power harrow, but maintains about 30% or more residue cover; unlike mouldboard plough which buries about 90% of residues (Stubbs et al., 2008).

It has been identified that conservational tillage improves soil structure, which contributes to better water storage and hence higher yield, as well as enhanced soil biological activity which encourages soil porosity and root penetration (Crittenden and Goede, 2016). Usually, conservational tillage combined with residue retention encourages aggregate stability that minimizes wind and water erosion and improves water infiltration (Stubbs et al., 2008). Furthermore, Kotzé and Du Preez (2007) reported that conservational tillage improved organic matter content in the top 50-150 mm of soil compared to conventional tillage. Correspondingly, Shao et al. (2016) reported that conservational tillage increased soil organic matter and hence available P and K in topsoil, resulting in a yield increase in wheat and maize in rainfed regions.

According to literature tillage systems have an influence on soil chemical properties. The concentration of especially immobile nutrients such as P, K and Zn is enhanced in the soil surface under conservational tillage (Du Preez, 2001; Kotzé and Du Preez, 2007; Loke et al., 2014). Substantial accumulation of organic matter in the soil surface increases organic P in conservational tillage (Rheinheimer and Anghinoni, 2003). Correspondingly, a long-term study by Lozano-García and Parras-Alcántara (2014) demonstrated that the highest concentration of exchangeable Ca and Mg was found in conservational tilled soils, compared to conventional tilled soils, after 25 years. However, the accumulation of nutrients in the soil surface under conservation tillage can be detrimental to their absorption by crops during dry periods, resulting in reduced crop yields (Loke et al., 2014).

The treatments of no-till, sub-soiling, and ridge planting resulted in a significant increase of available P in the 0-200 mm topsoil by 38.8%, 37.8%, and 36.9%, respectively (Shao et al., 2016). Similarly, Loke et al. (2013) reported that P concentrations increased significantly under conservational tillage when compared to conventional tillage; especially at or near the soil surface. Furthermore, Kotzé and Du Preez (2008) demonstrated that conservational tillage resulted in a build-up of P, K, Ca and Mg in the upper 100-150 mm of soil when conventional tillage served as a reference.

Although conservation tillage has been identified to be beneficial for soil fertility and crop yield, its adoption has become a challenge in many parts of the world, including South Africa. In South Africa, only 380 000 ha of the 16.7 million ha are potentially arable land is under conservational tillage (Loke et al., 2013). However, in the United States the acceptance of conservational tillage is constantly increasing, with approximately 25 million ha currently under conservational tillage (Bayer et al., 2009; Uri, 2010). The adoption rate is affected *inter alia* by a lack of knowledge and hence the experience of no-till practice, transition cost, uncertainties with crop yield and the farmer’s resistance to change (Stubbs et al., 2008). In addition, escalated weed infestation, disease incidences, and nutrient immobilization are also reported as barriers (Shrestha et al., 2008).

It is therefore necessary to demonstrate the benefits of conservational tillage on soil fertility and crop yield. Previous investigations reported that the choice of tillage practice influences the concentration and the distribution of plant nutrients, including P in soils (Loke et al., 2013). The distribution of macro- and micronutrients throughout the soil profile is modified by the tillage system (Debiase et al., 2016). However, information on the change in P fractions in response to tillage practice still requires extensive study. Long-term studies yield a sound conclusion about various management practices in agriculture and adverse effects are usually observed after a long run. Therefore, an evaluation of the changes in P fractions after a protracted period is essential.

2.4 Chemical and mechanical weed control

In agricultural soils, weed infestation commonly occurs and is a major biological constraint in crop production that results in significant yield losses in any cropping system (Gopinath et al., 2009; Scherner et al., 2016). Weeds are any plant species that compete with the main crop for water, nutrients, and sunlight; thereby interfering with essential plant functions and suppressing crop growth and development (Elkoca et al., 2010; Jabran et al., 2015).

In Africa, weeds account for an average of 50-90% yield losses and these losses are much higher than those caused by pests (Chikoye et al., 2005). Uncontrolled weeds result in yield losses of 72% in lentils (*Lens culinaris* Medic.), 74-94% in peas and 80% in maize (Kayan and Adak, 2006; Gopinath et al., 2009; Stepanovic et al., 2015). In wheat, 30% of grain yield losses are observed in early weed infestation during the growing season (Khan et al., 2016). A heavy infestation of grassy and broad-leaved weeds is reported as a major biological constraint under wheat production (Das and Yaduraju, 2012). Similarly, Scherner et al. (2016) reported that frequent cropping of winter cereal under conservational tillage encouraged the growth of annual grass weeds (*Apera spica-venti* and *Vulpia myuros*). In addition, weeds do not only decrease yield but also reduce crop quality and consequently increase the cost of production and harvesting.

Naturally, wheat is not a very tall crop and it lacks a substantial protective canopy to prevent weed growth, thus making it a poor competitor with weeds, especially early in the growing season (Kayan and Adak, 2006; Elkoca et al., 2010). Henceforth, sustainable and effective measures of weed control are a prerequisite for profitable and successful wheat farming system, and possibly many other cropping systems. As a result, various techniques of weed control have been developed and tested across the globe. Generally, there are two commonly used approaches to control weeds, viz; chemical and mechanical control.

Traditionally, mechanical cultivation has been a common practice by farmers in an attempt to control weeds, especially where row crops are normally grown (Stepanovic et al., 2015). Conventional tillage operations (i.e. mouldboard plough) reduce weed infestation by killing weeds and burying weed seeds deeper in soil to prevent regrowth (Dastgheib et al., 1999; Renton and Flower, 2015). On the other hand, conservational tillage systems encourage vigorous weed infestation (Mulvaney et al., 2011; Shahzad et al., 2016); especially in areas where herbicide use is prohibited (Scherner et al., 2016). Although conventional tillage controls weeds, several researchers reported that frequent and continuous use of conventional tillage enhances soil degradation by increasing erosion, aggregate instability and organic matter losses (Dastgheib et al., 1999; Kotzé and Du Preez, 2007; Loke et al., 2012; Blaise et al., 2015). In addition, cultivation leaves a strip of uncontrolled weeds within 50-100 mm on either side of the crop row which directly impacts on crop yield (Stepanovic et al., 2015).

Alternatively, the development of non-chemical techniques of controlling weeds has been established; hand-weeding and hand-hoes are such approaches. According to Gopinath et al. (2009) hand-weeding and hand-hoes can significantly decrease weed density on the field; however, the timing and frequency are critical. Furthermore, it was demonstrated that hand weeding resulted in the highest weed control efficiency compared to other methods (mulching, stale seedbed, and hand hoeing). Correspondingly, Kayan and Adak (2006) postulated that hand weeding resulted in the lowest weed biomass with the highest lentil yields compared to other weed control methods. In Africa, management of weeds suffers from the limited use of chemical herbicides, chemical fertilizers and the lack of available labourers for weeding (Mhlanga et al., 2016). Emerging farmers in rural districts commonly use hand hoeing to control weeds. However, hand-weeding and/or hand-hoeing is labour-intensive and expensive (Spenanovic et al., 2015), and is thus impractical for large-scale farmers. Moreover, this method does not prevent the effect of weeds on crop yield if delayed (Elkoca et al., 2010).

In the past decades, weed control has been limited to labour-intensive and time-consuming mechanical practices. A breakthrough came through the manufacturing of herbicides that could suppress weed growth and development (Pieterse, 2013). Herbicides effectively reduce weed infestation by killing or injuring weed shoots and roots while they are still underground (Elkoca et al., 2010). Usually, herbicides are effective across a wide spectrum of weed species (Singh et al., 2015). The use of herbicides is more economical and labour effective when mechanical weeding is used as a reference. An investigation by Mhlanga et al. (2016) demonstrated that the proper use of herbicides can significantly reduce yield losses. Correspondingly, Walters et al. (2008) postulated that the use of herbicides in winter rye significantly improved the control of broadleaf weed in comparison with those that received no herbicides. Hence, most farmers in developed countries across the globe rely more on the use of herbicides for weed control (Das and Yaduraju, 2012).

The increasing reliance on the use of herbicides in developed and some developing countries, including South Africa, has resulted in an escalated level of resistance to certain weed species (Monaco et al., 2002; Pieterse, 2013; Gianessi, 2014; Kazemeini et al., 2016). Consequently, herbicide efficiency in controlling weeds has somehow declined (Mahajan and Timsina, 2011). This has led to increased dosages of herbicides which contribute to soil and water pollution, crop injury as well as health hazards (Khan et al., 2016; Mhlanga et al, 2016). Additionally, most herbicides have a narrow-to-moderate weed-killing spectrum, whilst in the field there is a high diversity of weed species (Das and Yaduraju, 2012).

In literature, there is limited information on how mechanical and/or chemical weeding methods influence the availability and concentration of essential plant nutrients in soils. However, the study by Kotzé and Du Preez (2007) demonstrated that chemically weeded plots had more organic matter content to a depth of 100 mm than mechanically weeded plots, which resulted in the accumulation of nutrients such as N, P and K in the upper 100 mm of soil when mechanical weeding served as reference. Furthermore, mechanical weeding decreases plant-available nitrogen in the soil surface compared to chemical weeding (Wiltshire and Du Preez, 1993). On the other hand, Loke et al. (2013) reported that the increase in P under chemical weed control could be attributed to the application of pesticides. Interestingly, the total S in soil increased under mechanical weeded plots compared to chemical weed control (Loke et al., 2012). Therefore, an extensive study needs to be done in demonstrating the influence of these weed management practices in semi-arid regions.

2.5 Phosphorus fractionation

Phosphorus is the most deficient nutrient in South African soils and possibly in many parts of the world (Gaind and Singh, 2015); this is due to low native P and high fixation by iron and aluminium oxides in acidic soil conditions (Qiao, 2012). This emphasises the need for additional P in order to obtain optimum crop yields. The available approaches for farmers are, in the main, the application of inorganic and/ or organic fertilizer (Giuffré et al., 2007). However, in the year of application approximately 10-20% of the applied P is available for crop uptake because 80-90% is adsorbed on soil constituents (Gikonyo et al., 2008). The soluble form of P in soils is the readily available source for crop uptake. As the concentration of P decreases in the soil solution, due to crop uptake or leaching, it is then buffered by dissolution (from primary and secondary minerals) and/or desorption (labile inorganic P) (Shariatmadari et al., 2007). The process of mineralization of organic P compounds from plant residues through microbial activity also replenishes P in the soil solution.

Crops absorb P in the soil solution, which includes various fractions of fertilized inorganic P, mineralized inorganic P and small-molecular-weight organic P molecules (Qiao, 2012). The other P fractions replenish P in the soil solution when it is depleted due to crop uptake and/or leaching (Irshad et al., 2008). In soils, P is partitioned into different fractions and pools; generally, they are divided into organic and inorganic P fractions. These are then further divided into sub-classes relative to their biological availability. Information on the availability and distribution of different P fractions in soil is useful in crop production. The organic and inorganic P fractions showed significant relations with the amount and/or concentration of P in wheat tissues at 4 and 10 weeks after sowing (Shariatmadari et al., 2007). However, the aluminium bound P (Al-P), octacalcium phosphate equivalents (Ca_8-P), and non-labile organic P had a lower relation to P found in wheat tissues.

2.5.1 Inorganic P fractions

In soils, crops largely absorb inorganic P in the form of orthophosphate ($H_2PO_4^-$ and HPO_4^{2-}), and these fractions control the biological P availability (Braos et al., 2014). Inorganic P fractions are normally greater than organic P fractions; in calcareous soil, inorganic P constitutes 70-90% whilst organic P contributes 10-30% of the total P (Wang and Zhang. 2012). Elemental P can exist in different forms by bonding with calcium (Ca-P), iron (Fe-P) or aluminium (Al-P) or being occluded (O-P) (Shariatmadari et al., 2007; Qiao, 2012); these are divided into active and inactive forms (Soremi et al., 2017). The inactive fractions are the primary (apatite) and secondary minerals (Fe-P, Al-P, and Ca-P), as well as occluded P (Conyers and Moody, 2009), whilst the active forms are those bonded on the clay surface (labile). Labile fractions are loosely bound which makes them available for plant uptake under favourable soil conditions. The inorganic P fractions vary in their solubility and are largely affected by soil biochemical properties and water conditions (Wang and Zhang. 2012). The investigation by Shen et al. (2004) indicated that Ca-P is a dominant inorganic P fraction, followed by Fe-P, occluded P, and Al-P, and concluded that Ca-P and Al-P fractions are the sinks of plant-available P.

Inorganic P can be found in soil solution (P-solution) and fixed through the adsorption phenomenon (Fe, Al and Ca-oxide) (Costa et al., 2016). Generally, the concentration of P in soil solution is relatively low compared to the adsorbed or fixed P. The labile P is easily fixed in soils, resulting in low P availability for plant uptake (Wang and Zhang, 2015). Depending on soil pH, P can precipitate as a secondary mineral. According to Lui et al. (2010) P precipitates as Fe-P and Al-P in acidic soils whilst in alkaline soils it precipitates as Ca-P; that is renders it unavailable for plant uptake. Correspondingly, Caione et al. (2015) reported that about 85-90% of added P fertilizer is unavailable for the plant during the first year of application, due to adsorption and precipitation by Fe, Al and Ca bondings. Similarly, Verma et al. (2016) reported that less than 20% of applied P fertilizer is available for plant uptake in the year of application. However, about 70-95% of the applied P becomes available for succeeding crops (Du Preez and Claassens, 1999).

2.5.2 Organic P fractions

Inorganic P normally controls the availability of P in soils, although, the contribution of organic P should not be neglected; especially in a system with low P fertilization (Braos et al., 2014). Organic P is formed by phosphate ions that bind to C and is directly related to the decomposition of organic material. Soil organic P is an important component of the soil P cycle and it constitutes approximately 15-80% of total P in soil (Shafqat et al., 2009). In a natural ecosystem, plant residues and animal wastes are the primary sources of Po. This occurs through the process of soil organic matter decomposition and hence the release of plant nutrients to the soil (Du Preez et al., 2001). The conversion of natural ecosystems into agricultural systems results in a rapid decline of Po, especially in arid and semi-arid regions (Braos et al., 2014). Correspondingly, Rheinheimer and Anghinoni (2003) reported that the concentration of Po fractions is altered by different soil tillage and cropping systems. Long-term investigations showed a significant decline in soil Po fractions under a frequent conventional tillage system combined with no fertilization (Motavalli and Miles, 2002).

Organic P fractions can be categorised based on the chemical extraction used. The Po extracted by $NaHCO_3$ is labile and available to plants and microorganisms, whilst the Po extracted by NaOH is moderately labile. Either soluble or insoluble Po is extracted by HCl and both seem resistant to uptake (Sharpley and Smith, 1985; Conyers and Moody, 2009). The study by Rheinheimer and Anghinoni (2003) indicated that the labile Po content was not affected by tillage system or crop rotation in soils that have very high clay content.

The labile Po compounds undergo mineralization by phosphatase enzymes or are stabilized into humic acids during microbial conversion (Shafqat et al., 2009). However, the transformations also depend on the C:P ratio of the substrate added to the soil. Organic material with a C:P ratio of more than 300 would encourage the immobilization of Pi, whereas a C:P ratio of less than 100 favours mineralization. The Po transformations in soils are affected by the factors that influence soil microbial activity: water content, aeration, pH and availability of organic material.

The long-term changes in soil P fractions can be investigated by separating soil P into various Po and Pi fractions. Hedley et al. (1982) proposed a sequential fractionation procedure for soil P, where loosely bound labile Po and Pi fractions are extracted first, followed by more stable P forms. Chemical extractants are used to differentiate between P compounds according to the chemical properties, which in turn can be related to biological availability (Du Preez and Claassens, 1999). According to Hedley et al. (1982) the standard sequential procedure of soil P fractionation is shown in Figure 2.1.

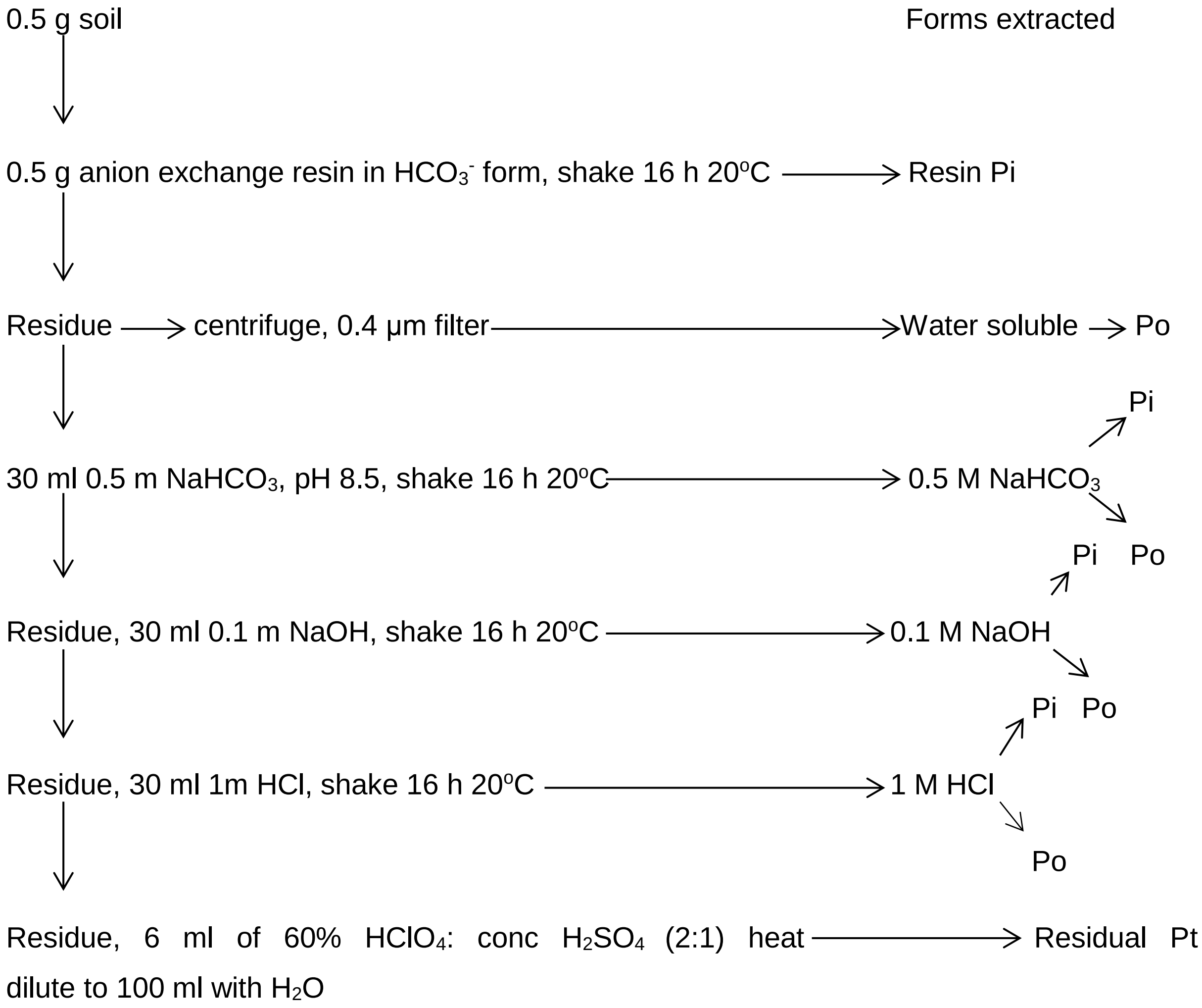

Figure 2.1: Sequential soil P fractionation procedure into inorganic (Pi), organic (Po) and Pt fractions (Hedley et al., 1982).

According to this procedure, the anion-exchange resin (Dowex 1 x 8-50, > 500 µm bead size) was contained in polyster mesh bags (Estal mono PE, 400 µm) and the extraction was performed by modification of the Sibbeben method (1978). The soil from the resin bag was recovered by washing with distilled water in a filter paper (0.4 µm Nuclepore). The soil with a minimum volume of distilled water was then returned to the main soil suspension. After centrifugation at 4000 rpm for 10 min, the supernatant was filtered (0.4 µm Nuclepore filter) to provide the water-soluble Po fraction. For each of the following extracts the same procedure was followed. Soil collected on the filter paper was returned to the extraction tube by washing with the next extractant in the sequence. The final soil residue was digested in 6 ml of a 2:1 mixture of 60% $HClO_4$ and concentrated H_2SO_4. This mixture was also used to digest the whole soil to determine the total soil P content.

The extractions were carried out as illustrated in Figure 2.1 for the following reasons.

1. Resin-extractable P_i has been found to be a source of plant available P.
2. A resin pre-treatment decreases the concentration of P_i in the following extractions and therefore reduces the risk of insoluble phosphates precipitating under alkaline conditions.
3. $NaHCO_3$ (0.5 M, pH 8.5) extracts additional Pi that is available to plants and also extracts the more labile forms of soil Po. The labile P fraction is more available for crop uptake since they adhere weakly to the clay surfaces and therefore easily buffer P in the soil solution.
4. The more strongly alkaline 0.1 M NaOH solution extracts moderately labile soil Po; it also dissolves phosphates bound in Fe- and Al-oxides and desorbs Pi from the surface of sesquioxides. These P fractions are moderately available to plant absorption since they are held by Fe and Al-oxides. However, they replenish P when labile P fraction decreased.
5. Following the alkaline extractions, 1 M HCl dissolves acid-soluble Pi, probably in the form of calcium phosphates and some Pi which is occluded within sesquioxides and released on the partial dissolution of these oxides. These P fractions are known to be stable and less available to plant uptake. This is because they have precipitated as a secondary mineral which is less soluble.
6. The remaining occluded phosphate appears in the residual P fraction, combined with the most stable organic phosphates. Residual P fractions are held strongly by chemical soil constituents and as a result they are not available for plant absorption and are regarded as the most inactive fractions of P in soils.

According to Hedley et al. (1982) the modification of this procedure was to resolve the nature of residual P, by using more concentrated alkaline extractants. Thirty ml of 1 M NaOH was used for 16 h after the 0.1 M NaOH extraction to remove more P from the soil residue. This was then followed by the 1 M HCl extraction, and finally half of the replicate samples of the soil residue was ashed at 380°C for 6 h. Both ashed and non-ashed samples were extracted in 3 ml of concentrated HCl at 90°C for 1 h. The mixture of soil and acid was diluted with distilled water to 40 ml, filtered and the P concentrations measured. Organic P was taken as the difference in P between duplicate pairs of ashed and non-ashed samples.

2.6 Phosphorus fractions in relation to production management practices

The added P in soil undergoes complicated chemical reactions (Zhang and Kovar, 2000). This renders the existence of P in various forms which vary in bioavailability and solubility. Phosphorus in soil mostly occurs as inorganic forms that are associated with Ca, Al and Fe, while Po fractions are derived from crop residues and soil flora and fauna. In relation to crop P nutrition, Pi fractions provide a major supply of P. However, Po also contributes significant amounts, although in lesser concentrations than Pi (Reddy et al., 2014). Generally, it is accepted that in highly weathered soils, phosphates are adsorbed by Al and Fe oxides and hydroxides (Rheinheimer and Anghinoni, 2003). On the other hand, in slightly weathered soil carbonates react with soil P (Uygur et al., 2017).

The distribution of P in different fractions is determined by soil parent material, degree of weathering, and soil physical, chemical and biological properties. Moreover, production management practices have also been reported to influence the distribution of P fractions and stratification of P through the soil profile. A long-term study on oat production demonstrated that no-till increased Po fractions compared to ploughing, particularly in the upper two soil layers than in the deeper soil layers (Rheinheimer and Anghinoni, 2003). In addition, no-tilled plots had higher Po concentrations compared to conventionally tilled soils, after 12 years. This soil Po consists of inositol phosphates, phospholipids, nucleic acids, phosphoprotein and various sugar phosphates (Zhang and Kovar, 2000). However, Po fractions represent a small portion of the total P in the soil and are quickly mineralized to supply Pi to crop roots.

Adoption of minimum or no-tillage has become popular in the farming industry in the past few decades. Shafqat and Pierzynski (2010) conducted a study to monitor the effects of tillage methods on P fractions and the results obtained demonstrated that no-till had higher labile and moderately labile P fractions than conventional tillage. The decomposition process of organic matter releases organic acid which then acts as ligands to form Fe bound P in soil, resulting in the highest value of labile P (Mitran et al., 2015). In addition, the Fe-P is the major contributing P fraction to the P nutrition of the crop in soils.

The residue management options include, for example, surface retention, incorporation of residues or alternatively *in situ* burning. According to Loke et al. (2014) burning of wheat residues enhanced the concentration of K, Ca, Mg and Na, as well as their solubility. After the burning of wheat residues, the ashes are directly added to the soil, which is an important source of P and micronutrients (Loke et al., 2012). Consequently, a significant increase in crop yield has been reported in the long run (Ventrella et al., 2016). The investigation by

Reddy et al. (2014) demonstrated that surface retention and incorporation of wheat residues improved the labile inorganic P ($NaHCO_3$-Pi) from 3.2 to 5.0 mg kg^{-1}, and the labile organic P ($NaHCO_3$-Po) from 2.4 to 4.4 mg kg^{-1}, respectively, compared to residue burning.

2.7 Conclusion

Phosphorus is an essential nutrient for crop growth. However, it is among the least available nutrients in many South African soils and many parts of the world. Liebig's law stipulated that "the least available nutrient is the first factor that restricts crop growth and yield response". This implies that it would be impossible for crops to complete both vegetative and reproductive growth stages when P is deficient in the soil. Therefore, additional P is necessary for optimum crop development and maximum yield. It has been demonstrated that in the evaluation of soil fertility, total P alone is of less importance as an indicator. This is because not all the total extracted P is readily available for crop uptake since it reacts with soil constituents.

Therefore, P fractions are important as indicators of the fertility potential of soil. This is due to the potential of various P fractions to buffer P in the soil solution when it decreases due to crop uptake or leaching. Based on the literature, different wheat production management practices have an influence on the concentration and stratification of P fractions, which affects the availability of P for crop uptake. It is therefore necessary to evaluate and quantify the change in the soil P fractions in response to these management practices over the long-term.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental site and soil

The experimental site is situated at the ARC-Small Grain Institute (28^{o}13’S and 28^{o} 18’ E; 1680 m above sea level) near Bethlehem in the Eastern Free State of South Africa. A trial for the purpose of studying the effects of different wheat production management practices on soil fertility and crop productivity was established on this site in 1979.

The trial has been running for 38 years. Measurements with respect to crop productivity were made every year when wheat was planted. Compared to these measurements, soil fertility measurements were made approximately every 10 years. Before the trial was established on the site, the trial site had been cultivated for at least 20 years. Other management details, however, are not known. The climatic data of the site is shown in Table 3.1.

The site is located on land type Ca6n which covers an area of about 420 000 ha (Land Type Survey Staff, 2001). This land type is classified as a plinthic catena where upland duplex and/or margalitic soils are common. The parent material of these soils comprises Beaufort mudstone, shale, sandstone, and grit, with dolerite sills in places.

Table 3.1 Long-term climate data as retrieved from weather station 1983 at the ARC-Small Grain Institute near Bethlehem (ARC-ISCW, 2011)

Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Rain (mm)	120.7	104.4	86.6	45.1	19.0	11.3	7.0	24.8	29.7	83.7	107.6	103.1	742.9
E_0 (mm)	205.4	160.5	159.8	120.4	104.1	81.6	93.3	128.1	167.8	186.1	195.3	211.9	1814.9
AI	0.59	0.65	0.54	0.37	0.18	0.14	0.07	0.19	0.18	0.45	0.55	0.49	0.41
Tmax (^{0}C)	26.8	26.2	24.7	22.1	19.3	16.3	16.5	19.2	22.6	23.7	24.8	26.3	22.4
Tmin (^{0}C)	13.7	13.4	11.5	7.2	2.1	-1.7	-2.2	0.7	4.9	8.6	10.7	12.6	6.8
Tm (^{0}C)	20.3	19.8	18.1	14.7	10.7	7.3	7.1	10.0	13.7	16.1	17.8	19.4	14.6

E_0 = Class A pan evaporation

AI = Aridity index, which is the ratio of rainfall to class-A pan evaporation

Tmax = Mean daily maximum temperature

Tmin = Mean daily minimum temperature

Tm = Mean daily temperature, *viz*. (Tmax + Tmin)/2

According to the Soil Classification Working Group (1991), the trial is laid out on a soil of the Mafikeng family, which had previously been classified as Soetmelk series (MacVicar et al., 1977), of the Avalon form, covering about 17% of land type Ca6n, and occurs on a terrain unit 3 with a 2-3% north facing slope. Correspondingly, the United States Department of Agriculture (USDA) system classifies the soil under the great group Plinthustalfs (Soil Survey Staff, 1987). This Plinthosol (FAO, 1998) is made up of three distinct horizons, viz. an orthic Ap (0-300 mm), yellow-brown apedal B1 (300-650 mm) and soft plinthic B2 (>650 mm), containing 18, 23 and 36% clay, respectively.

3.2 Experimental design and treatments

The experiment was laid out in a randomized complete block design with three blocks as replicates (I, II and III) across a north-facing slope, with block I being the highest and block III being the lowest. Each block contains 36 field treatments: two methods of straw management (burned and unburned) × three methods of tillage (ploughing, stubble mulch and no-tillage) × two methods of weed control (mechanical and chemical) × three levels of nitrogen fertilization (20, 30, and 40 kg N ha^{-1} until 2003, thereafter 20, 40 and 60 kg N ha^{-1} were used). Only the 40 kg N ha^{-1} plots were sampled.

The plots (30 m long and 6 m wide, with 10 m paths between head and foot of adjacent plots) are cropped annually with winter wheat (*Triticum aestivum*), without any substitution with a summer crop. In an attempt to restore soil water, a bare fallow period of five months is maintained in this trial between harvesting and planting, during which most of the rainfall events are expected. In 1990, 1991, 2004 and 2010, oat (*Avena sativa* L) was, however, used as a replacement crop, in an attempt to reduce soil-borne diseases (for example Take-all, *Gaeumannomyces graminis*) that arose in some treatments. No yield was realised in 1992 due to drought.

Immediately after harvesting in December, wheat straw in the no-tilled, stubble mulched and ploughed plots is burned or left unburned. In the ploughed plots, immediately after burning, a two-way offset disc is used to incorporate unburned wheat straw or the wheat straw ashes to 150 mm depth. After disking, the plots were mouldboard ploughed to 250 mm depth in February, when the soil is sufficiently moist and easy to work. The stubble mulched plots were not disked, instead they were cut at 100-150 mm depth using a V-blade and then ripped with a chisel plough (50 mm wide chisels spaced 300 mm intervals) to the same depth as mouldboard ploughing. The no-tilled plots were not ploughed or chiselled.

In the five-month fallow period (between harvesting and seeding) weed control was done once during the relevant treatments when necessary. Weeding was done either by mechanical cultivator (rod-weeder or V-blade, depending on soil water level until 2003). Since then a light tiller was used or by spraying herbicides. At first, Roundup herbicide was commonly used in this experiment. Later the broad-spectrum (non-selective) herbicides glyphosate and Paraquat were used alternatively to avoid chances of herbicide resistance developing. Weeds were then allowed to decompose in situ.

A combined seeder-fertilizer drill was used for sowing *Triticum aestivum* L. cv Betta and applying 3:2:0 (25) + 0.75% Zn fertilizer to all the treatment plots. The planter applied the mixed fertilizer at a rate that results in N, P, K and Zn applications of 20, 13, 0 and 1 kg ha^{-1}, respectively. Limestone ammonium nitrate was thoroughly mixed with this fertilizer mixture and applied to supplement the N levels to 30 and 40 kg ha^{-1} in the relevant treatments. However, since 2003, a DBS no-tillage planter was used, which made it unnecessary to premix the fertilizer by hand. Consequently, limestone ammonium nitrate and single superphosphate were used as fertilizer sources. The planter was set to accurately apply 20, 40 and 60 kg N ha^{-1}, and a constant application of 12.5 kg P ha^{-1}. As Betta has become obsolete, a newer cultivar, Elands, was introduced in 2005.

3.3 Soil sampling, preparation, and analysis

In 2016, the same sampling procedure was followed as with the previous sampling events for comparison purposes. Nevertheless, there might only be a difference in the sampling depth and month. In 1990, soil sampling was done in May at intervals of 0–50, 50–150, and 150–250 mm, whilst in 1999 and 2010 soil samples were taken in June at intervals of 0–50, 50–100, 100–150, 150–250, 250–350, and 350–450 mm. For comparison purposes, representative soil samples were collected at the headlands covered with perennial grass (Table 3.2) outside the trial, with a 70 mm diameter auger. Subsamples were collected at two sites 50 m apart, 100 m from the highest, and at two sites, 50 m apart, and 100 m from the lowest corner of the trial and mixed thoroughly. In each treatment plot, three auger cores (70 mm diameter) were taken from the centre-line and mixed thoroughly. Soil samples from both outside and within the trial were taken at different layers: 0-50, 50-100, 100-150, 150-250, 250-350 and 350-450 mm.

Similar to the samplings described for 1990, 1999 and 2010 above, representative soil samples were collected after the rainy season just before planting in June 2016, so as to allow maximum soil settling after the last cultivation. Only the plots treated with 40 kg N ha^{-1}

were sampled. The samples were allowed to dry at room temperature, sieved through a 2 mm sieve, and then stored for analysis. Chemical analyses were done in triplicate according to standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990). In addition, analyses were also performed following Hedley et al. (1982) sequential P fractionation procedure, starting the 0.5 M $NaHCO_3$ extraction as depicted in Figure 2.1.

Table 3.2 Mean values of some of the soil fertility indicators in the headlands with perennial grass outside the trial (Loke et al., 2012)

Depth (mm)	**N (%)**	**P (mg kg^{-1})**	**K (mg kg^{-1})**	**Ca (mg kg^{-1})**	**Mg (mg kg^{-1})**	**Na (mg kg^{-1})**	**CEC (cmol$_c$ kg^{1})**	**pH (H_2O)**
0-50	0.13	12.0	276	1034	167	39	7.96	5.7
50-100	0.11	6.7	221	1039	154	63	7.36	5.7
100-150	0.07	5.0	195	1028	139	72	6.63	5.9
150-250	0.06	5.1	170	1136	144	86	6.45	6.0
250-350	0.06	3.8	140	1087	136	82	6.63	6.0
350-450	0.06	2.2	101	1083	151	84	6.62	6.1

3.4 Statistical analysis

Analyses of variance were calculated for every soil layer using measurement means of the P fractions. The computations were done at a 95% confidence level with the SPSS software package. This software was also used to compare treatment means with Tukey’s procedure at a 95% confidence level.

CHAPTER FOUR

RESULTS

The results of the main treatments that included straw disposal, tillage and weeding methods on the inorganic (Pi), organic (Po) and total (Pt) soil P fractions are presented, followed by those of the different treatment combinations. Each of the Pi, Po and Pt fractions will be dealt herewith regard to labile P (easily accessible for plant uptake), moderately labile P (moderately accessible for plant uptake) and stable P (poorly accessible for plant uptake). A slightly modified sequential extraction procedure was used to determine the labile (extracted by 0.5 M $NaHCO_3$), moderately labile (extracted by 0.1 M NaOH) and stable (extracted by 1.0 M HCl) Pi and Po fractions, while the Pt fractions were estimated by the summation of these two fractions. The residual Pt (not accessible for plant uptake) was obtained by digestion with concentrated HCl.

4.1 Main effects

4.1.1 Straw disposal methods

Based on the summary of analysis of variance, straw disposal methods in all four soil layers had a significant influence on the inorganic labile and stable P fractions only (Table 4.1). Surprisingly, the moderately labile Pi fraction was similar regardless of the straw disposal method. Neither one of the Po fractions nor one of the Pt fractions differed significantly among the two methods of straw disposal. The variation in the P stratification in between the soil depths was almost negligible in all of the P fractions.

Table 4.1 Summary of analysis of variance showing the significant effects of straw disposal methods on P fractions in a soil layer

Fraction	**Soil layer (mm)**			
	0-50	**50-100**	**100-150**	**150-250**
Inorganic P				
Labile	*	*	*	*
Moderately labile	ns	ns	ns	ns
Stable	*	*	*	*
Organic P				
Labile	ns	ns	ns	ns
Moderately labile	ns	ns	ns	ns
Stable	ns	ns	ns	ns
Total P				
Labile	ns	ns	ns	ns
Moderately labile	ns	ns	ns	ns
Stable	ns	ns	ns	ns
Residual	ns	ns	ns	ns

*=significant at $P < 0.05$; ns = not significant

4.1.1.1 Labile P fraction

The labile Pi fraction was significantly higher in all four soil layers of the plots where the straw was burned (ranged between 10.09 and 11.21 mg kg^{-1}) than in the plots where the straw was not burned (ranged between 8.88 and 9.99 mg kg^{-1}), as displayed in Figure 4.1a. Using these data, a weighted average Pi content to 250 mm depth of 9.40 mg kg^{-1} for the burned and 10.65 mg kg^{-1} for the unburned plots was estimated. In the unburned plots the labile Pi gradually decreased with soil depth. This P fraction was however more variable with soil depth in the burned plots.

The labile Po content was less than half of the labile Pi content, irrespective of whether the straw was burned or not (Figure 4.1b). Although insignificant, higher labile Po contents were observed in the burned rather than the unburned plots, except for the deepest soil layer. The labile Po of the burned plots increased from 3.14 mg kg^{-1} in the 0-50 mm soil layer to 3.94 mg kg^{-1} in the 150-250 mm soil layer. A similar pattern for labile Po was observed in the unburned plots.

The labile Pt of the 0-50 mm soil layer was 13.33 mg kg^{-1} in the unburned plots and 14.36 mg kg^{-1} in the burned plots. This trend was repeated in the deeper soil layers (Figure 4.1c). For example, in the 150-250 mm soil layer a Pt content of 12.68 mg kg^{-1} in the unburned plots and of 13.68 mg kg^{-1} in the burned plots was observed. These differences in Pt between the burned and the unburned plots were of little significance (Table 4.1).

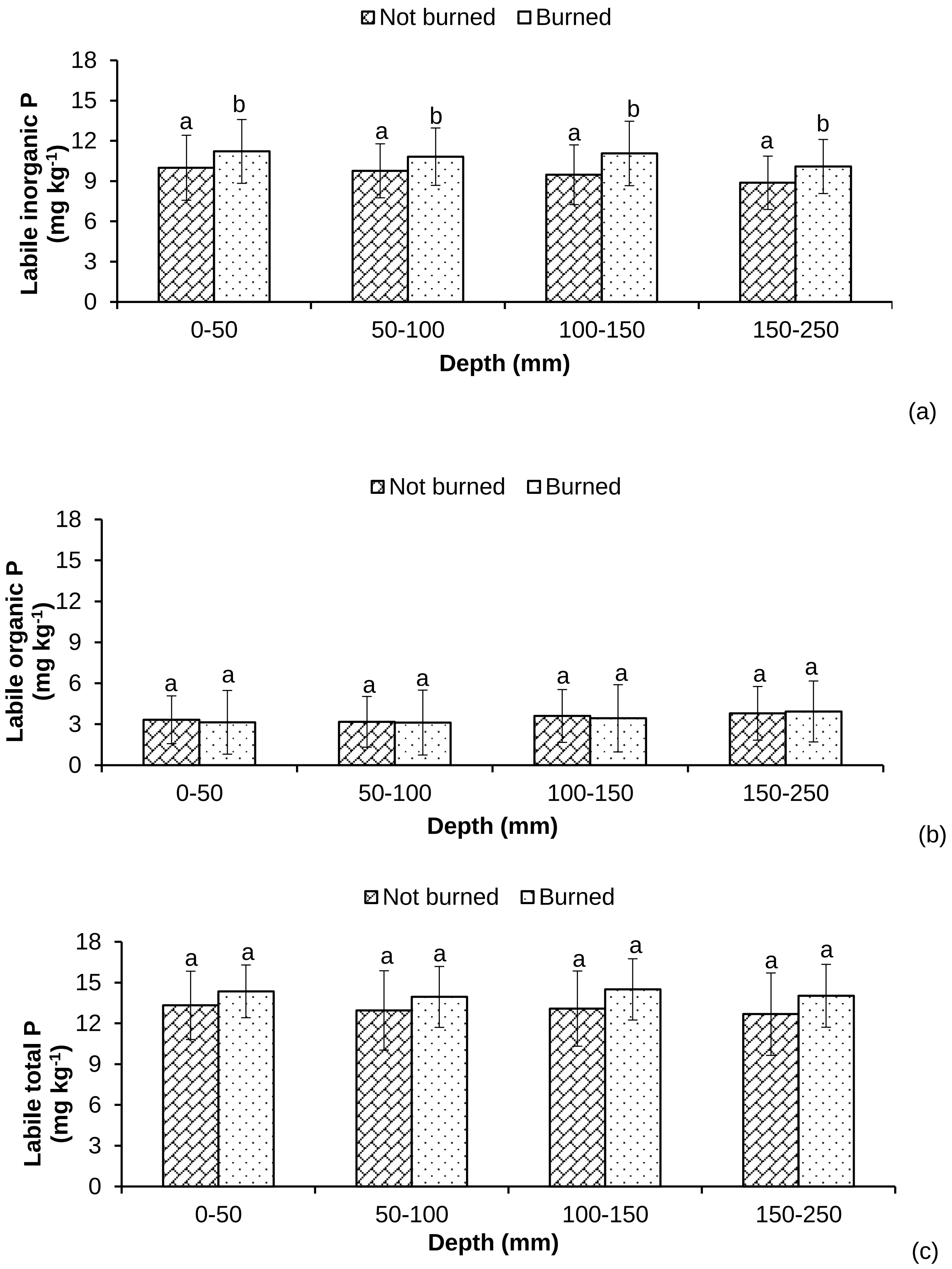

Figure 4.1 Effect of straw disposal on labile inorganic, organic and total P fractions at different soil depths. Significant differences (*P*<0.05) are indicated by different letters for each straw disposal method. Vertical bars with horizontal caps indicate standard deviation.

4.1.1.2 Moderately labile P fraction

The contents of moderately labile Pi, Po and Pt in the four soil layers of the unburned and burned plots are shown in Figure 4.2. None of the three P fractions was significantly affected by the straw disposal methods (Table 4.1). However, a close inspection of Figure 4.2a showed that the moderately labile Pi was slightly higher in the 0-50 and 50-100 mm soil layer of the unburned than in the burned plots. However, the unburned plots had a slightly higher moderately labile Pi in the 150-250 mm soil layer compared to the burned plots.

Likewise, the differences of moderately labile Po between unburned and burned plots were almost non-existent. However, the burned plots had a slightly higher moderately labile Po than the unburned plots, particularly in the 0-50 mm soil layer. In the 50-100 and 150-250 mm soil layer a opposite pattern was observed, the unburned plots had a slightly higher moderately labile Po compared to the burned plots. In the 100-150 mm soil layer the difference was negligible.

Although the moderately labile Pt was double the moderately labile Po, the differences among the straw disposal methods were insignificant. The burned plots had higher moderately labile Pt in the 0-50, 100-150 and 150-250 mm soil layer compared to the unburned plots. However, the unburned plots had higher moderately labile Pt than the burned plots, particularly in the 50-100 mm soil layer. The moderately labile Pi, Po and Pt tended to decrease somewhat with soil depth, except when straw disposal methods affected one of the fractions in a soil layer. In all four soil layers the moderately labile Pi exceeded the moderately labile by approximately 3 mg kg^{-1}.

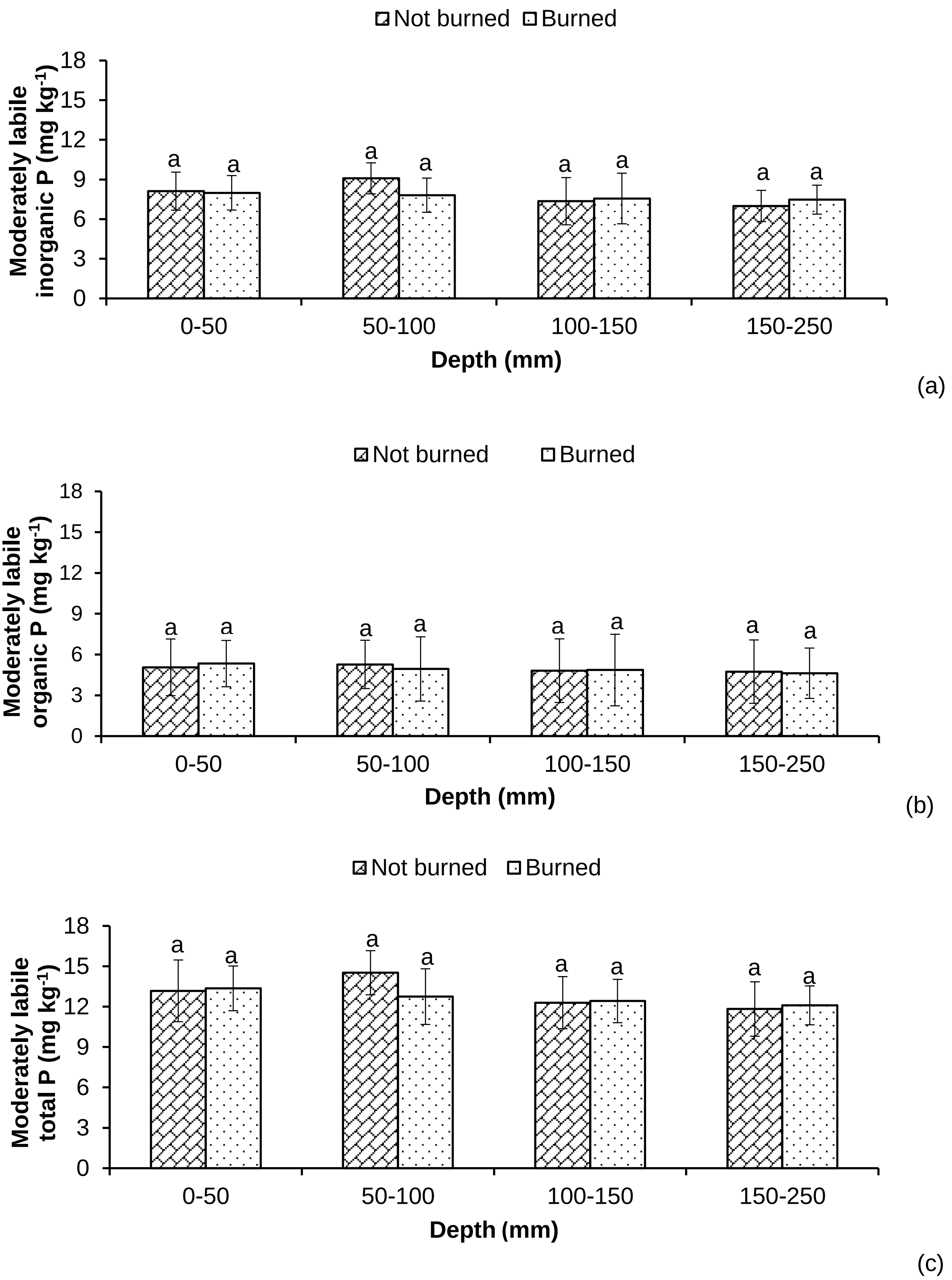

Figure 4.2 Effect of straw disposal on moderately labile inorganic, organic and total P fractions at different soil intervals. Significant differences (P<0.05) are indicated by different letters for each straw disposal method. Vertical bars with horizontal caps indicate standard deviation.

4.1.1.3 Stable P fraction

In all four soil layers stable Pi was significantly influenced by the straw disposal methods, but not stable Po or Pt (Table 4.1). The stable Pi content of the burned plots exceeded that of the unburned plots to 250 mm depth with weighted average values of 4.07 mg kg^{-1} and 4.51 mg kg^{-1}, respectively (Figure 4.3a). The higher stable Pi concentrations were recorded in the 100-150 mm soil layer, irrespective of the straw disposal method. Contrary to either the labile or moderately labile P fractions, where Pi was higher than Po, the Po was higher than Pi for the stable P fractions

In the upper soil layer (0-50 mm), the unburned plots had a slightly higher stable Po than the burned plots, although the difference was negligible (Figure 4.3b). In the three deeper soil layers (50-100, 100-150 and 150-250 mm) the burned plots had a higher stable Po content compare to the unburned plots. The stratification of stable Po concentration was almost uniform across all four soil layers.

The stable Pt of the burned plots was higher than that of the unburned plots in all four soil layers, although not significant (Figure 4.3c). The higher stable Pt values were recorded in the 100-150 mm soil layer for the burned plots while for the unburned it was observed in the 0-50 mm soil layer. None of the stable Pt fractions in the unburned and burned plots showed any trend with soil depth.

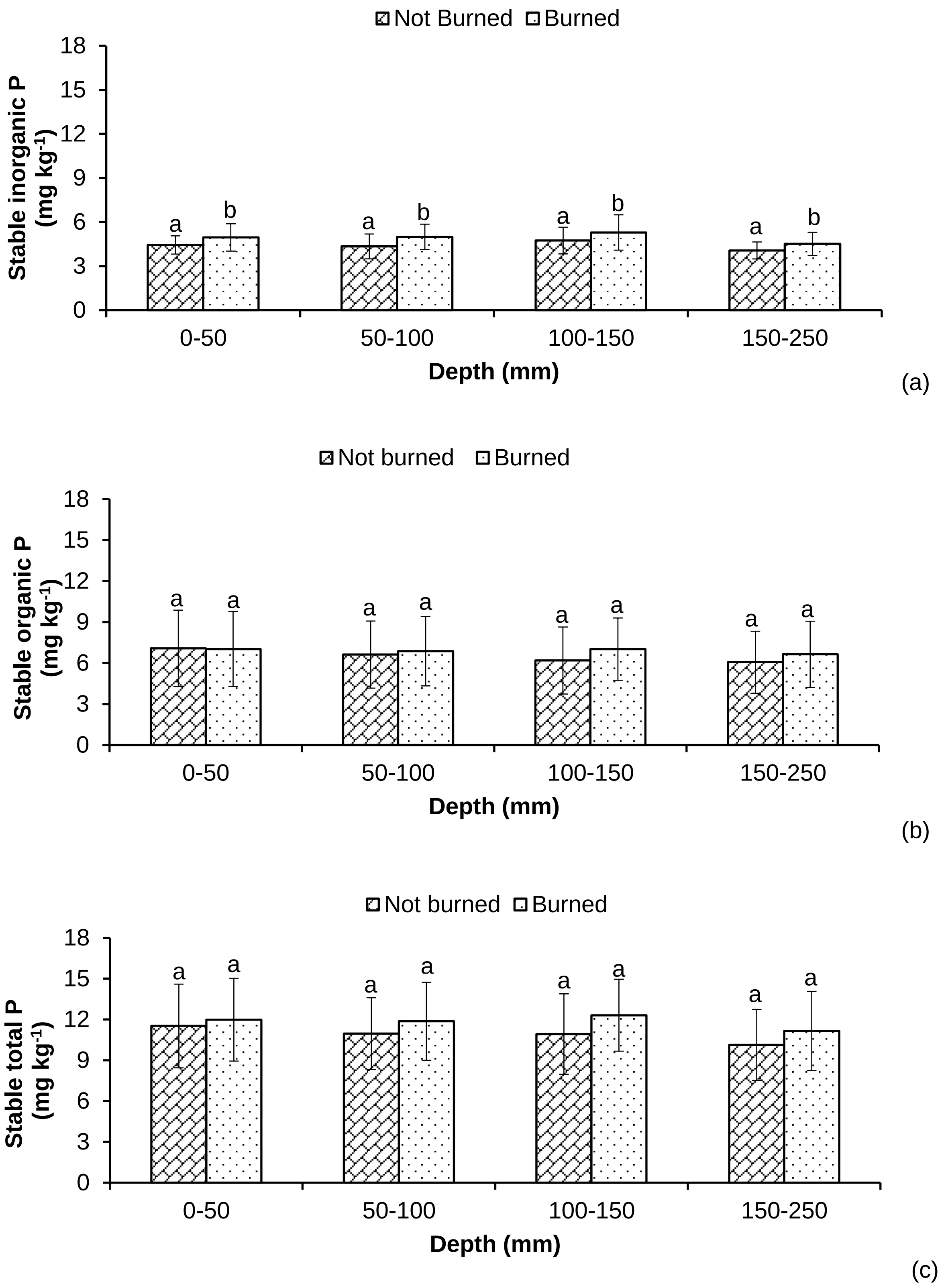

Figure 4.3 Effect of straw disposal on stable inorganic, organic and total P fractions at various soil depths. Significant differences ($P<0.05$) are indicated by different letters for each straw disposal method. Vertical bars with horizontal caps indicate standard deviation.

4.1.1.4 Residual P fraction

Only the residual Pt content was determined, and no significant differences were observed between the burned and unburned plots (Table 4.1). The Pt in the 0-50 mm and 50-100 mm soil layers was almost similar (Figure 4.4). This P fraction was however slightly higher in the 100-150 mm and 150-250 mm soil layers of the burned plots than the unburned plots. The residual Pt showed neither an increasing nor decreasing trend with soil depth.

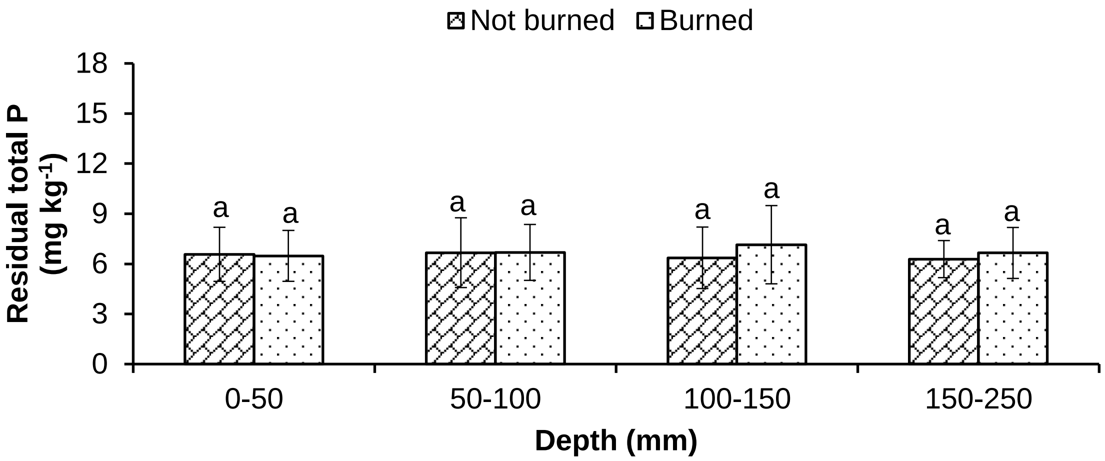

Figure 4.4 Effect of straw disposal on residual total P fractions at various soil depths. Significant differences (*P*<0.05) are indicated by different letters for each straw disposal method. Vertical bars with horizontal caps indicate standard deviation.

4.1.2 Tillage methods

According to the summary of the analyses of variance which tillage methods produced a significant influence on the inorganic labile and stable P fractions in all four soil layers and also in the moderately labile P, particularly in the 0-50 mm soil layer (Table 4.2). For the organic fraction, only labile P showed a significant difference in the upper soil layer (0-50 mm). Interestingly, the tillage methods had a significant influence in the total labile P on the upper two soil layers; while for the total moderately labile P, a significant difference was recorded in all soil layers except in the 50-100 mm layer. On the other hand, the tillage methods had a significant influence on the total stable P fraction, in the upper soil layer only.

Table 4.2 Summary of analyses of variance showing the significant effects of tillage methods on P fractions in a soil layer

Fraction	**Soil layer (mm)**			
	0-50	**50-100**	**100-150**	**150-250**
Inorganic P				
Labile	*	*	*	*
Moderately labile	*	ns	ns	ns
Stable	*	*	*	*
Organic P				
Labile	*	ns	ns	ns
Moderately labile	ns	ns	ns	ns
Stable	ns	ns	ns	ns
Total P				
Labile	*	*	ns	ns
Moderately labile	*	ns	*	*
Stable	*	ns	ns	ns
Residual	ns	ns	ns	ns

*= significantly at $P < 0.05$; ns = not significant

4.1.2.1 Labile P fraction

The labile Pi fraction was significantly higher in all four soil layers of the plots that were no-tilled (ranged between 10.60 and 12.50 mg kg^{-1}) than in the stubble mulched (ranged between 9.4 and 11.14 mg kg^{-1}) or ploughed plots (ranged between 8.01 and 8.29 mg kg^{-1}), as displayed in Figure 4.5a. Using these data, weighted average Pi values to 250 mm depth of 11.41 mg kg^{-1} for the no-tilled plots, 10.53 mg kg^{-1} for the stubble mulched plots, and 8.15 mg kg^{-1} for the ploughed plots were estimated. The higher Pi concentrations were measured in the upper soil layer (0-50 mm) and gradually decreased with depth, irrespective of tillage method.

In the labile Po fraction, an opposite pattern to that of labile Pi fraction was observed (Figure 4.5b). The tillage method had a significant effect on the labile Po fraction, particularly on the 0-50 mm soil layer. The ploughed plots had a higher labile Po content, followed by stubble mulched and no-tilled plots. Unlike the labile Pi fraction in the no-tilled plots, the labile Po increased from 2.11 mg kg^{-1} in the 0-50 mm soil layer to 3.39 mg kg^{-1} in the 150-250 mm soil layer. However, the labile Po fraction of the stubble mulched plots increased only slightly from 3.39 mg kg^{-1} in the 0-50 mm soil layer to 3.40 mg kg^{-1} in the 150-250 mm soil layer. A very similar trend was observed with labile Po in the ploughed plots. Nevertheless, the labile Po content was also less than half the labile Pi content, regardless of the tillage methods.

The tillage methods had a significant influence on labile Pt fraction particularly in the upper two soil layers of 0-50 mm and 50-100 mm. The no-tilled plots had the highest P content of 14.60 mg kg^{-1} in the 0-50 mm soil layer and 14.49 mg kg^{-1} in the 50-100 mm soil layer. Conversely, the ploughed plots had the lowest labile Pt content with 12.39 mg kg^{-1} in the 0-50 mm soil layer and 11.93 mg kg^{-1} in the 50-100 mm soil layer (Figure 4.5c). The labile Pt concentration gradually decreased with depth. This pattern was observed across all the methods of tillage.

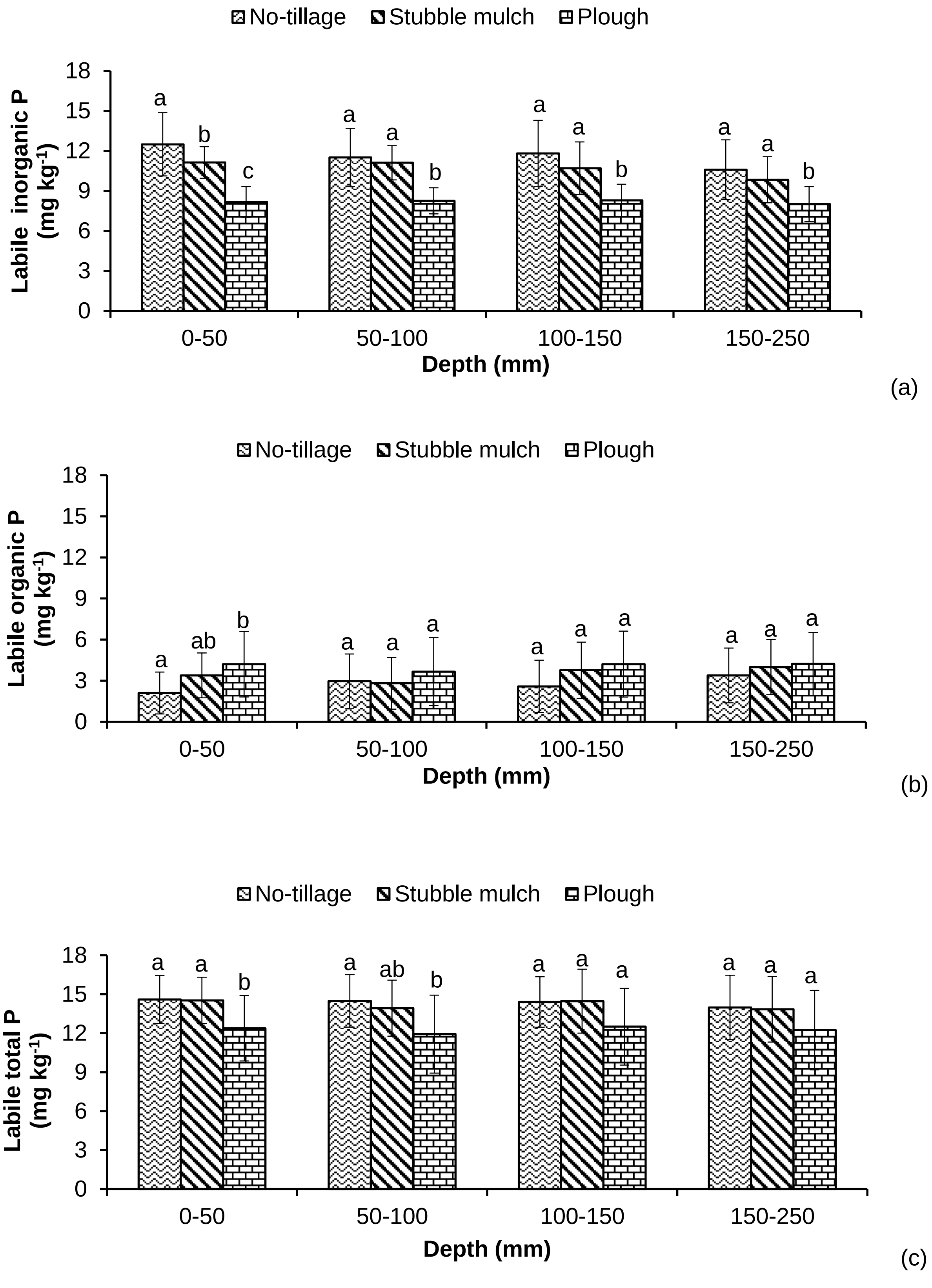

Figure 4.5 Effect of tillage methods on labile inorganic, organic and total P fractions at various soil depths. Significant differences (*P*<0.05) are indicated by different letters for each tillage method. Vertical bars with horizontal caps indicate standard deviation.

4.1.2.2 Moderately labile P fraction

The concentration of the moderately labile Pi, Po and Pt fractions in the four soil layers of no-tilled, stubble mulched and ploughed plots are displayed in Figure 4.6. Tillage methods influenced the moderately labile Pi fraction to a significant degree only in the 0-50 mm soil layer (Table 4.2). In this upper layer the content of the moderately labile P fraction in the no-tilled plots was 8.87 mg kg^{-1}, 8.31 mg kg^{-1} in the stubble mulched plots and 6.97 mg kg^{-1} in the ploughed plots. As indicated in Figure 4.6a, the Pi on the no-tilled plots was not significantly different from the stubble mulched plots. However, both these tillage practices were significantly different from those of the ploughed plots. In this P fraction there was more variation with soil depth, irrespective of tillage methods.

The moderately labile Po content was less than half of the moderately labile Pi content, regardless of the tillage method. Although negligible, a similar trend to that of moderately labile Pi was observed. A close inspection of Figure 4.6b indicated that no-tillage plots had higher moderately labile Po content (ranging between 5.01 and 5.53 mg kg^{-1}), followed by stubble mulched plots (ranging between 4.87 to 5.17 mg kg^{-1}) and by ploughed plots (ranging between 4.08 to 4.62 mg kg^{-1}), in the three lower soil layers. In the 0-50 mm soil layer, the stubble mulched plots had a higher moderately labile Po content than the no-tilled and ploughed plots.

In almost all of the studied soil layers, the moderately labile Pt was significantly influenced by tillage method (Table 4.2). The no-tilled plots had the highest moderately Pt (ranging between 12.63 to 14.12 mg kg^{-1}), followed by the stubble mulched plots (ranging between 12.37 to 14.02 mg kg^{-1}) and the ploughed plots (ranging between 10.88 to 13.92 mg kg^{-1}). In the no-tilled and stubble mulched plots the moderately labile Pt gradually decreased with soil depth, unlike in the ploughed plots which increased from 11.66 mg kg^{-1} in the 0-50 mm soil layer to 13.92 mg kg^{-1} in the 50-100 mm soil layer. In the latter two soil layers stubble mulched plots had the highest Po content followed by the ploughed and the no-tilled plots. This P fraction gradually decreased with depth, irrespective of tillage method.

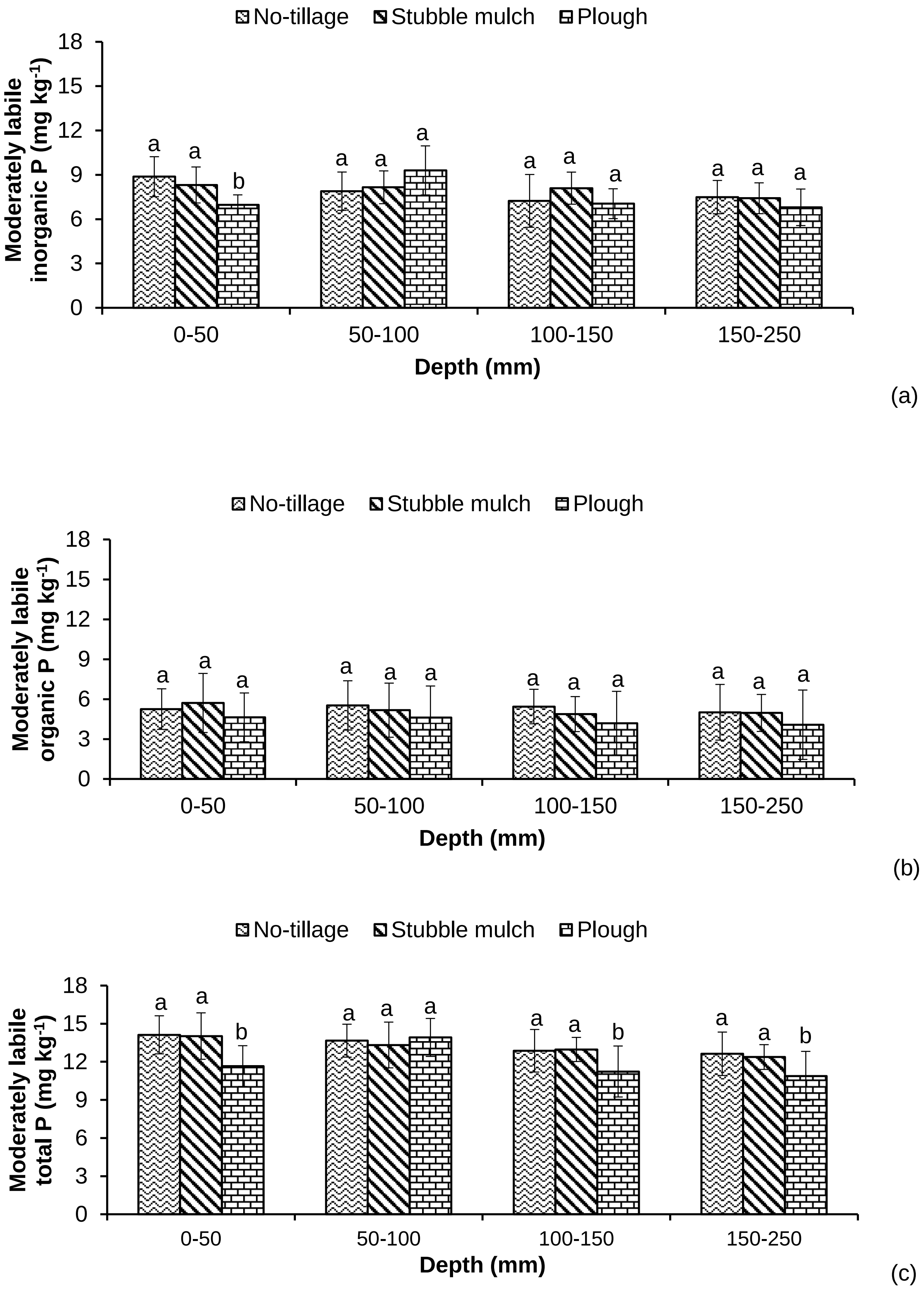

Figure 4.6 Effect of tillage on moderately labile inorganic, organic and total P fractions at various soil depths. Significant differences (*P*<0.05) are indicated by different letters for each tillage method. Vertical bars with horizontal caps indicate standard deviation.

4.1.2.3 Stable P fraction

The stable Pi fraction was significantly influenced by the tillage method in all four soil layers (Table 4.2). The no-tilled plots had the highest stable Pi content (ranging between 4.51 and 5.76 mg kg^{-1}), followed by the stubble mulched plots (ranging between 4.48 and 5.19 mg kg^{-1}) except in the 50-100 mm soil layer as shown in Figure 4.7a. Using these data, a weighted average of stable Pi content to 250 mm depth of 4.95 mg kg^{-1} content for the no-tilled, 4.83 mg kg^{-1} for the stubble mulched and 3.99 mg kg^{-1} for the ploughed plots were estimated. As shown in Figure 4.7a, across all four soil layers the no-tilled plots were not significantly different to the stubble mulched plots. However, both tillage practices were significantly different from the ploughed plots.

In the stable Po fraction, the content was higher than that of stable Pi, regardless of tillage method (Figure 4.7b). Although the difference between the tillage methods was not significant, the no-tilled plots (7.79 and 7.31 mg kg^{-1}) had a higher Po content than the stubble mulched (7.04 and 6.64 mg kg^{-1}) and ploughed plots (6.32 and 6.26 mg kg^{-1}) in the 0-50 and 50-100 mm soil layers. In the last two soil layers (100-150 and 150-250 mm), the stubble mulched had higher Po content followed by ploughed and no-tilled plots. This P fraction gradually decreased with depth, irrespective of the tillage method.

The stable Pt content was significantly affected by tillage method only in the 0-50 mm soil layer (Table 4.2). In this soil layer Pt was 12.88 mg kg^{-1} in the no-tilled plots, 11.92 mg kg^{-1} in the stubble mulched plots and 10.45 mg kg^{-1} in the ploughed plots. As displayed in Figure 4.7c with respect to Pt, the no-tilled plots were not significantly different from the stubble mulched plots but significantly different from the ploughed plots. The stubble mulched plots did not differ significantly from either the ploughed plots or the no-tilled plots. The stable Pt content gradually decreased with soil depth.

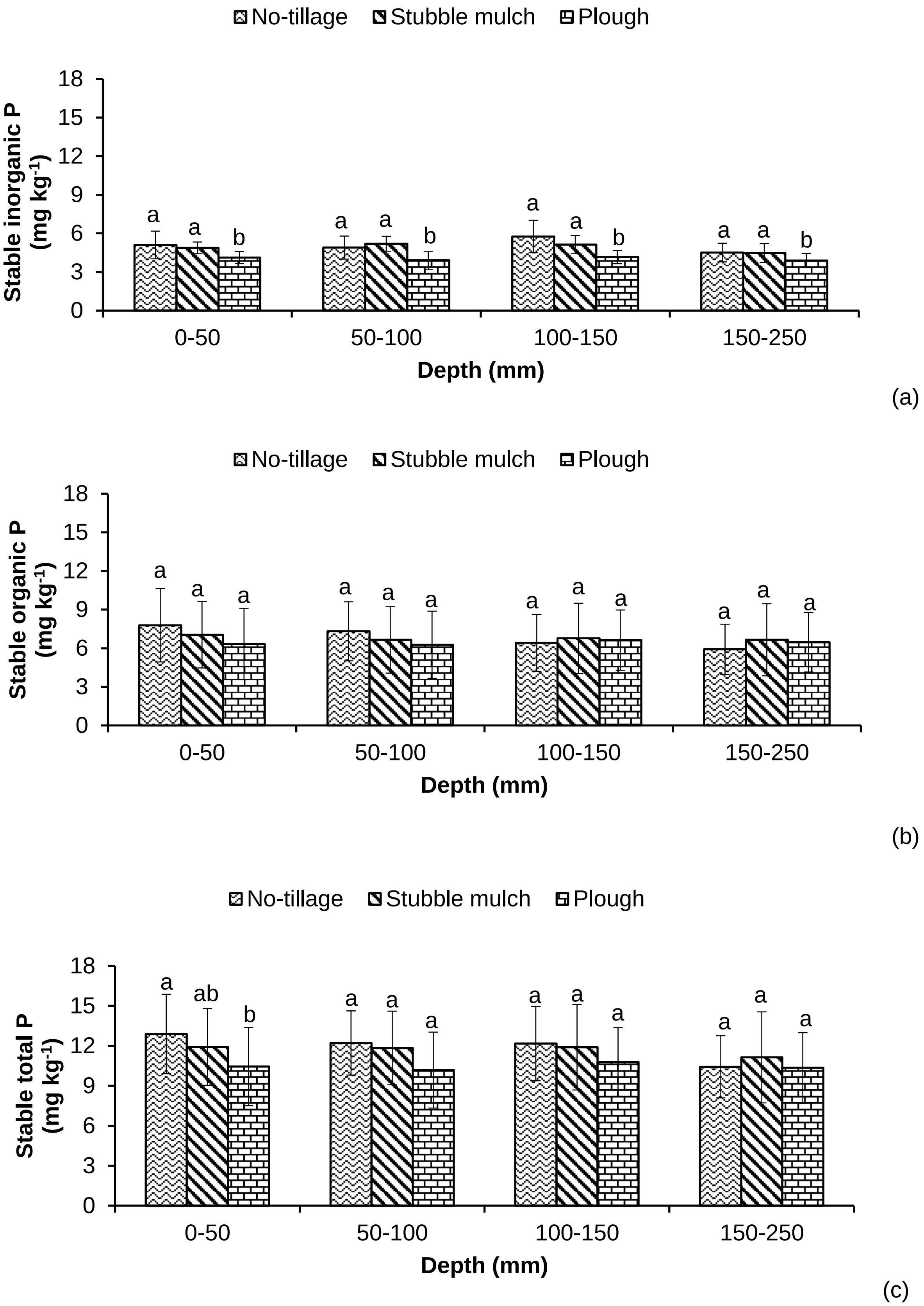

Figure 4.7 Effect of tillage on stable inorganic, organic and total P fractions at various soil depths. Significant differences (*P*<0.05) are indicated by different letters for each tillage method. Vertical bars with horizontal caps indicate standard deviation.

4.1.2.4 Residual P fraction

The tillage method had no significant effect on the residual Pt fraction across all the four soil layers (Table 4.2). Although no distinct trend was observed, the Pt in the 0-50 mm and 150-250 mm soil layers behaved similarly. A close inspection of Figure 4.8 reveals that the no-tilled plots had a higher Pt content across all four soil layers, except in the 50-100 mm soil layer. The residual Pt followed no particular pattern across soil depth.

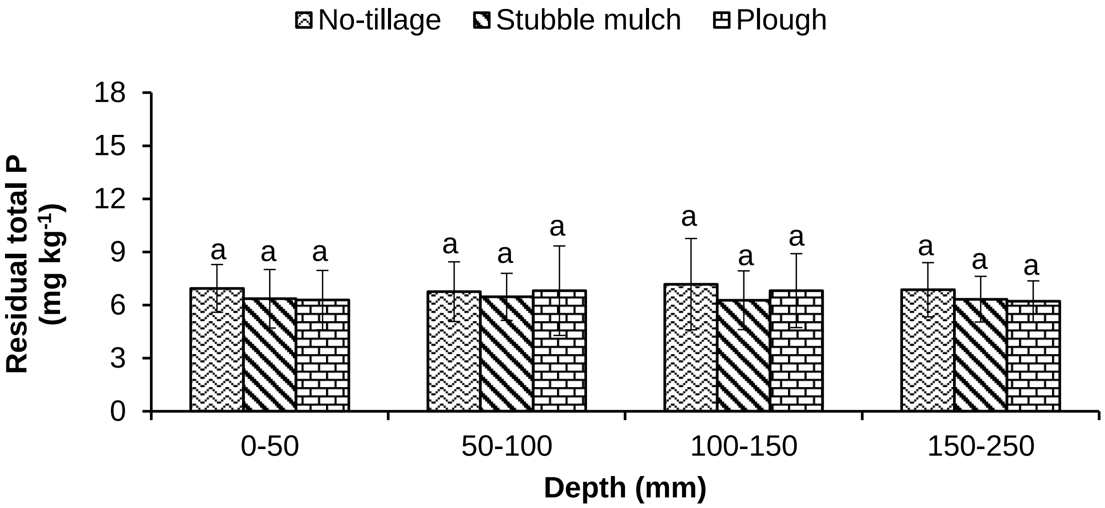

Figure 4.8 Effect of tillage on residual total P fractions at various soil depths. Significant differences (*P*<0.05) are indicated by different letters for each tillage method. Vertical bars with horizontal caps indicate standard deviation.

4.1.3 Weeding methods

The summary of the analysis of variance indicated that methods of weeding control had a significant influence on all of the P fractions in certain soil layers (Table 4.3). In all four soil layers, the stable Pt was significantly influenced by the weeding method whilst the labile Po, moderately labile Pt and residual Pt were not significantly affected.

Table 4.3 Summary of analyses of variance showing the significant effects of weeding methods on P fractions in a soil layer

Fraction	**Soil layer (mm)**			
	0-50	**50-100**	**100-150**	**150-250**
Inorganic P				
Labile	*	*	ns	*
Moderately labile	ns	ns	*	ns
Stable	*	ns	*	*
Organic P				
Labile	ns	ns	ns	ns
Moderately labile	ns	*	*	ns
Stable	ns	ns	*	*
Total P				
Labile	ns	ns	ns	*
Moderately labile	ns	ns	ns	ns
Stable	*	*	*	*
Residual	ns	ns	ns	ns

*= significantly at $P < 0.05$; ns = not significant

4.1.3.1 Labile P fraction

The labile Pi was significantly higher in the chemically weeded plots particularly in the upper two soil layers (0-50 and 50-100 mm) and the lower soil layer (150-250 mm) than was the case with the mechanical weeded plots (Table 4.3). The concentration of this fraction in the chemically weeded plots exceeded that of the mechanical weeded plots to 250 mm depth with weighted average values of 10.53 mg kg^{-1} and 9.53 mg kg^{-1}, respectively (Figure 4.9a). The labile Pi content ranged between 9.97 mg kg^{-1} and 11.15 mg kg^{-1} in the chemically weeded plots, whilst it ranged between 8.98 mg kg^{-1} and 10.06 mg kg^{-1} in the mechanically weeded plots. The labile Pi content gradually decreased with soil depth.

As displayed in Figure 4.9b, the concentration of labile Po, was less than half of that of labile Pi, regardless of the weeding method. Although no significant difference was observed, labile Po contents were noted as higher in the chemically weeded plots than in the mechanically weeded plots across all four soil layers. In the chemically weeded plots, the labile Po content increased from the 0-50 mm layer by 3.27 mg kg^{-1} and from the 150-260 mm soil layer by 4.32 mg kg^{-1}.

The weeding method had a significant effect on the labile Pt content in the 150-250 mm soil layer only. In the 150-250 mm soil layer, the Pt content was 14.31 mg kg^{-1} in the chemically weeded plots and 12.40 mg kg^{-1} in the mechanically weeded plots. Across all the four soil layers the chemically weeded plots had a higher labile Pt compared to mechanically weeded plots. The labile Pt concentration gradually decreased with soil depth.

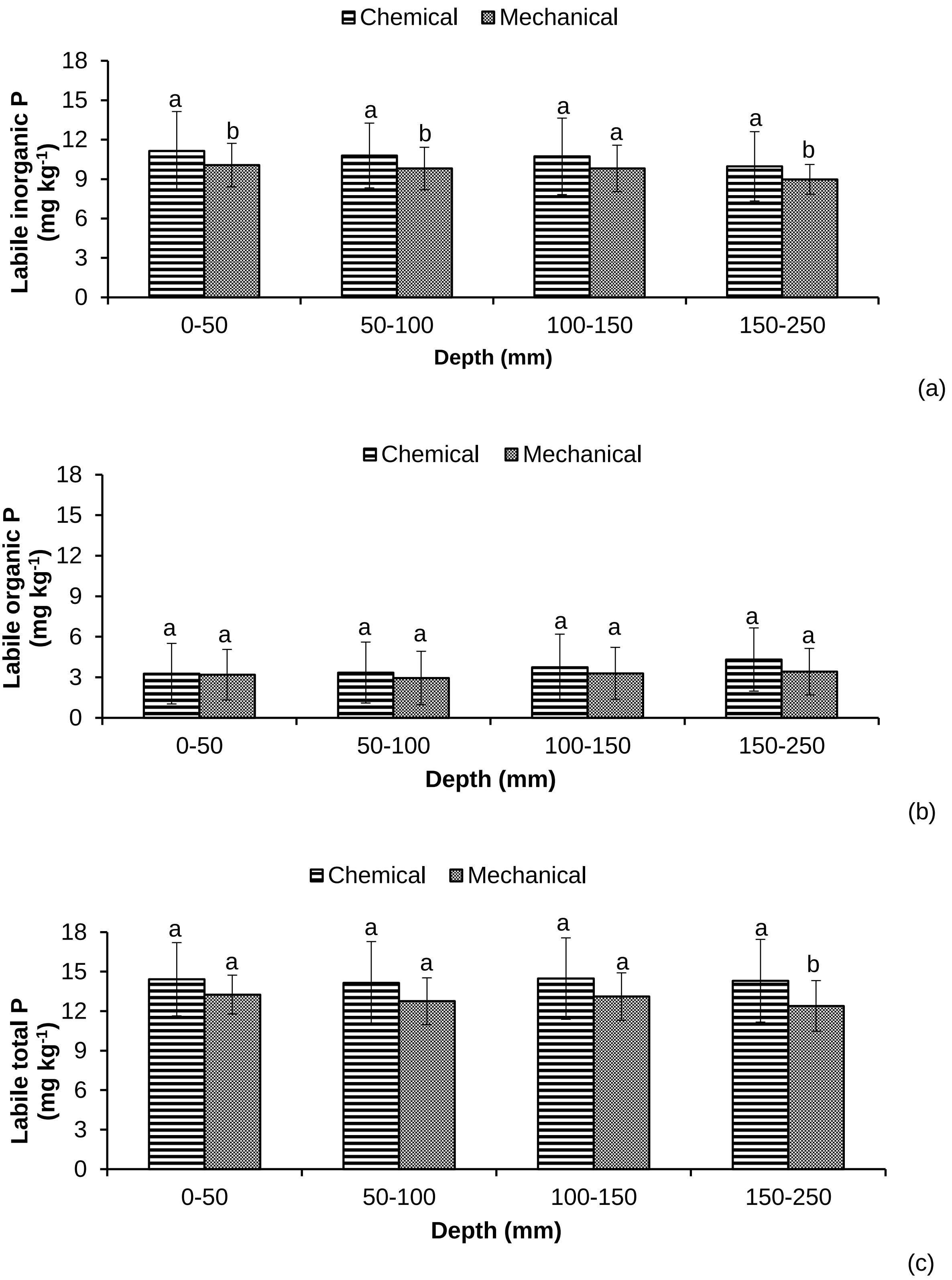

Figure 4.9 Effect of weed control method on labile inorganic, organic and total P fractions at various soil depth intervals. Significant differences (*P*<0.05) are indicated by different letters for each weeding method. Vertical bars with horizontal caps indicate standard deviation.

4.1.3.2 Moderately labile P fraction

The moderately labile Pi, Po and Pt content of the four soil layers as influenced by chemical and mechanical weed control is shown in Figure 4.10a. The moderately labile Pi fraction was significantly higher in the 100-150 mm soil layer only, with 8.14 mg kg^{-1} in the chemically weeded plots and 6.7 mg kg^{-1} in the mechanically weeded plots (Table 4.3). In almost all the four soil layers the chemically weeded plots had higher P content than mechanically weeded plots, except in the 50-100 mm soil layer.

Contrary to the moderately labile Pi fraction, the mechanically weeded plots had a higher moderately labile Po content than in chemically weeded plots across all the four soil layers (Figure 4.10b). The weeding method had a significant influence on moderately labile Po, particularly in the 50-100 and 100-150 mm soil layers (Table 4.3). The moderately labile Po content was 4.43 mg kg^{-1} in the 0-50 mm soil layer and 3.71 mg kg^{-1} in the 50-100 mm soil layer in the chemically weeded plots. In the mechanically weeded plots, the Po content was 5.7 mg kg^{-1} in the 50-100 mm soil layer and 5.97 mg kg^{-1} in the 50-100 mm soil layer. This moderately labile Po fraction was however more variable with soil depth, regardless of weeding methods.

A similar pattern for the moderately labile Pt fraction and the moderately labile Po fraction was observed (Figure 4.10c). The plots that were mechanically weeded had a higher Pt content than those that were chemically weeded, although not to a significant degree (Table 4.3). The moderately labile Pt content ranged between 11.46 to 12.92 mg kg^{-1} in the chemically weeded plots and between 12.47 to 14.83 mg kg^{-1} in the mechanically weeded plots. The moderately labile Pt gradually decreased with soil depth in the chemically weeded plots.

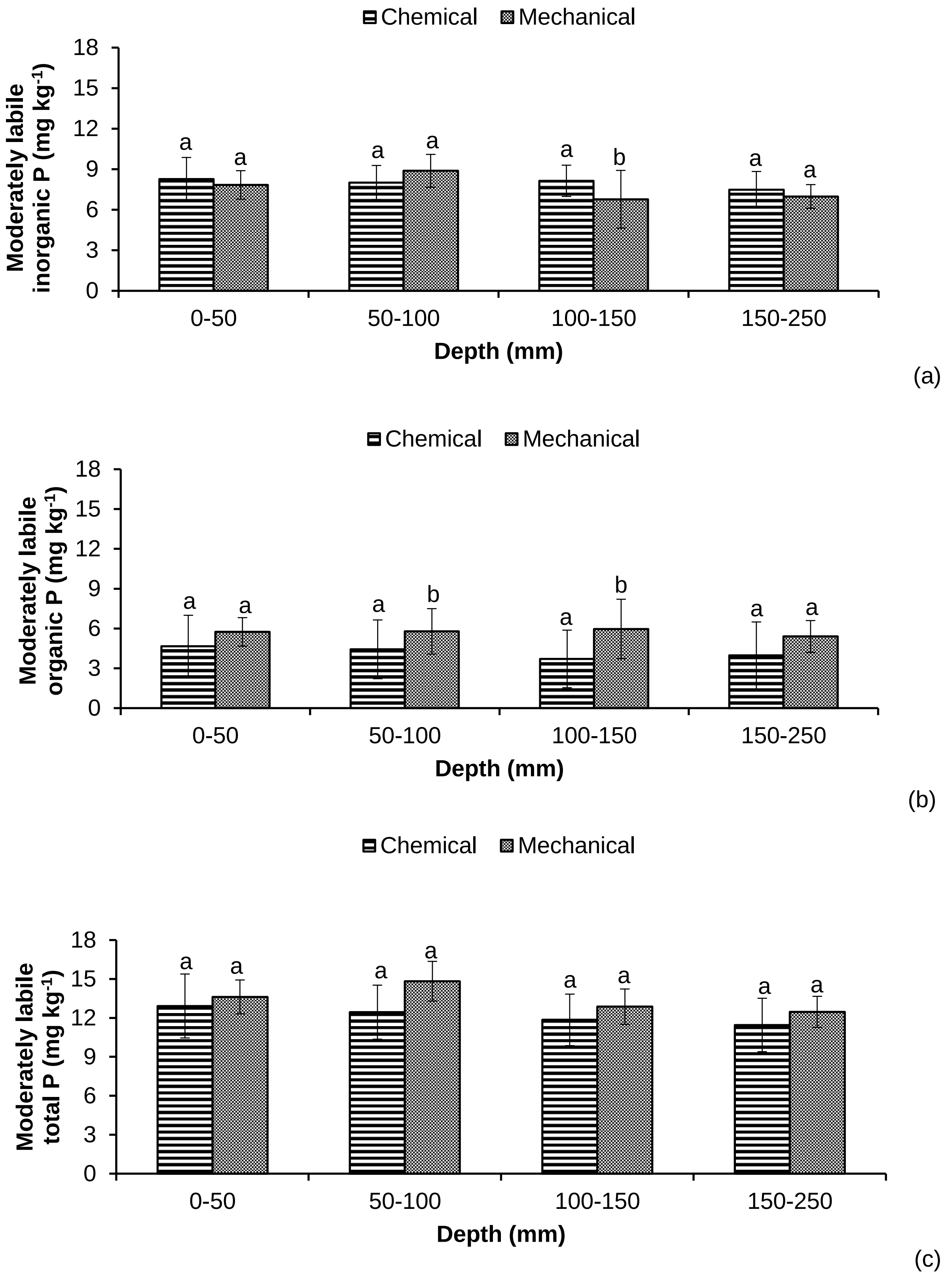

Figure 4.10 Effect of weed control method on moderately labile inorganic, organic and total P fractions at various soil depth intervals. Significant differences ($P<0.05$) are indicated by different letters for each weeding method. Vertical bars with horizontal caps indicate standard deviation.

4.1.3.3 Stable P fraction

The stable Pi was significantly higher in all four soil layers barring the 50-100 mm soil layer. Generally, the Pi content in the chemically weeded plots (ranging between 4.63 and 5.31 mg kg^{-1}) was higher than in the mechanically weeded plots (ranging between 3.95 and 4.71 mg kg^{-1}) as shown in Figure 4.11a. Using these data, a weighted average stable Pi content to 250 mm depth of 4.86 mg kg^{-1} for the chemically weeded plots and 4.32 mg kg^{-1} for the mechanically weeded plots was estimated.

The stable Po content was almost double that of stable Pi content, regardless of whether the weeds were chemically or mechanically controlled (Figure 4.11b). The stable Po concentration was significantly higher in plots that were chemically weeded rather than the mechanically weeded, particularly in the 100-150 and 150-250 mm soil layers. In the chemically weeded plots, the stable Po was 7.81 mg kg^{-1} in the 100-150 mm soil layer and 7.43 mg kg^{-1} in the 150-250 mm soil layer. On the other hand, the mechanically weeded plots evidenced a stable Po content of 5.39 mg kg^{-1} in the 100-150 mm soil layer and 5.26 mg kg^{-1} in the 150-250 mm soil layer. The stable Po content gradually decreased with depth.

When compared, the labile Pt fraction was significantly higher in all four soil layers of the chemically weeded plots (ranging between 12.05 and 12.77 mg kg^{-1}) than in those of the mechanically weeded plots (ranging between 9.21 and 10.73 mg kg^{-1}) as displayed in Figure 4.11c. Using these data, a weighted average Pt content to 250 mm depth of 12.47 mg kg^{-1} for the chemically weeded plots was estimated. In the mechanically weeded plots, stable Pt content gradually decreased with soil depth. A similar pattern was observed in the chemically weeded plots although there was an increase in the 100-150 mm (13.12 mg kg^{-1}) compared to the 50-100 mm soil layer (12.34 mg kg^{-1}).

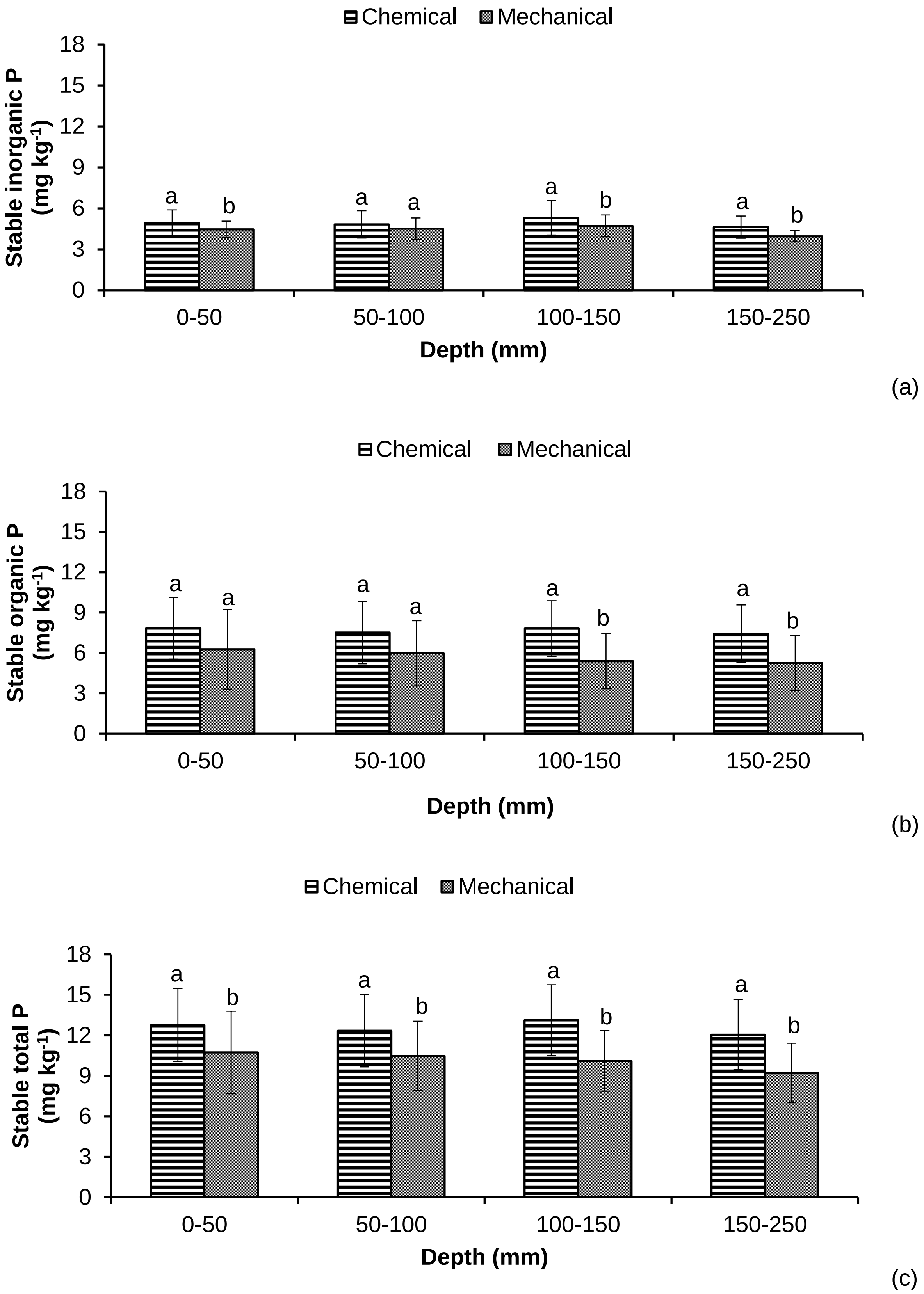

Figure 4.11 Effects of weeding control method on stable inorganic, organic and total P fractions. Significant differences (*P*<0.05) are indicated by different letters for each weeding method. Vertical bars with horizontal caps indicate standard deviation.

4.1.3.4 Residual P fraction

The weeding method had no significant effect on the residual P fraction across all the four soil layers (Table 4.3). The difference of Pt between the chemically and mechanically weeded plots for the 0-50 mm and 150-250 mm soil layers was negligible. A close inspection of Figure 4.12 reveals that the chemically weeded plots had a higher Pt content in the 50-100 mm soil layer only, than the mechanically weeded plots while the opposite was true in the 100-150 mm soil layer. The residual Pt followed no particular pattern with soil depth.

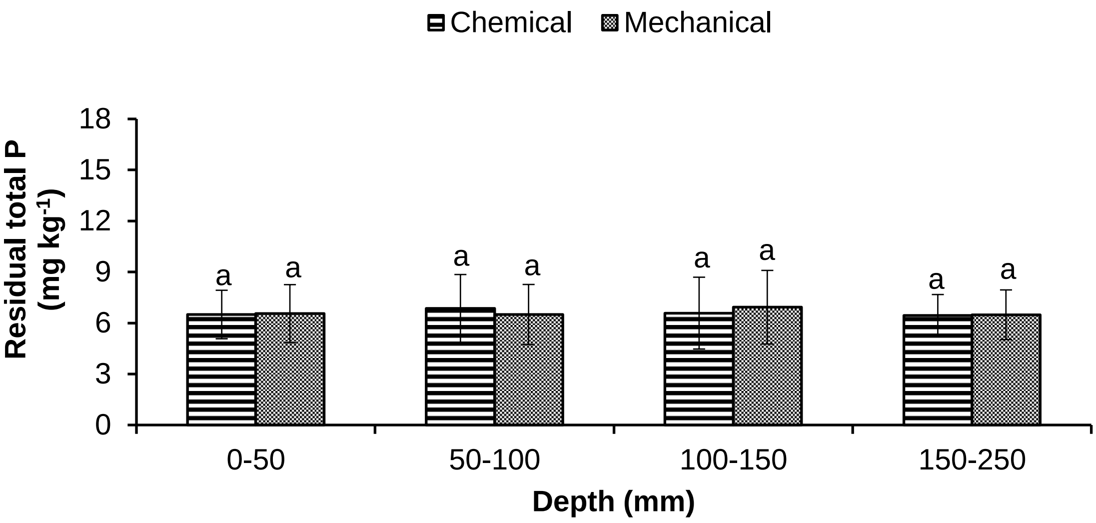

Figure 4.12 Effect of weeding method in residual P content. Significant differences (P<0.05) are indicated by different letters for each straw disposal method. Vertical bars with horizontal caps indicate standard deviation.

4.2 Interactions

4.2.1 Labile P fraction

The summary of analysis of variance indicated that the combination of the tillage and weeding methods had a significant influence on the labile Pi in all four soil layers (Table 4.4). None of the other treatment combinations influenced labile Pi significantly. The treatment combinations also had no significant influence on either the labile Po or Pt fractions across all four soil layers.

Table 4.4 Summary of analyses of variance showing the significant effects of the interaction of various treatments on the labile P fractions in all four soil layers

Treatment combination	**Soil layer (mm)**			
	0-50	**50-100**	**100-150**	**150-250**
Inorganic P				
AB	ns	ns	ns	ns
AC	*	*	*	*
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns
Organic P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns
Total P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns

A: Tillage, B: Straw disposal, C: Weeding method;

*= significantly at $P < 0.05$; ns = not significant

A close inspection of Table 4.5 indicated that the no-tilled plots in which weeds were chemically controlled, resulted in higher labile Pi content compared to stubble mulched or ploughed plots, irrespective of any straw disposal methods or mechanical weeding across all four soil layers. The labile Pi content decreased from the 0-50 mm to 150-250 mm soil layer, irrespective of any tillage method and weed control combination.

The labile Po content was on average approximately three times lesser than that of labile Pi in all four soil layers, regardless of treatment combination (Table 4.6). Although not significant (Table 4.4), an interesting trend was observed throughout the sampled soil layers. The plots that were unburned and combined either no-till or stubble mulch had slightly higher labile Po contents than the plots that were burned combined with either no-till or stubble mulch. On the other hand, the plots that were mechanically weeded had a slightly higher labile Po content than the no-tilled plots that were chemically weeded in all four soil layers. In contrast, the plots in which weeds were chemically controlled combined with stubble mulch or plough, had higher labile Po contents than those in which weeds were mechanically controlled.

In all four soil layers, the different treatment combinations had no significant influence on the labile Pt fraction (Table 4.4). However, a trend tendency was observed (Table 4.7). The labile Pt content was slightly higher in the burned plots than in the unburned plots, irrespective of the tillage methods, particularly in the three upper soil layers (0-50, 50-100 and 100-150 mm). A similar trend was observed in the chemically weeded plots which had a slightly higher labile Pt content than the mechanically weeded plots, regardless of tillage methods. An exception was noted in the 0-50 and 50-100 mm soil layers of the ploughed plots.

Table 4.5 Effect of the interactions between tillage, straw disposal and weeding methods on labile Pi (mg kg^{-1})

	Tillage			**Weeding**	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	11.79	10.72	7.49	10.29	9.70
Burned	13.21	11.56	8.87	12.01	10.42
Weeding Chemical	14.19	11.17	8.09		
Mechanical	10.81	11.11	8.26		
50-100 mm layer					
Straw Unburned	10.98	10.67	7.67	10.17	9.38
Burned	12.06	11.56	8.85	11.42	10.23
Weeding Chemical	13.10	11.08	8.19		
Mechanical	9.93	11.15	8.33		
100-150 mm layer					
Straw Unburned	10.96	10.04	7.44	9.53	9.43
Burned	12.68	11.37	9.14	11.93	10.20
Weeding Chemical	13.46	10.40	8.33		
Mechanical	10.18	11.01	8.25		
150-250 mm layer					
Straw Unburned	10.18	9.23	7.23	8.97	8.78
Burned	11.02	10.46	8.80	11.01	9.18
Weeding Chemical	12.42	9.75	7.80		
Mechanical	8.77	9.94	8.23		

Table 4.6 Effect of the interaction between tillage, straw disposal and weeding methods on labile Po (mg kg^{-1})

	Tillage			Weeding	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	2.46	3.80	3.73	3.48	3.17
Burned	1.75	2.98	4.69	3.06	3.22
Weeding Chemical	1.74	3.80	4.27		
Mechanical	2.47	2.98	4.14		
50-100 mm layer					
Straw Unburned	3.39	3.28	2.88	3.39	2.97
Burned	2.56	2.35	4.46	3.32	2.93
Weeding Chemical	2.91	3.44	3.71		
Mechanical	3.03	2.19	3.63		
100-150 mm layer					
Straw Unburned	3.21	4.40	3.22	3.97	3.25
Burned	1.97	3.13	5.21	3.53	3.34
Weeding Chemical	2.12	4.70	4.42		
Mechanical	3.05	2.82	4.01		
150-250 mm layer					
Straw Unburned	3.90	4.14	3.36	4.34	3.26
Burned	2.88	3.85	5.09	4.30	3.58
Weeding Chemical	3.35	4.82	4.78		
Mechanical	3.42	3.17	3.66		

Table 4.7 Effect of the interactions between tillage, straw disposal and weeding control on stable Pt (mg kg^{-1})

	Tillage			**Weeding**	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	14.25	14.52	11.21	13.78	12.87
Burned	14.96	14.55	13.56	15.06	13.64
Weeding Chemical	15.93	14.97	12.37		
Mechanical	13.28	14.09	12.41		
50-100 mm layer					
Straw Unburned	14.36	13.94	10.55	13.56	12.35
Burned	14.62	13.91	13.31	14.73	13.16
Weeding Chemical	16.01	14.52	11.90		
Mechanical	12.97	13.34	11.95		
100-150 mm layer					
Straw Unburned	14.16	14.43	10.66	13.50	12.67
Burned	14.65	14.50	14.35	15.45	13.54
Weeding Chemical	15.59	15.10	12.74		
Mechanical	13.23	13.83	12.26		
150-250 mm layer					
Straw Unburned	14.07	13.37	10.59	13.32	12.04
Burned	13.89	14.31	13.88	15.30	12.76
Weeding Chemical	15.77	14.57	12.59		
Mechanical	12.19	13.12	11.89		

4.2.2 Moderately labile P fraction

The summary of analysis of variance indicated that the interaction between tillage, straw disposal and weeding methods had no significant influence on the moderately labile P fractions in any of the four soil layers analysed (Table 4.8), however, certain trends were observed.

Table 4.8 Summary of analyses of variance showing the significant effects of interaction of various treatments on the moderately labile P fractions in all four soil layers

Treatment combination	**Soil layer (mm)**			
	0-50	**50-100**	**100-150**	**150-250**
Inorganic P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns
Organic P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns
Total P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns

A: Tillage, B: Straw disposal, C: Weeding method;

*= significantly at $P < 0.05$; ns = not significant

A distinct trend was noticed in the response of the moderately labile Pi fraction in different treatment interactions (Table 4.9). The plots with unburned residues had a slightly higher moderately labile Pi content than the plots with burned residues, regardless of tillage method, particularly in the upper two soil layers (0-50 and 50-100 mm). The opposite pattern was true in the lower two soil layers (100-150 and 150-250 mm) where burned residues had slightly higher moderately labile Pi contents than those of the unburned residues, irrespective of tillage method. The chemically weeded plots had slightly higher contents of moderately labile Pi than the mechanically weeded plots, in the no-tilled and stubble mulched plots. As shown in Table 4.9 the no-tilled plots had slightly higher moderately labile Pi followed by stubble mulched plots and ploughed plots, irrespective of straw disposal or weeding methods.

Although not significant, the moderately labile Po content in mechanically weeded plots was slightly higher than in the chemically weeded plots, irrespective of tillage methods throughout the sampled soil layers (Table 4.10). The plots in which the residues were burned and the weeds chemically controlled had moderately labile Po content that was slightly higher compared to plots which were unburned and whose weeds were chemically controlled. However, the plots where burning of residues was combined with mechanical weeding had lower moderately labile Po content than the plots where burning of residues was combined with mechanical weeding.

The interactive effect between treatments on moderately labile Pt fraction in various soil layers is displayed in Table 4.11. Although not significant, the moderately labile Pt fraction in the burned plots combined with chemical weeding was slightly higher than that of the unburned plots combined with mechanical weeding, in all the four soil layers. Conversely, the unburned plots combined with mechanical weeding had slightly higher moderately labile Pt content than the burned plots combined with mechanical weeding across the four soil layers. The no-tilled plots combined with unburned residues had slightly higher moderately labile Pt compared to either the stubble mulched or ploughed plots, in which residues were burned.

Table 4.9 Effect of the interactions between tillage, straw disposal, and weed control methods on moderately labile Pi (mg kg^{-1})

	Tillage			**Weeding**	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	8.97	8.37	6.99	8.33	7.90
Burned	8.77	8.25	6.95	8.21	7.78
Weeding Chemical	9.51	8.22	7.07		
Mechanical	8.23	8.41	6.87		
50-100 mm layer					
Straw Unburned	7.61	8.22	11.43	7.87	10.30
Burned	8.18	8.09	7.16	8.16	7.46
Weeding Chemical	8.69	8.31	7.04		
Mechanical	7.10	7.99	11.55		
100-150 mm layer					
Straw Unburned	7.01	8.05	7.01	8.01	6.71
Burned	7.46	8.14	7.08	8.28	6.84
Weeding Chemical	8.77	8.29	7.37		
Mechanical	5.70	7.90	6.72		
150-250 mm layer					
Straw Unburned	7.30	7.20	6.49	7.17	6.82
Burned	7.62	7.62	7.11	7.80	7.15
Weeding Chemical	8.10	7.60	6.75		
Mechanical	6.88	7.22	6.85		

Table 4.10 Effect of the interactions between tillage, straw disposal, and weed control methods on moderately labile Po (mg kg^{-1})

	Tillage			Weeding	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	5.88	5.17	4.13	4.08	6.05
Burned	4.62	6.25	5.13	5.23	5.44
Weeding Chemical	4.20	5.87	3.89		
Mechanical	6.30	5.56	5.37		
50-100 mm layer					
Straw Unburned	5.91	4.81	5.10	4.40	6.16
Burned	5.14	5.53	4.14	4.47	5.41
Weeding Chemical	4.12	5.54	3.63		
Mechanical	6.94	4.80	5.61		
100-150 mm layer					
Straw Unburned	5.70	4.64	4.10	3.45	6.18
Burned	5.18	5.11	4.28	3.96	5.75
Weeding Chemical	3.54	4.77	2.81		
Mechanical	7.34	4.98	5.57		
150-250 mm layer					
Straw Unburned	5.33	4.83	4.07	3.86	5.63
Burned	4.69	5.09	4.09	4.09	5.16
Weeding Chemical	4.06	4.90	2.95		
Mechanical	5.96	5.03	5.20		

Table 4.11 Effect of the interactions between tillage, straw disposal, and weed control methods on moderately labile Pt (mg kg^{-1})

	Tillage			Weeding	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	14.85	13.55	11.12	12.40	13.95
Burned	13.39	14.50	12.19	13.44	13.29
Weeding Chemical	13.71	14.08	10.97		
Mechanical	14.54	13.97	12.35		
50-100 mm layer					
Straw Unburned	14.01	13.03	12.53	12.26	16.79
Burned	13.03	13.62	11.31	12.63	12.87
Weeding Chemical	12.80	13.85	10.67		
Mechanical	14.53	12.79	17.16		
100-150 mm layer					
Straw Unburned	13.10	12.69	11.11	11.45	13.14
Burned	12.64	13.26	11.37	12.24	12.60
Weeding Chemical	12.31	13.06	10.18		
Mechanical	13.43	12.88	12.29		
150-250 mm layer					
Straw Unburned	12.88	12.04	10.56	11.03	12.62
Burned	12.38	12.72	11.20	11.88	12.31
Weeding Chemical	12.16	12.50	9.71		
Mechanical	13.10	12.25	12.05		

4.2.3 Stable P fraction

The summary of the analysis of variance showed that the interaction between tillage, straw disposal and weeding methods had no significant influence on the stable P fractions in the four soil layers (Table 4.12), although certain patterns were noted.

Table 4.12 Summary of analyses of variance showing the significant effects of interaction of various treatments on the stable P fractions in all four soil layers

Treatment combination	**Soil layer (mm)**			
	0-50	**50-100**	**100-150**	**150-250**
Inorganic P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns
Organic P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns
Total P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns

A: Tillage, B: Straw disposal, C: Weeding method;

*= significantly at *P*< 0.05; ns = not significant

The stable Pi fraction (Table 4.13) in the burned plots was slightly higher than in the unburned plots, regardless of the tillage or weed control method. Similarly, the no-tilled plots in which the residues were burned had higher stable Pi content than either the stubble mulched or ploughed plots across all four soil layers. Interestingly, chemically weeded plots had higher stable Pi content than mechanically weeded plots, irrespective of tillage method throughout the soil layers.

The burned plots had a slightly higher stable Po content than the unburned plots, regardless of tillage method, particularly in the 100-150 and 150-250 mm soil layers, although not a significant extent. Correspondingly, the burned plots had a slightly higher stable Po content than the unburned plots irrespective of weeding method, particularly in the 100-150 and 150-250 mm soil layers. In the upper two layers, the combination of chemical weeding with unburned residues had higher stable Po content than the combination of chemical weeding with unburned residues (Table 4.14).

Although not significant, the stable Pt was found to be higher in the chemically weeded plots than in the mechanically weeded plots, irrespective of tillage method, in all the four soil layers. Similarly, the burned plots had a slightly higher stable Pt content than the unburned plots regardless of the tillage method, in the all four soil layers, except in the 0-50 mm soil layer. The no-tilled or stubble mulched plots had slightly higher stable Pt content than the ploughed plots, regardless of the weeding or straw disposal method. A higher concentration of stable Pt was found in the upper soil layer (0-50 mm) compared with the lower soil layer (150-250 mm) for all treatment combinations (Table 4.14).

Table 4.13 Effect of the interactions between tillage, straw disposal, and weed methods control on stable Pi (mg kg^{-1})

		Tillage			Weeding	
		None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	4.59	4.79	3.95	4.58	4.30
	Burned	5.61	4.96	4.29	5.29	4.62
Weeding	Chemical	5.49	4.95	4.36		
	Mechanical	4.70	4.80	3.88		
50-100 mm layer						
Straw	Unburned	4.43	5.15	3.45	4.44	4.24
	Burned	5.36	5.24	4.38	5.21	4.78
Weeding	Chemical	5.16	5.29	4.03		
	Mechanical	4.63	5.10	3.79		
100-150 mm layer						
Straw	Unburned	5.26	4.97	3.98	4.86	4.62
	Burned	6.25	5.29	4.33	5.77	4.81
Weeding	Chemical	6.44	5.25	4.26		
	Mechanical	5.08	5.01	4.05		
150-250 mm layer						
Straw	Unburned	4.26	4.24	3.70	4.23	3.90
	Burned	4.75	4.71	4.07	5.02	4.01
Weeding	Chemical	4.99	4.79	4.10		
	Mechanical	4.03	4.17	3.66		

Table 4.14 Effect of the interactions between tillage, straw disposal, and weed control method on stable Po (mg kg^{-1})

		Tillage		**Weeding**	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	8.48	6.40	6.35	8.27	5.89
Burned	7.09	7.69	6.30	7.40	6.65
Weeding Chemical	7.45	8.72	7.33		
Mechanical	8.12	5.36	5.33		
50-100 mm layer					
Straw Unburned	7.64	5.92	6.29	7.61	5.63
Burned	6.99	7.37	6.24	7.42	6.31
Weeding Chemical	7.23	8.52	6.79		
Mechanical	7.40	4.77	5.74		
100-150 mm layer					
Straw Unburned	6.24	6.36	5.95	7.53	4.83
Burned	6.59	7.16	7.30	8.08	5.95
Weeding Chemical	6.96	8.90	7.56		
Mechanical	5.87	4.62	5.69		
150-250 mm layer					
Straw Unburned	5.57	6.45	6.14	7.06	5.05
Burned	6.25	6.87	6.79	7.80	5.47
Weeding Chemical	6.59	8.57	7.14		
Mechanical	5.24	4.75	5.79		

Table 4.15 Effect of the interactions between tillage, straw disposal, and weed control on stable Pt (mg kg^{-1})

	Tillage			Weeding	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	13.07	11.19	10.30	12.84	10.19
Burned	12.70	12.65	10.60	12.69	11.27
Weeding Chemical	12.94	13.67	11.69		
Mechanical	12.82	10.16	9.21		
50-100 mm layer					
Straw Unburned	12.07	11.07	9.74	12.05	9.87
Burned	12.35	12.60	10.62	12.63	11.09
Weeding Chemical	12.40	13.81	10.82		
Mechanical	12.03	9.87	9.54		
100-150 mm layer					
Straw Unburned	11.50	11.33	9.93	12.39	9.45
Burned	12.84	12.45	11.63	13.85	10.76
Weeding Chemical	13.39	14.15	11.83		
Mechanical	10.95	9.63	9.74		
150-250 mm layer					
Straw Unburned	9.84	10.69	9.84	11.29	8.95
Burned	11.01	11.58	10.86	12.82	9.48
Weeding Chemical	11.57	13.35	11.24		
Mechanical	9.27	8.91	9.45		

4.2.4 Residual P fractions

The summary of the analysis of variance indicated that the interactions between tillage, straw disposal and weeding methods had no significant influence on the residual P fractions across all four soil layers (Table 4.16).

Table 4.16 Summary of analyses of variance showing the significant effects of interaction of various treatments on the residual P fractions in all four soil layers

Treatment combination	**Soil layer (mm)**			
	0-50	**50-100**	**100-150**	**150-250**
Inorganic P				
AB	ns	ns	ns	ns
AC	ns	ns	ns	ns
BC	ns	ns	ns	ns
ABC	ns	ns	ns	ns

A: Tillage, B: Straw disposal, C: Weeding method;

*= significantly at $P< 0.05$; ns = not significant

Although no significant difference was found, certain trends were observed (Table 4.17). The no-tilled plots had higher residual Pt content than either stubble mulched or ploughed plots when the residues were burned. Similarly, the no-tilled plots accompanied by chemical weeding had higher residual Pt concentration than either the stubble mulched or ploughed plots accompanied by chemical weeding, across all the soil layers. In the upper two layers, the treatment combination of unburned residues with chemical weeding had a higher residual Pt content than the treatment combination of burned residue and chemical weeding. Although the difference was almost negligible, the residual Pt content was slightly concentrated in the 0-50 mm soil layer and subsequently decreased slightly with depth.

Table 4.17 Effect of the interaction between tillage, straw disposal, and weed control methods on residual Pt (mg kg^{-1})

	Tillage			**Weeding**	
	None	Stubble mulched	Ploughed	Chemical	Mechanical
0-50 mm layer					
Straw Unburned	6.58	6.45	6.69	6.71	6.44
Burned	7.30	6.26	5.87	6.29	6.67
Weeding Chemical	7.18	6.25	6.07		
Mechanical	6.70	6.46	6.49		
50-100 mm layer					
Straw Unburned	6.53	6.38	7.10	7.25	6.09
Burned	6.98	6.55	6.53	6.46	6.91
Weeding Chemical	7.19	6.38	7.01		
Mechanical	6.33	6.55	6.62		
100-150 mm layer					
Straw Unburned	5.80	6.37	6.92	6.44	6.29
Burned	8.56	6.18	6.71	6.73	7.57
Weeding Chemical	7.01	5.96	6.78		
Mechanical	7.35	6.59	6.85		
150-250 mm layer					
Straw Unburned	5.94	6.59	6.32	6.33	6.24
Burned	7.79	6.07	6.09	6.57	6.73
Weeding Chemical	7.00	6.42	5.94		
Mechanical	6.73	6.25	6.48		

CHAPTER FIVE

DISCUSSION

5.1 Main effects

5.1.1 Straw disposal methods

5.1.1.1 Labile P fraction

In this study, the labile P fraction was significantly influenced by the straw disposal methods (burned and unburned) throughout the four soil layers as shown in Table 4.1. In each soil layer, the plots with burned crop residues had higher P concentrations than the plots with unburned crop residues (Figure 4.1a). This is attributed to the quick release of nutrients in a plant available form from the wheat residues when they are burned compared to when they are unburned. Similar findings were reported by Reddy et al. (2014) namely, that the ashes that remain after burning of wheat residues become a valuable source of P, K and several micronutrients, which consequently improved soil fertility.

Correspondingly, Loke et al. (2012; 2014) reported that the burning of wheat residues directly adds ashes into the soil which increases both the concentration and solubility of P and other nutrients. On the other hand, release of P in the unburned plots depends on the C:P ratio. This implies that P can be subjected to immobilization by soil microbes if the ratio is greater than 300:1 (Shafqat et al., 2009). The investigation by Kotzé and Du Preez (2008) demonstrated that crop residue retained in the soil surface can decrease soil pH and thereby induce acidic conditions. Under such conditions, P can precipitate as secondary mineral strengite ($FePO_4.2H_2O$) and variscite ($AlPO_4.2H_2O$), which is less available to plant uptake.

In this study, the labile Pi had higher values in the top 0-50 mm soil layer and then gradually decreased with soil depth, irrespective of straw disposal method. In soils, P is usually regarded as an immobile nutrient, implying that surface application of burned and/or unburned wheat residues increased the P content more in the upper soil layers than in the deeper soil layers. Similarly, Kotzé and Du Preez (2007) reported that the concentration of nutrients, especially the immobile ones, increased in the upper layers when the soil is not turned by mouldboard plough.

The results of labile Po showed an opposite pattern to that of labile Pi, although not to a significant extent (Table 4.1). A slightly higher labile Po content was recorded in the unburned compared to the burned plots, particularly in the upper three soil layers (Figure

4.1b). The soil organic P is largely in the form of inositol phosphates, phospholipids and nucleic acids which are tied up in soil microbes (Zhang and Kovar, 2000; Piccoli et al., 2016). These soil microbes obtain their food and energy from crop residues that remain on the soil surface or are incorporated therein. Although burning of wheat residues showed an increase in labile Pi, it had a lesser impact on labile Po. The study by Butterworth (1985) demonstrated that soil living organisms are affected by high temperatures during the burning of crop residues, resulting in reduced microbial population which is the major driver of the labile Po fraction.

In the results of this study, it was noted that the Po constitutes only a small portion of 25% on average, while Pi covers 75% of the Pt, throughout the four soil layers, regardless of the straw disposal method. This trend is consistent with the findings of Shariatmadari et al. (2007) who indicated that the Po fraction constitutes an average of 20% while the Pi had an average of 80% in soils. This could be due to a rapid conversion of organic P forms to inorganic forms through mineralization in supplying P to plant roots. As indicated in Figure 4.1c, the burning of wheat residues leads to a slight increase in labile Pt, although not to a significant extent.

5.1.1.2 Moderately labile P fraction

When the labile P fraction decreases in the soil solution due to plant absorption and/or leaching, it is then replenished by the moderately labile P fraction (NaOH-P) (Conyers and Moody, 2009). The moderately labile P fraction is bound to iron and aluminium oxides, and surface of sesquioxides (Hedley et al., 1982) which makes them an active fraction in buffering P in the soil solution. The results obtained in this study indicated (Figure 4.2a) that the unburned plots had a moderately labile Pi content that was slightly higher than that of the burned plots in the top two soil layers, although it was not statistically significant (Table 4.1). Similar findings were reported by Reddy et al. (2014), who indicated that the surface retention and/or incorporation of wheat residues escalates the labile Po as well as the moderately labile Pi when burning of wheat residues served as a reference.

Furthermore, the investigation by Mitran et al. (2016) demonstrated that retention of crop residues adds organic matter to the soil, thereby increasing moderately labile Pi (e.g. Fe-P) fractions significantly and consistently. Similarly, the study by Kotzé and Du Preez (2008) demonstrated that the accumulation of organic matter at/or near the soil surface increases the concentration of nutrients, especially the immobile ones.

In the 100-150 and 150-250 mm soil layers the burned plots had slightly higher moderately labile Pi than the unburned plots. This could be due to the quick release of nutrients in an available form ($H_2PO_4^-$ and HPO_4^{2-}), which increases the solubility of P (Singh and Rengel, 2007). This implies that during high intensity rainfall, the water percolating through the soil surface has the potential of carrying P and other nutrients to the deeper soil layers.

Although there was no significant difference in the moderately labile Po between the treatments (Table 4.1), the following trends were observed. The moderately labile Po content decreased from top to bottom, irrespective of a straw disposal method. Both the unburned and burned wheat residues elevated the moderately Po content to a greater extent in the 0-50 mm soil layer than in the 150-250 mm soil layer. A similar trend was also noted by Shafqat and Pierzynski (2010) who reported that the moderately labile Po was increased by surface retention of crop residues compared to the burning of crop residues.

The burned plots had a slightly higher moderately labile Pt content than the unburned plots, except in the 50-100 mm soil layer. Similarly, Reddy et al. (2014) reported that the moderately labile P fraction was greater in the plots where wheat residues were burned than in the plots where wheat residues were left on the soil surface or incorporated into the soil. As indicated by previous studies (Du Preez et al., 2001; Loke et al., 2012; Ventrella et al., 2016), burning of wheat residues resulted in an accumulation of P in the upper soil layers, which could explain the results of this study. This means that wheat crops grown in plots where the straw is burned may have a constant supply of P from the moderately labile P fraction, when P in the soil solution decreases. Interestingly, the study by Costa et al. (2016) postulated that the availability of P in the soil solution depends largely on replenishing of other inorganic P fractions.

In addition, the ash from the burned residues have a natural liming effect, implying a potential increase of soil pH from acidic to neutral or slightly alkaline. The burning of residues therefore reduces the chances of P to precipitate as Fe and Al-phosphates and thereby enhances the release of P from the surface of clay minerals into soil solution. A slightly lower labile P in the unburned plots could be attributed to considerable amounts of P that were still trapped in the residues. For example, Singh and Sidhu (2013) reported that approximately 25-30 % of P is retained in wheat residues, which can all be released into the soil during and after residue decomposition.

5.1.1.3 Stable P fraction

The assumption about this P fraction is that it has been precipitated as Ca-phosphates which are trapped within sesquioxides and derived from primary minerals such as apatite (Hedley et al., 1982; Costa et al., 2016). Stable P has a strong chemical nature due to the bonding energy between P and soil constituent (Saljnikov and Cakmak, 2011; Caione et al., 2015). Although this P fraction is more resistant and biologically unavailable it can be slowly transformed into more available forms.

The results obtained in the study demonstrated an interesting pattern for the stable Pi fraction (Figure 4.3a). In most instances the burned plots had a significantly higher stable Pi content than the unburned plots. This is attributed to the quick release of P into the soil system from the wheat residues (Loke et al., 2012) unlike the slow process of residue decomposition when the straw is left unburned on the soil surface (Chesworth, 2007). As indicated in Figure 4.3a, higher concentrations of stable Pi were found in the upper three soil layers and lower P concentrations in the 150-250 mm soil layers, regardless of the straw disposal method. This trend is similar to the findings of Loke et al. (2013) who indicated that surface retention of crop residues increases the concentration of nutrients in soil, including P and micronutrients.

Although there was no significant difference, the stable Po fraction (Figure 4.3b) behaved similarly to the stable Pi fraction. The burned plots had slightly higher P values than the unburned plots in all the soil layers, except for the 0-50 mm soil layer with a difference of 0.05 mg kg^{-1}. Zhang and Kovar (2000) demonstrated in their study that soil Po is derived from residues and mainly consists of inositol phosphates, phospholipids, nucleic acids and phosphoprotein. These usually constitute a small fraction of the Pt in soil and are rapidly converted into Pi to supply P to plant roots.

In the case of the stable Pt fraction the burned plots had a slightly higher content than the unburned plots across all four soil layers (Figure 4.3c). The implication here is that P is released more quickly from the burned crop residues directly into the soil system than when the unburned crop residues are left on the soil surface to decompose. In addition, the higher P solubility in burned plots can also be the cause of increased stable Pt content in the burned plots. The content of the stable Pt decreased from the upper to the bottom soil layer regardless of the straw disposal method. This is attributed to the substantial accumulation of nutrients on the soil surface with either burned or unburned straw.

In this study, the stable Pt was 13.61% (0-50 mm), 15.37% (50-100 mm), 16.57% (100-150 mm) and 20% (150-250 mm) lower than the labile Pt in the unburned plots. The stable Pt in burned plots was 16.51% (0-50 mm), 15.00% (50-100 mm), 15.11% (100-150 mm) and 20.55% (150-250 mm) lower than the labile Pt. These results are consistent with the results obtained by Costa et al. (2016) which demonstrated that the occluded or stable total P fraction was lesser than the total labile and moderately labile P fractions. Although stable Pt fractions may seem smaller compared to labile Pt, they contribute in replenishing P for plant absorption. The P that is held strongly in the stable P fraction plays an important role in preventing the leaching of P from the soil system, during high intensity rainfalls.

5.1.1.4 Residual P fraction

The residual P fraction is known as the most inactive form of P in soil. This P fraction is derived from primary minerals which are insoluble. According to Saljnkov and Cakmak (2010) this fraction acts as a primary (e.g. apatite) source for P in natural soil ecosystems. The results obtained in this study indicated that the residual Pt fraction was not significantly influenced by the straw disposal method (Table 4.1). This observation is echoed by Reddy et al. (2014) who reported that the residual P remains unaffected by the method of straw disposal (burning vs no burning). However, inspection of Figure 4.4 indicates that the difference between the burned and the unburned plots in the upper two soil layers (0-50 and 50-100 mm) was negligible. However, in the deeper two soil layers (100-150 and 150-250 mm) a difference could be observed, although not to a significant degree.

The higher nutrient uptake by crops from the upper soil layers could explain the behaviour of this P fraction. As much as this P fraction is less affected by management practices it can to some extent replenish the P in the stable P fraction when it decreases. The investigation by Saljnkov and Cakmak (2010) indicated that the application of P through fertilization leads to the formation of amorphous compounds that are adsorbed on the surface of clay minerals and physically precipitate as secondary minerals.

5.1.2 Tillage method

5.1.2.1 Labile P fraction

In this study, tillage methods had a significant influence on the labile Pi fraction across all four soil layers (Table 4.2). Inspection of Figure 4.5a showed that the no-tilled plots had the highest labile Pi content, followed by stubble mulched and ploughed plots to 250 mm depth. The labile Pi in the no-tilled plots was 10.88% higher than in the stubble mulched and 34.56% higher than in the ploughed plots for the 0-50 mm soil layer. For the three deeper soil layers the labile Pi was on average 6.68% and 27.49% higher in the no-tilled plots and in the stubble mulched and the ploughed plots, respectively. The higher labile Pi content in the no-tilled plots could be as a result of a higher organic matter content, which acts as a primary source of nutrients. Similarly, the study conducted by Shao et al. (2010) demonstrated that the no-tilled plots enhanced soil organic matter content which then increases nutrient concentration such as P. Correspondingly, Shafqat and Pierzynski (2010) demonstrated that the no-tilled plots had a higher labile Pi content than the ploughed plots and concluded that the limited mixing of soil constituents under no-till had to some extent reduced the P fixation, and thereby remained in a soluble form in the soil solution. In addition, no-till encourages microbial growth which is responsible for residue decomposition which releases P into the soil ecosystem.

On the other hand, intensive frequent ploughing caused a decline of soil organic matter (Raiesi and Kabir, 2016); especially in arid and semi-arid areas (Kotzé and Du Preez, 2007). The results of this study are consistent with the findings of Shao et al. (2016) who indicated that no-till resulted in a significant increase of the labile P in the upper 0-200 mm of soil when other tillage methods served as reference. Furthermore, Kotzé and Du Preez (2008) reported that conservational tillage resulted in a build-up of P, K, Ca and Mg in the upper 100-150 mm of soil compared to conventional tillage. Inspection of Figure 4.5a showed that higher P values were recorded in the upper soil layer and then gradually decreased with soil depth across all tillage methods. However, in the ploughed plots there was a small difference in the stratification of the labile Pi content. This is attributed to the mixing of the soil particles during mouldboard plough operations.

Although there was no significant difference in labile Po fractions, a reverse trend to that of the Pi fractions was noticed. The ploughed plots had a labile Po content that was slightly higher than stubble mulched and no-tilled plots across the four soil layers. There was no explanation found in literature to explain this phenomenon. However, on the contrary, ploughing has been reported to decrease the soil organic matter content (Raiesi and Kabiri, 2016) due to oxidation (Wiltshire and Du Preez, 1993), especially in arid and semi-arid areas.

According to Zhang and Kovar (2000) soil Po consists of inositol phosphates, phospholipids, phosphoproteins, nucleic acids and various sugar phosphates. These organic P fractions are derived from the decomposition of crop residues in the soil. Therefore, it is possible that due to the incorporation of wheat residues into the soil and the escalating rate of decomposition, these soil organic constituents are released into the soil system. On the other hand, stubble mulching incorporates a portion of residues and leaves approximately 30% or more residues on the soil surface while with no-till a minimum soil disturbance occurs. This implies that there is less residue decomposition in the no-tilled and stubble mulched plots than in the ploughed plots. This possibly leads to escalated P release from the wheat residues into the soil system.

Inspection of Figure 4.5c demonstrated that tillage method had a significant influence on the labile Pt in the upper two soil layers (Table 4.2). The no-tilled plots had a slightly higher Pt content, followed by the stubble mulched and then the ploughed plots. The Pi fraction in the Pt fraction constituted 85.6% in the no-tilled, 76.7% in the stubble mulched and 66% in the ploughed plots with respect to the 0-50 mm soil layer. On the other hand, Po fractions constituted 14.4% (no-till), 23.3% (stubble mulch) and 34% (plough) in the 0-50 mm soil layer. The trend of these results was similar to the findings of Rheinheimer and Anghinoni (2006) who demonstrated that the Pi fraction constituted about 69% whilst the Po fraction constituted about 31% of the Pt fraction. This is attributed to the rapid conversion of organic P into inorganic forms which is more available for crop uptake. Correspondingly, Zhang and Kovar (2000) reported that in soils the Po fractions are quickly converted into Pi fractions.

5.1.2.2 Moderately labile P fraction

This P fraction is of great importance in soil fertility due to its supply of P to crop roots during the growing season. The moderately labile P fraction contributed most to the P nutrition of crops. Therefore, the influence of different tillage methods on moderately labile P needs to be demonstrated under local conditions. The results obtained in this study indicated that there is a significant influence on the moderately labile Pi fraction, particularly in the first upper 0-50 mm soil layer. This is attributed to the accumulation of organic matter being higher in the upper soil layer in the no-tilled plots than in the stubble mulched and ploughed plots. Correspondingly, Du Preez et al. (2001) reported that the retention of wheat residues on the soil surface leads to the accumulation of nutrients such as K in the upper 150 mm of the soil.

The moderately labile Po fraction displayed certain patterns. A slightly higher P content was measured in the no-tilled plots than in the stubble mulched and ploughed plots, except in the 0-50 mm soil layer. This implies that frequent intensive ploughing of soil not only leads to a detrimental impact on the soil physical properties but also to soil fertility. This is probably due to the oxidation of soil organic matter which was more severe in the ploughed plots than in the no-tilled and stubble mulched plots (Wiltshire and Du Preez, 1993).

Similarly, the study by Raiesi and Kabir (2012) showed that intensive and frequent conventional tillage resulted in a decline in soil productivity by reducing soil organic matter. This soil organic matter is the primary source of essential nutrients. On the other hand, no-tillage leads to the substantial accumulation of soil organic matter on the soil surface. Therefore, this soil organic matter could have contributed to higher P values in the no-tilled plots compared to other tillage methods.

An evaluation of Figure 4.6c indicated that the moderately labile Pt in the no-tilled and stubble mulched plots was significantly higher than in the ploughed plots, with respect to the 0-50, 100-150 and 150-250 mm soil layers. This is due to the accumulation of organic matter in the no-tilled and stubble mulched plots (Loke et al., 2014). A decline of soil organic matter was reported in the ploughed plots by Raiesi and Kabir (2016) and Wiltshire and Du Preez (1993). The moderately labile Pt content gradually decreased from the 0-50 mm soil layer to the 150-250 mm soil layer, irrespective of the tillage method. This can be attributed to the immobility of P in soils, which implies that P accumulates more in the upper soil layer where there is an application of wheat residues.

5.1.2.3 Stable P fraction

The results displayed in Table 4.2 indicated that the tillage methods had a significant influence on the stable Pi fraction across the four soil layers. Plots that were no-tilled and stubble mulched had a significantly higher stable Pi content than the ploughed plots. This could be as a result of organic matter content which was influenced by the tillage methods. The ploughed plots had lower organic matter content than the no-tilled and stubble mulched plots. This could be due to frequent and intensive cultivation which escalated the oxidation of soil organic matter especially in arid and semi-arid regions (Wiltshire and Du Preez, 1993). Conversely, the no-tillage usually increases soil organic matter content, especially near the soil surface.

Although there was no significant difference observed between tillage methods for the stable Po fraction, an interesting pattern was noted (Figure 4.7b). In the upper two soil layers (0-50 and 50-100 mm) the no-tilled plots had a slightly higher stable Po content than the stubble mulched plots, followed by the ploughed plots. However, in the deeper two soil layers (100-150 and 150-250 mm) an opposite pattern was observed. The stubble mulched plots had the highest stable Po content, followed by the ploughed and then the no-tilled plots (Figure 4.7b). Similarly, Rheinheimer and Anghinoni (2006) reported that the Po content was affected by the tillage method and concluded a higher Po content in the upper two soil layers than in the deeper two soil layers for the no-tilled plots. The trend could be due to the immobility of soil P that remained in the upper two soil layers of the no-tilled plots, whereas in the ploughed and stubble mulched plots P was mixed with soil particles of the deeper layers.

The stable Pt fraction showed no significant difference across all four soil layers (Table 4.7), nevertheless, the following pattern evolved. Stable Pt was slightly higher in the no-tilled plots than in the stubble mulched and ploughed plots for the upper three soil layers (0-50, 50-100 and 100-150 mm) but not for the deepest soil layer (150-250 mm). This could primarily be attributed to the influence of tillage methods on soil organic matter content which impacted the P content in soils.

5.1.2.4 Residual P fraction

This fraction was not significantly influenced by the various tillage methods (Table 4.2). Nevertheless, an inspection of Figure 4.8 revealed that the no-tilled plots had slightly higher residual Pt than the stubble mulched and ploughed plots in all soil layers except the 50-100 mm soil layer. This could be due to the fact that the P that is released from the soil organic matter, contributes to higher residual Pt content in the no-tilled plots compared to the stubble mulched and ploughed plots. In addition, the dissolution of the residual Pt fraction could have occurred at a greater rate in ploughed and stubble mulched plots than in no-tilled plots over the experimental period.

5.1.3 Weeding methods

5.1.3.1 Labile P fraction

In the agricultural industry, weed infestation is the major biological constraint that affects crop growth and the desired yields. Consequently, both large- and small-scale farming systems apply various methods to control weeds for successful crop growth. The methods are mainly categorised into chemical and mechanical weed control (Mhlanga et al., 2016). As much as these initiatives have been proven to be successful in controlling weeds in a wide range of cropping systems, there is limited information on how these weeding methods influence P fractions, particularly in arid and semi-arid regions.

The methods of weed control had a significant influence on labile Pi (Table 4.3) in all soil layers except the 100-150 mm soil layer. A higher labile Pi content was recorded in the chemically weeded plots than in the mechanically weeded plots. This can be attributed to the direct influence on soil organic matter by these weeding methods. The implication is that soil organic matter acts as a source of P and other nutrients. Similarly, Kotzé and Du Preez (2008) postulated that chemical weeding increased soil organic matter and hence the accumulation of P to a depth of 100 mm when compared to mechanical weeding. Furthermore, chemical weeding kills both the shoots and the roots. The dead root remaining underground leads to quicker decomposition and hence release of nutrients that are trapped in the weed roots.

In the field trial of this study, mechanical weeding was initially done by either a rod-weeder or V-blade but after 2003 a lighter tiller was used. Frequent soil disturbance, including that of mechanical weeding contributes to a decrease in soil organic matter; especially in semi-arid regions (Loke et al., 2012). This could therefore explain the lower labile Pi content in mechanical weeded plots when chemical weeded plots are used as a reference. Furthermore, the weeds that are left on the soil surface after slashing contribute to soil organic matter. However, in some cases, they are completely removed from the soil surface which leads to nutrient exports from the soil system.

Interestingly, a similar behaviour to that of labile Pi was observed for the labile Po and labile Pt in all four soil layers, although a significant difference of labile Pt was recorded only in the 150-250 mm soil layer (Figure 4.9b and c). The chemically weeded plots had slightly higher labile Po and Pt content than the mechanically weeded plots across the four soil layers. According to Zhang and Kovar (2000), the organic P fractions in soils are largely composed of inositol phosphates, phospholipids, nucleic acids, phosphoproteins and organic microbial biomass. These components are derived from the decomposition of organic matter. Hence, chemical weeding encourages an accumulation of organic matter near the soil surface, resulting in higher labile Po and Pt contents compared to mechanical weeding.

5.1.3.2 Moderately labile P fraction

The chemically weeded plots had a significantly higher moderately labile Pi content than the mechanically weeded plots only in the 100-150 mm soil layer (Figure 4.10). This could be due to a higher organic matter content that accumulates in chemical weeding than under mechanical weeding and this may lead to a larger release of nutrients like P (Kotzé and Du Preez, 2008). On the other hand, Smith et al. (2011) reported that the use of a V-shaped sweep in an attempt to control weeds results in lower organic matter content due to soil disturbance, especially in the upper 100 mm of soil compared to the use of mechanical weeding. This could have been due to lower labile levels in mechanically weeded plots than in chemically weeded plots. In addition, the study by Kotzé (2004) demonstrated that chemical weeding resulted in a higher concentration of nutrients such as P and K in comparison with mechanical weeding.

On the contrary, moderately labile Po and Pt fractions showed an opposite trend to that of moderately labile Pi. An inspection of Figure 4.10b and c displayed that the mechanical weeding had a slightly higher P concentration in all four soil layers, although only to a significant degree in the 50-100 and 100-150 mm soil layers for moderately labile Po. According to Zhang and Kovar (2000), soil Po is tied up in microbial biomass which mainly consists of nucleic acids, polyphosphates and inositol phosphates. This implies that the soil microbial community plays a significant role in Po fractions. Correspondingly, Smith et al. (2001) postulated that repeated application of herbicides has a negative impact on the soil microbial communities. This could have contributed to the slightly higher P content in mechanically weeded plots than chemically weeded plots.

5.1.3.3 Stable P fraction

The weeding methods had a significant influence on the stable Pi fraction in all soil layers, except for the 50-100 mm soil layer. A slightly higher stable Pi content was recorded in the chemically weeded plots compared to the mechanically weeded plots (Figure 4.11a). Similar trends were also observed with the stable Po and Pt fractions. In support of this phenomenon, Smith et al. (2011) reported that mechanical removal of weeds makes use of a high residue cultivator with wide V-shaped sweeps of a low angle, to cut the roots of weeds under the soil surface. This soil disturbance leads to oxidation which reduces the organic matter content in the soil (Wiltshere and Du Preez, 1993). In addition, an investigation by Loke et al. (2012) demonstrated that mechanical weeding sometimes leads to a complete removal of weeds, which could have added to the content of soil organic matter from the soil surface.

On the other hand, the long-term study by Kotzé and Du Preez (2008) demonstrated that application of herbicide to control weeds resulted in more soil organic matter compared to mechanical weeding. This implies that soil organic matter plays a significant role with respect to stable P fractions. Du Preez et al. (2001) reported that soil organic matter is a source of essential plant nutrients.

5.1.3.4 Residual P fraction

The residual P fraction showed no significant response to weeding methods in all four soil layers. However, the residual P fraction followed a similar trend to that of the stable P fraction. The chemically weeded plots had a slightly higher P content than the mechanically weeded plots across all four soil layers. This can be attributed to the increase in organic matter content in chemical weeding when the mechanically weeded plots served as reference.

5.2 Interactions

5.2.1 Labile P fractions

Farmers normally use a combination of production management practices. These include the combination of tillage methods (no-till, stubble mulch and plough), straw disposal methods (burn and unburned) and lastly weeding methods (chemical and mechanical). Therefore, the evaluations of these interactions are of great importance. The effect of the interaction between tillage, straw disposal and weeding methods on labile Pi is displayed in Table 4.6.

The plots with no-tillage combined with chemical weeding had a higher labile Pi content compared to the chemically weeded combined with stubble mulched and ploughed plots, in all four soil layers. In the upper 0-50 mm soil layer chemically weeded plots had a higher labile Pi content than in the mechanically weeded plots that were no-tilled and stubble mulched. Similar results were found by Loke et al. (2012), who demonstrated that chemically weeded plots had a higher P content compared to mechanically weeded plots, especially in the 0-50 mm soil layer. The combination of straw disposal method with tillage method gave an interesting trend, although no significant difference was established. Burning wheat residues combined with any tillage method or weeding method had slightly higher labile Pi contents compared to the unburned plots across the four soil layers. Correspondingly, Du Preez et al. (2001) indicated that the burned plots had a significantly higher P content compared to the unburned plots regardless of tillage or weeding method. Likewise, Kotzé (2004) found that the burning of residues resulted in slightly higher P concentration compared to the unburned plots, irrespective of the tillage or weed control methods. These higher labile Pi values can be attributed to increased organic matter content under the no-tilled and chemically weeded plots, and also a quick release of nutrients into the soil for the burned plots.

The stratification of the labile Pi fraction is clearly visible in the no-tilled and stubble mulched plots when the ploughed plots served as reference. This can be attributed to the immobility of P in soils, resulting in its increased accumulation in the surface soil layers. On the other hand, ploughing resulted in a small difference between the concentrations of P in the upper soil layers than in the deeper soil layers due to the mixing of soil particles.

The interaction of treatments had no significant effect on the labile Po fraction; however, some trends were observed. For instance, the unburned plots that were no-tilled or stubble mulched had a slightly higher labile Po content than the burned plots that were no-tilled or stubble mulched. The study by Smith et al. (2011) indicated that no-tillage combined with unburned residues leads to a substantial accumulation of organic matter, with a possible benefit to the labile Po fraction. On the other hand, the combination of mouldboard ploughing and residue burning had slightly higher Po content than the combination of mouldboard ploughing and residue unburning. Similarly, Loke et al. (2012) reported that the burning of residues combined with mouldboard ploughing resulted in a higher P content compared to the burning of residues combined with no-tillage. Correspondingly, Kotzé (2004) postulated that burned and ploughed plots had higher P concentrations than unburned and ploughed plots.

The interaction of these production management practices had an influence on both the labile Pi and Po fractions, which also determine the overall impact on the labile Pt fraction. As displayed in Table 4.4, the interaction of these practices on the Pt fraction was not significant. However, the burned plots had a slightly higher labile Pt content than the unburned plots, irrespective of tillage method. This trend is similar to the findings by Du Preez et al. (2001) and Kotzé (2004) who reported that the burned plots had a significantly higher P content than the unburned plots, regardless of tillage or weeding methods. As indicated in Table 4.7, chemical weeding resulted in a higher labile Pt content than mechanical weeding, irrespective of tillage method. Similarly, Loke et al. (2014) reported that chemically weeded plots had a higher P content than the mechanically weeded plots, regardless of tillage or straw disposal method.

5.2.2 Moderately labile P fraction

The combination of the treatments indicated an influence on the moderately labile P fraction, although not to a significant degree (Table 4.9). A slightly higher moderately labile Pi content was observed in the unburned plots than in the burned plots regardless of tillage method. This is particularly true for the 0-50 mm soil layer. However, in the deeper soil layers the burned plots had more moderately labile Pi than the unburned plots, irrespective of tillage and weeding methods. Similarly, the results obtained by Loke et al. (2012) indicated that the burning of wheat residues resulted in higher P content, especially in the upper 250 mm of soil, compared to the unburned plots, irrespective of tillage method. As already noted, the burning of crop residues quickly releases P into soil, which is not the case when crop residues are not burned.

The moderately labile Po fraction behaved differently from the moderately labile Pi fraction. Inspection of Table 4.10 indicated that the interaction of the treatments had no significant influence on the moderately labile Po fraction. However, the combination of mechanical weeding with any tillage method caused a slightly higher moderately labile Po content than chemical weeding across the soil layers. Similar findings were reported by Loke et al. (2012), namely that mechanically weeded plots had a P value that was slightly higher than that of the chemically weeded plots when either ploughed or no-tilled.

The moderately labile Pt content (Table 4.11) indicated that no-tillage, combined with unburned straw, resulted in higher P concentrations than either stubble mulch or plough; combined with unburned straw. Conversely, Kotzé (2004) reported that unburned plots which were no-tilled had a lower P content than the burned plots which were no-tilled, irrespective of soil layer. On the other hand, Loke et al. (2013) demonstrated that the unburned residues combined with no-tilled had the highest P concentration while the unburned plots that were ploughed had the lowest P concentration.

5.2.3 Stable P fraction

The stable Pi fraction in all four soil layers was not influenced significantly by any treatment combination. However, the combination of tillage method with either straw disposal or weed control methods influenced the stable Pi fraction. In all four soil layers the burned plots had a slightly higher stable Pi content than the unburned plots, regardless of the tillage and weeding method. The same trend was also noted with the stable Po fraction, particularly in the 100-150 and 150-250 mm soil layers. The stable Pt fraction showed a similar trend in all soil layers except for the 0-50 mm soil layer. Du Preez et al. (2001) reported further that the burned plots had a P content that was significantly higher than that of the unburned plots to a depth of 250 mm, irrespective of tillage or weeding method. Correspondingly, Kotzé (2004) reported a higher P content in the burned plots than in the unburned plots, irrespective of tillage and weeding method.

According to Loke et al. (2014), the burning of wheat residues increased the concentration of nutrients as well as their solubility through the addition of ashes to the soil surface. The retention of wheat residues on the soil surface also adds nutrients to the soil, although their release is slower. Similarly, Singh and Rengel (2007) postulated that nutrients in residues are released more rapidly through burning than decomposition. This could explain that P values are higher in burned plots than in unburned plots. Inspection of Table 4.15 displayed the fact that the chemically weeded plots had a higher P content than the mechanically weeded plots irrespective of tillage or straw disposal method. A similar observation was made by Loke et al. (2012).

5.2.4 Residual P fraction

The treatment combination had no significant influence on the residual P fraction (Table 4.16). Moreover, there was no evidence of a specific pattern evolving due to the treatment combination (Table 4.17). This is attributed to the fact that residual P is the most inert fraction and took a longer period to respond.

CHAPTER SIX

SUMMARY, RECOMMENDATION AND CONCLUSION

6.1 Summary

In soils, P is known as one of the essential plant macro nutrients for crop growth and development. However, P is regarded as the most deficient plant nutrient in soils of South Africa and many parts of the world (Wang and Zhang, 2012; Soremi et al., 2017). Unfortunately, P is subjected to very complex chemical reactions in soil and occurs therefore in a number of fractions which vary in their biological availability. Interestingly, total P is not sufficient to evaluate soil fertility, since total P is poorly related to the P available for crop uptake (Mortvedt et al., 1999). The objectives of this study were therefore to; (1) evaluate the effects of different tillage methods on soil P fractions and their stratification in soil under wheat production after 37 years in a semi-arid climate, (2) evaluate the effect of straw disposal methods on soil P fractions and their stratifications under wheat production after 37 years in a semi-arid climate, (3) determine the effect of weeding methods on soil P fractions and their stratification under wheat production management practices after 37 years and (4) evaluate the interactions between the wheat production management practices on soil P fractions.

This study was conducted in a long-term wheat trial at the ARC-Small Grain Institute near Bethlehem in the Eastern Free State on an Avalon soil, where the effect of two straw disposal methods (burned and unburned), three tillage methods (no-till, stubble mulch and plough) and two methods of weed control (mechanical and chemical) and three levels of nitrogen application (20, 30 and 40 kg ha^{-1} until 2003 and since then 20, 40 and 60 kg ha^{-1}) were examined. To achieve the objectives of the study, soil samples were taken from inside of the trial from the intermediate nitrogen application only, in order to determine the influence of wheat production management practices on soil P fractions. The soil samples were collected at various depth intervals (0-50 mm, 50-100 mm, 100-150 mm and 150-250 mm) to analyse the stratification of soil P fractions. A slightly modified sequential extraction method proposed by Hedley et al., (1982) was used. Inorganic, organic and total P of the labile (0.5 M $NaHCO_3$) moderately labile P (0.1 M NaOH), stable (1 M HCl) and residual (concentrated HCl) fractions were ultimately quantified. This trial was a complete randomized block design, consisting of three blocks.

The various soil P fractions were influenced differently by the methods of straw disposal, tillage and weed control. The burned plots had a higher labile P content than the unburned plots across all four soil layers. A higher labile P concentration was observed in the 0-50 mm soil layer which gradually decreased with depth, regardless of the straw disposal method. The moderately labile P fraction showed a similar trend to that of labile P fraction. However, the unburned plots had slightly higher moderately labile P values than the burned plots in the 0-50 mm and 50-100 mm soil layers. A very similar trend was observed in the moderately labile Po and Pt fractions, particularly in the 50-100 mm soil layer.

In the burned plots a higher stable Pi content than in the unburned plots was recorded. The only exception was with the stable Po fraction where the unburned plots had a slightly higher content than the burned plots, particularly in the 0-50 mm soil layer. The same pattern was also observed for the residual P fraction where the unburned plots had a slightly higher Pt in the 0-50 mm soil layer than the burned plots. However, in the 100-150 mm and 250-250 mm soil layers the opposite was true.

The tillage methods affected the P fractions and their stratification. No-tilled plots had slightly higher labile Pi and Pt contents followed by the stubble mulched and the ploughed plots. The P concentration was highest in the 0-50 mm soil layer and gradually decreased with depth in the 150-250 mm soil layer. However, the labile Po fraction showed an opposite pattern with the ploughed plots, that had slightly higher P values followed by stubble mulched and the no-tilled plots. A less distinct pattern evolved for the moderately labile P fraction than was the case in the labile and stable P fractions. The no-tilled plots had slightly higher moderately labile Pi contents in the 0-50 mm and 150-250 mm soil layers. Moderately labile Po followed the same trend except in the 0-50 mm soil layer where the stubble mulched plots had the highest P content, followed by the no-tilled and the ploughed plots.

On the other hand, tillage methods showed a more distinct pattern for the stable P fraction. A higher labile Pi content was recorded in the no-tilled plots followed by the stubble mulched and the ploughed plots, especially in the upper three soil layers. An opposite pattern was observed in the 150-250 mm soil layer where the no-tilled plots had a lower P content, especially the stable Po and Pt fractions. The same trend was observed in the residual P fraction where the no-tilled plots had a slightly higher P content, than either the stubble mulched (0-50 and 150-250 mm) or ploughed plots (50-100 and 100-150 mm).

The chemically weeded plots had a higher labile P content than the mechanically weeded plots across all four soil layers. Interestingly, the same trend was also observed with the stable P fraction. Nevertheless, the moderately labile P content was higher with mechanical weeding than with chemical weeding. This was clearly noticed for the moderately labile Po and Pt fractions. A similar trend was noticed in the residual P fraction, except in the 50-100 mm soil layer where chemically weeded plots had a slightly higher residual Pt content than mechanically weeded plots.

The treatment combinations also influenced the P fractions. No-tillage that coincides with chemical weed control had significantly higher labile Pi contents than either stubble mulched or ploughing, that coincide with chemical weed control. Neither straw disposal methods nor mechanical weeding influenced the labile Pi. This is attributed to the substantial accumulation of organic matter in the no-tilled plots combined with chemical weeding. This organic matter then acts as a primary source of P which reacts with soil constituents and subsequently exists in various P fractions. Although negligible, the burned plots had a slightly higher labile Pt content than the unburned plots, irrespective of the tillage method. Nevertheless, an opposite pattern was observed for moderately labile Pi, where the unburned plots that had higher P contents than the burned plots. Furthermore, the chemically weeded plots had slightly higher stable Pt contents than the mechanically weeded plots, irrespective of the tillage method.

In general, the results of this study are similar to the results obtained by Du Preez et al. (2001), Kotzé (2004), Singh and Rengel (2007), Shafqat and Pierzynski (2011), Loke et al. (2012), Mitran et al., (2016) and Ventrella et al., (2016). The wheat production management practices that lead to an increase or decrease in soil organic matter contributes to the concentration of the various soil P fractions and their stratification.

6.2 Recommendations

Based on the results of the study, the following recommendations can be made:

- In order to comprehend the biological availability of P in soils, it is important to understand the behaviour of P fractions in the soil, as they act as a sink for supplying P for crop growth throughout the growing season.
- The use of a no-till system in a semi-arid climate largely increases the labile, moderately labile and stable P fractions in soils, followed by stubble mulch and mouldboard plough. In addition, the burning of wheat residues is also beneficial in increasing the concentration and solubility of soil P fractions which buffer P in the soil solution.
- Apart from controlling weeds, chemical weeding is beneficial in enhancing soil P fractions. Nevertheless, a more detailed study on the relationship of these fractions with crop nutrient uptake and yields warrants further investigation.

6.3 Conclusion

The results obtained in this study demonstrate that the various wheat production management practices had an influence on the concentration and stratification of soil P fractions. The burning of wheat residues lead to a substantial accumulation of labile, moderately labile, stable and residual P fraction especially in the upper two soil layers when the unburned is used as a reference. In the tillage methods, the no-tilled treatments lead to an increased P concentration in the entire extracted P fractions, followed by stubble mulched treatments and lastly the ploughed treatments. In the method of weeding, the same pattern was also observed, where chemical weeding had higher P concentrations than the mechanically weeded plots. The interaction of no-tillage combined with chemical weeding enhanced the labile and moderately labile P fractions compared to other treatment interactions.

Due to the immobility of P in soils, higher P values were observed in the upper soil layers and thus gradually decreased with soil depth. However, due to the mixing of soil particles, these differences were less distinct in the ploughed plots. The labile P fractions almost doubled the concentration of the residual P fraction. This implies that labile and moderately labile P fractions were highly influenced by wheat management practices compared to the residual P fractions in all four soil layers. Lastly, the inorganic P fractions, had a more significant response to no-tillage than organic P fractions.

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