SOIL PHOSPHORUS AVAILABILITY AND UTILIZATION EFFICIENCY BY SOYBEAN [GLYCINE MAX (L.) MERR.] UNDER A SHORT TERM NO-TILL IN SMALLHOLDER FARMS IN SOUTH AFRICA

by

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Exact wording of the title of the dissertation as appearing on the electronic copy submitted for examination:

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I declare that the above dissertation is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

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KEY TERMS:

Phosphorus, no-till, P use efficiency, P uptake, soybean, smallholder farmers, alkaline phosphatase, acid phosphatase, yield

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LIST OF ACRONYMS AND ABBREVIATIONS

SSA	: Sub-Saharan Africa
SA	: South Africa
P	: Phosphorus
N	: Nitrogen
K	: Potassium
Al	: Aluminium
Fe	: Iron
Ca	: Calcium
Mg	: Magnesium
CT	: Conventional tillage
NT	: No-till
t/ha	: Tons per hectare
kg/ha	: Kilograms per hectare
mg/kg	: Milligrams per kilogram
ppm	: Parts per million
%	: Percentage
SOM	: Soil organic matter
NPP	: Number of pods per plant
ACP	: Acid phosphatase
ALK	: Alkaline phosphatase

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ABSTRACT

The main limiting factor in soybean production in South Africa is low native soil phosphorus (P) availability and poor utilization efficiency of added P. Phosphorus fertilization, use of improved or high yield potential cultivars and appropriate cropping systems could increase soybean yields. The objective of this study was to determine the effects of tillage, cultivar and fertilization levels on nutrient uptake and P use efficiency, as well plant growth, yield, grain protein and oil content, in a soybean cropping system. The study was conducted under dryland conditions at Sheepmoor, Mpumalanga. A field experiment was established in a randomized complete block design. Treatments were arranged in a 2 x 3 x 3 split-split-plot structure. There were two tillage systems [no-till (NT) and conventional tillage (CT)], three cultivars (PAN 1614R, PAN 1521R and PAN 1532R), and phosphorus rate (0, 30 and 60 kg/ha). All treatment combinations were replicated three times. Phosphorus application rate, tillage and cultivar had significant effects ($P < 0.05$) on NPK uptake, Partial factor productivity (PFP), grain yield and soybean yield attributes. P uptake improved with P application at 30 and 60 kg/ha although it was statistically similar whilst PFP was significantly higher at 30 kg/ha P. Interactions of the main treatments did not significantly affect P uptake and PFP. There were statistically significant interactions between P application rate, cultivar and tillage on soybean yield. Yield was significantly higher at 30 kg/ha P application under NT. P application at 30 and 60 kg/ha significantly reduced oil content by 11.3% and 7.16% respectively, but had inverse effects on protein content. The activities of acid phosphatase (ACP) and alkaline phosphatase (ALP), concentrations of soil Ca, Mg, N, P, K and total P also increased with P application. Improvement of soybean yield and its attributes, grain quality, P uptake, PFP, soil physicochemical and microbial properties emphasize the need for fertilizers and sustainable cropping systems. Therefore, no-till and application of fertilizers improves soil fertility and soybean yield under small farm conditions.

Keywords: Phosphorus, no-till, P use efficiency, P uptake, soybean, smallholder farmers, alkaline phosphatase, acid phosphatase, yield

CHAPTER 1: INTRODUCTION

A major limiting factor for soybean [*Glycine max* (L.) Merr.] production in South Africa is low soil phosphorus (P) availability together with inefficient utilization of added P (Aulakh et al. 2003; Mabapa et al. 2010). Compounding this are the risks of crop failure posed by climate change (Mall et al. 2017; Mohanty et al. 2017). Soybean is one of South Africa's main commodities and its production, promotion and processing has gained some priority in the country's industrial plans since 2010 (Dlamini et al. 2013). In Africa, soybean demand is very high and increasing with the increasing population (Dlamini et al. 2013; Phiri et al. 2016; Ronner et al. 2016). Currently, Mpumalanga province produces about 42% of the total soybean nationwide, making it the leading producer in South Africa (DAFF, 2018). The area under production has relatively increased since 1942 when the crop was initially introduced to the country (Dlamini et al. 2013), however, average yields are still lower than experimental yields due to drier climate and poor arable soils (Dlamini et al. 2013; Phiri et al. 2016; Ronner et al. 2016; Sithole et al. 2016). Nonetheless, the Department of Agriculture, Forestry and Fisheries (DAFF) is embarking on the promotion of soybean production to cushion smallholder farmers against crop failure through crop diversification. The use of sustainable cropping systems and the need to evaluate soybean cultivars in terms of yield to meet the demands for consumption and biodiesel production in South Africa becomes imperative. Furthermore, increasing phosphorus availability and use efficiency, as well as determining appropriate fertilizer rates is key to improving yields in soybean production (Mabapa et al. 2010).

Phosphorus may be found in very huge amounts in many soils (Owen et al. 2015), with a range of between 100 – 2000 mg/kg soil which represents nearly 350 – 7000 kg/ha P in the top 25 cm layer of soil, nevertheless, less than 0.1 % is in orthophosphate form which plants can easily uptake (Garland et al. 2018; Grant et al. 2005; Raliya et al. 2016). There are several factors contributing to low P availability including soil texture, aeration, temperature, compaction and moisture (Better Crops, 1999). Furthermore, since soil P moves through diffusion and mass flow, when temperatures are high, soil moisture levels decrease thereby restricting P movement (Grant et al. 2005).

Phosphorus availability for plant use declines during periods of moisture stress (Armstrong 1999), because P uptake rate is proportional to water uptake rate and orthophosphate concentration in soil solution (Grant et al. 2005). This is a major problem where production is under rainfed conditions (Nciizah et al. 2015; Smith et al. 2016) especially in most smallholder areas. Climate change is therefore another factor that compounds food production in dryland areas (Nciizah et al. 2015). Due to climate change, weather patterns change and cause a shift in temperature and rainfall regimes (Hartman et al. 2011; Smith et al. 2016), increasing drought and flood frequencies (Nciizah et al. 2015), which affects P availability as explained above.

Therefore, when plant available P is low, efficient applications of inorganic fertilizers (Monoammonium phosphate , Diammonium phosphate , Triple super phosphate), rock phosphate, mycorrhizae, bio-inoculants, and liming for extremely acid soils may improve crop yields (Grant et al. 2005). However, these options are not economically viable for poor smallholder farmers and therefore not sustainable (Ramesh et al. 2014). Most smallholder farmers use very little to no fertilizers (Baudron et al. 2015; Njeru et al. 2013; Ronner et al. 2016), they rely on residual phosphorus from the previous cycle (Mokoena 2013). Apart from the financial constraints, there is scarcity of raw material resources (phosphate rock) to be used in producing phosphate fertilizers (Eberhardt 2012; Owen et al. 2015; Riskin et al. 2013).

Alternative cropping systems, which improve soil properties by enhancing moisture availability to crops as well as increasing soil organic carbon (SOC) could improve yields. This is because soil organic matter (SOM) contains higher levels of available phosphorus that is gradually released as organic P and converted to inorganic P for plant nutrition (Better Crops, 1999). However, in order to retain P in organic matter

(OM) efficiently, OM should be accruing (Eberhardt 2012). In smallholder farming areas, organic matter accumulation is a serious challenge since retention of crop residues is not a priority. This is due to several requirements that compete for residues such as cooking domestic fuel and fodder (Baudron et al. 2015; Valbuena et al. 2012). Residue levels retained in smallholder farmers may be insufficient to attain soil cover benefits such as increasing soil carbon due to poor crop productivity, especially in short to medium term (Baudron et al. 2015; Johansen et al. 2012). According to Paul et al. (2013), residues of 2 t/ha which is the realistic maximum rate for SSA smallholder farmers, may be too low to uncover such beneficial effects.

An intervention being advocated for enhancing soil and water productivity in cultivated areas is no till. This is due its cost effectiveness, environmental sustainability and efficient in P conservation and cycling (Moraru et al. 2013; Ramesh et al. 2014). Promoting practices such as no-till, which improve soil aggregate stability and hence soil organic carbon concentrations within the aggregates could also increase availability of phosphorus in smallholder arable lands (Busari et al. 2015). No-till favours an increase of organic phosphorus (Po) levels and/or a decrease of inorganic phosphate (Pi) adsorption through accumulation, decomposition and mineralization of SOM by improving soil properties, enhancing enzymatic activities and soil microbial diversity (Sithole et al. 2016; Wei et al. 2014).

Furthermore, no-till increases water use efficiency which improves crop growth even in drier climate and makes soils resilient to degradation (Kihara et al. 2012; Moraru et al. 2013). Environmental conditions under no-till are more conducive compared to conventional tillage (Ji et al. 2013), because of factors mentioned earlier; in particular, more stable aggregates (Sithole et al. 2016), which improves nutrient cycling, water infiltration and ultimately reduces soil erosion (Zhang et al. 2012). The latter is a crucial factor in conserving soil P that would otherwise be eroded, and not only cause a decline in soil P levels but would also cause accumulation of P in nearby aquatic environments resulting in eutrophication (Ramesh et al. 2014; Riskin et al. 2013).

Moreover, tillage effects on the formation, stability of aggregates and their size distribution influences P distribution in varying fractions of aggregate size (Deng et al. 2018; Zheng et al. 2018) through its influence on soil P adsorption as well as dissolution by aggregates (Deng et al. 2018; Garland et al. 2018).

No-till increases micro-organisms' diversity by improving soil structure, soil organic matter in the surface layer and water holding capacity (Vukicevich et al. 2016). Micro-organisms in the soil and rhizosphere belonging to the group referred to as phosphate solubilizing micro-organisms (PSMs), play an important role in P-cycling by employing solubilizing mechanisms in the release of complexing or mineral dissolving compounds, liberation of extracellular enzymes and the release of phosphorus during substrate degradation (Alori et al. 2017; Sharma et al. 2013). Phosphate solubilizing micro-organisms (PSMs) such as *Acinetobacter* (Mulissa et al. 2016), *Pseudomonas* (Yang et al. 2018), *Enterobacter* (Kumar et al. 2018), *Bacillus* (ARIF et al. 2017), *Paenibacillus* (Alori et al. 2017), *Rhizobium* (Nikitha et al. 2017; Zhang et al. 2019) are very crucial in P-crop availability by mineralizing organic P and solubilizing aluminium-bound and iron-bound P (Ramesh et al. 2014). The latter is thought to be through chelating of Iron (Fe) and Aluminium (Al) (Syers et al. 2008).

No-till also increases and stratifies soil enzymatic activities (Bowles et al. 2014; Rincon-Florez et al. 2016), probably resulting from increases in organic matter and microbial activity (Sithole et al. 2016). However, activities of specific enzymes may vary according to crop, fertilizer used (Dou et al. 2016), nutrients available in the soil and soil physical characteristics (Bowles et al. 2014). Enzymes catalyse key biochemical reactions for rhizospheric bacteria, bring stability to the soil through decomposition and degradation of wastes to mediate cycling of nutrients (Turan et al. 2017). Soil enzymes such as phosphatases are very crucial in cycling phosphorus through hydrolysis of different P fractions and have a significant role in phosphorus acquisition by plant roots (Dhariwal et al. 2016; Raliya et al. 2016). They also hydrolyse phytic acid (source of organic P) to make inorganic phosphorus (Turan et al. 2017).

There is enormous literature on soil P dynamics and crop responses to phosphorus fertilization, however in South Africa (SA), the effects of P fertilization on soybean under no-till is still lacking. Moreover, most of the studies were carried out on experimental farms rather than smallholder farmer's fields. Blanket recommendations for fertilizer applications have been made, however they may not meet the requirements of a small farm specific needs (Mabapa et al. 2010). Contributing to that is the fact that research on no-till practices especially within small-holder production systems in SA is still very low. According to Sithole et al. 2016, the adoption rate for conservation agriculture practices such as no-till stands at 2.8% on the total country's agricultural land. Therefore, the present study aimed to determine the availability and utilization efficiency of soil P to maximise soybean yields under no-till. The study also sought to introduce and promote no-till as a sustainable means of crop production in the small-scale farmer's production system.

Objectives:

1) To determine the effects of different levels of mineral P fertilization on soybean growth, yield and grain protein & oil content.
2) To determine the effects of different levels of mineral P fertilizer on nutrient uptake (NPK), P use efficiency and partial factor productivity (PFP) on a soybean cropping system.
3) To determine the effects of different levels of mineral P fertilizer and tillage on selected soil chemical and physical parameters
4) To determine the relationship between activities of acid and alkaline phosphatases, soil properties and management practices on a soybean cropping system.

Hypotheses:

- P application at 30 and 60 kg/ha rate and no-till system have positive effects on soybean growth, yield, grain protein and oil content.

- Application P fertilizers at 30 kg/ha and no-till improves nutrient (NPK) P uptake, partial factor productivity and P use efficiency greater than application of P at 60 kg/ha in a soybean cropping system.
- No-till system has positive effects on selected soil chemical and physical parameters.
- No-till and application of P will lead to increased acid and alkaline phosphatase activities near the soil surface on a soybean cropping system.

CHAPTER 2: LITERATURE REVIEW

2.1. Soybean production in South Africa

Soybean is the world's most traded oil seed (Lee et al. 2016) and has the potential of being Africa's Cinderella crop (Kolawole 2012). Soybean production in sub-Saharan Africa (SSA) has increased over the years, however yield is still fixed at an average of 1.1 t/ha for decades (Khojely et al. 2018) (Table 1). South Africa's production in 2017 was approximately 1 374 700 tons at 1.7 t/ha on average. Mpumalanga province is a leading producer in the country with a production of approximately 40% of the total national soybean production (DAFF 2018) (Figure 1). South Africa mainly processes soybean for oil, oilcake, human consumption, full fat, seed and feed (Manthata 2018).

Table 1: Yield (kg/ha) on average for SSA top soybean producers from 2012 – 2016. Source: Khojely et al. 2018

Country	Year				
	2012/2013	2013/2014	2014/2015	2015/2016	2016/2017
Uganda	630	650	600	600	600
Nigeria	1000	1000	1000	960	960
Zambia	1200	1200	1560	2020	1940
South Africa	1300	1620	1450	1480	2290

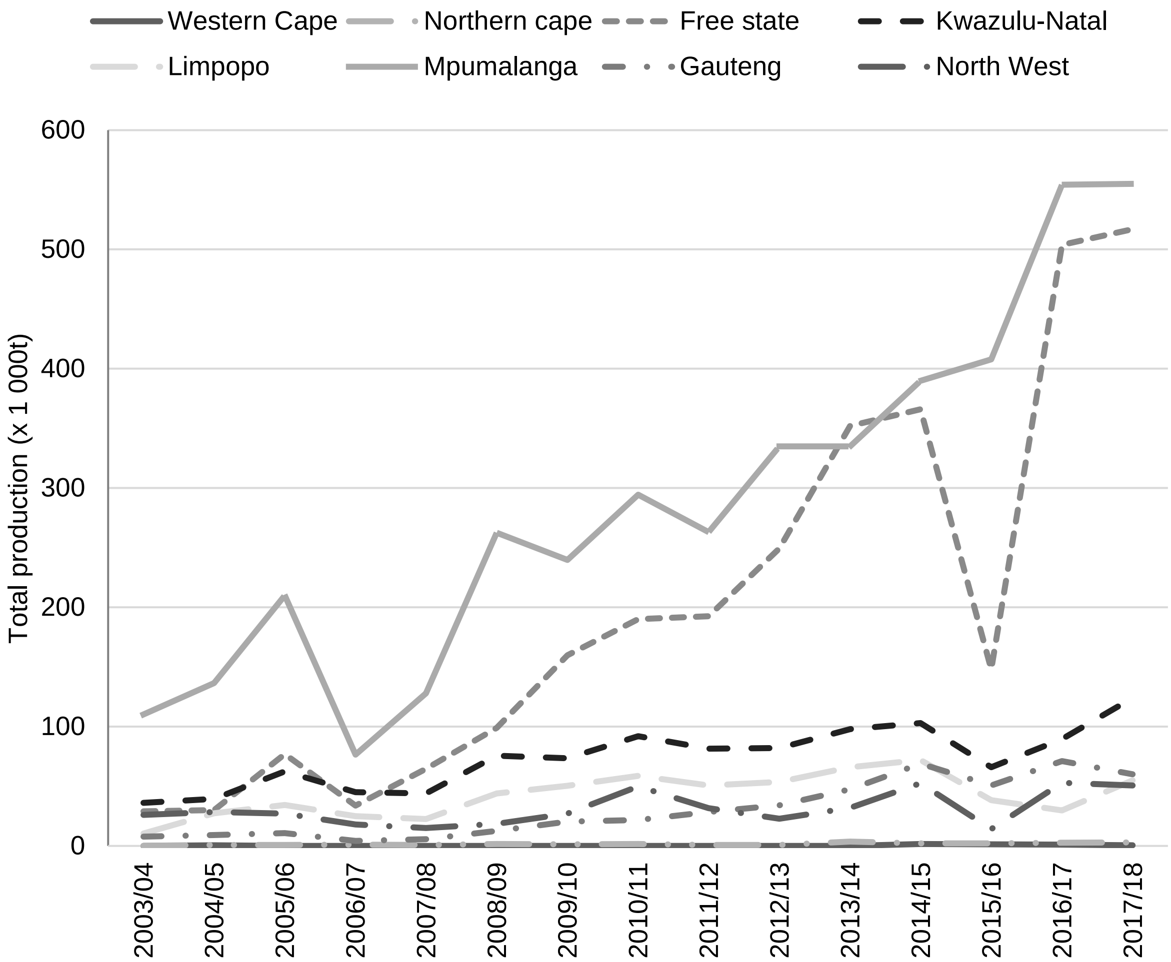


Figure 1: South Africa's soybean production from 2003 – 2018. Production from eight provinces. Adapted from: DAFF (2018).

2.2. Agronomic uses and production of soybean

Apart from economic benefits, soybean is used as a forage, nitrogen-fixing and green manure crop. It improves soil conditions, conserves high levels of moisture, reduces the occurrence of insect pests and diseases, and increases soil fertility (Busari et al. 2015). The latter makes it a more attractive crop in many cropping systems as it requires low levels of chemical fertilizers to grow. This is an advantage for production in Africa because of financial constrains to acquire mineral fertilizers (Sinclair et al. 2014). Soybean requires between 300 to over 450 mm of water, and substantial amount of P during its growing period. Adaptation to or mitigation against the risks of future climate change projection will require identifying cultivars that are heat tolerant as well as water and P-use efficient (van de Wiel et al. 2016).

2.3. The role of Phosphorus in soybean growth and yield

The most crucial nutrient for soybean is P because of its fundamental role in root establishment, grain formation and enhancement of vegetative growth (Chien et al. 2011; Shen et al. 2011). One of the vital functions of P is regulating various enzymatic activities (Mitran et al. 2018) and is required for energy intensive processes in root nodule (Liu et al. 2018) and improved N-fixation (van de Wiel et al. 2016). Phosphorus also promotes higher yield and better grain quality (Mokoena 2013; Win et al. 2010). Abbasi et al. (2010) observed a positive linear regression between the crop's P uptake and seed yield on a soybean study in Rawakalot. Phosphorus availability could improve P uptake and root morphology even when water deficiencies occurred at reproductive stage (Zheng et al. 2010). In addition, improved root morphology increases P uptake by crops (Li et al. 2016). Phosphorus uptake has proven to improve plant biomass and increase P utilization efficiency (Abbasi et al. 2010). A report by Sharma et al. (2011), shows an average increase of 10% on P uptake after application of 30 kg/ha P to different cultivars. The increase was significantly related to biomass production.

2.4. Phosphorus utilization efficiency in soybean

Enhancing P utilization efficiency is vital in improving crop yields (Hasan et al. 2016) and reducing eutrophication risks (Heuer et al. 2017). However, the utilization efficiency is affected by factors such as, P availability, P fertilization rate (Syers et al. 2008) and seed genotype (Mitran et al. 2018). Therefore, a sustainable soybean production especially in smallholder farming environments requires an increased supply of phosphorus through application of fertilizers (Aulakh et al. 2003; Nziguheba et al. 2016). Research report by Darwesh et al. (2013), shows increased P plant uptake by 99 - 280.49% on various soybean cultivars after application of superphosphate at 75 kg/ha. Furthermore, 44NK cultivar recorded an increase of up to 10.08 and 55.56% on phosphorus fertilizer use efficiency (FEP) as well as physiological phosphorus use efficiency (PUE*p*), respectively. Furthermore, Abbasi et al. (2010), observed P uptake increase on soybean seed by 26 and 32% and soybean straw by 11 and 28%, at 50 kg/ha and 100 kg/ha P rate correspondingly. However, as P rates increased P-use efficiency decreased. Syers et al. (2008), observed similar findings. Abbasi et al. (2010), concluded that the low recovery efficiency could be a result of high P fixation rate by Ca compounds or Fe/Al oxides.

2.5. Soil Phosphorus availability

Fixation of P is a common challenge in many agricultural soils (Shanker et al. 2014). Approximately 50% of the world's productive lands are deficient of P (Heuer et al. 2017) with approximately 30% (van de Wiel et al. 2016) having a high P-fixation capacity (Menezes-Blackburn et al. 2018). Consequently, even when phosphorus is available at large volumes in the soil, it is often unavailable for plant use due to the phosphate-binding agents (van de Wiel et al. 2016). Fixation of available P by Al and Fe oxides is high when pH is low but as pH increases to between 6 and 7, it becomes available. However, as pH increases, Mg and Ca precipitate P and its availability declines (Darwesh et al. 2013) (Figure 2). The main negative effect of Al on plants is the inhibition of root growth, which affects nutrient uptake (Heuer et al. 2017). Furthermore, clayey soils tend to fix P more than other soil textures (Shanker et al. 2014).

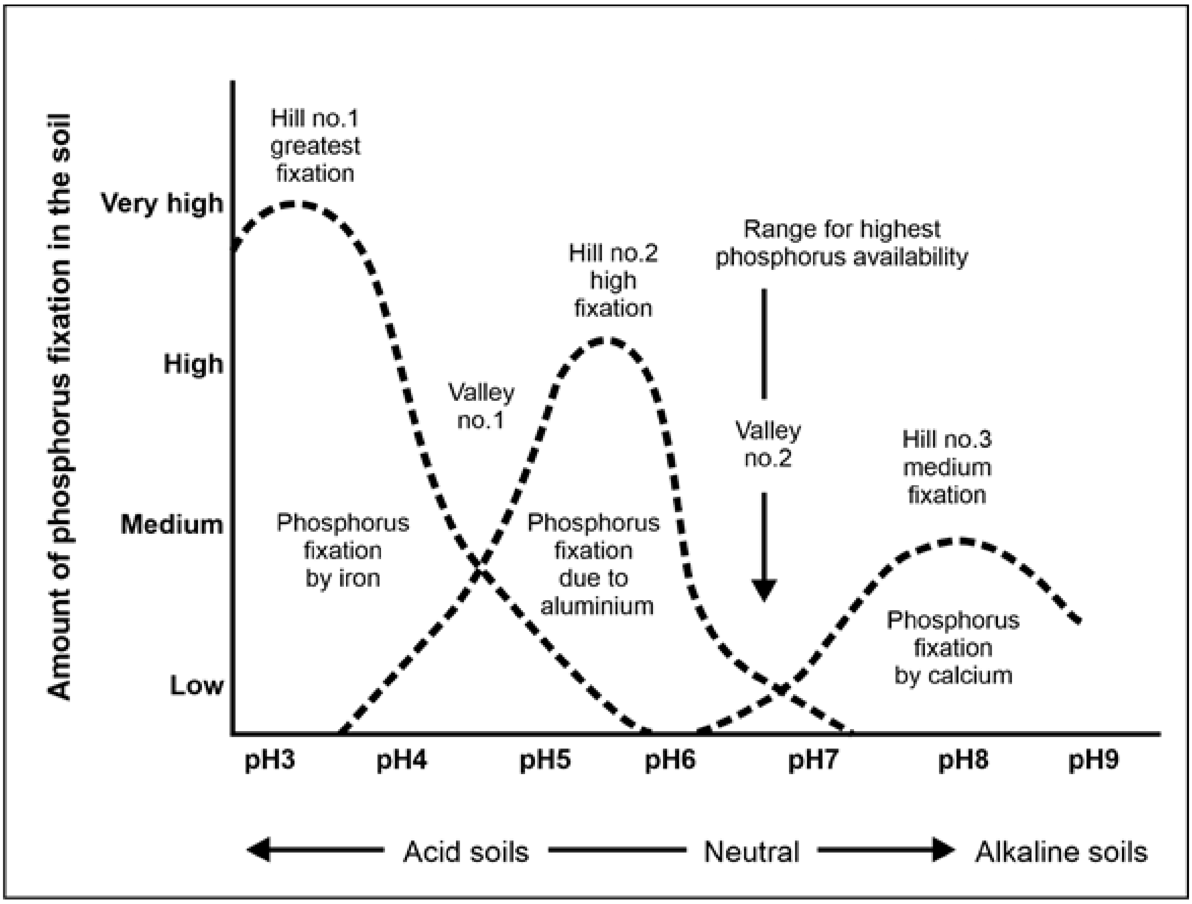


Figure 2: Phosphorus fixation hills and valleys. Source: Barrow (2017)

Recent studies, however, do not support the general perception of fixation of all soil residual phosphorus. Syers et al. (2008) proposed that inorganic phosphorus in the soil moves through four different P pools that vary in availability (Figure 3). The availability of P depends on the amount accessible to plant roots or extractability by reagents for analysis. The first two pools contain readily available and extractable P with the first pool having immediately available P for plant use. The last two pools contain P that is not readily available; however, the third pool can slowly release P over weeks to months.

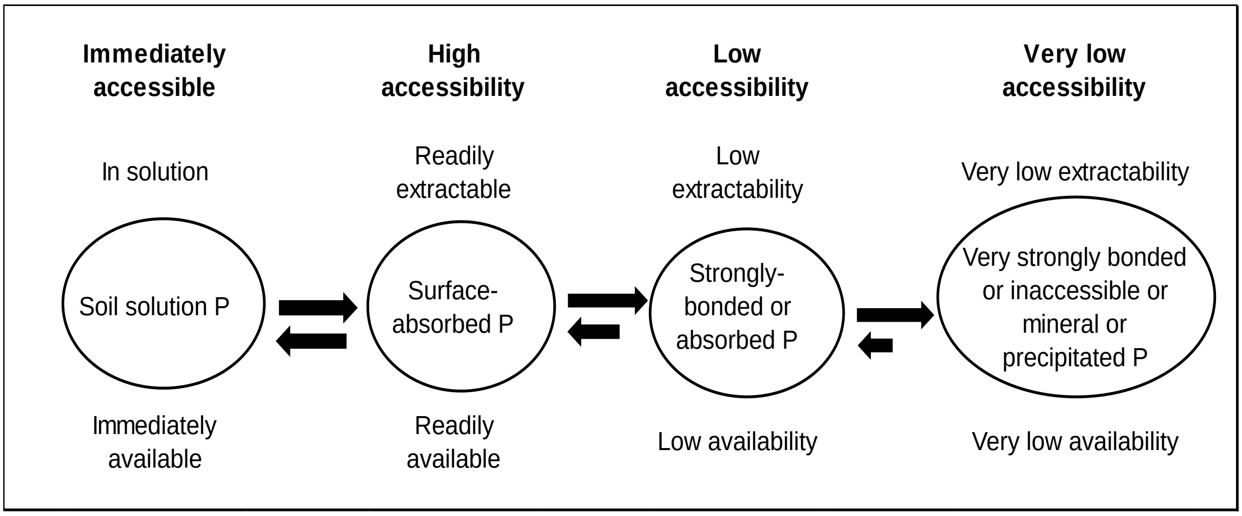


Figure 3: Theoretical diagram for soil inorganic P forms classified according to plant availability, accessibility and extractability. Adapted from Theobald (2016).

Most of the P applied, accounting to approximately 80% turn out to be unavailable to the plant immediately after application because of the above-mentioned processes (Roberts et al. 2015; Zhu et al. 2018). It has been shown that crops take up to 25% of overall phosphorus applied with the remainder becoming residual. Increasing P availability in the soil to optimum levels requires soil amendments such as liming to extremely acid soils, additions of chemical fertilizers or organic inputs should be made. For optimal yields, soybean requires between 15 – 18 mg/kg P in the soil (Fertasa 2016).

2.6. The role of fertilizer inputs in soybean production

Since most soils, especially in smallholder farms have insufficient available P to cater for crop’s demands throughout the growing season, replenishing soil nutrients is crucial (Nziguheba et al. 2016). For P-fixing soils, a high application of mineral P is crucial to increase soil available P (Heuer et al. 2017). Sources of P include rock phosphate, organic inputs (manure and compost) and chemical fertilizers (Mitran et al. 2018; Mokoena 2013; Zhu et al. 2018). A number of studies reported increasing soybean yield following mineral fertilizer additions. Mangaraj et al. (2017) observed a significantly high soybean yield of about 3217 kg/ha following N/P fertilizer application at a ratio of 0.70 (18 kg N, 46 kg P205 + 7 kg N/ha foliar) (Table 2). This same treatment also recorded a significant increase of yield attributes such as number of filled pods (44.73), total number of pods (47.57), 100-seed mass (15.40 g) and plant grain mass (18.31 g).

Table 2: Soybean yield after application of different ratios and levels of N and P. Source: (Mangaraj et al. 2017)

Treatment	N	P	K	Foliar N		Number of pods per plant	Pod mass	Seed mass
	kg/ha (Applied at sowing)			kg/ha			grams per plant	
T_1	0	0	0	0	0	31.20e	14.48h	9.53c
T_2	0	0	25	0	0	33.77e	16.51g	11.97b
T_3	40	80	25	0	0	38.13d	18.57f	13.73b
T_4	33	80	25	7	0	41.83bc	21.87cd	16.09b
T_5	18	46	25	7	7	47.57a	24.73a	18.31a
T_6	18	69	25	7	7	42.77bc	22.00b-d	16.21b
T_7	18	80	25	7	7	40.50cd	21.75cd	15.76b
T_8	26	45	25	7	7	42.50bc	20.06d-f	14.96b
T_9	26	69	25	7	7	41.83bc	21.38c-e	15.51b
T_{10}	26	80	25	7	7	41.77bc	21.59c-f	15.73b
T_{11}	40	46	25	7	7	39.93cd	19.51c-f	14.27b
T_{12}	40	69	25	7	7	47.33a	24.01ab	18.17a
T_{13}	40	80	25	7	7	45.23ab	22.74a-c	16.71b

Levels not connected by same letter are significantly different (p= 0.05). N – nitrogen; P – Phosphorus; K - Potassium

The cost of fertilizers increases with growing inflation and there is challenges with affordability in most developing countries (Nziguheba et al. 2016). No-till could curb crop production costs. Buah et al. (2017) performed an economic analysis using partial budget procedure in a study with smallholder farmers from Ghana in 2013 and 2014

(Table 3). Results show monetary returns under no-till higher than CT, and the input cost on CT was 58 USD - 73 USD higher than no-till for soybean. Therefore, the adaptation of no-till would help farmers save on the cost of fertilizers. This is because no-till provides a conducive environment for microorganisms that aid in P solubilisation.

Table 3: Economic analysis of tillage and fertilizer effects on soybean at Doggoh. Source: (Buah et al. 2017)

Variable	2013				2014			
	Conventional Tillage unfertilized	Conventional Tillage fertilized	No-till unfertilized	No-till fertilized	Conventional Tillage unfertilized	Conventional Tillage fertilized	No-till unfertilized	No-till fertilized
Yield of soybean (kg/ha)	293	493	366	547	567	993	980	1380
Grain price (USD / kg)	0.69	0.69	0.69	0.69	0.77	0.77	0.77	0.77
Gross return (USD / hectare)	202.07	340.00	252.41	377,24	438.97	768.77	758.71	1068.39
Ploughing (USD / hectare)	51.72	51.72	0.00	0.00	48.39	48.39	0.00	0.00
Herbicide and application costs (USD / hectare)	0.00	0.00	31.38	31.38	0.00	0.00	32.93	32.93
Weed control (labour) (USD / hectare)	86.21	86.21	43.10	43.10	80.65	80.65	40.32	40.32
Fertilizer and application costs (USD / hectare)	0.00	229.31	0.00	229.31	0.00	215.96	0.00	215.96
Total variable cost (USD / hectare)	137.93	367.24	74.48	303.79	129.03	344.99	73.25	289.21
Net benefits (USD / hectare)	64.14	(27.24)	177.93	73.45	309.94	425.23	686.13	781.29
MRR (%)		-40		-46		53		44

2.7. Effects of no-till on soil enzymes

There are a number of a number of P activators including PSM's (Nikitha et al. 2017), phosphatase enzymes (Bardella 2016) and enzyme activators (Zhu et al. 2018) for improving soil available P. Acid and alkaline phosphatases are the most abundant enzymes involved in solubilizing organic P compounds and can be easily detected due to their sensitivity to disturbance (Balota et al. 2004). Phosphatases also play a role to mobilize soil P and reallocate plant's internal P (van de Wiel et al. 2016). Nonetheless, soil biological as well as physicochemical factors such as OM, pH, nutrients and microorganisms affect their activities (Kizilkaya et al. 2007; Piotrowska-Długosz et al. 2014).

Phosphatases highly correlate with organic matter and several studies reported significantly high activities of ACP and ALP following manure or compost application (Mohammadi 2011; Zhu et al. 2018). Heidari et al. 2016, noted an improvement in ACP, ALP and Dehydrogenase activities by up to 90, 60 and 148% on a treatment that had a combination of farmyard manure and compost as compared to control (Table 4). This is because organic inputs improve soil microbial activities and increase microbial biomass (Heidari et al. 2016). Moreover, soil organic matter acts as an organic medium for soil enzymes (Lemanowicz et al. 2016). Mineral fertilizers also have effects on phosphatase activity. Nonetheless, contrasting results have been reported. Some authors have reported an increase in phosphatase activities following fertilization, and some reported the opposite. Chen et al. (2018) reported the highest activities of phosphatase from a treatment that had a combination of P, K and N fertilizer at 39, 112, and 276 kg/ha respectively, from a study with six fertilizer treatments conducted in China. However Zhang et al. (2015), noted a significant decrease of ACP activities at a range between 11 and 63% following application of 59 and 88 kg/ha of NPK mineral fertilizer respectively.

Observations on chemical fertilizer effects on enzymatic activities are positive, negative and neutral because they respond differently to additions of nutrients due to varying environmental and management factors (Dong et al. 2015). Therefore, to have a better understanding of their complex interactions, further research on enzyme response to soils that vary with type and management practices is required.

Table 4: Tillage and fertilization effects on enzyme activities and soil organic carbon. Source: (Heidari et al. 2016)

Fertilizer	SOC (g/kg)	Acid phosphatase (µg PNP/ g/ h)	Alkaline phosphatase (µg PNP/ g/ h)
FYM	16.261a	136.611d	2347.912b
Compost	16.312a	168.392c	2317.288b
Chemical fertilizer	16.198a	135.901d	2076.918c
FYM + Compost	16.401a	199.162a	3183.612a
FYM + Chemical	16.308a	171.694bc	2094.191c
Compost + Chemical	16.289a	173.215bc	2086.506c
FYM + Compost + Chemical fertilizer	16.279a	179.424b	3122.299a
Control	16.198a	104.926e	2049.105c
Tillage			
No-Till	16.322a	189.172a	2879.633a
Minimum Tillage	16.286a	159.857b	2358.958b
Conventional Tillage	16.217a	125.976c	1989.693c

Mean values in each column with the same letter(s) are not significantly different using LSD tests at 5% probability. (FYM: farmyard manure).

CHAPTER 3: MATERIALS AND METHODS

3.1. Site description

The study was conducted in Sheepmoor, Mpumalanga. The farm is situated at 26°45”18’S, 30°13’’58’E at an altitude of 1537 m (meters above sea level) in Gert Sibande District Municipality, approximately 45 km from Ermelo town (Figure 4). The larger part of the District is situated on the Highveld Grasslands of Mpumalanga and thus generally features an undulating to strongly undulating landscape with intermittent hills. The intensity of the undulations generally increases from west to east, in the direction of the Drakensberg Escarpment and Swaziland. Sheepmoor is described as Temperate, Dry Winter, Warm Summer. Average rainfall threshold is about 756 mm per annum. Minimum temperatures are between 7 – 8 °C and maximum temperatures are between 26 – 30 °C.

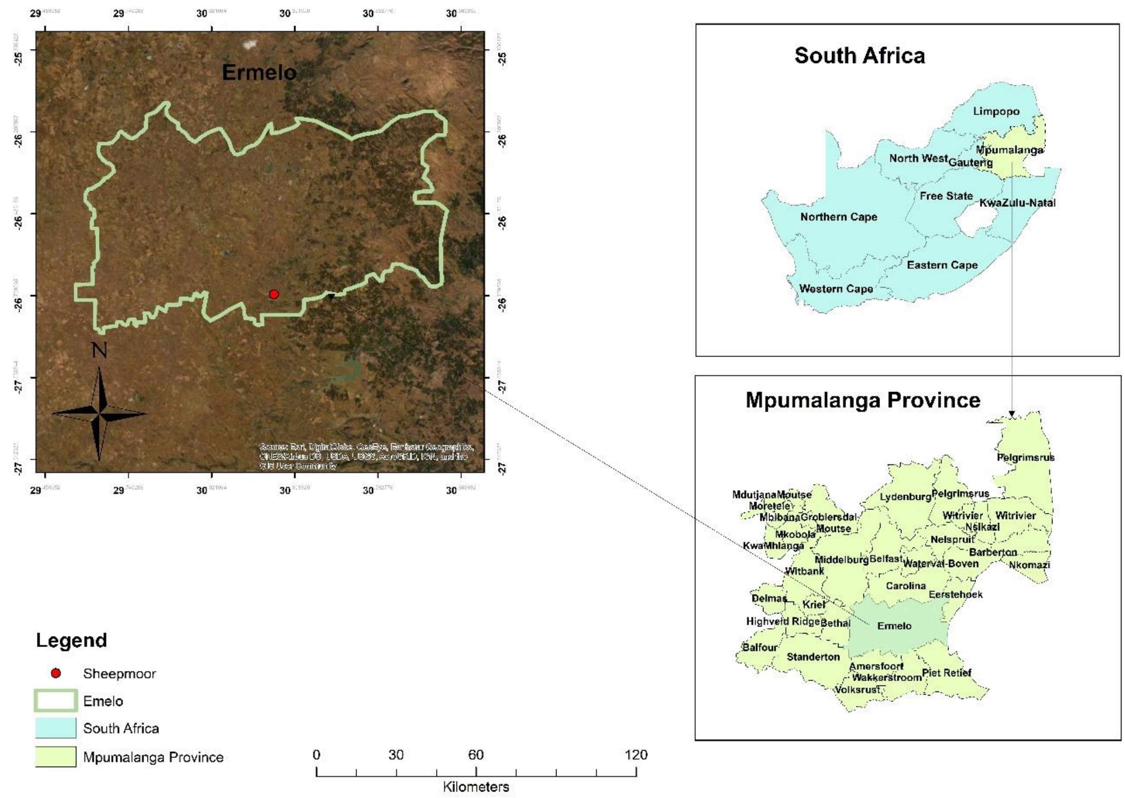


Figure 4: Map of the study site

Climate data for the planting period 2017/2018 is presented on Figure 5. Planting was done on 6 December 2017. Good rainfall of >100 mm was experienced during planting period which led to a good germination and vegetation of crops. This was unfortunately followed by a dry spell that occurred at the beginning of flowering stage in February 2018. The crops however, quickly recovered with increased rainfall of > 120 mm that occurred during pod formation in March 2018. Average minimum temperatures were higher than the normal average during the dry spell period in February 2018 (±13 ^{o}C); however, maximum temperatures remained almost steady (±25 ^{o}C) from planting in December 2017 to pod formation in March 2018. Both average minimum and maximum temperatures began to drop in April 2018 as the winter season was setting in.

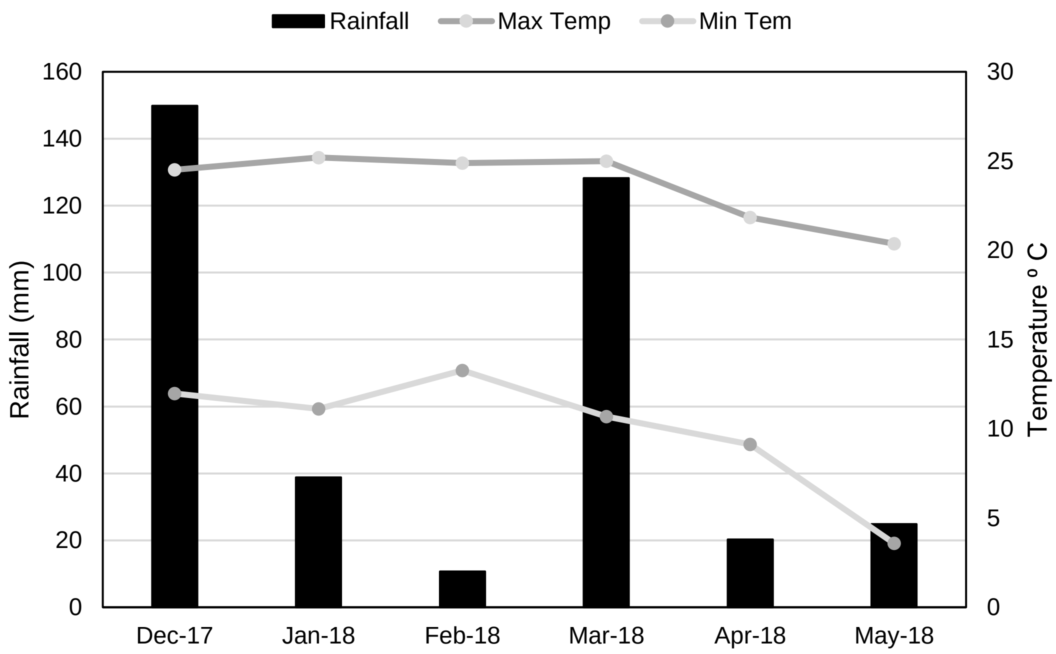


Figure 5: Average rainfall and temperature during the planting season from December 2017 to May 2018

3.2. Soil Sampling

Prior to establishment of experiments, soil samples were randomly collected at a depth of 0 to 30 cm. Samples were air dried and passed through a 2 mm and then used for initial characterization (SSSSA, 1990). Table 5 shows the initial soil characterization of the study site prior trial establishment.

Table 5: Initial soil characterization of the study site

Soil property	Units
pH	4.6
EC (mS/cm)	22
Total N %	0.072
Organic C %	1.19
P (mg/kg)	11,14
K (mg/kg)	159.4
Ca (mg/kg)	160.07
Mg (mg/kg)	66.7
Na (mg/kg)	0.56
Bulk density g/cm³	1.2
Sand %	70
Silt %	10
Clay %	20

Soils of the study site were sandy loam with a strongly acidic pH of 4.6. The particle size analysis indicated the soils had 20% clay, 10 % silt and 70% sand on 0-30cm depth. Soil available P was 11.14 mg/kg, which according to FERTASA (2016) is low for soybean production and justifies the need for P amendments in the soil. The soil also had lower concentrations of soil exchangeable Ca, Mg and K, which were 160.07, 66 and 159.4 mg/kg respectively. Organic C and total N were 1.19 and 0.072%.

3.3. Soil Characterization

Particle size distribution was determined using the hydrometer method after oxidizing SOM with hydrogen peroxide as described by Gee et al. (2002). The SOC content was determined following the Walkely-Black procedure as described by SSSSA (1990) by taking 1 g of air-dry soil and transferring it into 500 mL Erlenmeyer flask. A 10 ml $K_2Cr_2O_7$ solution was added to the sample by a pipette, then 20 ml concentrated sulphuric acid was added rapidly to the solution whilst swirling the flask to disperse the soil in the solution. Thereafter, 1 ml of indicator was added and excess dichromate was titrated with iron (II) ammonium sulphate solution. Soil solution pH was measured in water at a 1:2.5 soil water ratio as described by Okalebo et al. (2002) using a Eutech pH 700 meter after 1 hour. The same suspension was used to measure electrical conductivity (EC) with WTS Multi 9310 IDS EC meter, after shaking for 30 minutes and filtering with Whatman ashless no. 40 filter paper (SSSSA 1990). Total N and total C were determined using the dry combustion method using the Carlo Elba machine. Approximately 10 mg soil sample was weighed using sensitive balance, folded in a tin capsule and subjected to elemental analysis (EA) procedures where the weight of percent of N and C in the sample was determined through a complete oxidation process. Soil available P was determined using P-Bray 1 method by taking 6 g of soil and placing it into a 45 ml P-bray extractant. The tubes were horizontally placed in a reciprocal shaker and were shaken for 5 min at 200 strokes per minute. After shaking, the soil suspension was filtered (Whatman ashless no. 40) and the P concentration of the collected extract was determined calorimetrically using Seal-AA3 flow analyser (SSSSA 1990). Extractable K, Ca, Na and Mg were extracted with ammonium acetate solution and analysed with an Inductively Coupled Plasma (ICP-OES). Fe was determined using 5g soil extracted with 20 mL HCl, then filtered into a tube using Whatman ashless no.40 filter paper and then analysed with ICP-OES. Al was determined using titratable acidity method using 10 g of soil and 100 ml to extract, then titrated with Sodium Hydroxide (SSSSA 1990).

3.4. Experimental design

A randomized complete block design (RCBD) arranged in a 2 x 3 x 3 strip-split-plot layout was used to study the availability of soil P and utilization efficiency of added P in a soybean cropping system. The treatments were composed of two tillage systems, No-till (NT) and Conventional tillage (CT) as main plots. It also consisted of three Phosphorus fertilizer rates (0, 30 and 60 kg/ha) as sub plots, three soybean roundup ready cultivars (PAN 1532R; PAN 1521R and PAN 1614R) as sub-sub plots replicated thrice to give 54 plots. Phosphorus fertilizer source used was Monoammonium phosphate (MAP). Fertilizer was applied by banding at 5 – 7 cm away from the seed furrow. Each plot consisted was 7 m long and 3 m in width with six soybean rows that had an inter and intra-row spacing of 60 and 5 cm respectively (gross plots), targeting a population of 300 000 seeds per hectare. The net plots consisted of four middle rows of the gross plots. Soybean cultivars were selected based on performance in a preliminary study conducted by the Agricultural Research Council – Soil Climate and Water at the study site.

3.5. Trial management

The experiment was established under dryland conditions. During the first season after trial demarcation, conventional tillage was done using a mouldboard plough. Plots demarcated for no-till were prepared using a disc harrow to remove weeds and loosen the soil for planting because the land was virgin. A follow-up with a non-selective systemic herbicide (Roundup (N-[phosphono-methyl] glycine, 360 g L-1)) was used to eradicate any remaining weeds. Furrows for direct seeding were created using hand hoes and seeds were placed manually in the furrows using a marked row after direct fertilization had been done.

During the second season, the conventional tillage plots were prepared as before, however the no-till plots were not disked but rather, a glyphosate herbicide (Roundup) was applied to remove weeds at a rate of 4L per hectare following the instruction manual. Planting was done as described above. During the growing season, weeds were again eradicated using Roundup herbicide. Scouting for pests and diseases was done randomly during the growing season, however, no agro chemicals were administered as there were no diseases and harmful pests observed.

3.6. Objective 1: To determine the effects of different levels of mineral P fertilization on soybean growth, yield and grain protein & oil content.

A measuring stick was used to measure plant height during crop maturity by measuring crop length from base to the top leaf. Days to 50% flowering were recorded as the day on which half the crops in each plot flowered. The number of pods per plant (NPP), pod length and number of seeds per pod were counted manually from three plants randomly selected from the net plots at crop maturity. The maturity date was recorded when the crops had turned golden yellow. Soybean net plots were harvested manually into grain bags; grain weight was measured with a digital scale after shelling. Three plants from boundary rows were used to measure wet shoot biomass with a digital scale and then taken to the laboratory for dry biomass measurements after oven drying the samples for 24 hours at 70 ºC. A moisture meter (Dramiński Twistgrain) was used to measure grain moisture at harvest according to the instrument's instruction manual. 100-seed weight was measured by counting 100 seeds and then weighing them on a digital scale. Grain protein and oil content were measured by NIR DA 7250 machine following a non-disruptive method as stipulated in the instruction manual of the instrument. The sample was poured into an open-faced dish and placed in the machine. Results were viewed on the screen of the machine. Yield was calculated using Equation 1 below and expressed in tons per hectare:

$$Y\left(t/ha\right)=\frac{100-moisture\%}{100-12}\times seed\ mass$$ **[Equation 1]**

Where 12% is the adjusted moisture (Verde et al. 2013)

3.7. Objective 2: To determine the effects of different levels of mineral P fertilizer on nutrient uptake (NPK), P use efficiency and partial factor productivity in a soybean cropping system.

Phosphorus uptake was determined using the block digestion method (using nitric acid, perchloric acid, hydrochloric acid and hydrogen peroxide) after the plant material had been oven-dried at 70 °C for 24 hours and ground to pass through a 1 mm screen. P use efficiency was calculated using the balance method and expressed as a percentage as shown on Equation 2 below. Unlike the difference method which only focuses on P fertilizer applied to the soil when calculating P use efficiency, the balance method considers available P in the soil from different sources such as residual from past applications, solubilisation of organic P from organic sources or even P applied during planting or during crop growth. When a small percentage of added P is taken up by the crop, then the remainder is supplied from soil P reserves. If P use efficiency determined by the balance method is greater than 100%, it indicates a depletion of soil P reserves. However, if it has a small recover percentage, it could indicate that the amount of fertilizer applied is being used inefficiently by the crop (Roberts et al. 2015; Syers et al. 2008).

$$P\ use\ efficiency(\%) = \frac{P\ takenup\ by\ the\ crop\ (fertilized\ soil)}{Amount\ of\ P\ applied} \times 100$$ **[Equation 2]**

Partial factor productivity (PFP) measures utilization efficiency considering production. It indicates the productivity of a crop (yield) in comparison to the fertilizer applied (Roberts et al. 2015). Partial factor productivity was determined using equation 3 below:

$$Partial\ factor\ productivity\ (PFP) = \frac{Yield}{Amount\ of\ P\ applied}$$ **[Equation 3]**

3.8. Objective 3: To determine the effects of different levels of mineral P fertilizer and tillage on selected soil chemical and physical parameters

Soil chemical properties (pH, exchangeable Ca and Mg, Fe, Al, soil available P, K, total N, total P and total C) were determined following methods described in 3.3 above. Bulk density was determined using the core method as described by Bonin et al. (2012). Three random samples were collected from each plot using a core sampler. The samples were weighed immediately after collection and later transported to the laboratory for drying. Samples were dried for 24 hours at 105 °C and then weighed again. Bulk density was calculated using Equation 4 below:

$$Bulk\ density\left(g \cdot cm^{-3}\right) = \frac{mass\left(g\right)}{volume\left(cm^{3}\right)}$$ **[Equation 4]**

Penetration resistance was randomly measured from five points in a plot using a push-cone penetrometer with a measuring range of 0 – 40 mm. The penetrometer measured a resistance of soil by pushing a cone vertically into the profile scrapped evenly.

3.9. Objective 4: To determine the relationship between activities of acid and alkaline phosphatases, soil properties and management practices on a soybean cropping system

Activities of acid and alkaline phosphatase were evaluated as described by Tabatabai (1994). These enzyme activities were analysed using 1 g of air-dried soil in a 50-ml Erlenmeyer flask with their appropriate substrate and incubated for 1 h (37 °C) at their optimal pH (pH 6.5 for assay of acid phosphatase or pH 11 for assay of alkaline phosphatase). Enzyme activities were evaluated in duplicate with one control, to which, substrate was added after incubation and subtracted from the sample value.

3.10. Statistical analysis

Analysis of variance (ANOVA) as a factorial design and Pearson's correlation test were performed using JMP 14 (SAS Institute, 2018). Mean separations were done using Fisher's protected least significant differences (LSD) at $P < 0.05$.

CHAPTER 4: RESULTS AND DISCUSSION

This study was conducted for two planting seasons (2016/2017 – 2017/2018); however, results presented herein are from the second planting season (2017/2018).

4.1. Effects of fertilizer, tillage and cultivar on soybean yield, yield components and grain quality

4.1.1. Effects of fertilizer, tillage and cultivar on wet biomass and dry biomass

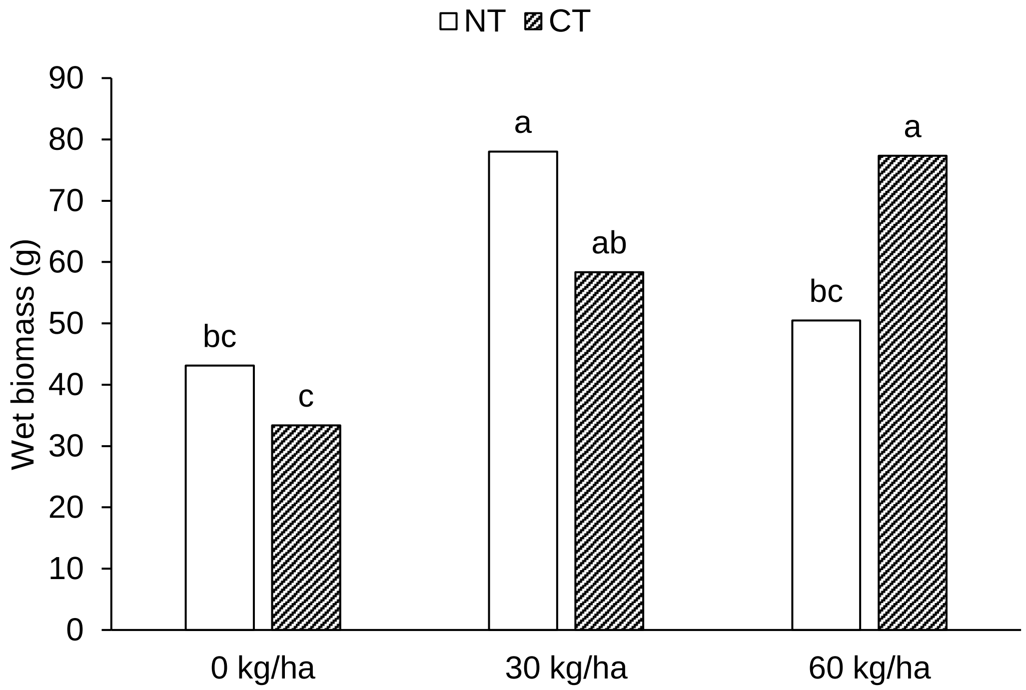
Significant interactions ($P < 0.05$) among main treatments (fertilizer and tillage) were observed on both wet and dry biomass (Table 6 and 7). However, cultivar did not have significant effects. Fertilizer application at 0 and 30 kg/ha led to higher wet biomass under NT than CT (Figure 6). In contrast, P applied at 60 kg/ha gave rise to higher wet biomass under CT than NT. The highest wet biomass was observed after P was applied at 30 kg/ha under NT and 60 kg/ha under CT. The same trend was observed for dry biomass (Figure 6). Ahiabor (2014) and Aulakh et al. (2003) also noted the highest increase of biomass production at 45 kg/ha P rate. The response of wet and dry biomass to P additions could be attributed to increased phosphates in the soil, which make orthophosphates readily available for plant uptake and are used for various essential plant processes such as growth, development and reproduction (Shen et al. 2011). Furthermore, no-till retains soils moisture and reduces erosion, which enhances P availability (Busari et al. 2015; Armstrong 1999). Moreover, OM decomposition under NT recycles organic P back into the soil.

Table 6: Analysis of variance for the effects of fertilizer, tillage and cultivar on wet biomass

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	2112.392	3.3412	0.2651
Tillage	1	1	8.899	0.0181	0.8938
Cultivar	2	2	1445.723	1.4710	0.2453
Fertilizer	2	2	8635.116	8.7858	0.0009*
Cultivar*Tillage	2	2	833.309	0.8479	0.4380
Cultivar*Fertilizer	4	4	2258.992	1.1492	0.3520
Tillage*Fertilizer	2	2	4932.393	5.0185	0.0129*
Cultivar*Tillage*Fertilizer	4	4	1457.193	0.7413	0.5711

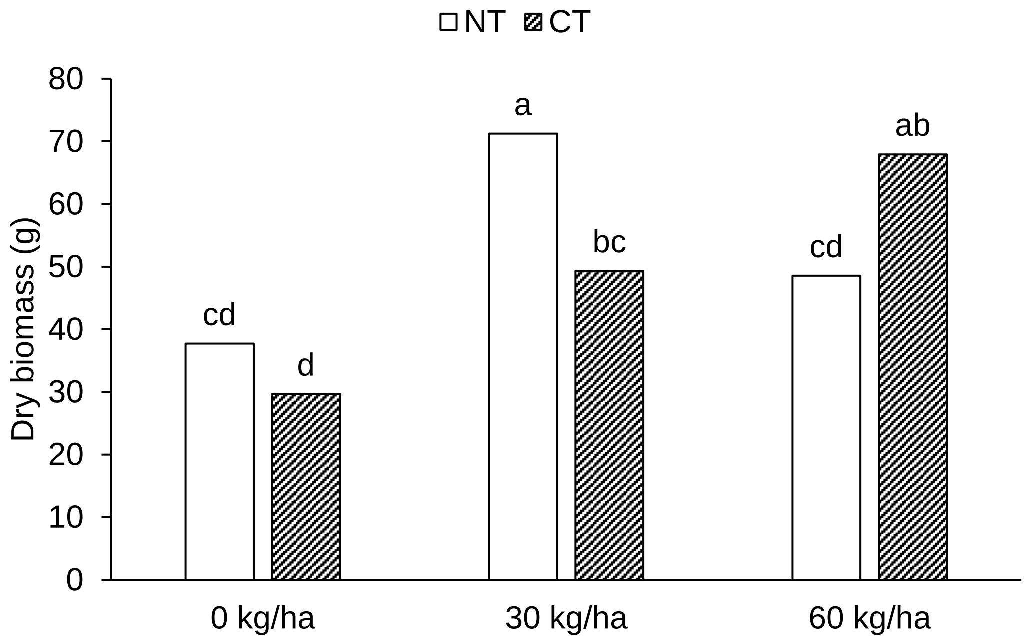
Table 7: Analysis of variance for the effects of fertilizer, tillage and cultivar on dry biomass

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	1345.5401	2.7985	0.3201
Tillage	1	1	154.1458	0.4222	0.5206
Cultivar	2	2	760.0318	1.0408	0.3652
Fertilizer	2	2	7218.1836	9.8851	0.0005*
Cultivar*Tillage	2	2	488.8814	0.6695	0.5192
Cultivar*Fertilizer	4	4	1502.8525	1.0291	0.4078
Tillage*Fertilizer	2	2	3631.1437	4.9728	0.0134*
Cultivar*Tillage*Fertilizer	4	4	989.7329	0.6777	0.6126



Bars with same letter are not significantly different at 5% probability level.

Figure 6: Interactive effects of tillage and fertilizer on wet biomass on a soybean cropping system



Bars with same letter are not significantly different at 5% probability level.

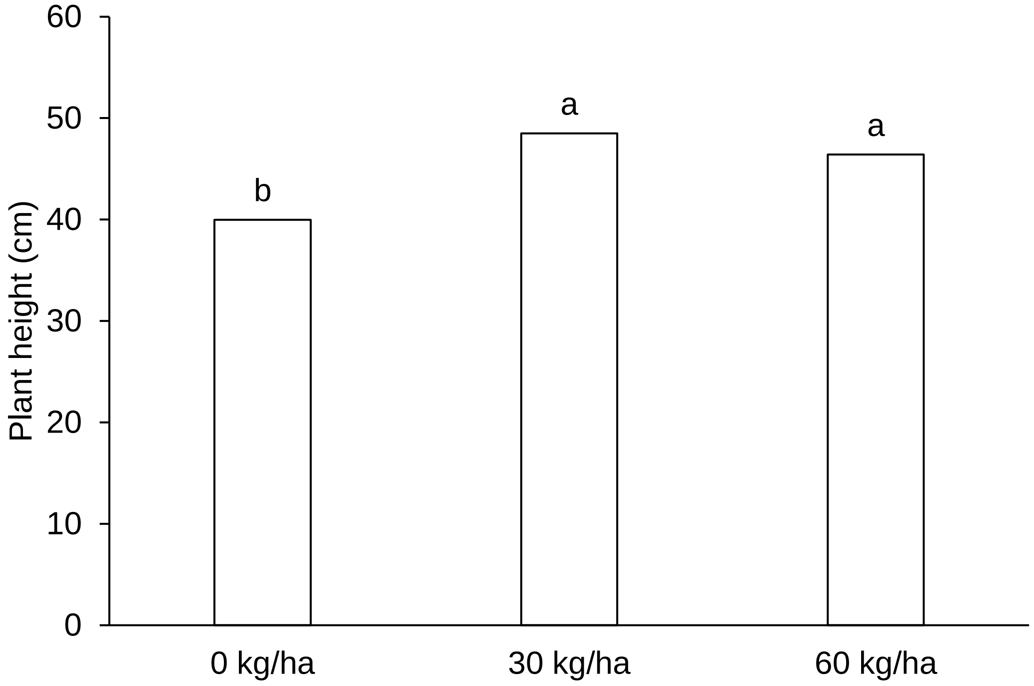
Figure 7: Interactive effects of tillage and fertilizer on dry biomass on a soybean cropping system

4.1.2. Effects of fertilizer, tillage and cultivar on plant height

Fertilizer application and cultivar affected plant height significantly ($P < 0.05$). However, tillage and the interactions did not have significant effects (Table 8). Fertilizer applied at 30 and 60 kg/ha gave rise to plants that were 21.31% and 16.06% taller than control respectively (Figure 8). However, plant height at 30 and 60 kg/ha P was statistically similar. According to Fertasa (2016), the recommended P level in the soil for soybean is between 15 and 18 mg/kg. In this experiment, soils under control (0 kg/ha P) had critically low soil available P (Figure 27) hence plants were shorter at control and taller at 30 and 60 kg/ha P treatments. Low supply of P imposes major restrictions in vegetative growth and reproduction of soybean (Mitran et al. 2018). Results from Malik et al. (2006) support these findings. Taller plants were observed following P fertilization and seed inoculation. Furthermore, genotype had significant effects on plant height. The three cultivars varied with height (Figure 9). PAN 1614R had the tallest plants 49.84 cm which was statistically same with PAN 1521R.

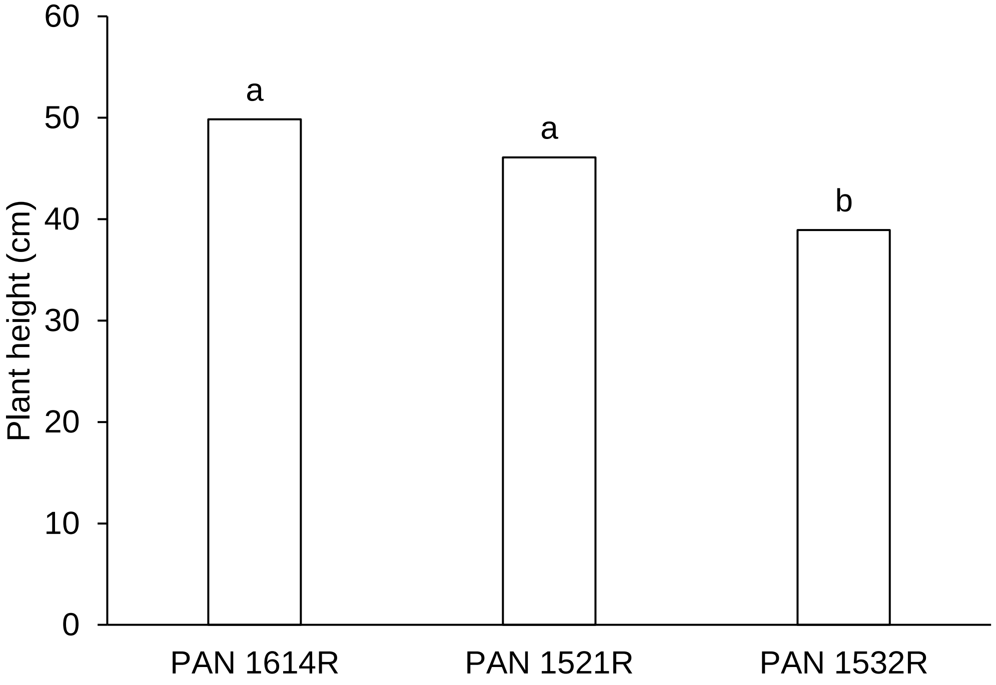
Table 8: Analysis of variance for the effects of fertilizer, tillage and cultivar on plant height

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	62.5454	0.8013	0.1016
Tillage	1	1	32.1101	0.8528	0.3629
Cultivar	2	2	1013.3209	13.4560	<.0001*
Fertilizer	2	2	648.8244	8.6158	0.0011*
Cultivar*Tillage	2	2	65.1372	0.8650	0.4310
Cultivar*Fertilizer	4	4	87.4854	0.5809	0.6787
Tillage*Fertilizer	2	2	93.9543	1.2476	0.3012
Cultivar*Tillage*Fertilizer	4	4	295.9750	1.9651	0.1245



Bars with same letter are not significantly different at 5% probability level.

Figure 8: Effects of fertilizer on plant height on a soybean cropping system



Bars with same letter are not significantly different at 5% probability level.

Figure 9: Effects of cultivar on plant height on a soybean cropping system

Improved height could also be attributed to increasing K concentration following P application at 30 and 60 kg/ha (Figure 29). This is because K is directly involved in photosynthesis and plant growth and therefore needed in larger volumes by crops. Consequently, plant height and K had a positive linear relationship (*P* = 0.001285; R^2= 0.91) (Figure 10). Literature shows that plant height is not always correlated with yield (Diondra et al., 2008), and this was confirmed in the current study.

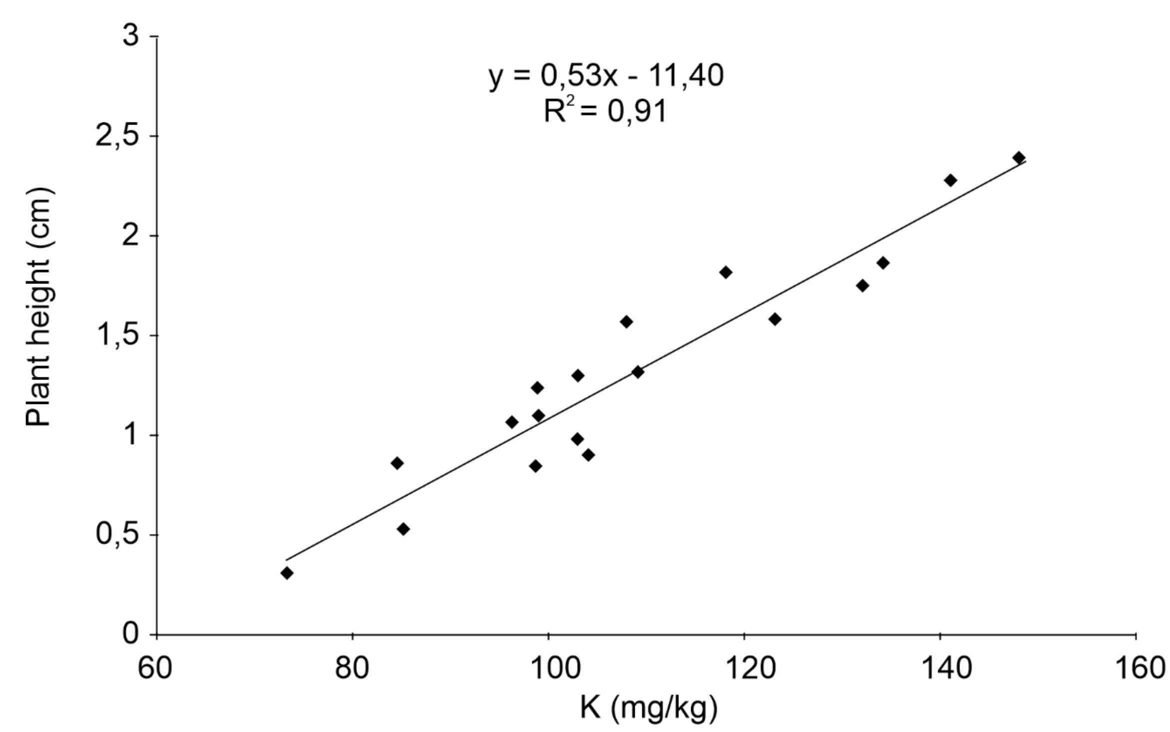


Figure 10: Relationship between K and plant height on a soybean cropping system

4.1.3. Effects of fertilizer, tillage and cultivar on 100-seed weight

Fertilizer application and tillage did not have any significant effects (P <0.05) on 100-seed weight (Table 9). However, cultivar did have significant effects (P <0.05) on this parameter. Mokwena (2013) also reported that P fertilizer had no effects on 100-seed weight. PAN 1614R recorded the highest weight of 100 seeds which was at par with

PAN 1521R. According to Krisnawati et al. (2015), several genes are liable for soybean seed size traits. Moreover, mature seed sizes are simultaneously determined by embryo, cytoplasm and maternal effects (Adie et al., 2018).

Table 9: Fertilizer application, cultivar and tillage effects on 100 seed weight

Treatment	100 seed (g)
Fertilizer (F)	
0	15.98a
30	15.6a
60	16.65a
P value	0.1467
Cultivar (C)	
PAN 1614R	16.85a
PAN 1521R	15.95ab
PAN 1532R	15.43b
P value	0.0369
Tillage (T)	
NT	16.13a
CT	16.02a
P value	ns
Interactions (*P* value)	
C x T	ns
C x F	ns
T x F	ns
C x T x F	ns

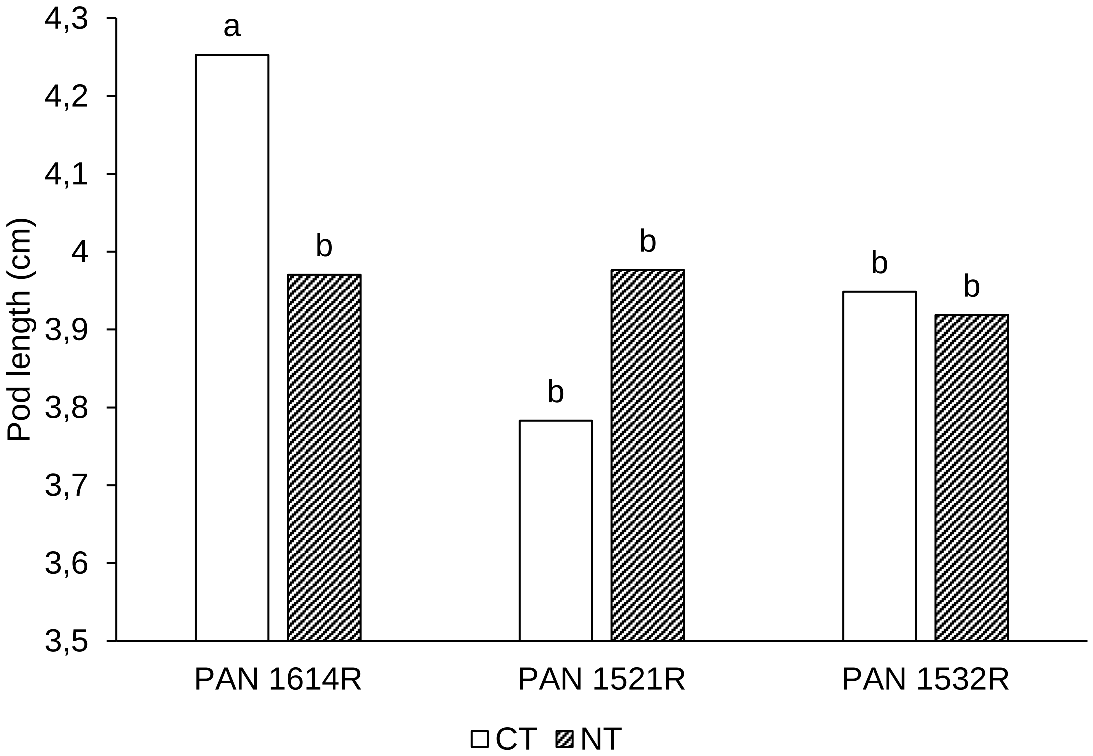
Levels not connected by same letter are significantly different (P< 0.05; Fisher’s test). NT – no-till, CT – conventional tillage, ns - not significant

4.1.4. Effects of fertilizer, tillage and cultivar on pod length

The interaction between cultivar and tillage significantly (P<0.05) affected pod length (Table 10). However, P application and interactions of the other treatments were not significant. PAN 1614R under CT produced the longest pods, whilst PAN 1521R and PAN 1532R were lower and performed similarly statistically under both tillage systems (Figure 11). This could be because of seed genotype and adaptability to tillage system.

Table 10: Analysis of variance for the effects of fertilizer, tillage and cultivar on pod length

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	0.20680428	1.1696	0.3007
Tillage	1	1	0.03415547	0.6908	0.4123
Cultivar	2	2	0.44077734	4.4572	0.0199*
Fertilizer	2	2	0.18256620	1.8461	0.1748
Cultivar*Tillage	2	2	0.40758438	4.1215	0.0259*
Cultivar*Fertilizer	4	4	0.18977665	0.9595	0.4435
Tillage*Fertilizer	2	2	0.10037583	1.0150	0.3741
Cultivar*Tillage*Fertilizer	4	4	0.15895566	0.8037	0.5322



Bars with same letter are not significantly different at 5% probability level.

Figure 11: Interactive effects of cultivar and tillage on pod length on a soybean cropping system

4.1.5. Effects of fertilizer, tillage and cultivar on number of pods per plant (NPP), 2-seeded pods and 3-seeded pods

All three main treatments significantly affected ($P < 0.05$) on NPP, 2-seeded pods and 3-seeded (Table 11). However, none of their interactions had significant effects. Number of pods per plant together with 3-seeded pods significantly increased with P application, however, they were statistically similar at 30 and 60 kg/ha P. At the afore mentioned P rates, NPP increased by up to 66.15 and 61.41% respectively over control. Similar to NPP, P rate at 30 and 60 kg/ha also increased 3-seeded pods by up to 88.89 and 111.11% at P respectively over control. Phosphorus in soybean is responsible for pod formation (Fageria et al. 2013); therefore, P applied becomes available at an increased concentration for plant uptake. The significant increase in NPP plant following fertilization is consistent with results from Ahiabor (2014), who observed an increasing number of NPP as P rate increased. Consequently, there were yield increases at 30 and 60 kg/ha P treatments resulting from increased NPP and 3-seeded pods. A significant positive regression between yield with NPP ($P = 0.0084$; $R^2 = 0.90$) and 3-seeded pods ($P = 0.000973$; $R^2 = 0.89$) supported these findings (Figure 12 and 13). 2-seeded pods were only significantly affected by cultivar (Figure 14). PAN 1614R recorded the highest number of 2-seeded pods, however it was statistically at par with PAN 1521R. This could be due to genotype.

Table 11: Fertilizer application, cultivar and tillage effects on NPP, 3-seeded pods and 2-seeded pods on a soybean cropping system.

Treatment	NPP	Pods with 3 seeds	Pods with 2 seeds
Fertilizer (F)			
0	40b	9b	31a
30	67a	17a	48a
60	65a	19a	46a
P value	0.0445	0.0194	ns
Cultivar (C)			
PAN 1614R	46a	17a	54a
PAN 1521R	49a	14a	38ab
PAN 1632R	46a	15a	33b
P value	ns	ns	0,0483
Tillage (T)			
NT	54a	15a	39a
CT	61a	15a	44a
P value	ns	ns	ns
Interactions (*P* value)			
C x T	ns	ns	ns
C x F	ns	ns	ns
T x F	ns	ns	ns
C x T x F	ns	ns	ns

Levels not connected by same letter are significantly different ($P < 0.05$; Fisher's test). NT – no-till, CT – conventional tillage, NPP – Number of pods per plant, ns - not significant

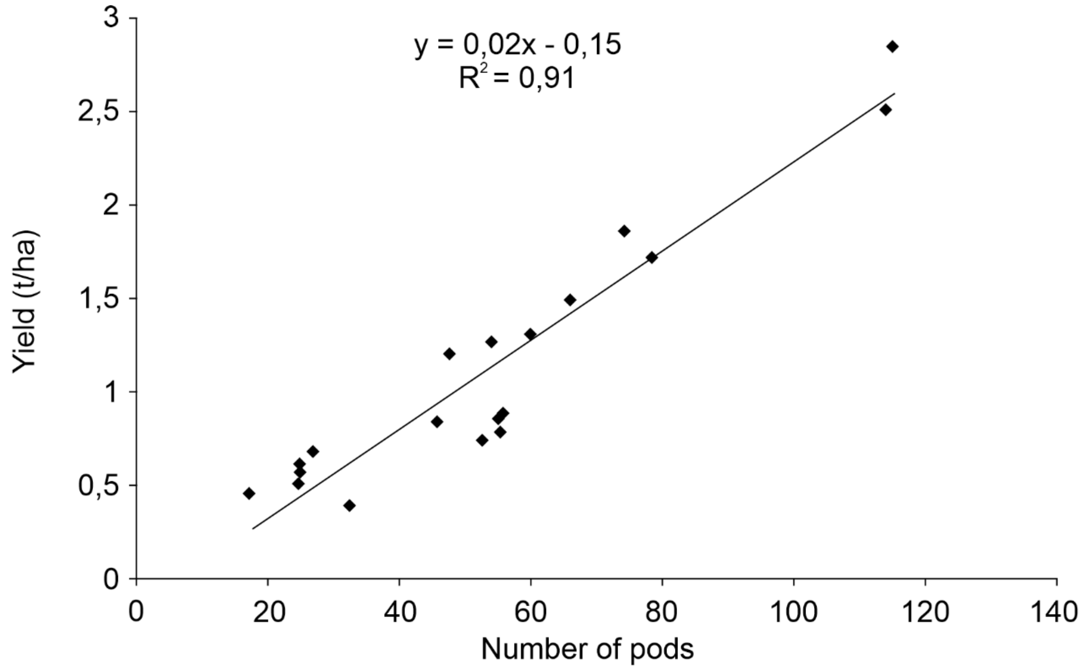


Figure 12: Relationship between soybean yield and NPP on a soybean cropping system

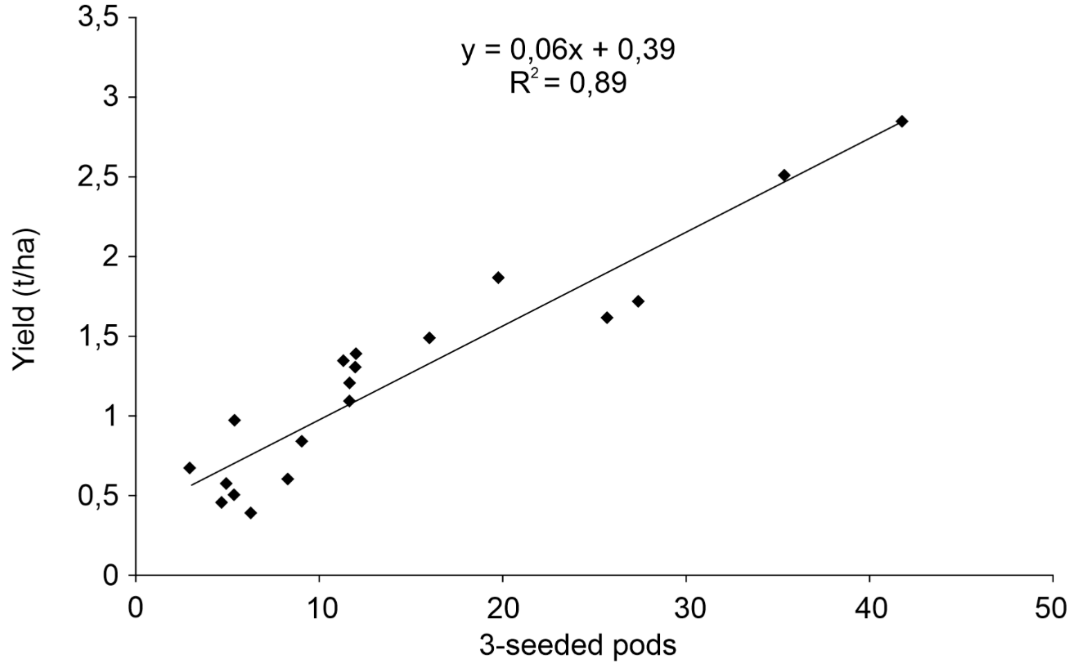
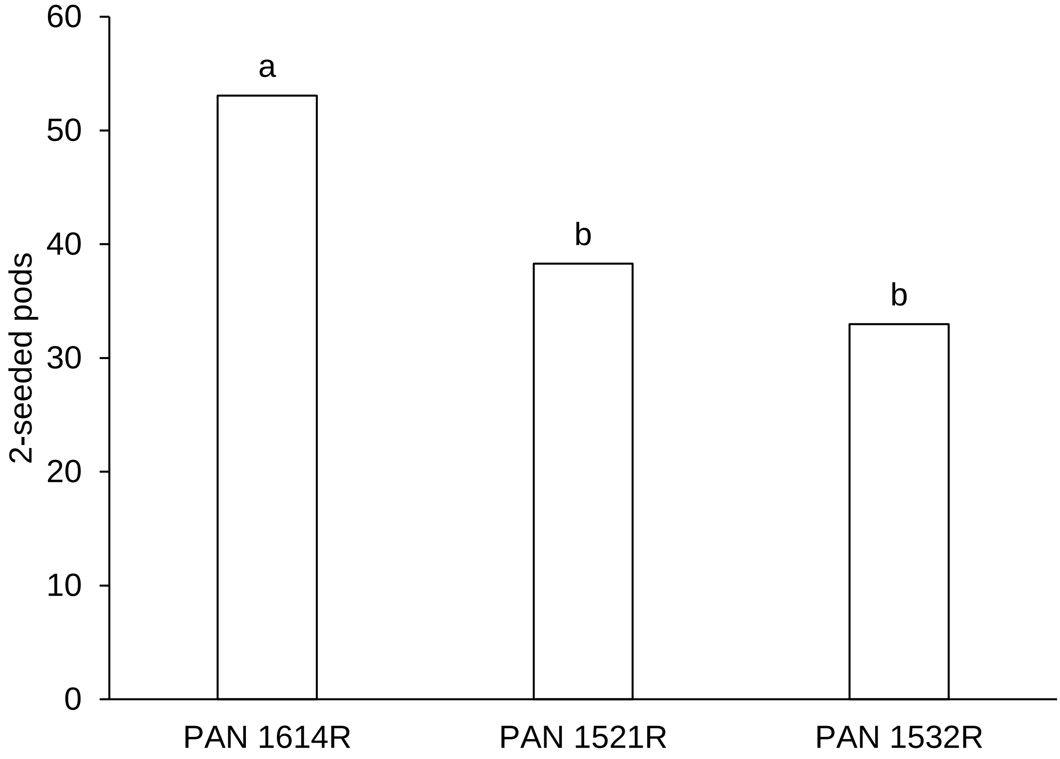


Figure 13: Relationship between soybean yields and 3-seeded pods on a soybean cropping system



Bars with same letter are not significantly different at 5% probability level.

Figure 14: Effects of cultivar on 2-seeded pods on a soybean cropping system

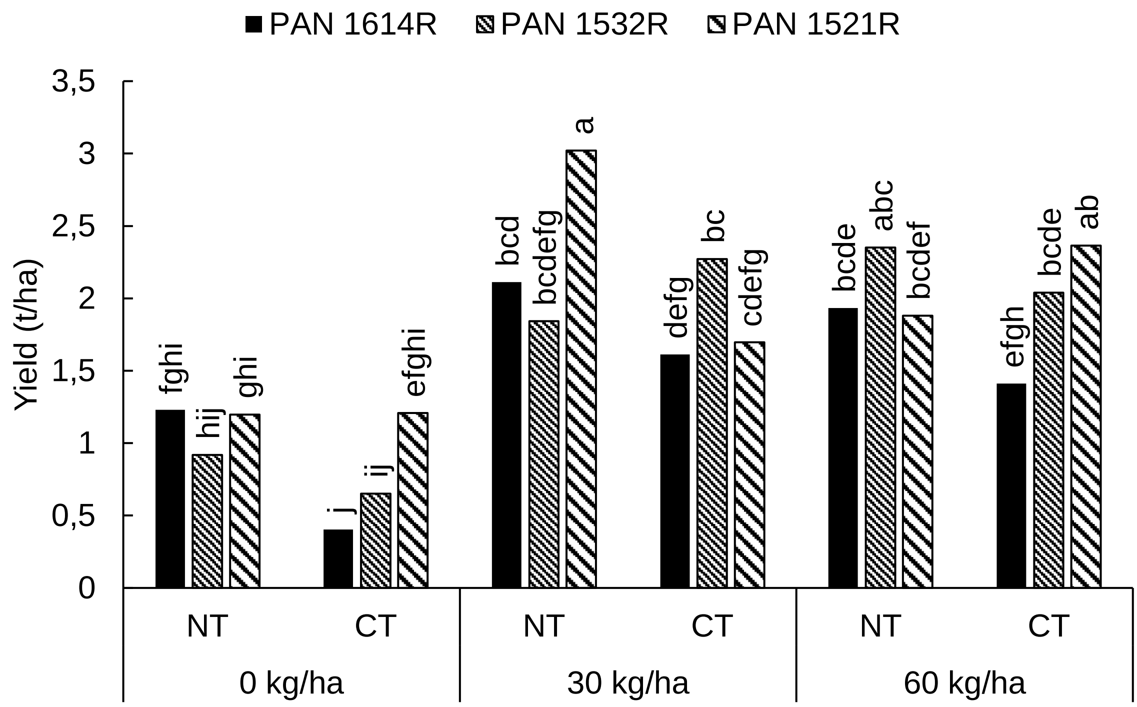
4.1.6. Effects of fertilizer, tillage and cultivar on soybean yield

There were statistically significant interactions between P application rate, cultivar and tillage on soybean yield (Table 12). Yield was highest at 30 kg/ha P application under NT for PAN 1521R, however it was statistically at par with PAN 1532R under NT and PAN 1521R under CT at 60kg/ha P (Figure 15). The findings are in agreement with Abbasi et al. (2012), who reported yield increases of up to 53% with increased P application. Aulakh et al. (2003), observed increasing seed yield following P rates of up to 80 kg/ha, however, yield at 80 kg/ha P was statistically similar to 100 kg/ha P on irrigated soybean. This is because Phosphorus fertilizer improves yields and better grain quality (Mabapa et al. 2010; Malik et al. 2006). This is shown by positive relationship (P <0.0001, R^2 = 0.93) between soybean yield and plant P uptake (Figure 16). Nonetheless, the statistically similar yield performance of PAN 1521R at 30 kg/ha

P under NT, PAN 1532R at 60 kg/ha P under NT and PAN 1521R at 60 kg/ha P under CT could be because crops usually take up to 25% of the applied phosphorus in the soil (Roberts et al. 2015). Therefore, adding more fertilizer only raises the soil's P balance and causes luxury consumption (Havlin et al. 2005). A statistically similar soybean yield between 90 and 120 kg/ha was also noted by P Malik et al. (2006).

Table 12: Analysis of variance for the effects of fertilizer, tillage and cultivar on soybean yield

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	0.619551	0.6182	0.4201
Tillage	1	1	1.224407	8.1180	0.0077*
Cultivar	2	2	1.628659	5.3991	0.0097*
Fertilizer	2	2	13.581633	45.0240	<.0001*
Cultivar*Tillage	2	2	1.666609	2.2098	0.1267
Cultivar*Fertilizer	4	4	0.518072	0.8587	0.4995
Tillage*Fertilizer	2	2	0.262371	0.8698	0.4290
Cultivar*Tillage*Fertilizer	4	4	2.623489	4.3485	0.0066*



Bars with same letter are not significantly different at 5% probability level.

Figure 15: Interactive effects of fertilizer, cultivar and tillage on soybean yield on a soybean cropping system

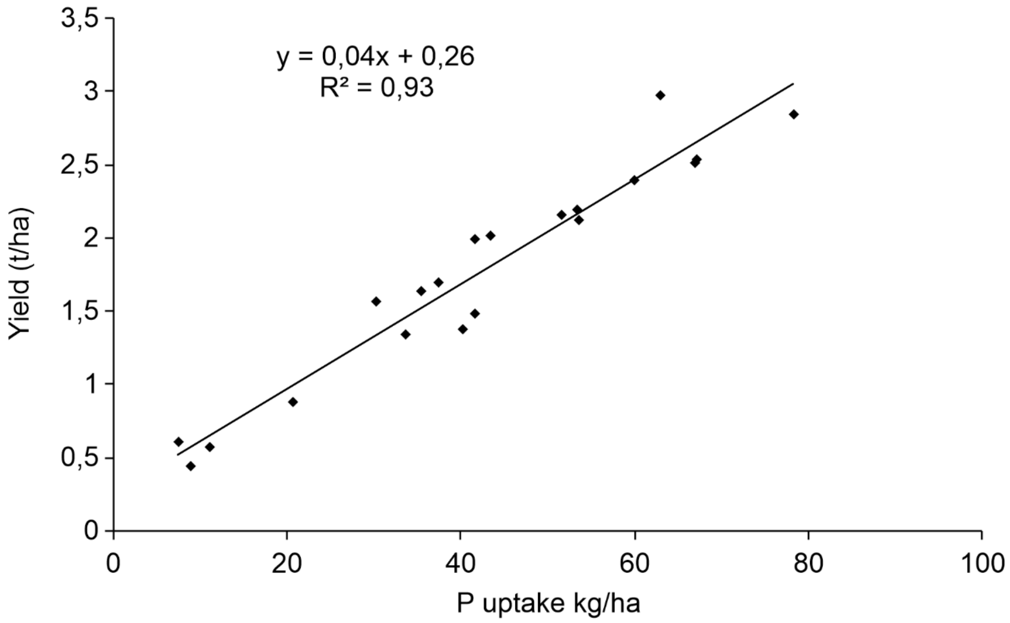


Figure 16: Relationship between soybean yield and P uptake on a soybean cropping system

Buah et al. (2017), noted an increasing yield by up to 54% under NT in 2014 on a study in Ghana. Yield increases under no-till can be attributed to improved nutrient cycling through the P release by crop residues, mineralization of OM by microorganisms (Turan et al. 2017; Zhu et al. 2018), improved infiltration and storage of water, and conservation P by reducing erosion (Busari et al. 2015; Jabro et al. 2011). Yield increases under no-till especially during drier periods were reported (Busari et al. 2015).

Improved yield components ultimately resulted in yield increase. This is supported by a positive relationship between yield and NPP, and 3-seeded pods (Figure 12 and 13), wet biomass (P <0.0001, R^2 = 0.94) and dry biomass (P <0.0001, R^2 = 0.91) (Figure 17 and 18). Furthermore, continuous assimilation of N through nodulation and nitrogen fixation activities is very important in obtaining high soybean yields (Ohyama et al. 2017; Salvagiotti et al. 2008). Research has shown that there is a correlation between assimilated N in plant shoots and yield. In this study, a linear correlation (P = 0.0207; R^2 = 0.92) between plant nitrogen and yield was observed (Fig 19).

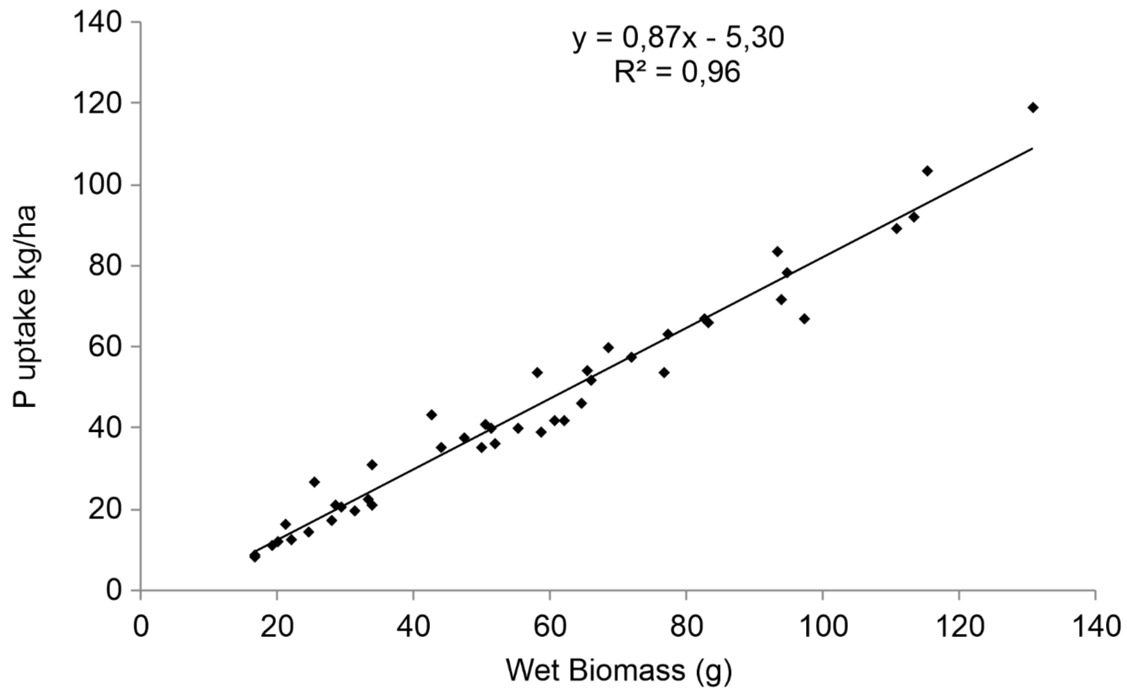


Figure 17: Relationship between soybean yield and wet biomass on a soybean cropping system

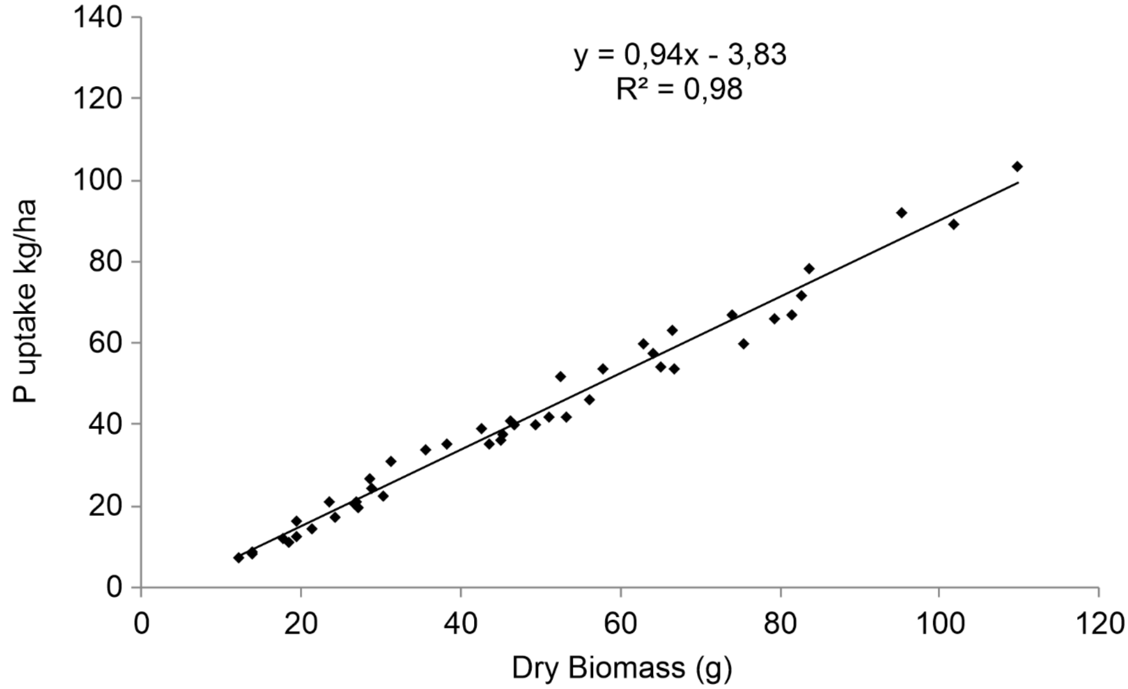


Figure 18: Relationship between soybean yield and dry biomass on a soybean cropping system

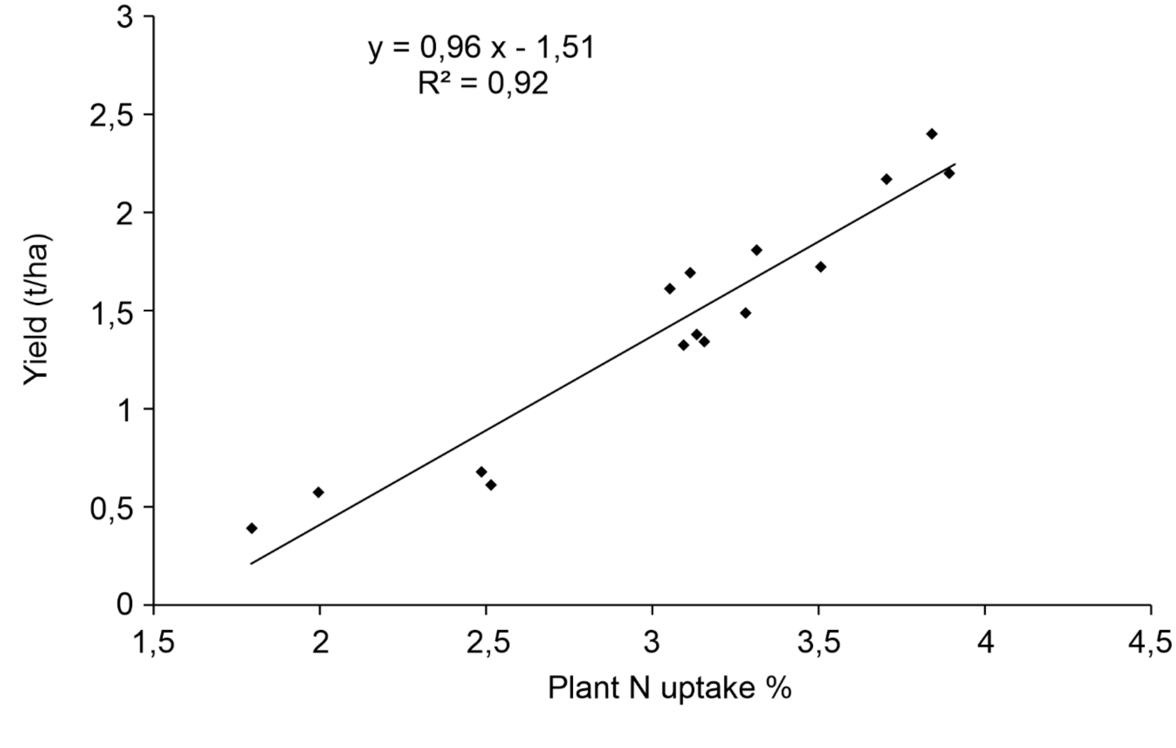


Figure 19: Relationship between Plant N and yield on a soybean cropping system

4.1.7. Effects of fertilizer, tillage and cultivar on soybean protein and oil content

Significant effects ($P < 0.05$) of phosphorus application rate, tillage and cultivar were observed on protein and oil content (Table 13). However, none of the interactions had significant effects. P application at 30 and 60 kg/ha significantly reduced oil content by 11.3% and 7.16% but had inverse effects on protein content increasing it by 0.83% and 1.06%, respectively over control. These results confirm findings by Mokoena (2013) of decreasing oil production with increasing protein content due to P application. Furthermore, protein increase following P application at three rates (60, 90 and 120 kg/ha) was also observed by Abbasi et al. (2012), however the increase at 90 and 120 kg/ha P was not significant. In addition, findings by Yin et al. (2016), of increasing protein content with decreasing oil content following fertilization were also reported. However, the response of oil and protein content to P application have contrasting reports in literature. Some authors have reported a decrease of protein content with no significant difference in oil content following P fertilization (Win et al. 2010), whilst others have reported an increase of both oil and protein content following P application (Abbasi et al. 2012; Malik et al. 2006). As indicated by Yin et al. (2016), when P is deficient in the soil, P additions improve N fixation which enhances seed protein content. Phosphorus is necessary for growth, development, yield and nutritive quality of soybean seed, however, excess applications may depress oil and protein content (Win et al. 2010).

Table 13: Fertilizer application, cultivar and tillage effects on oil and protein content on a soybean cropping system.

Treatment	Oil %	Protein %
Fertilizer		
0	11.42a	34.93b
30	10.51b	35.25a
60	10.03b	35.33a
P value	0.0003	0.0286
Cultivar		
PAN 1614R	11.31a	34.63c
PAN 1521R	10.41b	35.12b
PAN 1532R	10.23b	35.77a
P value	0.0026	<0.0001
Tillage		
NT	10.41a	34.4a
CT	10.89a	34.6a
P value	ns	ns
Interactions (*P* value)		
C x T	ns	ns
C x F	ns	ns
T x F	ns	ns
C x T x F	ns	ns

Levels not connected by same letter are significantly different (P< 0.05; Fisher's test). NT – no-till, CT – conventional tillage, ns - not significant

Significant effects of cultivar were observed on both oil and protein content. PAN 1614R had much higher oil of up to 11.31% as compared to other cultivars, but the same cultivar had the lowest protein content of 34.63%. Contrastingly, PAN 1532R had the lowest oil content of 10.23% and the highest protein content of 35.77%. Nonetheless, correlation between oil and protein content was not significant, and this is supported by Yin et al. (2016). Other factors affecting soybean protein and oil content are genotype and the environment (Yin et al. 2016). The cultivar effect on oil and protein content could be due to 100-seed weight. It was observed that the cultivar with significantly higher 100 seed weight (PAN 1614R) contained significantly high oil and low protein content. Whereas the cultivar with significantly low 100 seed weight (PAN 1532R), the opposite is true. A positive linear relationship between oil and 100 seed weight (P = 0.0458; R^2 = 0.97), and a negative linear relationship between 100-seed weight and protein (P = 0.002; R^2 = 0.94) support these findings (Figure 20 and 21).

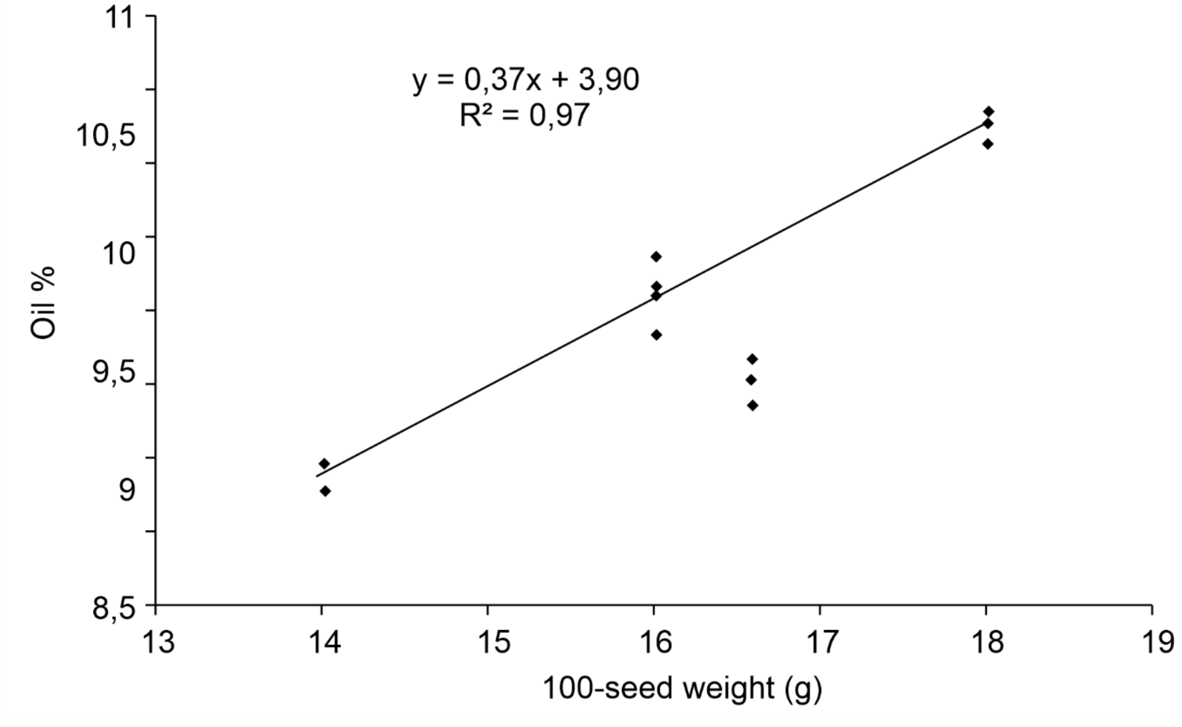


Figure 20: Relationship between 100 seed weight and oil content on a soybean cropping system

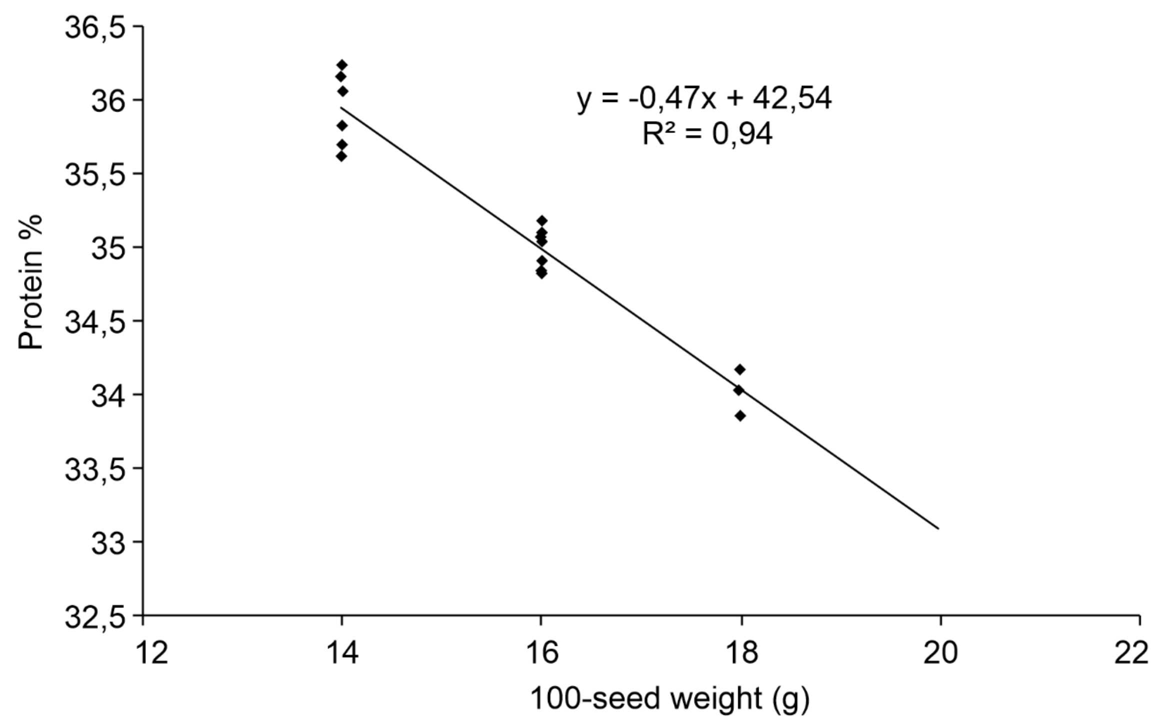


Figure 21: Relationship between protein content and 100-seed weight on a soybean cropping system.

4.2. Effects of fertilizer, tillage and cultivar on plant nutrient uptake (NPK), P utilization efficiency and partial factor productivity

4.2.1. Effects of fertilizer, tillage and cultivar on plant nutrient uptake (NPK)

Significant effects (P <0.05) of fertilizer application were observed on plant NPK uptake (Table 14). No other treatments nor their interactions were observed. Nitrogen uptake increased significantly with increasing rate of fertilizer such that Nitrogen uptake in the fertilized plots was up to 22.72% and 36.68% at 30 and 60 kg/ha respectively over control. Contrastingly, P and K uptake was highest at 60 kg/ha, although the uptake was statistically similar to 30 kg/ha P rate. Nutrient uptake increase at 30 and 60 kg/ha P was up to 91.48 and 119.75% in the case of P, and 69.06 and 75.05% in the case of K, respectively over control. Application of P improved uptake of other macronutrients significantly. However, excessive application of P did not enhance uptake. Aulakh et al. (2003) reported similar results where P uptake increased by up to 0.56% at 100 kg/ha P rate. However, excessive P did not have agronomic benefits such as increase in yield or biomass nor biomass partitioning to grain. Sharma et al. (2011), observed similar outcomes. Findings of the current study confirmed reports from several researchers who argued that nutrient uptake is correlated with production of biomass (Darwesh et al. 2013; Fageria et al. 2013; Sharma et al. 2011) (Table 15).

Table 14: Effects of fertilizer, cultivar and tillage on plant nutrient uptake (NPK) on a soybean cropping system.

Treatment	%	kg/ha	
Fertilizer (F)	N	P	K
0	0.23c	11.20b	70.62b
30	0.28b	21.45a	119.38a
60	0.31a	24.62a	124.12a
P value	0.026	0.017	0.043
Cultivar (C)			
PAN 1614R	46a	17a	54a
PAN 1521R	49a	14a	38ab
PAN 1632R	46a	15a	33b
P value	ns	ns	0.0483
Tillage (T)			
NT	54a	15a	39a
CT	61a	15a	44a
P value	ns	ns	ns
Interactions (*P* value)			
C x T	ns	ns	ns
C x F	ns	ns	ns
T x F	ns	ns	ns
C x T x F	ns	ns	ns

Levels not connected by same letter are significantly different (P< 0.05; Fisher's test). NT – no-till, CT – conventional tillage, ns - not significant

Table 15: Correlation test on plant nutrient uptake (N,P,K) with wet biomass and dry biomass on a soybean cropping system

	kg/ha			g	
	P	K	N	Wet biomass	Dry biomass
Wet Biomass	0.79	0.81	0.79	1	
P value	<0.0001	<0.0001	<0.0001	<0.0001	
Dry Biomass	0.71	0.73	0.70	0.98	1
	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

4.2.2. Effects of fertilizer, tillage and cultivar on P utilisation efficiency and partial factor productivity

Main treatments and their interactions had no significant effects (P <0.05) on P use efficiency (Table 16). This could be justified by the fact that P uptake at 30 and 60 kg/ha P was statistically similar. Nonetheless, partial factor productivity (PFP) was significantly affected (P <0.05) by P rate which consequently increased it by up to 105.79% at 30 kg/ha over 60 kg/ha P (Table 16). This therefore means P supply at 60 kg/ha rate exceeded the requirement for optimum crop production.

Table 16: Fertilizer effects on P use efficiency and Partial factor productivity on a soybean cropping system.

Fertilizer	P use efficiency	Partial factor productivity
	%	Kg/kg P
0 kg/ha	-	-
30 kg/ha	19.76a	68.46a
60 kg/ha	15.82a	33.26b
P value	ns	<.0001

Levels not connected by same letter are significantly different (*P* < 0.05; Fisher's test). ns - not significant

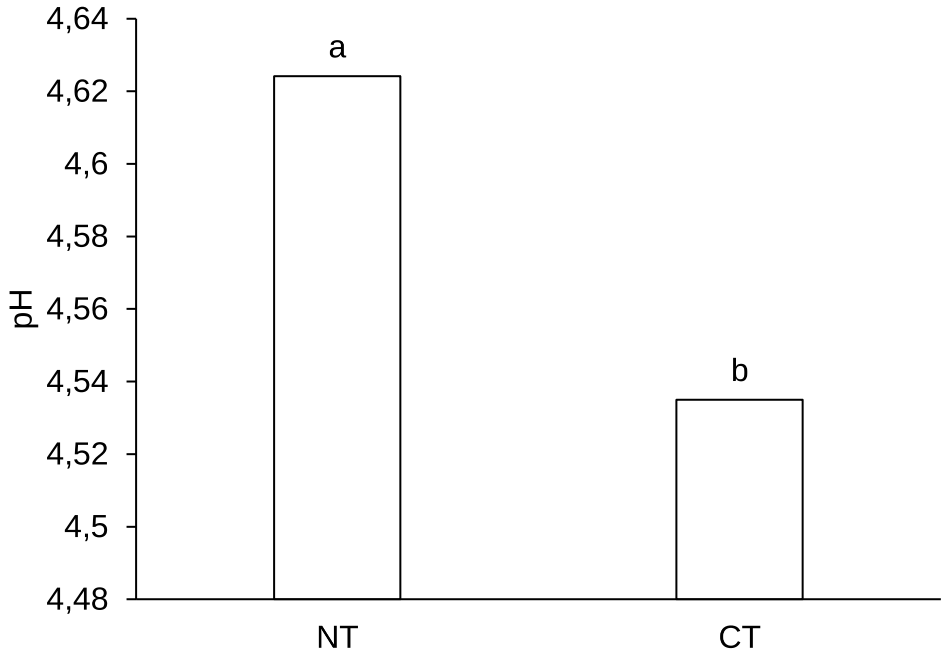
4.3. Effects of fertilizer, tillage and cultivar on selected soil chemical and physical parameters

4.3.1. Effects of fertilizer, tillage and cultivar on soil pH

Significant effects (P <0.05) of tillage were observed on pH (Table 17), however fertilizer and cultivar did not have any significant effects. There were also no interactions of main factors observed. No-till led to the increase of pH by up to 1.76% over CT with values of 4.62 under NT and 4.52 under CT (Figure 22). This could be a result of the increase of Ca and Mg in soil solution through organic matter mineralization under NT (Sithole et al. 2016).

Table 17: Analysis of variance for the effects of fertilizer, tillage and cultivar on soil pH

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	0.06266809	1.9621	0.1576
Tillage	1	1	0.09896346	6.1971	0.0184*
Cultivar	2	2	0.02716068	0.8504	0.4370
Fertilizer	2	2	0.06729696	2.1071	0.1387
Cultivar*Tillage	2	2	0.00566127	0.1773	0.8384
Cultivar*Fertilizer	4	4	0.14560950	2.2795	0.0831
Tillage*Fertilizer	2	2	0.00757064	0.2370	0.7904
Cultivar*Tillage*Fertilizer	4	4	0.02453933	0.3842	0.8182



Bars with same letter are not significantly different at 5% probability level.

Figure 22: Effects of tillage on soil pH on soybean cropping system

The above results are further supported by a positive correlation between pH and both exchangeable Mg (*P* = 0.008; R^2 = 0.81) and Ca (*P* <0.0001; R^2 = 0.86) (Figure 23 and 24). Furthermore, Busari et al. (2015), noted that increasing tillage disturbance decreases soil surface pH.

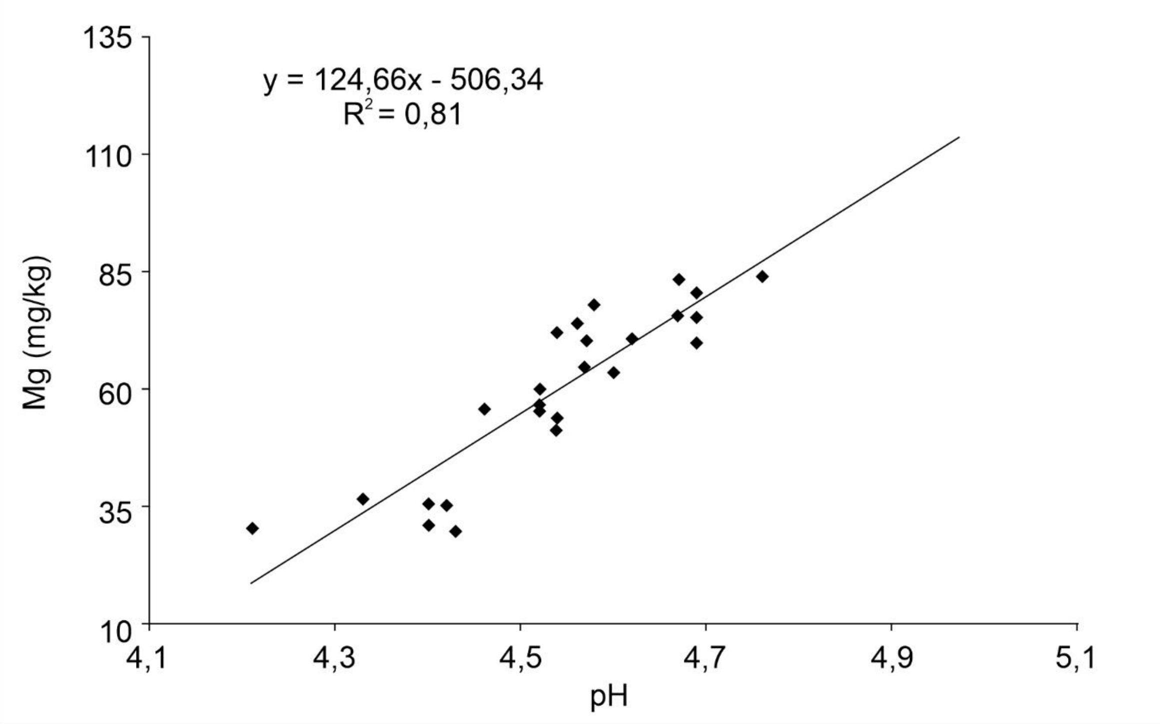


Figure 23: Relationship between Mg and pH on soybean cropping system

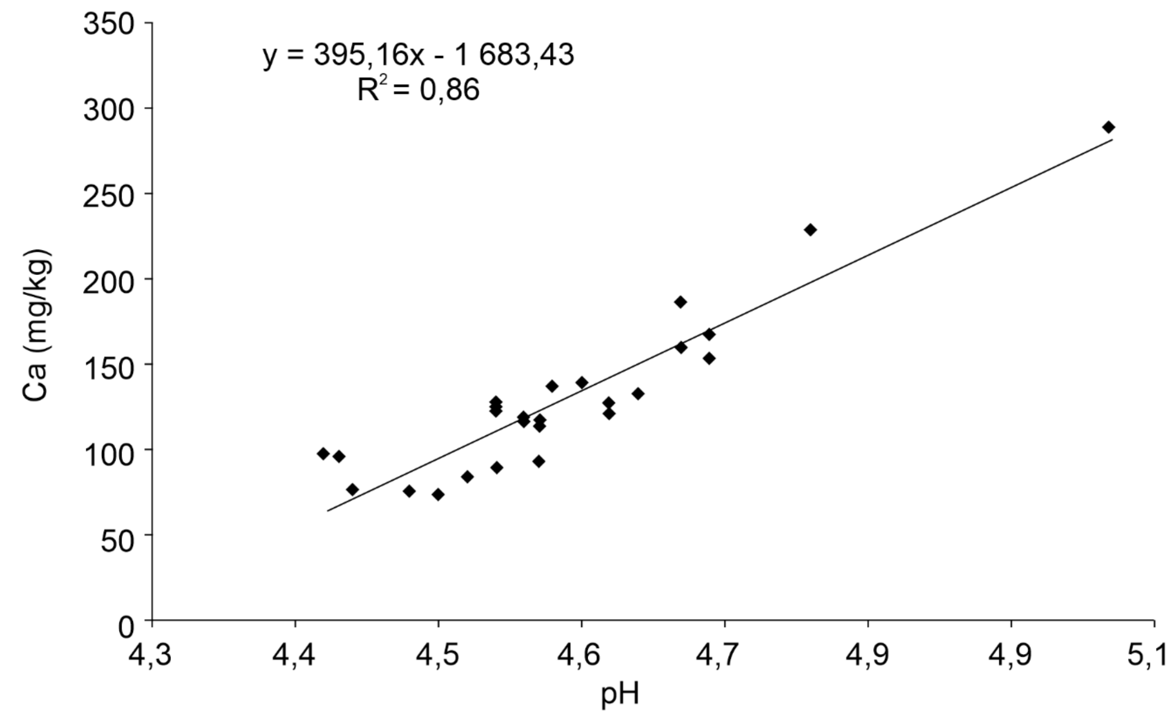


Figure 24: Relationship between Ca and pH on soybean cropping system

4.3.2. Effects of fertilizer, tillage and cultivar on exchangeable Ca and Mg

Fertilizer treatments and tillage significantly affected (P <0.05) exchangeable Ca and Mg (Table 6). However, neither cultivar nor interactions of main treatments had significant effect on both these parameters. No-till led to an increase of exchangeable Ca and Mg by up to 20.64 and 23.77% over CT respectively with concentrations of 137.44 and 59 mg/kg under no-till. Fertilizer application at 30 kg/ha P also led to a significant increase of both Ca and Mg by up to 47.4 and 31.94% over CT. Concentrations of Ca and Mg on 30 kg/ha P were 164.2 and 66.34 mg/kg. According to Busari et al. (2015), CT shifts top fertile soils into the sub-soil, and the less fertile sub-soils onto the surface. Moreover, due to a loose soil structure under CT, loss of nutrients through erosion is also a possibility. Sithole et al. (2016), attributed the increase of Ca and Mg under no-till to higher organic matter accumulation, which through decomposition, releases nutrients back into the soil. Results obtained on the current study support findings of Małecka et al. (2012) who also observed increasing Mg due to nutrient cycling under NT. Application of 30 kg/ha P significantly (P <0.05) increased both exchangeable Ca and Mg by up to 61.87% and 52.91% respectively over control. Nonetheless, application of P at 30 kg/ha led to higher Ca and Mg than observed after applying 60 kg/ha P.

Table 18: Fertilizer, cultivar and tillage effects on exchangeable Ca and Mg on a soybean cropping system

Treatment	Ca (mg/kg)	Mg (mg/kg)
Fertilizer (F)		
0	101.44b	43.39b
30	164.2a	66.34a
60	111.4b	50.28b
P value	<0.0001	<0.0001
Cultivar (C)		
PAN 1614R	118.11a	50.56a
PAN 1521R	125.89a	55.11a
PAN 1632R	118.11a	54.34a
P value	ns	ns
Tillage (T)		
NT	137.44a	59.00a
CT	113.92b	47.67b
P value	0.0081	0,001
Interactions (*P* value)		
C x T	ns	ns
C x F	ns	ns
T x F	ns	ns
C x T x F	ns	ns

Levels not connected by same letter are significantly different (P< 0.05; Fisher's test). NT - no-till, CT - conventional tillage, ns - non significant

It is generally agreed that cations such as Ca and Mg are usually low in strongly acidic soils (Fageria, 2005). The increase of Ca and Mg at 30 kg/ha P could be because of lower Fe concentration in soil solution and vice versa at 60 kg/ha P application (Table 19). Suresh (2005) in a review on characteristics of soils prone to Fe toxicity and management reported that, as Fe concentration increased in the soil, the cations were displaced from exchange sites. Results of the current study are further supported by a significant negative correlation between Fe with both Ca (*P* = 0.0006; $R^2 = 0.84$) and Mg (*P* <0.0001; $R^2 = 0.86$) (Fig 25 and 26).

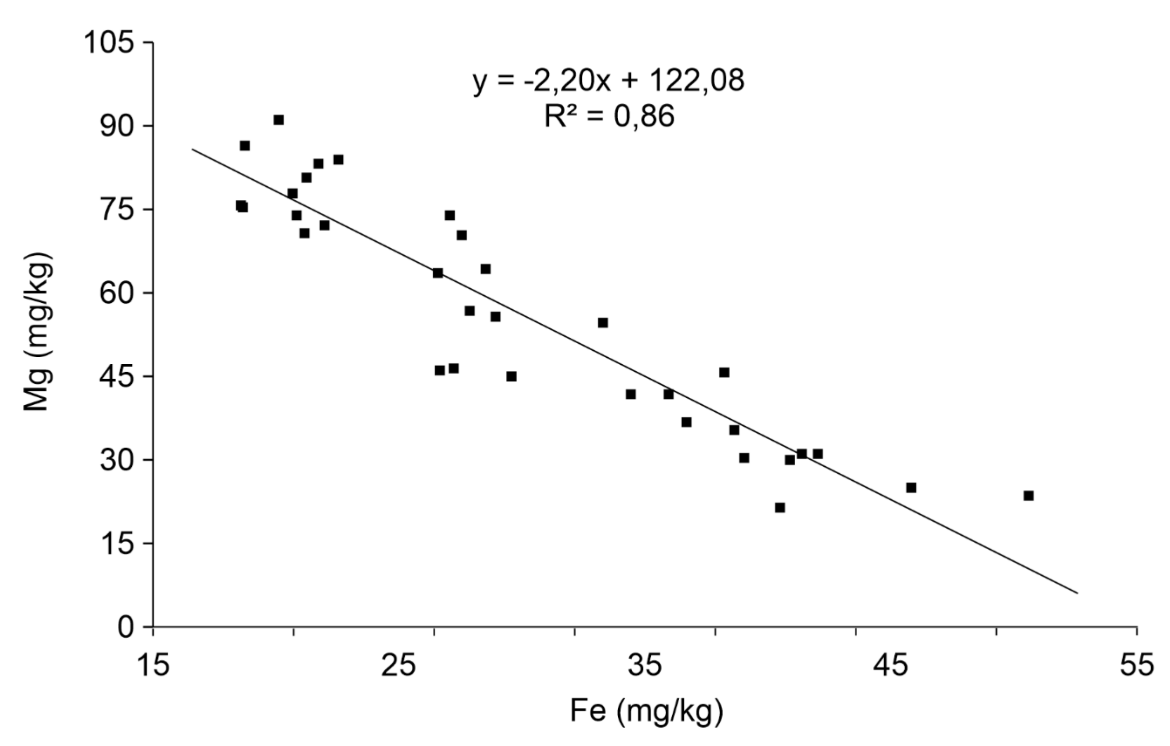


Figure 25: Relationship between Fe and exchangeable Mg on a soybean cropping system

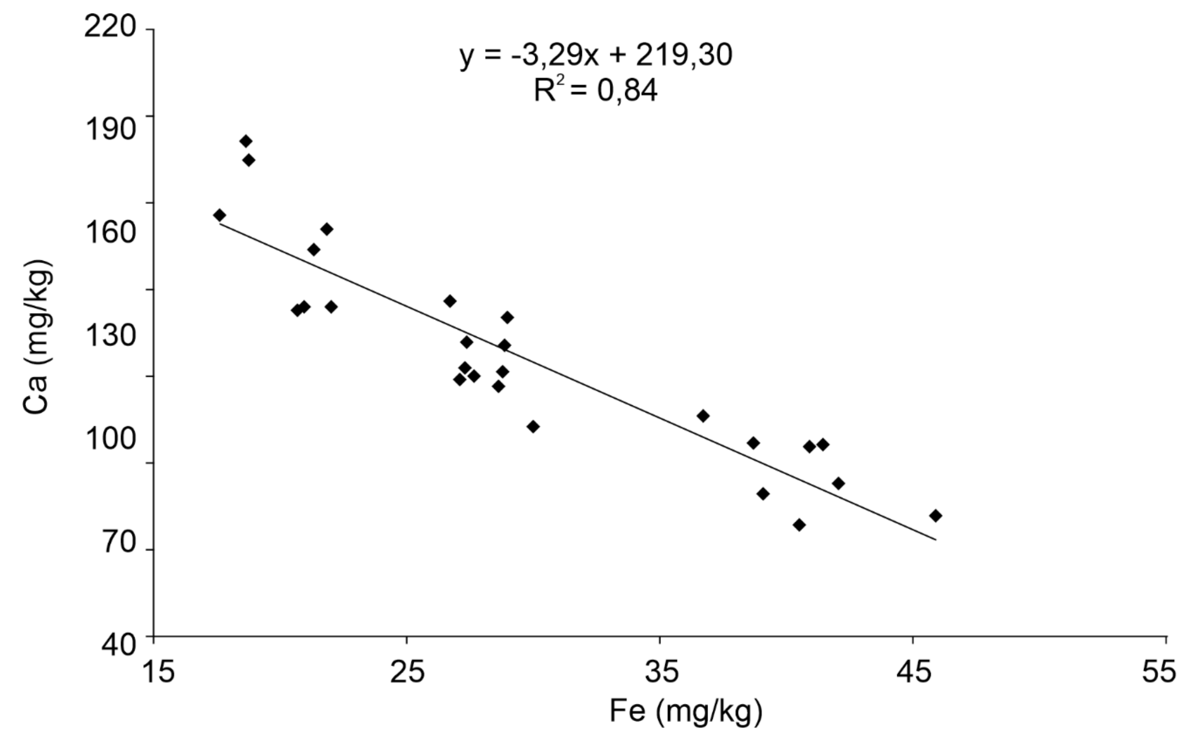


Figure 26: Relationship between Fe and exchangeable Ca on a soybean cropping system

4.3.3. Effects of fertilizer, tillage and cultivar on soil Fe and Al

Amongst the main treatments, only fertilizer rate significantly affected ($P < 0.05$) Fe concentration (Table 19). Phosphorus applied at 60 kg/ha significantly increased Fe concentration, whilst no differences were noted between 0 and 60 kg/ha P. Iron and Aluminum, like many metals, are predominantly found in strongly acidic soils such as the experimental site (Armstrong 1999; Lemanowicz et al. 2016). Soil fixation processes could explain the decrease in Fe concentration: Fe/Al oxides fix more than 80% of applied P; this reaction may reduce Fe and P within the soil solution (Armstrong 1999; Zhu et al. 2018). Furthermore, literature has shown that Fe uptake is sensitive to excessive P (Murphy et al.1981); therefore, surplus P may cause inhibition of Fe from plant root uptake, and thus making Fe available at higher concentrations within the soil solution (Fageria 2001; Murphy et al. 1981). No significant effects were observed for Al.

Table 19: Fertilizer, cultivar and tillage effects on Fe and Al on a soybean cropping system

Treatment	Fe mg/kg	Al mg/kg
Fertilizer (F)		
0	31.59a	1.66a
30	24.62b	1.86a
60	30.35a	1.79a
P value	0.0031	ns
Cultivar (C)		
PAN 1614R	27.27a	1.84a
PAN 1521R	29.02a	1.65a
PAN 1632R	30.27a	1.84a
P value	ns	ns
Tillage (T)		
NT	27.8a	1.72a
CT	29.91a	1.83a
P value	ns	ns
Interactions (*P* value)		
C x T	ns	ns
C x F	ns	ns
T x F	ns	ns
C x T x F	ns	ns

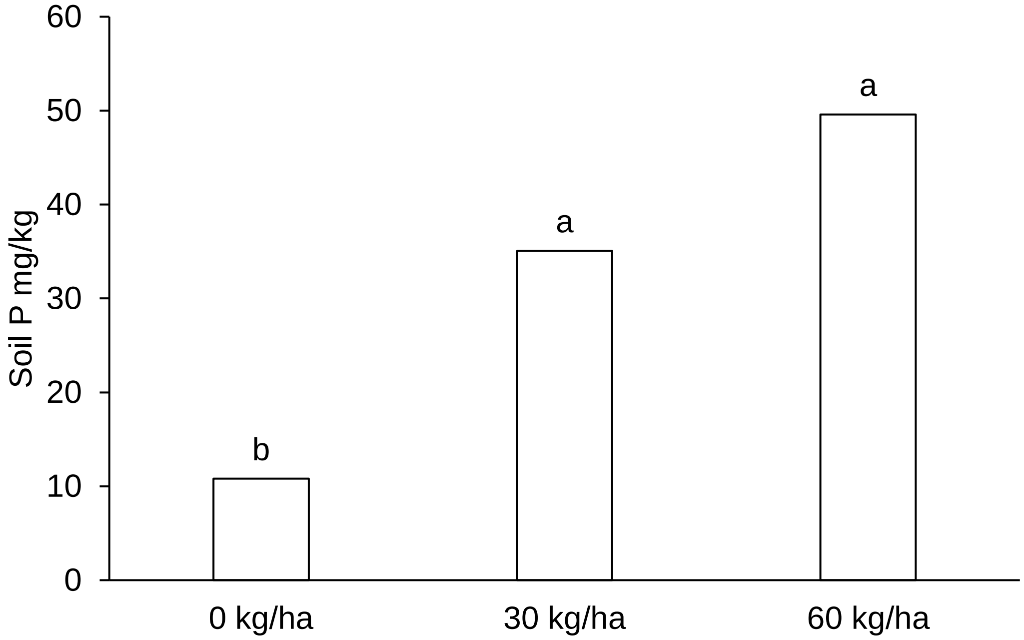
Levels not connected by same letter are significantly different (P< 0.05; Fisher's test). NT - no-till, CT - conventional tillage, ns - not significant

4.3.4. Effects of fertilizer, tillage and cultivar on soil available P

Significant effects (P <0.05) of fertilizer application rate were observed on soil available P (Table 27). Tillage, cultivar and interaction of all main factors did not have significant effects on soil available P. A progressive increase of available P was observed with increasing rate of fertilizer (Figure 27), which indicated that application of fertilizer improved its availability. At 30 and 60 kg/ha application rates, P increase of up to 97.23% and 236.16% respectively over control was recorded. The results are in line with reports from several authors who observed inorganic P increases due to P fertilization (Aniekwe et al. 2014; Reddy et al. 1999; Olander et al. 2000; Yin et al. 2016).

Table 20: Analysis of variance for the effects of fertilizer, tillage and cultivar on soil available P

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	1761.426	1.4215	0.2566
Tillage	1	1	161.994	0.2615	0.6127
Cultivar	2	2	472.139	0.3810	0.6863
Fertilizer	2	2	12653.697	10.2120	0.0004*
Cultivar*Tillage	2	2	239.804	0.1935	0.8250
Cultivar*Fertilizer	4	4	2137.740	0.8626	0.4972
Tillage*Fertilizer	2	2	485.308	0.3917	0.6792
Cultivar*Tillage*Fertilizer	4	4	1392.792	0.5620	0.6919



Bars with same letter are not significantly different at 5% probability level.

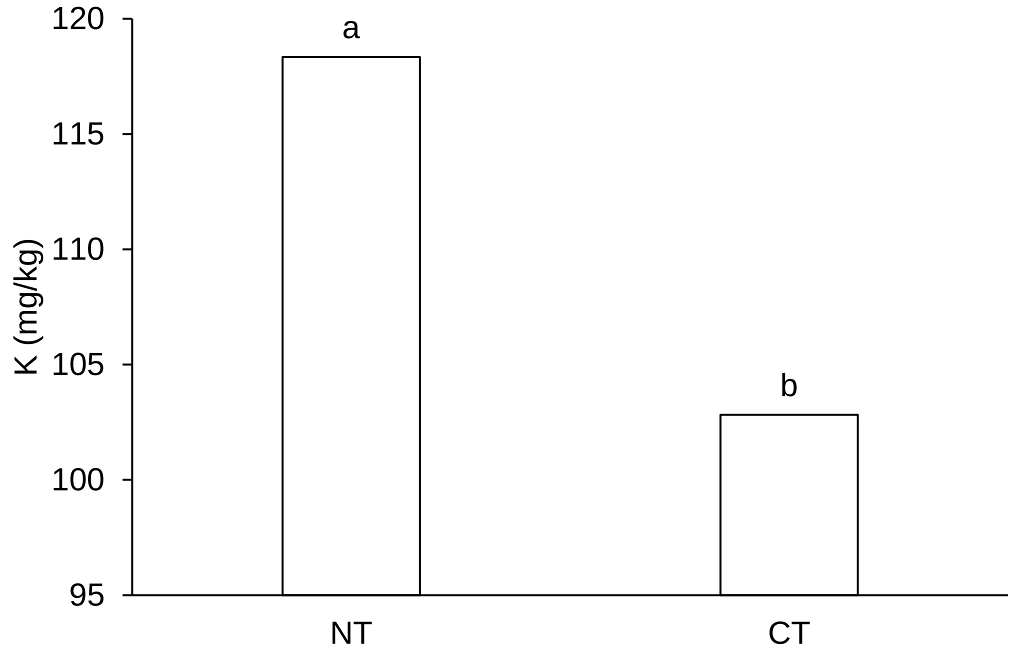
Figure 27: Soil P response to fertilizer application on a soybean cropping system

4.3.5. Effects of fertilizer, tillage and cultivar on soil K

Potassium was significantly affected (P <0.01) by tillage and P application rate however, cultivar did not have any significant effects (Table 21). Under NT system, K significantly increased by up to 15.08% (Figure 28). Sithole et al. (2016) also reported increase of K under no-till. According to Małecka et al. (2012) the increase of K under no-till was due to nutrient cycling. Fertilizer P application at 30 kg/ha led to an increase in K values by up to 33.12% over the control, however K levels significantly decreased at 60 kg/ha P rate (Figure 29).

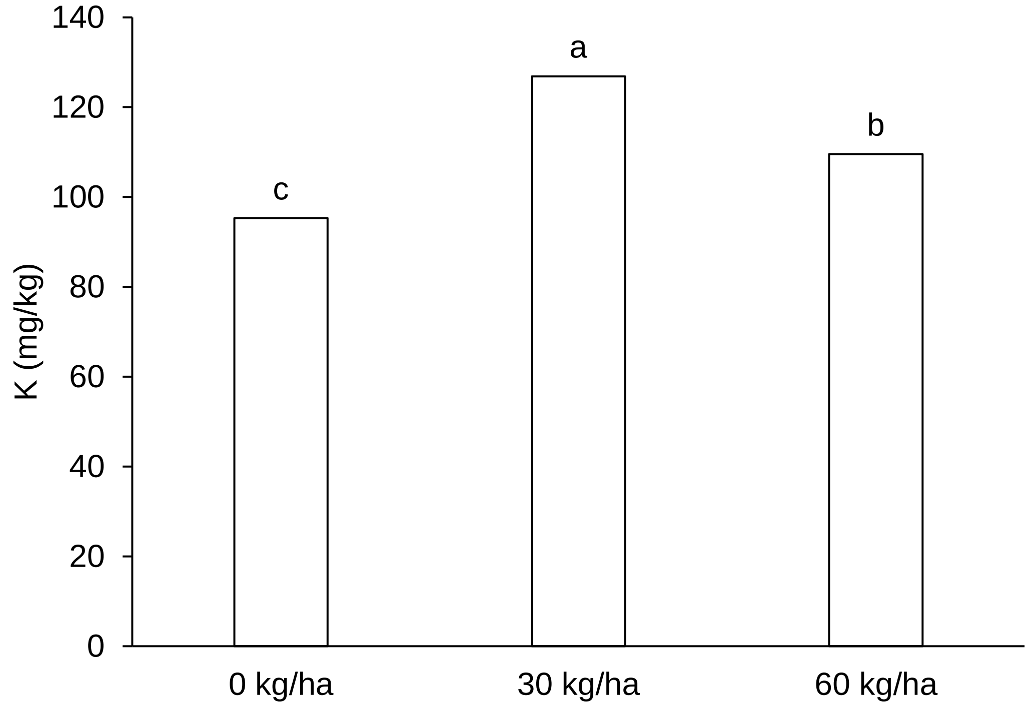
Table 21: Analysis of variance for the effects of fertilizer, tillage and cultivar on soil K

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	1125.0627	1.4878	0.8001
Tillage	1	1	2996.8397	16.0845	0.0004*
Cultivar	2	2	254.6101	0.6833	0.5124
Fertilizer	2	2	8252.0692	22.1451	<.0001*
Cultivar*Tillage	2	2	279.9068	0.7512	0.4802
Cultivar*Fertilizer	4	4	1959.6601	2.6295	0.0532
Tillage*Fertilizer	2	2	200.0582	0.5369	0.5899
Cultivar*Tillage*Fertilizer	4	4	246.7783	0.3311	0.8549



Bars with same letter are not significantly different at 5% probability level.

Figure 28: Effects of tillage on available K on a soybean cropping system



Bars with same letter are not significantly different at 5% probability level.

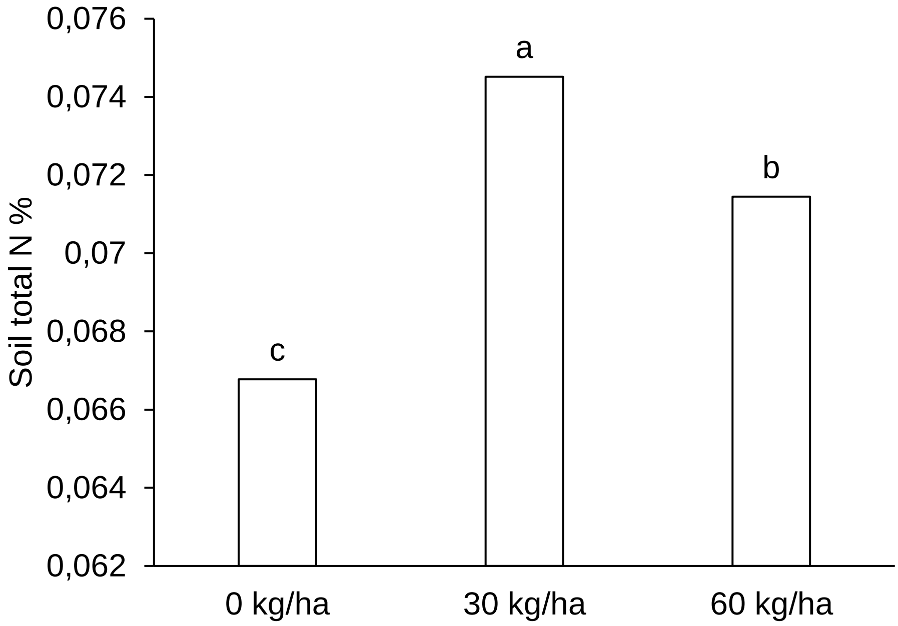
Figure 29: Effects of P application on available K on a soybean cropping system

4.3.6. Effects of fertilizer, tillage and cultivar on total soil N

Significant effects of fertilizer application (P <0.01) were observed on total nitrogen (TN) in the soil, however tillage, cultivar and interaction of main factors were not significant (Table 22). Application P at 30 kg/ha had a positive effect on TN increasing it by up to 11.59%, however, TN decreased significantly under at 60 kg/ha P (Figure 30). Zhang et al. (2015), reported similar findings of TN increasing under mineral fertilizer applications (NPK) at different ratios. Adequate supply of P in the roots of soybean increases root biomass and nodulation, which facilitates nitrogen fixation (Mitran et al. 2018). A decrease in N at 60 kg/ha P may be a result of plant N uptake, which was significantly higher at 60 kg/ha P (Table 11). Kumar Roy et al. (2018), reported decreasing soil N after an increased uptake by soybean. Findings of the current study are supported by a positive linear regression between soil P and plant N uptake (Figure 31).

Table 22: Analysis of variance for the effects of fertilizer, tillage and cultivar on total soil nitrogen

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	0.00012800	2.1574	0.1327
Tillage	1	1	0.00001698	0.5724	0.4550
Cultivar	2	2	0.00009068	1.5284	0.2328
Fertilizer	2	2	0.00023627	3.9820	0.0289*
Cultivar*Tillage	2	2	0.00002236	0.3768	0.6891
Cultivar*Fertilizer	4	4	0.00006350	0.5351	0.7109
Tillage*Fertilizer	2	2	0.00015082	2.5419	0.0950
Cultivar*Tillage*Fertilizer	4	4	0.00011034	0.9299	0.4594



Bars with same letter are not significantly different at 5% probability level.

Figure 30: Effects of P application on soil total N percentage on a soybean cropping system

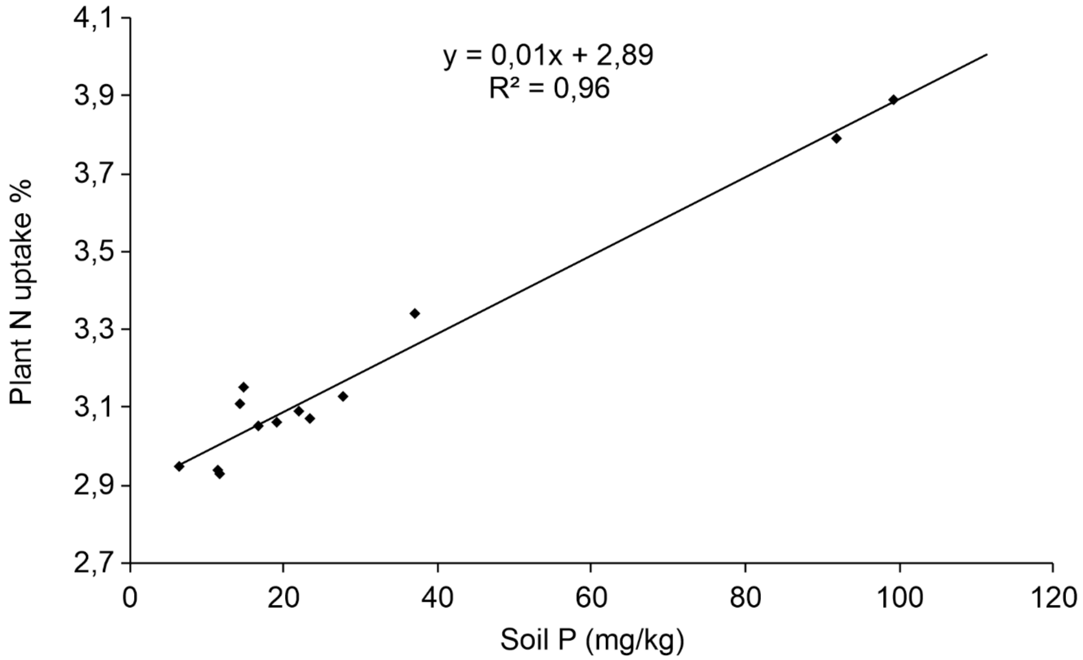


Figure 31: Relationship between plant N uptake and soil P on a soybean cropping system

4.3.7. Effects of fertilizer, tillage and cultivar on total P and total C %

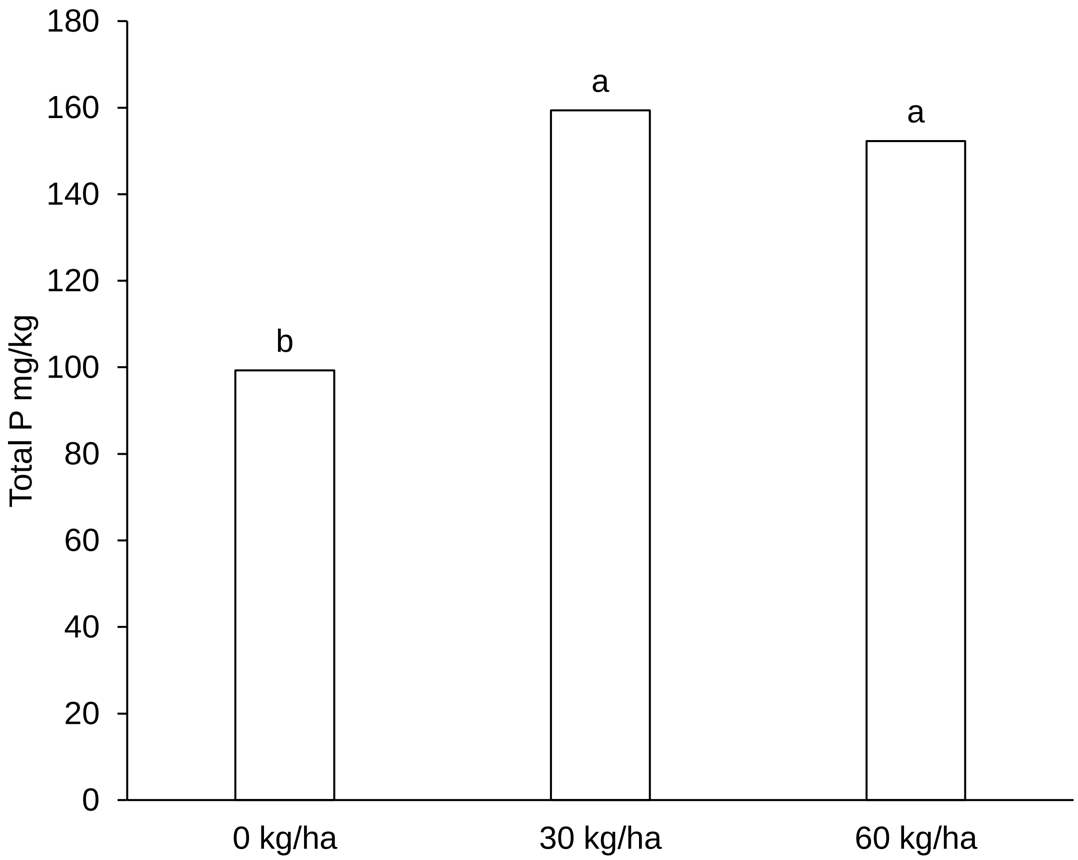
Amongst the main treatments, only P fertilizer rate significantly affected ($P < 0.05$) total P (Table 23). None of the treatments nor their interactions affected total soil carbon (Table 24). Total P increased with P application, nonetheless at 30 and 60 kg/ha P rate it was statistically similar (Figure 32). This could be a result of leaching. Phosphorus losses via erosion, overland flow and leaching are higher when P values are beyond the agronomical rage (Pautler et al. 2000; Wang et al. 2013; Xi et al. 2016). Khan et al. (2018) reported P accumulation at topsoil and P leaching at root zone when surplus P was added. Furthermore, Bai et al. (2013) noted a critical change point of Olsen-P value at 90 mg/kg in acidic soils of Qiyang in China, which if surpassed by increasing P fertilization, increases the risk of leaching. This is because excess additions of P can overwhelm the soil's adsorption capacity which may result in leaching (Djodjic et al. 2004). However, factors such as the desorption potential of soil, the subsoil's capacity of to fix or desorb P, and mechanisms for drainage were observed by Djodjic et al. (2004) as main causes of P-leaching in southern and central Sweden. Thus, in order to determine the rate and extent of phosphorus leaching, several factors have to be considered (Bai et al. 2013; Khan et al. 2018). Although no-till generally increases C sequestration, significant changes are usually observed in 5 – 10 years (Peeyush et al. 2016). The current experiment was only conducted for a short period, therefore there was limited time to observe changes in SOC between the two tillage systems.

Table 23: Analysis of variance for the effects of fertilizer, tillage and cultivar on total soil P

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	1071.823	1.3018	0.3101
Tillage	1	1	437.023	0.5741	0.4540
Cultivar	2	2	837.798	0.5503	0.5820
Fertilizer	2	2	36676.330	24.0899	<.0001*
Cultivar*Tillage	2	2	269.148	0.1768	0.8388
Cultivar*Fertilizer	4	4	3082.516	1.0123	0.4152
Tillage*Fertilizer	2	2	1661.269	1.0912	0.3476
Cultivar*Tillage*Fertilizer	4	4	3260.124	1.0707	0.3867

Table 24: Analysis of variance for the effects of fertilizer, tillage and cultivar on total soil P

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Replication	2	2	0.01669470	0.6467	0.5303
Tillage	1	1	0.00072700	0.0563	0.8139
Cultivar	2	2	0.00127926	0.0496	0.9517
Fertilizer	2	2	0.00009713	0.0038	0.9962
Cultivar*Tillage	2	2	0.00977123	0.3785	0.6878
Cultivar*Fertilizer	4	4	0.02122403	0.4111	0.7993
Tillage*Fertilizer	2	2	0.02713910	1.0513	0.3609
Cultivar*Tillage*Fertilizer	4	4	0.00793853	0.1538	0.9600



Bars with same letter are not significantly different at 5% probability level.

Figure 32: Soil total P response to P application on a soybean cropping system

4.3.8. Effects of fertilizer, tillage and cultivar on bulk density and penetration resistance

Lower penetration resistance (PR) and bulk density (BD) were obtained under NT when compared to CT, but only penetration resistance was affected significantly ($P < 0.05$) (Table 25). None of the other factors nor interactions of main factors had significant results. This is because PR is more sensitive to changes than BD (Moraru et al. 2013). Literature has contrasting reports on PR and BD under no-till. Some studies reported a stable or higher PR and BD on no-till especially at the 0 – 10 cm layer (Jabro et al. 2011; Małecka et al. 2012; Sithole et al. 2016; Villamil et al. 2015), whilst others observed lower values (Małecka et al. 2012; Peeyush et al. 2016). However, data from some long-term studies indicate a shift on bulk density as years' progress. Peeyush et al. (2016) observed higher soil BD under NT within the initial five years of the experiment, however after 10 years a reverse trend was observed. This makes the duration of the experiment an important factor especially for soil physical characteristics. The lower penetration resistance in the current study could be a result of soil moisture retained under crop residues, increased root zone through higher production of biomass, which ultimately improved soil structure under NT (Lampurlanés et al. 2003). The benefit of lower penetration resistance in no-till systems is root elongation , proliferation and plant nutrient uptake (Moraru et al. 2013).

Table 25: Effects of fertilizer cultivar and tillage on bulk density and penetration resistance on a soybean cropping system

Treatment	Bulk density ($g.cm^{-3}$)	Penetration resistance (kpa)
Fertilizer (F)		
0	1.50a	736.17a
30	1.47a	1112.78a
60	1.49a	1066.19a
P value	ns	ns
Cultivar (C)		
PAN 1614R	1.47a	909.89a
PAN 1521R	1.50a	1092.22a
PAN 1532R	1.48a	913.04a
P value	ns	ns
Tillage (T)		
NT	1.47a	693.64b
CT	1.50a	1249.79a
P value	ns	0.0017
Interactions (*P* value)		
C x T	ns	ns
C x F	ns	ns
T x F	ns	ns
C x T x F	ns	ns

Levels not connected by same letter are significantly different (P< 0.05; Fisher's test). NT – no-till, CT – conventional tillage, ns - not significant

4.4. Effects of fertilizer, tillage and cultivar on acid and alkaline phosphatases

Measurements for soil enzyme activities were recorded during three growth stages of soybean i.e. vegetative, reproductive and maturity. Out of the three main treatments, only tillage and P application significantly affected (P <0.05) soil enzymes activities. No interactions of treatments were observed (Table 26). The activities of ACP were generally higher than ALK during vegetative and reproductive stages. Acid phosphatase activities significantly increased by up to 36% at reproductive stage under no-till as compared to CT (Table 26). However, at vegetative and maturity stages tillage did not have any significant effects. Alkaline phosphatase was not affected by tillage during vegetative, reproductive and maturity stages. Phosphorus application at 30 kg/ha caused a significant increase of ACP activities by 48.93, 59.59 and 151.99% at vegetative, reproductive and maturity stage respectively over control (Table 26). The activities of ALP also significantly increased by up to 251.13% and 76.81% over control during reproductive and maturity stage respectively after adding of mineral fertilizer P at 30 kg/ha. However, phosphorus fertilizer application at 60 kg/ha decreased activities of ACP at vegetative and reproductive stages, whereas for ALP, a decrease was only at maturity. This effect however, was statistically not significant for both ACP and ALP.

The increased activities of ACP over ALP was due to the strongly acidic pH of < 5 of the experimental site. This is because acid phosphatase are usually the dominant group of enzymes involved in mineralizing P in acidic soils whilst alkaline phosphatase enzymes are dominant in alkaline soils (Olander et al. 2000). The increase of both ACP and ALP under no-till could be as a result of a more conducive environment for microbial growth due to increased soil moisture and improved soil structure (Sithole et al. 2016; Wei et al. 2014). Results of the current study are similar to findings of a study conducted at Kurdistan University. The authors of the afore mentioned study also reported a significant increase on the activities of both ACP and ALP under no-till, and they concluded that no-till is effective in improving soil enzyme activities in the short-term (Heidari et al. 2016). Sithole et al. (2016), stated that the increase in soil enzymes activities under no-till could be a results of the increase in stratification of enzymes close to the soil surface due to increased soil organic matter under no-till. Balota et al. (2004) also observed an increase of ACP and ALP up to 46 and 61% at top soil layer under no-till respectively.

Table 26: Fertilizer, cultivar and tillage effects on acid and alkaline phosphatase activities on a soybean cropping system

	p-nitrophenol mg/kg/h					
	Vegetative		Reproductive		Maturity	
Treatment	ACP	ALP	ACP	ALP	ACP	ALP
Fertilizer (F)						
0	2164.5b	219.88a	1656.45b	64.58b	2297.03b	169.49b
30	3223a	369.08a	2643.75a	226.76a	5788.20a	299.68a
60	2009.1b	242.52a	1518.98b	84.97b	2873.77b	159.47b
P value	0.0081	ns	0.0019	0.0265	<0.0001	0.0485
Cultivar (C)						
PAN 1614R	2455.77a	245.74a	1930.70a	104.88a	104.88a	220.09a
PAN 1521R	2353.38a	292.65a	2086.25a	114.88a	114.88a	182.05a
PAN 1532R	2587.47a	293.09a	1802.24a	156.55a	156.55a	226.50a
P value	ns	ns	ns	ns	ns	ns
Tillage (T)						
NT	2743.67a	240.11a	2235.62a	131.19a	4130.94a	234.46a
CT	2187.42a	314.21a	1643.83b	119.69a	3175.06a	184.63a
P value	ns	ns	0.0262	ns	ns	ns
Interactions (*P* value)						
C x T	ns	ns	ns	ns	ns	ns
C x F	ns	ns	ns	ns	ns	ns
T x F	ns	ns	ns	ns	ns	ns
C x T x F	ns	ns	ns	ns	ns	ns

Levels not connected by same letter are significantly different ($P < 0.05$; Fisher's test). ns - no significance, NT - no-till, CT - conventional tillage, ACP - Acid phosphatase, ALP - Alkaline phosphatase, ns - not significant

Activities of phosphatase at 60 kg/ha P could have been inhibited by an increase of inorganic phosphorus in the soil because more often, phosphatases activities are inversely proportional to available soil P concentration (Lemanowicz et al. 2016; Wang et al. 2013). Heidari et al. (2016) and Rakshit et al. (2016) also reported a suppression of phosphatase activities due to fertilization. Findings of Olander et al. (2000), on a 4-year study also show that P significantly decreased phosphatase activity following fertilization. However, when P was combined with N fertilizer the activities of phosphatase were stimulated. In the current study, a negative relationship between P with ACP and ALP at the different growth stages supports these findings although these correlations were not significant. Olander et al. (2000) argued that the presence of high levels of inorganic fertilizers does not directly inhibit enzyme activities; rather, it represses their production. This shows that phosphatase activity may be strongly inhibited by a negative feedback mechanism when high enough levels of phosphorus are reached (Olander et al. 2000). This may suggest that P rate up to 30 kg/ha could be the optimum level for high phosphatase activities in the study area because when P was applied at 30 kg/ha, activities of both ACP and ALK at reproductive and maturity stages were improved. Moreover, when P is applied to soils with low organic matter, phosphatase activities get stimulated (Adetunji et al. 2017).

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The first objective was to determine the effects of no-till, cultivar and varying mineral P fertilization levels on soybean growth, yield, grain protein and oil content. Results indicated that P application at 30 kg/ha under no-till increased yield, wet biomass and dry biomass. Phosphorus alone also increased NPP, 3-seeded pods and plant height at 30 kg/ha.

As for soybean grain quality, protein content increased under P application but had inverse effects on oil content. These two qualities also varied according to cultivars. The relationship between 100-seed mass with protein and oil content suggests that cultivars that have low 100-seed weight had better protein content, and those with a higher 100-seed weight produced better oil. Therefore, the choice of cultivars is very crucial for farmers and must be aligned with the objectives of farming, be it for biodiesel or protein feed. Furthermore, cultivars have varying adaptability to different agro ecological zones and as a result, yield differs.

The second objective was to determine the effects of no-till, cultivar and varying mineral P levels on P uptake and P use efficiency in a soybean experiment. Nutrient uptake increase when P was applied shows the importance of P and the need for its conservation in soybean production Phosphorus utilization efficiency calculated using the balance method did not differ statistically across P rates. Nonetheless, the PFP was significantly higher at the lowest rate of fertilizer. This implies that farmers should apply fertilizers at standard rates, as excess P is agronomically inefficient.

The third objective was to determine different levels of mineral P fertilizer and tillage on selected soil chemical and physical parameters. The results indicate that application of mineral P fertilizer improved the soil's nutrients status by raising the soil's pH and also concentrations of Ca, Mg, N, P, K and total P whilst reducing Fe which is one of the main causes of soil acidity. The results also indicate that none of the treatments affected bulk density. However, tillage affected penetration resistance. This confirms studies that indicate that penetration resistance responds very quickly to change. No-till also led to an increase in concentrations of soil extractable K. The increase of pH with increasing exchangeable Ca and Mg under no-till supports the theory of nutrient cycling under no-till and suggest that this system could be a viable option of managing acidity considering that accessibility of lime to smallholder farmers in South Africa is a big challenge. However, this cannot match the benefits of lime application.

The last objective was to determine the relationship between acid and alkaline phosphatases, soil properties and management practices. Results indicated that ACP activities, being the dominant enzyme in acidic soils, significantly increased following P application at 30 kg/ha across all growth stages, whereas for ALP the increase was only observed at reproductive and maturity stage. Excessive application of P did not improve activities of both ACP and ALP. Furthermore, the activities of both phosphatases increased under no-till at all growth stages, although only ACP at reproductive stage was significant. Phosphatase enzymes are very crucial especially in soybean production because of their role in solubilizing organic P.

5.2. Recommendations

- The use of mineral fertilizers in P deficient soils such as in smallholder farming environments is crucial to avoid yield losses.
- It is also recommended that farmers use high yield potential cultivars for their area.

- Improving efficiency would require studying different soil P pools on a much deeper level, as well as developing appropriate chemical methods for analysis, especially for the less available P pools due to their low extractability.
- Adaptation of no-till with retention of organic matter would improve soil's chemical, physical and microbial properties, which translate to better yields. Therefore, no-till is strongly recommended for soybean production because it produces a conducive environment for microorganisms.

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