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No-till improves selected soil properties, phosphorous availability and utilization efficiency, and soybean yield on some smallholder farms in South Africa

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Some of the limiting factors for smallholder farmer soybean production in South Africa are 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 P fertilization levels on P uptake and P use efficiency, as well as plant growth, yield, grain protein and oil content, in a soybean based 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 × 3 × 3 strip-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 three phosphorus rates (0, 30, and 60 kg/ha). All treatment combinations were replicated three times. P uptake improved with P application, although there were no differences between 30 and 60 kg/ha whilst PFP was significantly higher at 30 kg/ha P. Yield was significantly higher at 30 kg/ha P application under NT and varied with cultivars. 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) also increased with P application. Improvement of soybean yield and its attributes, grain quality, P uptake, PFP, soil physicochemical and microbial properties emphasize the importance of fertilizer application, sustainable cropping systems coupled with careful cultivar selection. Therefore, in order to improve soil fertility and soybean yield under small farm conditions, the application of no-till and optimum application of fertilizers should be prioritized.

KEYWORDS

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

Introduction

A major limiting factor for soybean production in South Africa is low soil phosphorus (P) availability together with inefficient utilization of added P (Mabapa et al., 2010; Roberts and Johnston, 2015). Compounding this are the risks of crop failure posed by climate change (Mall et al., 2017; Mohanty et al., 2017). Despite these challenges, soybean is the world's most traded oil seed and has the potential of being Africa's Cinderella crop (Kolawole, 2012; Lee et al., 2016). The demand for soybean is very high and increasing with the increasing population (Dlamini et al., 2013; Phiri et al., 2016; Ronner et al., 2016), however, yield is still fixed at an average of 1.1 t/ha for decades (Khojely et al., 2018). In South Africa, soybean is one of the country'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). The area under soybean production has relatively increased to about 800,000 ha since 1903 when the crop was initially introduced to South Africa (Khojely et al., 2018; DALRRD, 2020), however, average yields are still lower than experimental yields due to drier climate and low fertility soils (Phiri et al., 2016; Ronner et al., 2016; Sithole et al., 2016). For optimal yields, soybean requires between 15 and 18 mg/kg P in the soil (FERTASA, 2016). However, most soils in smallholder farming areas in South Africa are low in available P, averaging <10 mg/kg Bray 1 (Nziguheba et al., 2016).

Phosphorus is the most crucial nutrient for soybean due to its fundamental role in root establishment, grain formation and enhancement of vegetative growth (Chien et al., 2011; Shen et al., 2011). It also regulates various enzymatic activities, required for energy intensive processes in root nodule and N-fixation (van de Wiel et al., 2016; Liu et al., 2018; Mitran et al., 2018). Phosphorus also promotes higher yield and better grain quality (Mokoena, 2013). Significant positive correlations between the crop's P uptake and seed yield on soybean has been reported (Abbasi et al., 2010). According to Zheng et al. (2010), phosphorus availability could also improve root morphology even when water deficiencies occurred at reproductive stage. Phosphorus also improves plant biomass and increases P utilization efficiency (Abbasi et al., 2010). Therefore, enhancing P utilization efficiency is vital in improving crop yields and reducing eutrophication risks (Hasan et al., 2016; Heuer et al., 2017). However, the utilization efficiency is affected by factors such as, P availability, P fertilization rate and seed genotype (Syers et al., 2008; Mitran et al., 2018). A research report by Dalshad et al. (2013) from an experiment conducted at the University of Salahaddin/Erbil in Iraq, showed increased P plant uptake by 99–280.49% on various soybean cultivars after application of superphosphate at 75 kg/ha. Furthermore, one of the cultivars used, cultivar 44NK, 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. Abbasi et al. (2010) after observing an increased P uptake with soybean, also noted that as P rates increased P-use efficiency decreased, and therefore concluded that the low recovery efficiency could be a result of high P fixation rate by Ca compounds or Fe/Al oxides.

Fixation of P is a common challenge in many agricultural soils (Shanker and Shailendra, 2014). Although phosphorus may be abundant in many soils with a range of 100–2,000 mg/kg soil, representing nearly 350–7,000 kg/ha P in the top 25 cm layer of soil (depending on parent material, soil texture, vegetation cover and soil management history), ∼50% of the world's productive lands are deficient in P (Grant et al., 2005; Owen et al., 2015; Heuer et al., 2017). Furthermore, about 30% of global soils have a high P-fixation capacity (van de Wiel et al., 2016; Menezes-Blackburn et al., 2018). Consequently, even when phosphorus is available in large quantities in the soil, ∼80% is unavailable to the plant immediately after application (Roberts and Johnston, 2015; Zhu et al., 2018), because <0.1 % is in orthophosphate form, which plants can easily uptake (Raliya et al., 2016; Garland et al., 2018). Recent studies, however, do not support the general perception of fixation of all soil residual phosphorus (Roberts and Johnston, 2015; Zhu et al., 2018; Yan et al., 2020). Syers et al. (2008) proposed that inorganic phosphorus in the soil moves through four different P pools that vary in availability. The four main pools are (1) P in soil solution, (2) surface absorbed P, (3) strongly bonded or absorbed P, and (4) very strongly bonded or precipitated P. 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. The availability of P depends on the amount accessible to plant roots. Standard laboratory methods such as Bray, Mehlich and Olsen are often used to measure soluble P, which act as indices of available P, however, the extractants do not measure the P transformed in fixed forms.

There are of a number of P activators for improving soil available P. These include phosphate solubilizing microorganisms (PSM's), phosphatase enzymes and enzyme activators (Satyaprakash et al., 2017; Zhu et al., 2018). Acid and alkaline phosphatases are the most abundant enzymes involved in solubilizing organic P compounds. These can be easily detected due to their sensitivity to disturbance (Balota et al., 2004). Phosphatases play a role in mobilizing soil P and reallocating a 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 (Piotrowska-Dlugosz and Wilczewski, 2014). Phosphatases highly correlate with organic matter and some studies reported significantly high activities of Acid Phosphatase (ACP) and Alkaline phosphatase (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, which had zero fertilizer. This further supports that 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. The six treatments were as follows: CK—soil without fertilizer; N1—low N fertilizer; N2—high N fertilizer; N2P—N2 fertilizer and P; N2K—N2 fertilizer and K; N2PK—N2 fertilizer, P and K. 138 kg N/ha and 276 kg N/ha was applied in N1 and N2 treatments, respectively. 39 kg P/ha and 112 kg K/ha was applied in the N2PK treatment. 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.

An intervention being advocated for enhancing soil and water productivity in cultivated areas is no till. This is due to its cost effectiveness, environmental sustainability and efficient in P conservation and cycling (Moraru and Rusu, 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 increases micro-organisms' diversity (Vukicevich et al., 2016) and 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).

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). Furthermore there is limited research on no-till practices and P dynamics especially within smallholder production farms with acidic soils in SA. 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, this study aimed to determine the availability and utilization efficiency of soil P to maximize soybean yields under no-till.

Materials and methods

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 1,537 m in Gert Sibande District Municipality, ∼45 km from Ermelo town. Sheepmoor is described as temperate dry winter and warm summer. Average rainfall is about 756 mm per annum. Minimum temperatures are between 7 and 8°C and maximum temperatures are between 26 and 30°C. Soils of the study site are 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 in 0–30 cm 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. 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%.

Experimental design

A randomized complete block design (RCBD) arranged in a 2 × 3 × 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 (vertical rows), three soybean cultivars (PAN 1532R; PAN 1521R; and PAN 1614R) as sub plots (horizontal rows) and three Phosphorus fertilizer rates (0, 30, and 60 kg/ha) as sub-sub plots (intersection plots) replicated three times 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 of six 7 m long soybean rows with an inter and intra-row spacing of 60 and 5 cm, respectively (gross plots), targeting a population of 300,000 plants per hectare. The net plots consisted of four middle rows of the gross plots. The three soybean cultivars were selected based on performance in a preliminary study conducted by the ARC-SCW at the study site. The use of three soybean was done in order to determine possible differences in growth, productivity and P-use efficiency as influenced by contrasting soybean varieties.

Trial management

After trial demarcation, conventional tillage was done using a tractor-drawn mouldboard plow. Plots demarcated for no-till were treated with N-[phosphono-methyl] glycine, 360 g L-1 (Roundup) at a rate of 4 L per hectare to eradicate weeds; before planting and throughout the season. Weeds were eradicated through direct application using a knapsack sprayer to avoid contact with main crop. 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 at ratios explained on Section Experimental design. Scouting for pests and diseases was done every second week during the growing season, however, no agro chemicals were administered as there were no diseases and harmful pests observed.

Sampling and data collection

Prior to establishment of experiments, three composite soil samples from five sub samples per block were collected randomly at a depth of 0–30 cm in October 2016. Samples were air dried and passed through a 2 mm sieve and then used for initial soil characterization (SSSSA. Non-Affiliated Soil Analysis Work Committee, 1990). To evaluate the effects of treatments on soils, three sub-samples samples were randomly taken per plot with an auger at the 30 cm depth after harvest in July 2018. The following parameters were analyzed: soil solution pH was measured in water at a 1:2.5 soil water ratio as described by Okalebo et al. (2002) using a pH meter. The same suspension was used to measure electrical conductivity (EC) after allowing them to settle for 1 h using an EC meter (SSSSA. Non-Affiliated Soil Analysis Work Committee, 1990). Total N was determined using the dry combustion method using the Flash 2000 CHNS-O Analyzer. Phosphorus was extracted by P-bray 1 solution and analyzed with a flow analyzer, (SSSSA. Non-Affiliated Soil Analysis Work Committee, 1990). K+, Ca2+, Na+, and Mg2+ were extracted with ammonium acetate solution and analyzed with an Induced Coupled Plasma (ICP-OES). Fe was extracted with HCl and analyzed with ICP. Al was determined through titrable acidity method using sodium hydroxide (SSSSA. Non-Affiliated Soil Analysis Work Committee, 1990).

Bulk density was determined using the core method as described by Bonin and Lal (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 oven dried for 24 h at 105°C and then weighed again. Bulk density was then calculated as the ratio of mass of dry soil per unit volume of soil cores. 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. Activities of acid and alkaline phosphatase were evaluated as described by Tabatabai (1994). These enzyme activities were analyzed 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.

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 h at 70°C. 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 DA 7250 NIR analyzer (Perten Instruments, Hägersten, Sweden) 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 the following equation and expressed in tons per hectare:

$$Y\left(t/ha\right) = \frac{100 - moisture\ \%}{100 - 12} \times seedmass$$

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

Plant N was analyzed using the dry oxidation method on a Flash 2000 CHNS-O Analyzer whilst P and K were analyzed following digestion with Nitric + Perchloric acid on an Agilent 725 (700 Series) Inductively Coupled Plasma Optical Emission Spectrometric (ICP-OES).

P use efficiency was calculated using the balance method as follows:

$$P\ use\ efficiency\ (\%) = \frac{P\ taken\ up\ by\ the\ crop\ under\ fertilized\ soil}{amount\ of\ P\ applied} \times 100$$

Partial factor productivity (PFP), which measures the utilization efficiency considering production productivity was determined by dividing yield by amount of P applied. It indicates the productivity of a crop (yield) in comparison to the fertilizer applied Roberts and Johnston (2015).

Statistical analysis

Analysis of variance (ANOVA) and correlations were performed using JMP 14 (Ramirez and Ramírez, 2018). Mean separations were done using Fishers' protected least significant differences (LSD) at $P < 0.05$. Correlations were performed using Pearson's correlation test.

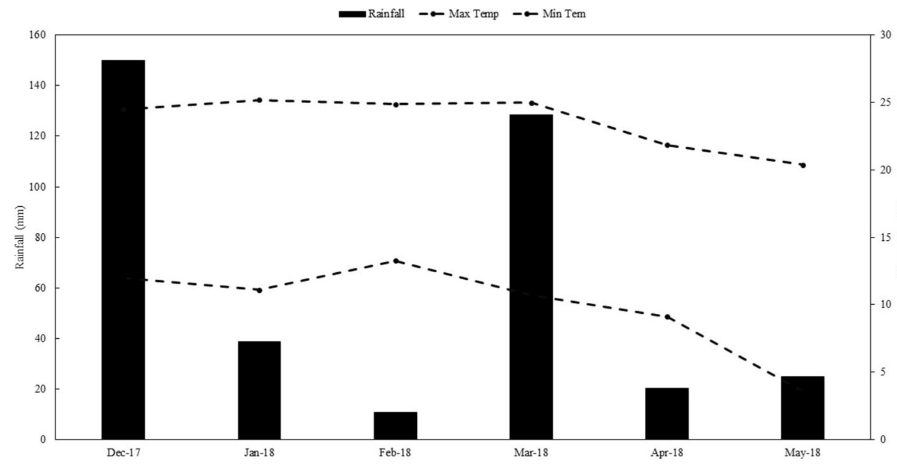

FIGURE 1
Climate data of the study site during the planting season.

Results and discussion

Climatic data during the planting season and results from the initial soil characterization are presented in Figure 1 and Table 1, respectively.

Fertilizer and tillage effects on soil properties

Significant effects ($P < 0.05$) of fertilizer application were observed on exchangeable calcium (Ca) and magnesium (Mg), Iron (Fe), total Nitrogen (TN), exchangeable phosphorus (P), and exchangeable potassium (K) concentrations (Table 2). Application of 30 kg/ha P significantly increased levels of extractable Ca, Mg, K, and TN by up to 61.87, 52.91, 33.12, and 11.59%, respectively, over the control. However, at the 60 kg/ha P rate exchangeable Ca, Mg, K, and TN were statistically lower than those observed after the application of 30 kg/ha P, whereas available P gradually increased up to 97.23% over control, and recorded the highest soil P levels at 60 kg P/ha application rate. On the contrary, application of 30 kg/ha P caused a significant decrease in extractable Fe, whereas at 60 kg/ha, the amount of Fe equivalent to control.

Soil pH was not significantly affected by fertilizer application whilst extractable Aluminum (Al) was not significantly affected by any of the main treatments. Meanwhile, pH, exchangeable Ca, Mg, and K were significantly affected ($P < 0.05$) by tillage (Figure 5). No-till led to the increase of pH, exchangeable Ca, Mg, and K by up to 1.76, 20.64, 23.77, and 15.08% over CT, respectively. Tillage had no significant effects on Fe, Al, and P (Table 2). Out of the selected physical properties, bulk density (BD) was not affected by any of the main treatments, whereas penetration resistance was significantly affected ($P < 0.05$) by tillage.

TABLE 1 Initial soil characterization.

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 cm^{-3}	1.2
Sand %	70
Silt %	10
Clay %	20

Exchangeable cations such as Ca and Mg are usually low in strongly acidic soils (Fageria and Baligar, 2005). However, the increase of Ca and Mg at 30 kg/ha P could be a result of lower Fe concentration at the same fertilizer rate and vice versa at 60 kg P/ha application. Iron and Aluminum, like many metals, are predominantly found in strongly acidic soils such as the experimental site (Lemanowicz et al., 2016; Heuer et al., 2017). Therefore, significant decrease of Fe at 30 kg/ha P could be due to fixation: Fe/Al oxides fix more than 80% of applied P; this reaction may significantly reduce Fe and available P in the soil solution (Heuer et al., 2017; Zhu et al., 2018). Literature has also shown that Fe uptake by plants is sensitive to excessive P

TABLE 2 Effects of fertilizer, cultivar and tillage on soil physico-chemical properties on a soybean cropping system.

Treatment			mg/kg						g/cm^3	kPa
	pH	TN %	Ca	Mg	Fe	Al	P	K	Bulk density	Penetration resistance
Fertilizer (F)										
0	4.58a	0.067c	101.44b	43.39b	31.59a	1.66a	11.054c	95.33c		
30	4.62a	0.075a	164.2a	66.34a	24.62b	1.86a	21.802b	126.90a		
60	4.53a	0.071b	111.4b	50.28b	30.35a	1.79a	37.159a	109.54b		
P-value	ns	0.0289	<0.0001	<0.0001	0.0031	ns	0.0004	<0.0001		
Cultivar (C)										
PAN 1614R	4.55a	0.052a	118,11a	50.56a	27.27a	1.84a	27.84a	107.55a		
PAN 1521R	4.61a	0.055a	125,89a	55.11a	29.02a	1.65a	32.24a	113.00a		
PAN 1532R	4.56a	0.055a	118,11a	54.34a	30.27a	1.84a	35.37a	111.21a		
P-value	ns	ns	ns	ns	ns	ns	ns	ns		
Tillage (T)										
NT	4.62a	0.054a	137,44a	59.00a	27.8a	1.72a	30.01a	118.35a	1.47a	693.64b
CT	4.53b	0.053a	113.92b	47.67b	29.91a	1.83a	33.62a	102.83b	1.50a	1,249.79a
P-value	0.0184	ns	0.0081	0.001	ns	ns	ns	0.0004	ns	0.0017
Interactions										
C × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C × F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T × F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C × T × F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

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

(Murphy et al., 1981); therefore, surplus P may cause inhibition of Fe from plant root uptake, and thus making Fe available at higher concentrations in the soil solution (Murphy et al., 1981; Fageria, 2001).

The increase of TN and a progressive increase of P from 30 to 60 kg/ha in soil solution could be a result of supply of phosphates and ammonia from fertilization (Aniekwe and Mbah, 2014; Zhang et al., 2015; Yin et al., 2016) (Table 2). A significant decrease in TN at 60 kg/ha P as compared to 30 kg/ha P (Table 2) may be a result of plant N uptake, which was significantly higher at 60 kg/ha P (Table 4). This is because adequate supply of P in the roots of soybean increases root biomass and nodulation, which facilitates nitrogen fixation (Mitran et al., 2018).

The increase of exchangeable Ca^{2+}, Mg^{2+}, and K^{+} under no-till could be due to residue retention (higher organic matter accumulation), which through decomposition, releases nutrients back into the soil (Malecka et al., 2012; Sithole et al., 2016). The increase of both Ca and Mg could be responsible for the increase in pH under NT. Similarly, Busari et al. (2015) noted that increasing tillage disturbance decreases soil surface pH, and that 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.

Lower PR and BD were observed under NT as compared to CT, but only PR was affected significantly ($P < 0.05$; Table 2). This is because PR is more sensitive to changes than BD (Moraru and Rusu, 2013). However, 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; Malecka et al., 2012; Villamil et al., 2015; Sithole et al., 2016), whilst others observed the opposite (Malecka et al., 2012; Sharma et al., 2016). However, data from some long-term studies indicate a shift on bulk density as years progress. Sharma et al. (2016) observed higher soil BD under NT within the initial 5 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 through higher production of biomass, which ultimately improved soil structure under NT (Bogunovic et al., 2019). The benefit of lower penetration resistance in no-till systems is root elongation, proliferation and plant nutrient uptake (Moraru and Rusu, 2013).

Soil enzyme activities were significantly affected ($P < 0.05$) by fertilizer and tillage at various growth stages (Table 3). The activities of ACP increased by up to 36% at reproductive stage under no-till as compared to CT. This is because no-till is

TABLE 3 Fertilizer application, cultivar and tillage effects on acid phosphatase and alkaline phosphatase activities on a soybean cropping system.

	p-nitrophenol mg/kg/h					
	Vegetative stage		Reproductive stage		Maturity stage	
Treatment	**ACP**	**ALP**	**ACP**	**ALP**	**ACP**	**ALP**
Fertilizer (F)						
0	2,164.5b	219.88a	1,656.45b	64.58b	2,297.03b	169.49b
30	3,223a	369.08a	2,643.75a	226.76a	5,788.20a	299.68a
60	2,009.1b	242.52a	1,518.98b	84.97b	2,873.77b	159.47b
P-value	0.0081	ns	0.0019	0.0265	$<$0.0001	0.0485
Cultivar (C)						
PAN 1614R	2,455.77a	245.74a	1,930.70a	104.88a	104.88a	220.09a
PAN 1521R	2,353.38a	292.65a	2,086.25a	114.88a	114.88a	182.05a
PAN 1532R	2,587.47a	293.09a	1,802.24a	156.55a	156.55a	226.50a
P-value	ns	ns	ns	ns	ns	ns
Tillage (T)						
NT	2,743.67a	240.11a	2,235.62a	131.19a	4,130.94a	234.46a
CT	2,187.42a	314.21a	1,643.83b	119.69a	3,175.06a	184.63a
P-value	ns	ns	0.0262	ns	ns	ns
Interactions (*P*-value)						
C × T	ns	ns	ns	ns	ns	ns
C × F	ns	ns	ns	ns	ns	ns
T × F	ns	ns	ns	ns	ns	ns
C × T × F	ns	ns	ns	ns	ns	ns

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

effective in improving soil enzyme activities in the short-term (Heidari et al., 2016). According to Sithole et al. (2016), 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. Balota et al. (2004) also reported an increase of ACP and ALP up to 46 and 61% at top soil layer under no-till, respectively.

Phosphorus application at 30 kg/ha caused a significant increase of ACP activities by up to 48.93, 59.59, and 151.99% at vegetative, reproductive and maturity stage, respectively, over control. Whereas for AL P, significant increases were only noted during reproductive and maturity stages by up to 251.13 and 76.81%, respectively, over control. The activities of ACP were generally higher than ALP due to the strongly acidic pH. According to Sharma et al. (2013), 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. The difference in enzyme activities were not significant at 60 kg/ha P. Phosphatase activities could have been suppressed by an increase of inorganic phosphorus in the soil because more often, phosphatases activities are inversely proportional to available soil P concentration (Wang et al., 2013; Lemanowicz et al., 2016). Heidari et al. (2016) also reported a suppression of phosphatase activities due to fertilization. This may suggest that P rate up to 30 kg/ha could be the optimum level for high phosphatase activities in the study area.

Plant NPK uptake and P utilization efficiency

Application of P improved uptake of N, P, and K significantly ($P < 0.05$), however, excessive application of P above 30 kg/ha did not enhance uptake significantly except for N (Table 4). For P and K, the highest uptake was observed at 60 kg/ha P rate, although it was statistically similar to 30 kg/ha P rate. Whereas for N, there was a significant progressive increase at 30 and 60 kg/ha P. Nutrient increases were as follows: at 30 kg/ha P rate, uptake of N, P, and K increased by up to 21.74, 91.51, and 69.05%, whilst at 60 kg/ha P rate the increase was up to 34.78, 119.82, and 75.76%, respectively, over control. Aulakh et al. (2003) and Sharma et al. (2011) also reported increase in nutrient uptake following P application, however, excessive P did not have agronomic benefits such as increase in yield, biomass or biomass partitioning to grain. Findings of the current study confirmed reports from several researchers who argued that

TABLE 4 Effects of fertilizer, cultivar and tillage on plant nutrient uptake 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 1532R	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 × T	ns	ns	ns
C × F	ns	ns	ns
T × F	ns	ns	ns
C × T × F	ns	ns	ns

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

TABLE 5 Pearson's correlation test on plant nutrient uptake (N, P, K) with dry biomass on a soybean cropping system.

	Kg/ha			g
	P	**K**	***N***	**Dry biomass**
Dry biomass	0.71*	0.73*	0.70*	1

*$P < 0.0001$.

nutrient uptake is correlated with biomass production (Sharma et al., 2011; Dalshad et al., 2013; Fageria et al., 2013) (Table 5).

Main treatments and their interactions had no significant effects ($P < 0.05$) on P use efficiency (Table 6). The utilization efficiency at 30 and 60 kg P/ha rate was 19.65 and 15.82%, respectively. This is considered to be a very low utilization efficiency. Usually, a P use efficiency calculated using the balance method should be in the range of 50–70% but can even be higher than 100% if the crop also utilized some of the P reserves in the soil. A very low P utilization efficiency recorded for this study could suggests a high fixation capacity of soils and/or more fertilizer was applied than what was needed for the crop (Roberts and Johnston, 2015). Nonetheless, partial factor productivity (PFP) which only focuses on seed yield indicating crop productivity in relation to its nutrient input was significantly affected ($P < 0.05$) by P rate. PFP increased by

TABLE 6 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	<0.0001

Levels with same letter are not significantly different ($P < 0.05$; Fisher's test).
ns, not significant.

up to 105.79% at 30 kg/ha over 60 kg/ha P. Syers et al. (2008) and Abbasi et al. (2010) reported that as P rate increase P-use efficiency decreased. This therefore means P supply at 60 kg/ha rate exceeded the requirement for optimum crop production (Roberts and Johnston, 2015).

Fertilizer application, tillage and cultivar effects on soybean growth, yield components, and grain quality

Fertilizer, cultivar and tillage had significant effects on crop growth and yield components (Table 7). Number of pods per plant (NPP) and plant height increased progressively with P application by up to 66.15 and 21.31%, respectively, over control. However, these increases were statistically similar at 30 and 60 kg/ha P. Tillage and cultivar did not have any significant effects ($P < 0.05$) on NPP, however, cultivar had significant effects on plant height. Tillage did not significantly affect plant height, and in addition, fertilizer and tillage did not significantly affect 100-seed mass and pod length. The 100-seed mass, pod length together with plant height were significantly affected ($P < 0.05$) by cultivar (Table 7). PAN 1614R recorded the highest 100-seed mass (16.85 g), longest pods (4.11 cm) and tallest plants (49.84 cm). However, for 100-seed weight the cultivars PAN 1614R and PAN 1521R were statistically similar.

A significant interaction between tillage and cultivar was observed for pod length. Under CT, PAN 1614R produced the longest pods, whilst PAN 1521R and PAN 1532R were shorter and performed similarly under both tillage systems. Under NT, PAN 1614R also performed statistically the same as PAN 1521R and PAN 1532R (Figure 2).

The increase in NPP and plant height after P application was because phosphorus in soybean is responsible for growth and pod formation (Fageria et al., 2013; Ahiabor et al., 2014). The recommended P level in the soil for soybean is between 15 and 18 mg/kg (FERTASA, 2016), and in this experiment, soils under control (0 kg/ha P) had critically low soil available P of about 11.05 mg/kg (Table 7) hence shorter plants and lower

TABLE 7 Effects of fertilizer, cultivar and tillage on number of pods per plant (NPP), pod length, plant height, and 100- seed mass on a soybean cropping system.

Treatment	NPP	Pod length cm	Plant height cm	100-seed mass
Fertilizer				
0	40b	3.93a	65.25 a	15.98a
30	67a	4.07a	64.17a	15.6a
60	65a	3.95a	46.39b	16.65a
P-value	0.0445	ns	<0.001	ns
Cultivar				
PAN 1614R	46a	4.11a	69.5a	16.85a
PAN 1521R	49a	3.9b	59.33b	15.95ab
PAN 1532R	46a	3.93b	47c	15.43b
P-value	ns	0.0199	<0.0001	0.0369
Tillage				
NT	54a	3.95a	59.33a	16.13a
CT	61a	4.01a	57.87a	16.02a
P-value	ns	ns	ns	ns
Interactions				
C × T	ns	0.0259	ns	ns
C × F	ns	ns	ns	ns
T × F	ns	ns	ns	ns
C × T × F	ns	ns	ns	ns

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

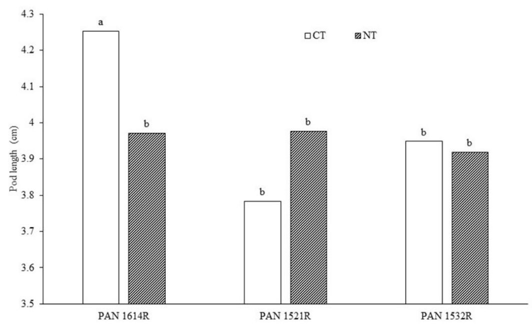

FIGURE 2
Interactive effects of cultivar and tillage on pod length on a soybean cropping system. Levels with same letter are not significantly different.

pods count. This is because low supply of P imposes major restrictions in vegetative growth and reproduction of soybean (Mitran et al., 2018). Results from Malik et al. (2006) also support these findings.

The differences in cultivar performance for 100-seed weight and plant height could be a result of genotype. This is because seed size traits are determined by several genes in a plant (Krisnawati and Adie, 2015), and mature seed sizes are simultaneously determined by embryo, cytoplasm and maternal effects (Adie and Krisnawati, 2018). Similar to 100-seed mass, plant height and the differences in pod length as a result of cultivar and tillage effects could be because of the seed genotype (Krisnawati and Adie, 2015), and adaptability to tillage system.

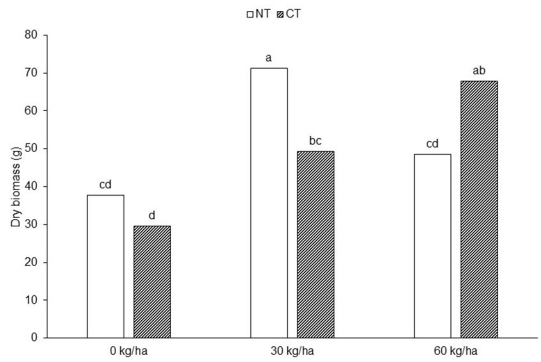

FIGURE 3
Interactive effects of fertilizer and tillage on dry biomass on a soybean cropping system. Levels with same letter are not significantly different.

Significant interactions ($P < 0.05$) between fertilizer and tillage treatments were observed on dry biomass (Figure 3). Dry biomass was significantly higher at 30 kg/ha P under NT and statistically same with 60 kg/ha P under CT. Increase of biomass after P applications have been noted by other authors (Aulakh et al., 2003; Ahiabor et al., 2014). The response of 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 and OM decomposition under NT recycles organic P back into the soil (Busari et al., 2015).

There were statistically significant interactions between P application rate, cultivar and tillage on soybean yield (Figure 4). The overall highest yield was recorded at 30 kg/ha P application under NT for PAN 1521R, however it was statistically similar to PAN 1521R under CT at 60 kg/ha and PAN 1532R under NT at 60 kg/ha P. Nonetheless, PAN 1532 performed statically same at 60 kg/ha under NT and 30 kg/ha under both NT and CT. Therefore, the optimum fertilizer rate and tillage system for all 3 cultivars was 30 kg/ha P under NT. Yield increases after P application are expected because P is the most essential element required for growth and reproduction in soybean (Chien et al., 2011; Shen et al., 2011). Phosphorus additions result in improved yields and better grain quality (Malik et al., 2006; Mabapa et al.,

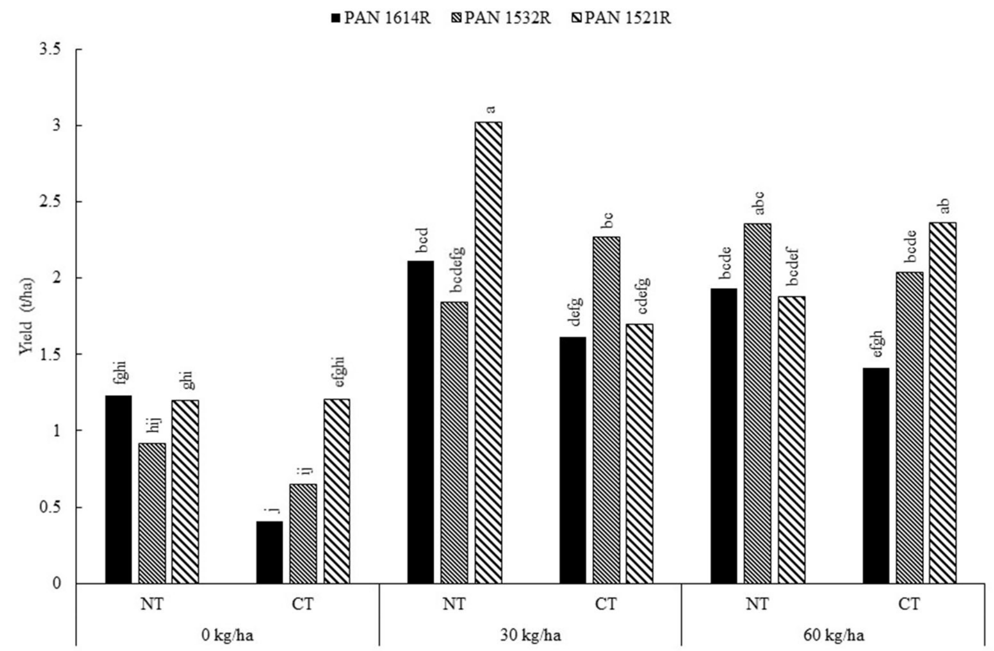

FIGURE 4
Interactive effects of fertilizer, cultivar and tillage on soybean yield on a soybean cropping system. Levels with same letter are not significantly different.

2010). This is shown by positive relationship ($P < 0.0001$, $R^2 = 0.93$) between soybean yield and plant P uptake (Figure 5).

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 and Johnston, 2015). Therefore, adding more fertilizer may only raise the soil's P balance where no direct yield response is expected (Chien et al., 2011). Abbasi et al. (2012), reported yield increases of up to 53% with increased P application, and Malik et al. (2006) observed a statistically similar soybean yield between 90 and 120 kg/ha. Moreover, Aulakh et al. (2003) also observed increasing seed yield following P application up to 80 kg/ha, and no yield response above 80 kg/ha P rate. As for tillage, Buah et al. (2017) noted an increasing yield of soybean by up to 54% under NT as compared to CT 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 (Jabro et al., 2011; Busari et al., 2015). Yield increases under no-till especially during drier periods were reported (Busari et al., 2015).

Yield increase at 30 and 60 kg/ha P treatments resulting from increased NPP was also recorded in this study and supported by significant positive correlation of yield with NPP ($P = 0.0084$; $R^2 = 0.90$) (Figure 5).

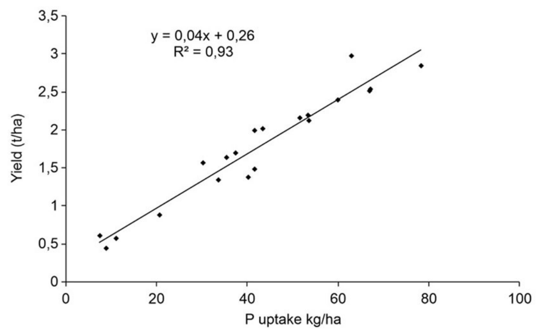

FIGURE 5
Relationship between P uptake and yield on a soybean cropping system.

Significant effects ($P < 0.05$) of phosphorus application rate and cultivar were observed on protein and oil content (Table 8). P application at 30 and 60 kg/ha significantly reduced oil content by 7.97 and 12.17% but had inverse effects on protein content increasing it by 0.92 and 1.15%, respectively, over control. These results confirm findings by

TABLE 8 Effects of fertilizer, cultivar and tillage 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	0.0634	0.7152

Levels with same letter are not significantly different.
ns, not significant; NT, no-till; CT, conventional tillage.
$^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$.

several authors of decreasing oil production with increasing protein content due to P application (Mokoena, 2013; Yin et al., 2016), and statistically similar protein content between P application rates (Abbasi et al., 2012). Nonetheless, 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 (Malik et al., 2006; Abbasi et al., 2012). However, when P is deficient in the soil, P additions improve N fixation which enhances seed protein content (Yin et al., 2016). 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).

Cultivar also had significant effects ($P < 0.05$) 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.

Conclusion and recommendations

This study showed that the application of mineral P fertilizer improved the soil's nutrients status by raising the soil's pH and also concentrations of exchangeable Ca, Mg, P, K, and TN whilst reducing Fe which is one of the main causes of soil acidity. 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. Moreover, results of this study supports studies that indicate that penetration resistance responds very quickly to change, and that increase in biomass could improve penetration resistance in short-term experiments. Phosphorus application also stimulated activities of both ACP and ALK, with ACP being the dominant enzyme because of acidity. Nonetheless, excessive application of P above 30 kg/ha did not improve activities of both enzymes. The activities of both phosphatases increased under no-till at all growth stages, although only ACP at reproductive stage was significant. This suggest that no-till has the potential for higher enzyme activity, which would lead to increased soil fertility because of their role in solubilizing organic P.

Tillage, cultivar and varying mineral P levels had significant effects on P uptake and P use efficiency in a soybean experiment. The application of P significantly improved N, P, and K uptake at both 30 and 60 kg/ha P, however, no differences were observed between 30 and 60 kg/ha P rates for P and K. The lowest N, P, and K uptake was observed under control (0 kg/ha P), this indicates the need for P application and its conservation in soybean production. Phosphorus utilization efficiency was very low and did not differ statistically across P rates. This may be an indication of a higher fixation capacity of the soil due to acidity. Nonetheless, the PFP which calculates P efficiency using seed yield was significantly higher at 30 kg/ha P. This implies that farmers should apply fertilizers at standard rates, as excess P is agronomically inefficient.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

PC: conceptualization, methodology, formal analysis, data collection, and writing—original draft. AN: conceptualization, methodology, writing—review and editing, project administration, and supervision. IW and FM: review and editing and supervision. SM, MM and IK: review and editing and funding. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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