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REGULAR ARTICLE

# Potato-legume intercropping on a sloping terrain and its effects on soil physico-chemical properties

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**Abstract**
*Aims* To assess the effects of potato-legume intercropping on selected soil physical and chemical properties after four consecutive growing seasons (from the short rains in 2014 to long rains 2016).
*Methods* The experiment was laid out in a randomised complete block design with four replicates. The treatments were potato-dolichos (PD); potato-garden pea (PG); potato-bean (PB) intercropping systems, and a pure stand of potato (PS). After every harvest, crop residues were ploughed back and selected soil physico-chemical properties were assessed after two years of cultivation.
*Results* Potato-legume intercropping resulted in a significant increase down the slope for clay and silt under PS, PG and PB whereas, an opposite observation was made for sand and bulk density. Nonetheless, under PD, slope position had no significant effect on soil physical properties. In all cropping systems, a significant increase was observed down the slope for pH and cation exchange capacity. Similar observations were made for phosphorous, nitrogen and organic carbon under all the cropping systems except PD.
*Conclusions* This study has established PD as a viable intercropping system, which could be adopted by farmers for improved soil fertility.

**Keywords** Soil fertility · Slope position · Spatial variation · Intercropping systems · Crop residue incorporation

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## Introduction

In Kenya, potato production is done mainly by smallholder farmers as a key food and cash crop on approximately 146,000 ha with average tuber yield of about 9 Mg ha$^{-1}$, which is still below the 30–40 Mg ha$^{-1}$ attainable under normal field conditions (FAOSTAT 2017; Gitari et al. 2018a, b). Due to the exponentially growing human population and decreasing land resources, potato growers are expanding cultivation to marginal areas with steep slopes where frequent high-energy rainstorms occur, hence predisposing soil to erosion (Gachene et al. 1997; Elias 2017; Nyawade et al. 2018a; Adimassu et al. 2019). In these areas, the potato is grown continuously with shortened fallows and without rotations leading to net nutrient mining, which jeopardizes the soil's ability to rejuvenate (Mallory and Porter 2007; Gitari 2013; Gitari et al. 2015, 2018a; Nyiraneza et al. 2015; Usowicz and Lipiec 2017).

Given that potato cultivation generally involves intensive soil movement through repeated tillage, soil degradation due to water erosion especially on a hilly land is inevitable and it has been identified as a key soil quality problem in the potato growing areas especially in developing countries (Cao et al. 1994; Pimentel and Burgess 2013; Nyawade et al. 2018a). Consequently, through soil erosion, essential plants nutrients, soil organic matter and fine clays are eroded hence, reducing the land's productivity (Hewawasam and Illangasinghe 2015; Kokulan et al. 2018; Nyawade et al. 2019; Adimassu et al. 2019). Thus, heterogeneity in soil physical and chemical properties and declining soil fertility is widespread, which in turn, influences crop growth and productivity. Soil moisture content (SMC), texture, bulk density (BD), pH, total nitrogen (N), available phosphorous (P), cation exchange capacity (CEC) and organic carbon (OC) are among the fundamental soil properties that govern soil productivity (Castrignano et al. 2000; Rosemary et al. 2017; Kokulan et al. 2018). Spatial variability of such soil properties within a farm field is primarily attributed to the disparity in transport and deposition of the eroded materials and anthropogenic activities related to soil management practices (Selassie et al. 2015; Rosemary et al. 2017). Therefore understanding the spatial heterogeneity of soil physical and chemical properties is very crucial for determining the best management practices that not only improve the productivity of potato-based intercropping systems but also enhance environmental sustainability (Selassie et al. 2015; Usowicz and Lipiec 2017).

One common way of restoring depleted nutrients is through use of chemical fertilizers (Mugwe et al. 2009; Gitari et al. 2018b). However, high fertilizer prices limit farmers in sub-Saharan countries from applying this input in recommended amounts to support high crop yields (Jansen et al. 2013; Gitari et al. 2018b). Consequently, farmers in these regions frequently face constraints of soils losing its ability to support high crop production (Ortiz-Escobar and Hue 2008; Sharma et al. 2017). Soil fertility deterioration can be stabilised through the addition of green manures (Mugwe et al. 2009; Maltais-Landry and Frossard 2015; Nyiraneza et al. 2015; N'Dayegamiye et al. 2017; Walia and Dick 2018). Use of green manure particularly from legumes such as *Glycine max, Lablab purpureus, Crotalaria ochroleuca* and *Mucuna pruriens* has been proven to have positive effects on yield, soil organic matter content, structure and fertility (Mallory and Porter 2007; Mugwe et al. 2009). Therefore incorporation of such legume residues into the soil improves soil quality, which is a key requirement for sustainable agriculture and a major concern for not only agricultural but also environmental objectives.

Legumes have an ability to fix atmospheric N, hence sequestering it by immobilizing nitrate-N into plant protein, which provides an appropriate competition to N loss pathways, such as denitrification and leaching (Dabney et al. 2010). This results in less competition for N among the companion intercrops (Ojiem et al. 2007; Hauggaard-Nielsen et al. 2009; Gitari 2018). For instance, Ojiem et al. (2007) had earlier reported that dolichos could contribute up to 42 kg N $ha^{-1}$ to soil N fertility, which was mainly attributed to their ability to fix atmospheric N. This is a clear indication that legumes add nutrients to the soil when their residues are incorporated into the soil as they undergo decomposition and mineralization processes (Cheruiyot et al. 2007; Ojiem et al. 2007; Soltangheisi et al. 2018). However, such studies involving incorporation of legume crop residues in potato production to boost soil fertility are rare, especially in sub-Saharan Africa.

Designing alternative intercropping systems remains a key research priority that can address the problem of food scarcity in sub-Saharan Africa to increase the productivity of the existing potato cropping systems given that land resources are diminishing. Ploughing back of crop residues reduces the loss of soil and nutrients through water erosion hence, improve soil fertility (Mugwe et al. 2009; N'Dayegamiye et al. 2017; Walia and Dick 2018). Such a practice could maintain and replenish soil chemical properties, which are pivotal in crop production. Nonetheless, information on the effect of potato-legume intercropping systems on soil physical and chemical properties is limited. Therefore, this study was carried out with an overarching focus to explore the effect of a two-year potato-legume intercrop on selected soil physical and chemical properties in a Humic Nitisol. It was hypothesised that: (i) the soil physical properties (soil moisture content, bulk density, sand, silt and clay) would increase down the slope under different potato-legume intercropping and (ii) the soil chemical properties (pH, available phosphorus, total nitrogen, organic carbon and cation exchange capacity) would increase following incorporation of crop residues.

## Materials and methods

### Site description

This study was carried out between 2014 and 2016 for four consecutive growing seasons at Kabete Field Station, University of Nairobi, located at 1° 15' S and 36° 44′ E, at 1860 m above sea level (Fig. 1). The study site falls under the sub-humid agro-ecological zone, which is typical of a Kenyan highland where potato cultivation takes place (Jaetzold et al. 2006; Gitari 2018). The soil (locally known as Kikuyu red loam) is classified as a Humic Nitisol (IUSS Working Group WRB 2015). It is derived from tertiary aged Nairobi trachyte lava that is dominated by non-expanding kaolinite clay minerals, is well drained, deeply weathered (> 1.8 m), with diffuse horizon boundaries (Gachene et al. 1997). The area receives rainfall in a bimodal pattern, with the first season from March to June often referred to as 'long rains' and second season (short rains) from October to December.

### Experimental setup and crop establishment

The experiment was laid in a terraced field with a slope of 10% with a well-maintained cut-off drain and embankment on the upper and lower side, respectively (Fig. 1). A randomised complete block design in four replicates was adopted with plots (laid along the slope) whose width was 4 m and length varied between 10 and 13 m along the slope. Nevertheless, since we were interested in investigating the variation of physico-chemical properties down the slope, the plots were further subdivided into three 2-m slope positions namely: the upper (2 m from the uppermost part of the plot), the middle (2 m at the middle of the plot) and the lower slope position (2 m from the lowest part of the plot) (Fig. 1). The treatments were potato-dolichos (*Lablab purpureus* L.) (PD); potato-garden pea (*Pisum sativum* L.) (PG); potato-bean (*Phaseolus vulgaris* L.) (PB) and a pure stand of potato (*Solanum tuberosum* L.) (PS).

At the onset of rainfall, pre-sprouted seed potatoes (25–50 g, var. Shangi) were manually planted at a spacing of 0.3 m within a row and 0.9 m between rows (plant density = 36,400 plants ha$^{-1}$). Legumes were planted between the potato rows at a spacing of 0.25 m within a row to give a plant density of 88,000 plants ha$^{-1}$.

At planting, potatoes were supplied with 200 kg ha$^{-1}$ of NPK (17:17:17) fertilizer and an equivalent quantity of calcium ammonium nitrate fertilizer 28 days after planting (DAP), which equated to 68 kg ha$^{-1}$ of N, and 34 kg ha$^{-1}$ of P and K. Weeding, hilling-up for potato and staking for bean was carried out manually at 28 DAP. Potatoes were sprayed with Ridomil Gold MZ 68 WG (Mefenoxam 40 g kg$^{-1}$ + Mancozeb 640 g kg$^{-1}$) alternated with Daconil 720 SC (Chlorothalonil 720 g L$^{-1}$) after every 14 days starting at 28 DAP to control late blight.

### Harvesting and biomass nutrient analyses

At crop maturity (75 days after planting for peas, 85 for potatoes and beans and 120 for dolichos), only tubers from potatoes and grains from legumes were taken from the intercropping systems. All crop residues were incorporated in situ as green manure to a depth of 0.3 m. Representative samples for potato and legume crop residues (excluding the roots) were taken at harvest from every plot, cut into small pieces and 500 g sub-samples were taken, oven dried to constant weight at 70 °C, ground and sieved through a one-millimetre sieve for analysis. Nitrogen was determined using micro-Kjeldahl (Bremner 1996) method in which the samples were digested using a block digester for 2 h at 361 °C in a digestion mixture containing selenium powder, lithium sulphate, hydrogen peroxide and sulphuric acid (Bremner 1960). Phosphorus was analysed colourimetrically as described by Murphy and Riley (1962).

### Data collection

During each crop-growing season, soil moisture content was measured per slope position and intercropping systems in a weekly basis using a digital soil moisture meter-HSM50. The soil moisture content was taken by inserting the probes in between

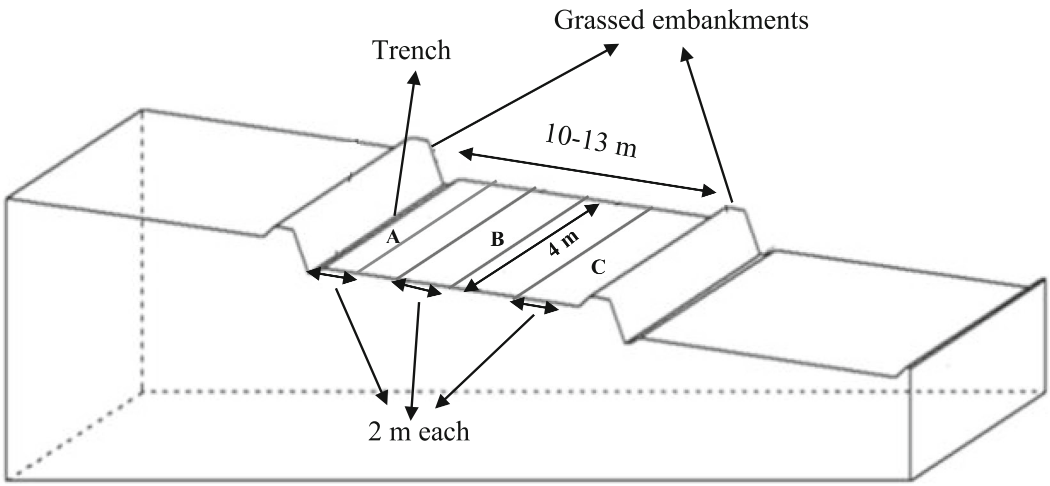


**Fig. 1** A cross-section sketch drawing of a plot showing the three slope positions, upper (**a**), middle (**b**) and lower (**c**)

potato plants. The data were recorded as cm $m^{-3}$ then pooled and reported as means for every season. Soil sampling was done at 0–0.3 m depth following the procedures described by Pennock and Yates (2008) using a soil auger (for disturbed samples and in stainless steel core rings (5 cm diameter) (for undisturbed samples). The sampling was done twice, first on October 2, 2014 (before establishing the experiment) and the second sampling was done within each slope position per plot on September 6, 2016, 60 days after incorporating crop residues for the last season (2016 long rains). With the introduction of terraces and different cropping systems significant changes were observed down the slope at the end of the experiment compared to the initial, more homogeneous properties, both in potato sole crop and intercropping treatments. Therefore the results have been presented with reference to initial soil status data in Table 1.

For soil physical properties, soil texture analysis was done by hydrometer method (Gee and Bauder 1979) whereas bulk density was determined as described by Doran and Mielke (1984) from the undisturbed samples. The disturbed soil samples were air-dried and sieved through a 2 mm sieve for chemical analyses. The pH was determined in a 1:2.5 (soil: water) ratio using a pH meter (Ryan et al. 2001). Total N was analysed by the modified micro-Kjeldahl digestion method (Bremner 1996), and organic carbon by modified Walkley and Black method (Nelson and Sommers 1996). Cation exchange capacity (CEC) was measured using the $NH_4$-acetate method as described by Rhoades and Polemio (1977). From the soil extract, available phosphorous was determined using a UV-vis spectrophotometer (Murphy and Riley 1962).

## Statistical data analysis

The effects of potato-legume intercrops on selected physical (sand, silt clay and bulk density) and chemical (pH, phosphorous, nitrogen, organic carbon and cation exchange capacity) soil properties were analysed statistically using R software version 2.2.3 (R Core Team

**Table 1** Initial soil physical and chemical properties of the study site

| | Slope Position | | | |
|---|---|---|---|---|
| | Upper | Middle | Lower | *p* Value |
| Physical properties | | | | |
| Sand (%) | 30.6[a] | 30.6[a] | 30.5[a] | 0.191 |
| Silt (%) | 27.0[a] | 27.1[a] | 27.3[a] | 0.101 |
| Clay (%) | 42.4[a] | 42.3[a] | 42.2[a] | 0.084 |
| Bulk density (g $cm^{-3}$) | 1.04[a] | 1.02[a] | 1.03[a] | 0.068 |
| Chemical properties | | | | |
| pH | 5.6[a] | 5.6[a] | 5.6[a] | 0.155 |
| Available P (mg $kg^{-1}$) | 17.2[b] | 17.0[a] | 17.3[b] | 0.044 |
| Total N (g $kg^{-1}$) | 2.6[a] | 2.7[b] | 2.7[b] | 0.024 |
| Organic C (g $kg^{-1}$) | 28.9[a] | 29.1[ab] | 29.2[b] | 0.006 |
| CEC ($cmol_c$ $kg^{-1}$) | 31.0[a] | 31.3[b] | 31.3[b] | 0.004 |

Values followed by the same superscript letter across the row are not significantly different ($p \leq 0.05$) by Tukey's HSD test

2015). The significant means were separated at $p \leq 0.05$ using Tukey's Honest Significant Difference (HSD). Pearson correlation was done to indicate the relationship between the assessed variables.

## Results

### Weather patterns during crop growing period

When compared with the 20-year (1994–2013) average rainfall (994 mm), the amounts received during the two years of the study were 28 mm and 79 mm higher for 2014/15 and 2015/16 years, respectively (Fig. 2). The average temperatures for the first and second years were 22.2 and 21.9 °C, respectively compared to the long-term average of 22.0 °C. In particular, February 2015 and March 2016 were the warmest months, and they were 0.4 °C cooler and 2 °C warmer, respectively when compared to the long-term averages. Normally, in this region, July is the coolest month with a long term average of 19.7 °C. Although a similar observation was made for 2014/15 (19.2 °C), in 2015/16, June was 0.4 °C cooler than July.

### Initial soil physical and chemical properties of the study site

Prior to the establishment of this study, the site was fallow for two years such that it was dominated by wild plants and weeds, and the soil's physical properties were almost homogeneous down the slope (Table 1). The soil had mean bulk density of 1.03 g cm$^{-3}$, with sand, silt and clay averaged at 31, 27 and 42%, respectively. Therefore, the soil could be described as having a clayey texture. The soil was slightly acidic with a mean pH of 5.6, which did not vary down the slope. Available P, total N, organic C and cation exchange capacity (CEC) showed a

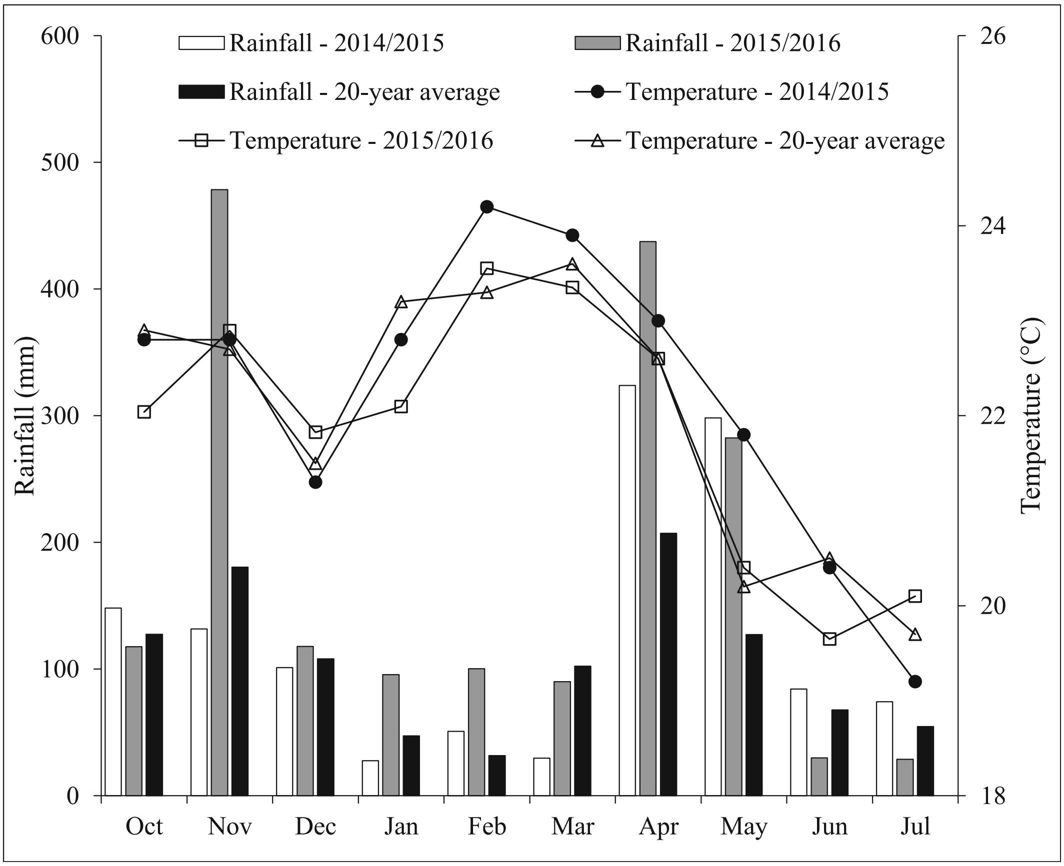


**Fig. 2** Monthly mean air temperature and the total rainfall during the growing seasons in 2014/15, 2015/16 and 1994–2013 average at Kabete Field Station. (Source: Kenya Meteorological Department, Kabete Weather Station)

significant ($p < 0.05$) increase down the slope with mean values of 17 mg kg$^{-1}$, 2.7 g kg$^{-1}$, 29 g kg$^{-1}$ and 31 cmol$_c$ kg$^{-1}$, respectively across the three slope positions.

## Crop residual biomass and their nutrient contents

As earlier reported, potato yield was significantly highest under pure stand and potato-dolichos intercropping system with beans and dolichos giving the highest and lowest yield, respectively (Gitari et al. 2018a, b). Dolichos produced significantly ($p \leq 0.05$) the highest biomass yield of 4.8 Mg ha$^{-1}$, which was 35, 54 and 58% higher than that produced by bean, potato and pea residues, respectively (Table 2). The dolichos residues had significantly ($p \leq 0.05$) the highest N content contributing an average of 146 kg N ha$^{-1}$ to the soil, which was 56, 89 and 103 kg N ha$^{-1}$ higher than that from the pea, bean and potato residues, respectively. Similarly, P contribution from dolichos residues was significantly ($p \leq 0.05$) higher by 43, 65 and 66% compared to the bean, pea and potato residues, respectively.

## Soil physical properties as influenced by slope position under different intercropping systems

Potato-legume intercropping systems influenced significantly ($p \leq 0.05$) soil physical properties such as moisture content, bulk density and texture (sand, silt and clay) and their values varied with slope position and growing seasons. Across the slope positions and seasons, SMC was 7, 9 and 23% higher in PB, PG and PD compared with PS (Fig. 3). A similar trend was depicted down the slope in all intercropping systems such that SMC at lower and middle slope positions were 17 and 5% higher than at upper slope position.

Bulk density varied significantly ($p < 0.001$) between intercropping systems in the order PD (1.07 g cm$^{-3}$) < PG (1.12) < PB (1.14) < PS (1.21) (Fig. 4), which marked percentage increase of 17, 4, 9 and 11, respectively relative to the baseline values (Table 1). Significant ($p \leq 0.05$) decrease in bulk density was observed down the slope in all intercropping systems except PD with an average of 1.01 g cm$^{-3}$ at upper slope position, 1.14 g cm$^{-3}$ at the middle slope position and 1.16 g cm$^{-3}$ at the lower slope position and these values were 11, 12 and 8% higher compared to the baseline values recorded prior to the start of this experiment (Table 1).

Sand, silt and clay content were significantly ($p \leq 0.05$) affected by slope positions with intercropping systems having a negligible influence (Fig. 5). Sand decreased significantly down the slope in PS, PG and PB whereas, in PD, it did not change in all the three slope positions. Averaged across the intercropping systems, sand decreased by 8 and 14% at middle and lower slope positions, respectively compared with upper slope position. When compared with baseline values (Table 1), sand content at the upper slope position was 6% higher whereas, at the middle and lower slope positions it was 2 and 8% lower, respectively.

In contrast, silt increased significantly down the slope in all intercropping systems except in PD (Fig. 5). Silt was significantly higher at middle slope position by 2% and at lower slope position by 5% compared with the upper slope position across the intercropping systems. Potato-legume intercropping resulted in a 1% decrease in silt content at upper slope position but at the middle and lower slope positions, it increased by 3% and 6%, respectively compared with baseline values (Table 1).

**Table 2** Fresh tuber and legume yield and the dry biomass yield for potato and legume residues and their N and P contribution into the soil

| Crop | Fresh tuber yield (Mg ha$^{-1}$)* | Fresh legume yield (Mg ha$^{-1}$)* | Dry biomass yield (Mg ha$^{-1}$) | Nitrogen | | Phosphorous | |
|---|---|---|---|---|---|---|---|
| | | | | N (%) | N (kg ha$^{-1}$) | P (%) | P (kg ha$^{-1}$) |
| Potato | 35.5$^a$ | – | 2.3$^c$ | 1.9$^c$ | 42.3$^d$ | 0.3$^c$ | 6.3$^c$ |
| Dolichos | 34.6$^a$ | 1.8$^c$ | 4.8$^a$ | 3.0$^a$ | 145.7$^a$ | 0.4$^a$ | 18.4$^a$ |
| Pea | 29.1$^b$ | 2.6$^b$ | 2.1$^c$ | 2.7$^b$ | 56.2$^c$ | 0.3$^b$ | 6.4$^c$ |
| Bean | 30.0$^b$ | 3.3$^a$ | 3.2$^b$ | 2.8$^b$ | 89.4$^b$ | 0.3$^b$ | 10.5$^b$ |

Means followed by different superscript letters down the column differ significantly at $p \leq 0.05$

* Data source (Gitari et al. 2018a)

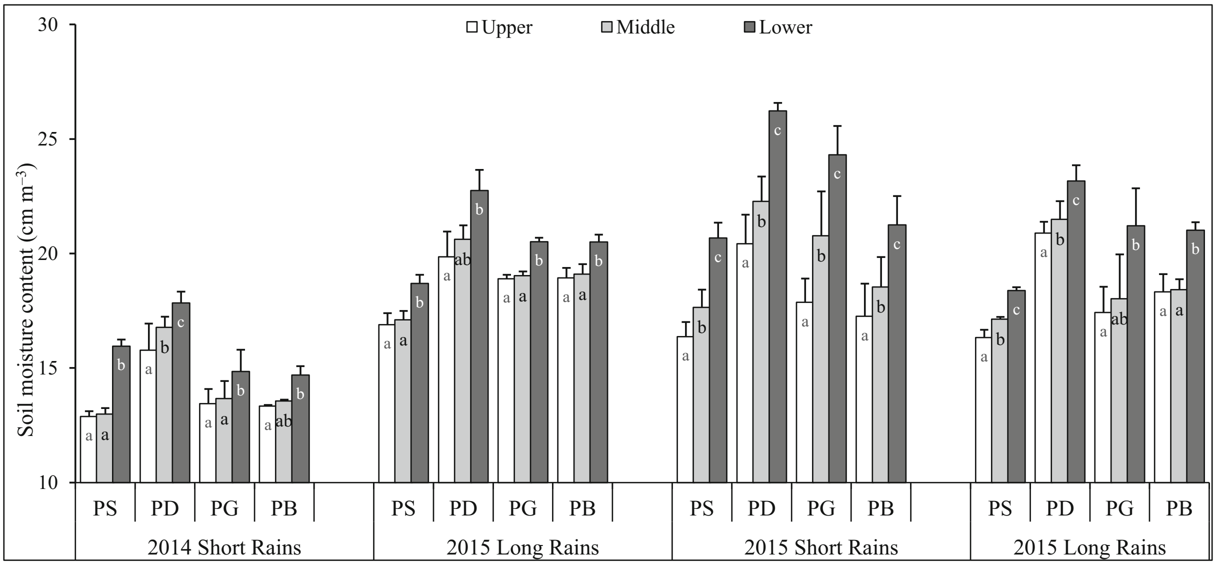


**Fig. 3** Soil moisture content as influenced by slope position under different potato-legume intercropping systems at different seasons. PS: pure potato stand, PD: potato-dolichos, PG: potato-pea, PB: potato-bean. Bars with the same letter within the same intercropping system and season denote means that are not significantly different at $p \leq 0.05$. Error bars depict standard error of the means

Similarly, clay content increased significantly down the slope in all treatments excluding PD (Fig. 5). Irrespective of the intercropping systems, clay content at the upper slope position decreased significantly ($p < 0.001$) by 4% whereas at the lower slope position it increased by 3% in comparison with the average value (42.2%) recorded prior to the establishment of this study (Table 1). The clay content at the middle and lower slope positions were 5 and 7% higher, respectively than at the upper slope position.

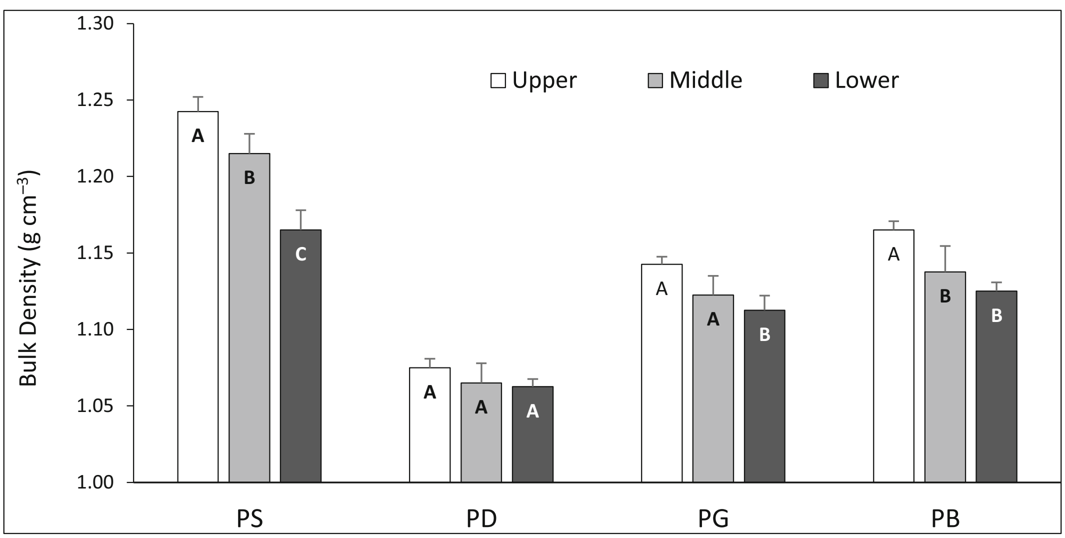


**Fig. 4** Soil bulk density as influenced by slope position under different potato-legume intercropping systems. PS: pure potato stand, PD: potato-dolichos, PG: potato-pea, PB: potato-bean. Bars with the same letter (by intercropping systems) are not significantly different at $p \leq 0.05$). Error bars signify standard error of the means

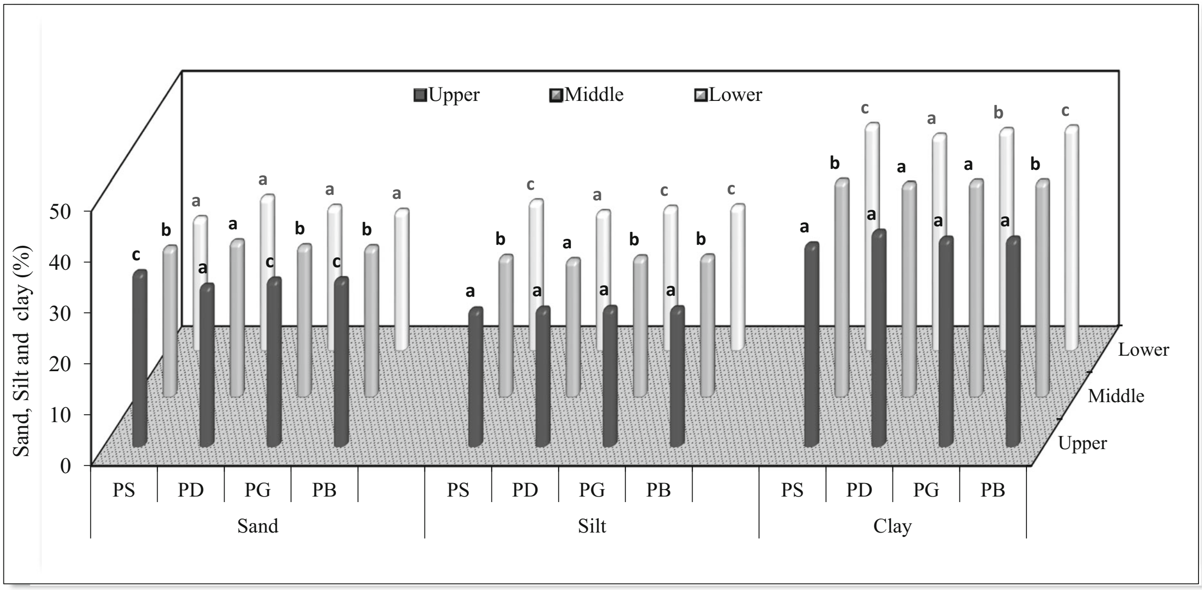


**Fig. 5** Sand, silt and clay as influenced by slope under different potato-legume intercropping systems. PS: pure potato stand, PD: potato-dolichos, PG: potato-pea, PB: potato-bean. Bars with the same letter (down the slope within the same intercropping system) depict means that are not significantly different at $p \leq 0.05$

### Soil chemical properties as influenced by slope position under different intercropping systems

There was significant ($p \leq 0.05$) influence of slope positions under different potato-legume intercropping systems on soil chemical properties (Table 3). The soil pH was higher by 0.1 unit in PG and 0.2 units in PD and PB compared with PS, and it increased significantly down the slope in all the treatments. The *P* value recorded in PS (23.5 mg kg$^{-1}$) at the lower slope position was significantly higher than at middle and upper slope positions by >8 mg kg$^{-1}$. There was no significant change in P content in PD in all the three slope positions. Irrespective of the slope position, P was in the order of PD (26.3 mg kg$^{-1}$) > PG (22.3) > PB (21.9) > PS (17.4), and they were 53, 23, 27 and 1% higher, respectively relative to the baseline values. Total N increased significantly down the slope in all the treatments except PD. Based on the intercropping systems, N differed significantly between cropping systems in the order PD (3.7 g kg$^{-1}$) > PB (3.3) > PG (3.2) > PS (3.1), and was 44, 28, 23 and 21% higher respectively, than baseline values. The OC recorded at the lower slope position in PS was significantly ($p \leq 0.05$) higher than at the middle and upper slope positions. A similar trend was observed in PG and PB whereas, in PD, OC was not affected by slope position. Soil organic carbon increased significantly by 20% in PG, 21% in PB and 42% in PD compared to PS.

### Relationship between the assessed variables of soil physical and chemical properties

Whereas, sand depicted no significant correlation with BD, it had significant and negative relationship ($r$ = 0.33–0.49; $p \leq 0.05$) with all the soil chemical properties namely pH, P, N, OC and CEC (Table 4). A similar relationship was observed between BD and these chemical properties. Nonetheless, all the soil chemical properties except pH had no significant correlations with silt. Clay, pH, P, N, OC and CEC had significant and positive correlations with each other with coefficients ranging from 0.38 to 0.84.

## Discussion

Spatial variability of soil physical and chemical properties is a common occurrence under potato-legume production systems. The high sand content recorded at the upper slope position in all treatments except potato-dolichos (PD) (Fig. 5) could suggest that the soil was

**Table 3** Soil chemical properties as influenced by slope position under different potato-legume intercropping systems

| Variable | Slope position | Pure potato stand | Potato-dolichos | Potato-pea | Potato-bean |
|---|---|---|---|---|---|
| Soil pH | Upper | 5.4 ± 0.1[a*] | 5.7 ± 0.0[a] | 5.7 ± 0.3[a] | 5.8 ± 0.2[a] |
| | Middle | 5.6 ± 0.1[b] | 5.9 ± 0.1[ab] | 5.8 ± 0.1[a] | 5.8 ± 0.3[a] |
| | Lower | 6.0 ± 0.2[c] | 6.0 ± 0.1[b] | 5.9 ± 0.1[b] | 5.9 ± 0.0[b] |
| | Mean | 5.7 ± 0.3C[#] | 5.9 ± 0.4A | 5.8 ± 0.2B | 5.8 ± 0.2B |
| Available P (mg $kg^{-1}$) | Upper | 13.6 ± 1.5[a] | 24.9 ± 1.0[a] | 19.6 ± 0.4[a] | 19.6 ± 0.5[a] |
| | Middle | 14.9 ± 2.0[a] | 26.3 ± 1.5[a] | 20.7 ± 1.4[ab] | 21.5 ± 3.3[ab] |
| | Lower | 23.5 ± 1.6[b] | 27.8 ± 1.2[a] | 23.2 ± 1.9[b] | 24.5 ± 0.8[b] |
| | Mean | 17.4 ± 4.8C | 26.3 ± 1.7A | 21.2 ± 2.0B | 21.9 ± 2.8B |
| Total N (g $kg^{-1}$) | Upper | 2.8 ± 0.4[a] | 3.7 ± 0.3[a] | 3.1 ± 0.6[a] | 3.2 ± 0.0[a] |
| | Middle | 3.0 ± 0.0[b] | 3.7 ± 0.3[a] | 3.2 ± 0.0[a] | 3.3 ± 0.7[b] |
| | Lower | 3.6 ± 0.1[c] | 3.8 ± 0.1[a] | 3.3 ± 0.2[b] | 3.5 ± 0.1[c] |
| | Mean | 3.1 ± 0.0D | 3.7 ± 0.3A | 3.2 ± 0.2C | 3.3 ± 0.3B |
| Organic C (g $kg^{-1}$) | Upper | 23.2 ± 3.1[a] | 36.4 ± 3.8[a] | 30.2 ± 3.3[a] | 27.6 ± 4.6[a] |
| | Middle | 24.6 ± 5.9[a] | 36.2 ± 3.8[a] | 31.6 ± 2.0[ab] | 32.5 ± 4.2[b] |
| | Lower | 31.8 ± 1.3[b] | 37.9 ± 1.6[a] | 33.4 ± 0.8[b] | 36.0 ± 2.5[c] |
| | Mean | 26.5 ± 4.1C | 37.5 ± 2.6A | 31.7 ± 2.3B | 32.0 ± 5.0B |
| CEC ($cmol_c$ $kg^{-1}$) | Upper | 25.4 ± 1.6[a] | 32.4 ± 0.5[a] | 30.6 ± 1.3[a] | 30.9 ± 0.5[a] |
| | Middle | 27.3 ± 1.5[a] | 32.8 ± 0.9[a] | 30.8 ± 0.7[a] | 31.3 ± 0.4[a] |
| | Lower | 31.0 ± 1.0[b] | 34.0 ± 0.6[b] | 32.2 ± 0.5[b] | 32.4 ± 0.4[a] |
| | Mean | 27.9 ± 0.3C | 33.0 ± 0.1A | 31.2 ± 0.1B | 31.6 ± 0.1B |

Analyses of variance (*p* values)

| Variable | Slope position | Intercropping system | Slope × System |
|---|---|---|---|
| pH | < 0.001 | < 0.001 | 0.007 |
| Available P | < 0.001 | < 0.001 | < 0.001 |
| Total N | < 0.001 | < 0.001 | < 0.001 |
| Organic C | < 0.001 | < 0.001 | 0.196 |
| CEC | < 0.001 | < 0.001 | < 0.001 |

[*, #] Upper and lowercase letters indicate comparisons for means (± standard deviation) among the slope positions and intercropping systems, respectively at $p \leq 0.05$ by Tukey's HSD test

prone to erosion hence detaching the finer particles from the surface and depositing them at the lower slope position. This is in agreement with the findings that report that clay, which is of finer and light materials, is more susceptible to erosion than sand particles (Hewawasam and Illangasinghe 2015; Elias 2017; Nyawade et al. 2018b). These results also concur with findings by Selassie et al. (2015) who reported significant sedimentation of clay particles at lower slope position compared to the upper part of the slope.

The non-significant variation in physical properties down the slope in potato-dolichos treatments could have been due to higher biomass production, which protected the soil particles from raindrop impact and being washed away by run-off. For instance, Gitari et al. (2018a) and Nyawade et al. (2018b) observed that during crop growth, potato-dolichos cropping system has a dense canopy that covers the soil, hence shielding it from the raindrop impact, which could result in detachment of fine clay particles. Secondly, as reported earlier by Nyawade (2015) and Gitari et al. (2018a), under intercropping systems there is high root density, which binds soil particles, hence reducing the susceptibility of the soil to erosion. This also supports the findings by Aranyos et al. (2016) that organic matter is vital in aggregating soil particles resulting in reduced compaction, hence promoting water infiltration and safeguarding the soil physical properties.

**Table 4** Correlation (Pearson) between the assessed variables: Soil moisture content (SMC), sand, silt, clay, bulk density (BD), soil pH, phosphorous (P) total nitrogen (N), organic carbon (OC) and cation exchange capacity (CEC)

| | SMC | Sand | Silt | Clay | BD | pH | P | N | OC |
|---|---|---|---|---|---|---|---|---|---|
| Sand | −0.36* | | | | | | | | |
| Silt | 0.17 ns | −0.89*** | | | | | | | |
| Clay | 0.42** | −0.97*** | 0.76*** | | | | | | |
| BD | −0.83*** | 0.20*** | 0.03 ns | −0.30* | | | | | |
| pH | 0.68*** | −0.49* | 0.40* | 0.49*** | −0.45** | | | | |
| P | 0.83*** | −0.34 ns | 0.16 ns | 0.40** | −0.76*** | 0.54*** | | | |
| N | 0.80*** | −0.38 ns | 0.18 ns | 0.44** | −0.84*** | 0.59*** | 0.84*** | | |
| OC | 0.71*** | −0.39 ns | 0.25 ns | 0.42** | −0.62*** | 0.56*** | 0.78*** | 0.77*** | |
| CEC | 0.70*** | −0.33 ns | 0.17 ns | 0.38** | −0.81*** | 0.49*** | 0.66*** | 0.72*** | 0.60*** |

Significant at $p < 0.001$ (***), $p < 0.01$ (**) and $p < 0.05$ (*). Ns denote not significant ($p > 0.05$)

The low soil bulk density (BD) that was reported under intercropping systems especially in PD than in pure potato stand (Fig. 4) could be explained in different ways. First, it is assumed that due to high canopy cover raindrops impact on the soil was reduced, which may have reduced compaction of the soil hence the observed low BD compared to monocropping, which had less ground cover. De Moraesa et al. (2016) observed that compaction tends to force soil particles together resulting in increased BD of the soil. In this study, there was high crop residue production under intercropping relative to monocropping systems, which after incorporation may have decomposed creating channels of biopores that could have reduced soil compaction, hence the low BD. Calonego and Rosolem (2010) and De Moraesa et al. (2016) observed that biopores increase friability of the soil, therefore, creating key pathways for water and air flow, and root growth. The low bulk density (BD) observed under intercrops relative to sole potato treatments is beneficial as it probably suggests greater porosity of the soil, which could facilitate water percolation and retention and movement of air and solutes. This reflects the ability of the soil to support plants growth, especially in sub-Saharan countries with erratic rainfall. The BD values reported in this study agrees with the 1.1 and 1.4 g $cm^{-3}$ range given by Arshad et al. (1996) for clayey soils as the ideal threshold for plant growth beyond which root growth is restricted. This was further reinforced by the significant correlations that were observed between textural indices and BD, and soil chemical properties such as CEC and pH (Table 4). The negative correlations observed between BD and chemical properties, particularly OC agrees with earlier findings (Aranyos et al. 2016; Annabi et al. 2017; Elias 2017).

In this study, the significantly higher pH and CEC values and higher concentrations of P, N and organic C in potato-legume intercropping systems (Table 3) support the importance of legume residues in improving soil fertility. For instance, the high N content in potato-legume treatments especially those involving dolichos could be attributed to the high-quality biomass that contains high levels of N and P (Table 2). This is in line with other findings reported by Cheruiyot et al. (2007) and Ojiem et al. (2007) that when legume residues such as that of dolichos are ploughed into the soil as green manure, they decompose rapidly to release N that is bound in them to the soil. This can explain the significantly higher pH, P, N, CEC and OC values that were observed under intercropping systems, especially in PD. Increase in P levels in intercrops above the potato pure stand agrees with Maltais-Landry and Frossard (2015) and Soltangheisi et al. (2018) who reported that legumes have the ability to mobilize P from the soil through solubilizing exudates such as carboxylates. This may explain the high P contents recorded in potato-legume plots compared to pure potato stand. The ability of legumes, particularly dolichos to take up nutrients and retaining them within their system, which later is released after decomposition could explain the observed uniformity in chemical properties under PD down the slope, which is in line with earlier findings (Gitari et al. 2018b; Soltangheisi et al. 2018). Therefore, inclusion of such a legume into potato production system in Kenyan Nitisols could mask the reduction of crop yield due to erosion; hence enhancing productivity (Gachene et al. 1997).

Indirectly, the significant increase that was observed in N and OC especially in potato-legume treatments (Table 3) could be linked to a microclimatic condition created by higher canopy during the crop growth period with low temperature (Gitari et al. 2018a; Nyawade et al. 2018a). Such conditions might have decreased soil N mineralisation resulting in less loss of N through leaching and erosion and could explain the high element levels after potato harvest in line with Neumann et al. (2012) finding that N mineralisation is slow when temperature decreases. Nonetheless, the ability of such green manures to release nutrients is dependent on factors such as their chemical composition, soil moisture and temperature (N'Dayegamiye et al. 2017). For instance, in accordance with Finney et al. (2016) and White et al. (2017) C:N ratio is the primary driver of N supply with legume crops with a low C:N ratio being able to assimilates high N content in their biomass, which results in a high N supply when their residues decompose compared to potato residues.

Conventionally, potato farmers apply di-ammonium phosphate fertilizer at planting and calcium ammonium nitrate for topdressing. Given that this study was carried out on a slopey terrain, some chemical elements from the applied fertilizers, especially in pure potato stand treatments, could have been washed away by runoff through soil erosion from the upper and middle slope positions to the lower slope position. These results agree with Nyawade (2015) who observed high losses of basic cations in pure potato stand compared to potato-legume intercropping systems. Such deposition of cations and other humic materials at the lower slope position could also explain the observed high CEC, N and OC, especially in pure stand treatment (Table 3) and reflect similar findings by Selassie et al. (2015) and Elias (2017).

Although P is less vulnerable to other losses pathways such as leaching, lateral flow of soluble P through erosion results in environmentally significant losses as attested by Burkitt et al. (2004) and Nyawade (2015). With carrying away of basic cation, it is expected that soil pH would decrease as it was observed especially at the upper slope position in pure potato stand treatment (Table 3). These results highlight the need for soil improving strategies to make Nitisols and other related tropical soils more productive under intensive potato-based cropping systems. In a similar study, Bekunda et al. (1997) reported that Nitisols tends to acidify with continuous cultivation without application of organic matter. Similar acidic conditions in Nitisols have been reported by Nyawade (2015) who observed lower pH value under pure potato stand compared with potato-legume intercropping systems, which was attributed to the transportation of cations through runoff. Moreover, as observed by Mallory and Porter (2007), prolonged uptake of the basic cations by potato with the minimal turnover of crop residues could also be responsible for decreased pH in pure potato stand.

The significant correlations that were observed between soil particle size indices and other soil properties such as CEC and pH (Table 4) was an indication that availability of soil nutrients is governed by texture, which is a key factor in improving soil quality. The observed positive correlation between clay and silt, and negative correlation with sand content and OC are consistent with past observations such as Elias (2017) in Ethiopia. The calcium ammonium nitrate fertilizer that was applied to all treatments might have supplied $Ca^{2+}$ (a key constituent of CEC), which could have resulted in the formation of strong $Ca^{2+}$-clay-OC bonds (Walia and Dick 2018). This could explain the observed strong correlations between CEC and OC. According to Rosemary et al. (2017), clay minerals and organic matter, which are negatively charged, are responsible factors for CEC as they act as anions to adsorb and hold the positively charged cations. Given that the major clay mineral in tropical Nitisols is kaolinite that has high negative charges then this could explain the high correlation between clay and CEC (IUSS Working Group WRB 2015; Elias 2017). The positive correlation among clay, P and OC also could be due to the adsorption of P onto organic matter and clay that is common on soils low in pH (Hopkins et al. 2014; Gitari et al. 2015).

The above results give an insight into soil improvements that could make Nitisols and other related tropical soils more productive under potato production systems. Ploughing back of crop residues, together with the soil protection provided by a more dense canopy in intercropping, could result in the greatest benefits in the long term by building up soil fertility and reducing soil erosion, hence enhancing their productivity (Ortiz-Escobar and Hue 2008; Maltais-Landry and Frossard 2015; Nyiraneza et al. 2015). Considering the high soil C and N observed in intercropping systems relative to potato pure stand, there is need to encourage farmers especially in sub-Saharan Africa to embrace intercropping systems that not only yield higher economic yield (Gitari et al.

2018a and b) but also yield higher organic biomass such as potato-dolichos.

## Conclusion

The results obtained in this study have indicated that potato-legume intercropping systems significantly influences important soil physical (bulk density) and chemical (pH, N, P, CEC and OC) properties. Soil texture was affected by the slope position with silt and clay increasing down the slope whereas sand recorded opposite results. Higher N, P, CEC and OC were observed at lower slope position than at middle and upper slope positions. These variables were significantly highest in PD than in other treatments, an indication that dolichos residues were more superior in not only improving soil fertility but also in reducing variability in soil physical and chemical properties at different slope positions. The study has shown that incorporation of crop residues into production systems is beneficial as it improves soil fertility probably by releasing the bound nutrients following their decomposition. This is worthwhile information for soil management that could not only enhance soil fertility of potato-based intercropping systems but also reduce variability of soil physical and chemical properties due to soil erosion. Therefore, potato-legume intercropping systems, especially those involving dolichos contribute to sustainable restoration of soil fertility over time, hence there is a need to upscale such intercropping systems to potato growing farmers in sub-Saharan Africa.

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