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Controlling soil erosion in smallholder potato farming systems using legume intercrops

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ABSTRACT

Soil and nutrient losses due to soil erosion are pronounced in potato growing areas of East Africa due largely to the rugged topography and high soil disturbance associated with potato cultivation. This study intercropped potato (*Solanum tuberosum* L.) with three grain legumes: lablab bean (*Lablab purpeurous* L.), garden pea (*Pisum sativa L.*) and climber bean (*Phaseolus vulgaris L.*) in runoff plots and assessed their impact on soil and nutrient losses in central Kenya highlands. Bare plots and sole potato stands were included as controls. Vegetal cover was measured at different potato growth stages while runoff and soil loss were quantified at every runoff generating event and used for nutrient analyses. Yields were expressed as potato equivalents (PEY) at the end of each season. Mean cumulative sediment yield decreased from 169 t/ ha in sole potato plots to 50–83 t/ ha in potato-legume intercropping, representing a reduction of 51–70%. The eroded sediment exported in large quantity the SOC (16.6–39.5 kg C ha^{-1} yr^{-1}), N (5.5–29.8 kg N ha^{-1} yr^{-1}), P (3.9–16.4 kg P ha^{-1} yr^{-1}) and K (5.2–14.6 kg K ha^{-1} yr^{-1}) and were consistently higher in sole potato plots relative to potato-legume intercropping. These losses occurred mainly at potato emergence following fertilizer application. Stronger associations of sediment nutrient enrichments was found with the micro-aggregates (250–50 μm) than with the macro-aggregates (>250 μm) pointing to the different degree of nutrient mobilization and distribution in eroded sediment. The PEY were significantly greater in potato-lablab bean system than in sole potato, while intercropping with garden pea and climber bean showed similar PEY to that of sole potato, suggesting that potato-lablab system may be preferred by the smallholder farmers. These results justify the need to intercrop potato with indeterminate legume intercrops, a strategy that must be done in a way guaranteeing high yield stability to the smallholder farmers.

1. Introduction

Soil erosion by water causes soil loss at a rate 20 to 40 times higher than that of soil formation on a global scale making it difficult to restore the destroyed soils within a time span that bears any relations to human history. This rate corresponds to an annual soil loss of 75 billion tons, which in economic terms is equivalent to USD 400 billion per year or approximately USD 70 per person per year (Lal, 1998). The process degrades 30,000 ha of arable land annually and causes nutrient depletion at a rate of 30 kg of nitrogen per ha and 15–20 kg of phosphorus per ha (Berry, 2003; EARO, 2002; Pender et al., 2002; UNDP, 2002). In Africa, yield reductions due to soil erosion ranges from 2 to 40%, with an annual mean of 8% (Lal, 1995). If the accelerated soil erosion rates are unabated in Africa, crop yield reduction of 9.2 million tons is projected to occur in roots and tubers by the year 2020 (Mitiku et al., 2006).

In East Africa, soil erosion occurs mainly in the highlands where land scarcity forces crop production on the steep hillsides with slopes ranging between 10 and 55% (Athanase, 2013; Gitari et al., 2019; Nyawade et al., 2019). In Kenya, soil erosion by water causes soil loss at a rate of 60 to 244 tons per ha per year (Khisa et al., 2002; Zobisch et al., 1993; Tongi, 1990; Gachene et al., 1997; Nyawade, 2015; Nyawade et al., 2018a, 2018b). Potato production is of special importance to soil erosion occurrence in Kenya as this activity is mainly carried out on the rolling topography without adequate soil conservation measures (Nyawade et al., 2018b; Gitari et al., 2018a, 2018b). The producers are mainly smallholder farmers cultivating this crop in pure stands. This is despite

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the fact that potato crop establishes protective cover only at 45–60 days after planting and does not yield sufficient surface mulch upon harvest (Nyawade, 2015).

In addition, cultivation of potato entails maximum soil disturbance as weeding and hilling activities are conducted twice, at about 10 and 30 days after potato emergence to build up adequate ridges for optimal tuber formation and bulking. These activities loosen the soil, making it susceptible to detachment by raindrop splash. Accelerated raindrop splash destroys the soil structure thus increasing runoff turbulence and the transporting capacity of surface flow (Han et al., 2010; Zheng et al., 2009). The higher the speed of this flow, the more soil is splashed and the larger the diameter of raindrops, the bigger will be the impact area. A study conducted by Nyawade et al. (2018b) demonstrated a decrease in soil splash intensity with increasing canopy density and decreasing canopy height. Ma et al. (2015) suggested that the reduction in the value of rainfall energy is proportionate to the changes in throughfall intensity and the diameter distribution of water drops under the canopy.

At a micro-scale, the splash effect of raindrop causes peeling of aggregates resulting in disproportionate distribution of soil aggregates. Thus when runoff occurs, the finer and lighter soil materials enriched with nutrients are preferentially entrained (Lal, 2001). The eroded soil material is therefore richer in nutrient elements compared to the source soil, resulting in higher nutrient enrichment ratios. For most of the eroded soil material, the nutrient enrichment ratio is greater than unity (Polyakov and Lal, 2004) and is particularly high for phosphorus, soil organic carbon and nitrogen due to their strong association with clay which is preferentially mobilized in the eroded sediment (Six et al., 2002; Quinton et al., 2001). Potassium is mobilized mainly in runoff water due to its high solubility and mobility (Bertol et al., 2007). Other nutrients such as calcium and magnesium, and the cation exchange capacity have in general recorded enrichment ratios greater than unity (Tongi, 1990; Zobisch et al., 1993; Nyawade, 2015; Gachene et al., 1998).

Indeterminate legume intercrops such as lablab bean (*Lablab purperous L.*) can ensure continuity of protective cover throughout the year and protect the soil aggregates against raindrop impact (Nyawade et al., 2018b). Ma et al. (2015) noted that the effect of crop canopy on splash erosion is modified not only by the crop coverage, but also by the rainfall characteristics, pointing to the need to consider other confounding factors such as soil surface roughness while evaluating the effects of cover crops on soil erosion. It is in this regard that this study intercropped potato with lablab bean, climber bean and garden pea and quantified runoff, sediment yield and nutrient export in eroded sediment. The eroded sediment nutrient load expressed as enrichment ratios were related to the soil surface roughness, vegetal cover and soil aggregates. Yields expressed as potato equivalents were measured to check against the adverse effect of each intercropping system. A legume intercropping system capable of controlling soil erosion and the associated nutrient export with positive effect on crop yield is an ecologically sustainable strategy necessary for restoring the impoverished soil productivity in smallholder potato farms.

2. Materials and methods

2.1. Study site

This study was carried out at Upper Kabete Research Farm of the University of Nairobi, Kenya during the rainy seasons of 2015–2016. The site is located along latitude 1° 15′ S and longitude 36° 44′ E at an altitude of 1854 m above sea level. Kabete is characterized by bimodal rainfall distribution which occurs in two seasons: March to June for the wet season (long rains) with average rainfall amount of 700 mm, and October to December for the dry season (short rains) with average rainfall amount of 400 mm. Mean annual air temperature ranges from 15 °C to 27 °C. Kabete has a characteristic rolling topography with slopes ranging between 8% and 30%, making soil erosion by water a major problem.

The soils in Kabete are clay-loam classified according to FAO soil classification system as Humic Nitisol (Gachene, 1989). These soils are equivalent of Alfisols in the USDA soil classification system. Nitisols occupy approximately 228,000 km^2 of land area in East Africa and are the dominant soils in the potato growing areas of Kenya (Swift et al., 1994; Muchena and Gachene, 1988). Nitisols are very deep soils and are well drained, dark red friable clay, showing an ABC sequence of horizon differentiation with clear and smooth boundaries. The top soil overlies an argillic B horizon and has an erodibility factor of 0.04 (Barber et al., 1979; FAO, 2012; Jaetzold et al., 2012). These soils have low to moderate inherent soil fertility. Soil characteristics of the surface profile (0–30 cm) before start of the experiment are given in Table 1. According to land evaluation specifications by Landon (1991), the exchangeable potassium, total nitrogen, CEC and total organic carbon contents were moderate, while contents of soil pH and available P and sand were low.

2.2. Experimental design and crop management

The study was conducted in bounded runoff plots laid out in a randomized complete block design on a 12% slope (Fig. 1). Each plot measured 2.4 m wide and 5.8 m long and was laid with the longest dimension parallel to the slope. The plots were located in between a *fanya-juu* terrace on the upper side of the slope and a cutoff drain on the lower end of the slope, and at right angle to the contours. The *fanya-juu* terrace served to intercept the runoff produced on the area above the plots and prevented it from entering the runoff plots site, while the cutoff drain disposed the runoff produced in the runoff plots site and the sediment discarded after sampling. The treatments comprised of bare soil, potato (*Solanum tuberosum* L.-cv Shangi) grown alone and intercropped with garden pea (*Pisum sativa L.*), climber bean (*Phaseolus vulgaris* L.) and lablab bean (*Lablab purpureus* L.), each replicated four times.

Potatoes were planted on pre-hilled ridges, a practice that allowed for legumes to be intercropped within the inter-rows between the potato ridges with ease of cultural activities. Pre-hilling was carried out by piling up the soil to a height of approximately 20 cm and 15 cm top width with hills oriented across the slope. Bare plots were also pre-hilled with the same dimensions and orientations just like the other treatments but were kept uncropped. Pre-sprouted tubers were planted on the ridges at a uniform depth of 10 cm and spaced at 30 cm within the ridges and 90 cm between the ridges giving a plant population of 37,037 plants per ha for the sole potato stands. For intercrops, one legume bean seeds per hole were planted at inter-row space between the two potato ridges (at approximately 45 cm from the potato row) and within row space of 30 cm giving total plant population of 74,074 plants per ha (i.e. potato + legumes).

Planting for legumes was done at the same time as that of potato. A plot of sole potato stands accommodated 8 rows of plants while that of intercrops accommodated 15 rows. Weeding was performed at 15 and 35 days after potato emergence when the plants were about 15–30 cm high. This activity was conducted using hand hoes which

Table 1
Baseline soil properties (0–30 cm) of the experimental site.

Soil property	Unit	Content
pH-H_2O (1:2.5)	–	5.21
Total soil organic carbon	%	2.62
Total nitrogen	%	0.26
Available phosphorus	ppm	16.91
Exchangeable potassium	cmol kg^{-1}	1.82
Clay	%	51.00
Silt	%	29.22
Sand	%	19.80
CEC	cmol kg^{-1}	24.00

Fig. 1. Runoff plots installed at right angle to the contours and parallel to the slope.

were used to revamp the pre-hilled ridges. Control bare plots were also revamped at these times and were kept bare throughout the season by plucking the emerging weeds every 7 days interval.

Fertilization constituted full amounts of 90 kg nitrogen (N) ha^{-1}, 90 kg phosphorus (P) ha^{-1}, and 90 kg potassium (K) ha^{-1} applied as basal at planting in the form of NPK (17:17:17). For the legumes, triple super phosphate (0:46:0) was applied at planting at a uniform rate of 50 kg P ha^{-1}. The potato crops were sprayed with alternations of Ridomil Gold MZ 68WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) and Dithane-M (Mancozeb) to control late blight infection while aphids, white flies and other insects were controlled using alternations of Duduthrin (Lambda-cyhalothrin 17.5 g L^{-1}) and Bestox 100 EC (Alpha-cypermethrin 50 g L^{-1}) sprayed on potatoes and legumes. Spraying for late blight and insects was done at 2 weeks interval from week one after potato emergence to physiological maturity.

Legume intercrops were harvested by plucking the pods at maturity, leaving the rest of the plant to continue providing postharvest vegetal cover. Potato crops were harvested at maturity by carefully rooting out the tubers from the whole plot using hand hoes, retaining the residues in the plots. All the dead plant matter was incorporated back into the soil at start of the subsequent season.

2.3. Soil sampling and nutrient analyses

Composite soil samples were collected from each plot using soil auger at 0–30 cm depths for baseline characterization. The soil samples were air-dried, passed through 2 mm sieve and analyzed for Soil pH using 1:2.5 ratio of soil to water, total N by the Kjeldahl digestion, available phosphorus and extractable potassium by Mehlich 1 procedures, and soil organic carbon by wet oxidation method (Okalebo et al., 2002). Soil texture was analyzed by hydrometer method as outlined by Anderson and Ingram (1998).

2.4. Meteorological and raindrop indices

Rainfall depth and intensity were measured using an onsite tipping bucket rain gauge with tip time recorded at 0.5 s accuracy using a data logger (HOBO Event MA, USA). Rainfall kinetic energy (KE) was computed using the Wischmeier and Smith (1958) model equation (Eq. 1).

$$KE = 11.9 + 11.8\ log_{10} I \tag{1}$$

where I is the rainfall intensity in mm h^{-1}.

Throughfall raindrops were quantified using a laser drop-sizing gauge (LX2-02; KEYENCE Corp., Osaka, Japan) (Nanko et al., 2006, 2008). The gauges were located in each plot directly under the canopy and were adjusted immediately after every rainfall event. Raindrop sizes were computed from the relationship between the interception rate and the output voltage. These gauges collected and measured water amounts inside and calculated rainfall intensity under the canopy.

Kinetic energy of open rainfall was calculated using Eq. (2).

$$KE_{mm[OP]} = 8.95 + 8.44\ log_{10} I_{1h} \tag{2}$$

where [OP] represents open rainfall, and I_{1h} is hourly rainfall intensity (mm h^{-1}).

Throughfall kinetic energy was calculated using Eq. (3).

$$KE_{mm}[TH] = p * KE_{mm} + (1-p) * KE_{mm} \tag{3}$$

$$KE_{mm}[DL] = \sqrt[c]{PH-d}$$

$$PH = H_{bottom} + \frac{1}{(LAI+1)}(H_{top} - H_{bottom})$$

where DL denotes the leaf drip, PH is the plant height index, Hbottom is the height from the first branch, Htop is the crop height at the top and LAI is leaf area index measured using a Sunfleck Ceptometer (Decagon Devices, Pullman, WA, USA). The coefficient of free throughfall (p) was assumed to equal 0.3 for a canopy in full leaf, and thereafter to increase linearly as the LAI decreased (Mulder, 1985). A hypothetical canopy with a LAI of zero should have a *p* of unity (Nanko et al., 2006, 2008). Thus we used a linear regression relating *p* to LAI to determine *p* when the LAI was not fully closed.

2.5. Crop cover estimation

Crop cover was quantified using point frame consisting of a single row of 10 pins spaced 10 mm with tripods measuring 2 m in height (Coxson and Looney, 1986). This activity started from 7 days after potato emergence, then progressively at 2 weeks interval (corresponding to different stages of potato growth) until 60 days after potato harvest. This was meant to capture the postharvest contribution of vegetal cover to soil erosion control. The frame was placed on the ground across the middle rows and the pins lowered until they touched plant leaves. The numbers of pins that touched the leaves were recorded and percent cover calculated using Eq. (4). The point frame was validated using datasets taken with sighting frame in the same study period.

$$Percent\ groundcover = \frac{Number\ of\ pins\ that\ hit\ plant\ leaves}{Total\ number\ of\ pins}\ x\ 100 \tag{4}$$

2.6. Estimation of soil surface roughness

Soil surface roughness (SSR) was estimated using pin relief meter (Kuipers, 1957). The relief meter consisted of 1 m^2 aluminum frame containing 20 pins with 0.8 m length and 0.05 m equidistant. Measurements were taken immediately after land preparation and progressively at 2 weeks interval. The relief meter was placed horizontally on the soil surface across the plant rows and the height of each pin above the top of the frame recorded. Measurements were made along a 1 m transect perpendicular to the tillage direction by moving the frame over 20 mm, along the length of the 1.0 m^2 plot. Soil surface roughness was computed using Eq. 5. Differences in measured surface elevations were corrected to remove the effect of arbitrary datum so that only soil micro-relief was represented. Since this study exhibited both random and oriented roughness, validation of dataset used for relief meter readings was performed as described by Nyawade et al. (2018a).

$$SSR\ (\%) = \log[stdev] * 100 \tag{5}$$

where SSR, soil surface roughness, log is the logarithm, stdev, the standard deviation of the pin height.

2.7. Quantification of soil loss and runoff

Eroded sediment was quantified in each runoff generating event following procedures described by Wendelaar and Purkins (1979). The runoff-sludge mixture was thoroughly stirred, allowing the resultant suspension to settle for 30 min. The runoff water overlying the settled sludge was decanted and measured using a graduated bucket. A 100 ml suspension sample was oven-dried at 105 °C for 48 h and expressed as dry soil mass in grams per liter. Total soil loss was computed using Eq. (6)–(9).

$$\mathit{Sediment\ wt}\ (kg) = \left[\frac{\frac{\mathit{Oven\ dry\ sediment\ sample\ wt}\ (g)}{\mathit{Wet\ sediment\ wt}\ (g)} * \mathit{Total\ field\ sediment\ wt}\ (g)}{1000}\right] \tag{6}$$

$$\mathit{Sediment\ conc}\ \left(kg\ l^{-1}\right) = \mathit{Total\ runoff} * \mathit{Sediment\ wt}\ (kg) \tag{7}$$

where runoff was calculated using Eq. (8).

$$\mathit{Runoff}\ (mm) = \frac{\text{Total Runoff Volume } (\text{m}^3)}{\text{Plot Area } (2.4 \text{ m x } 5.8 \text{ m})} \tag{8}$$

$$\mathit{Soil\ loss}\ \left(t\ ha^{-1}\right) = \left[\frac{\mathit{Total\ runoff}\ (l) * \mathit{sediment\ coc.}\left(g\ l^{-1}\right)}{1000}\right] \tag{9}$$

2.8. Determination of soil splash detachment

Soil splash detachment was measured from each plot using splash cups (Morgan, 1978) made of hollow plastic cylinders pushed into the ground so that the top was flush with the soil surface. The cups had a circular catching tray and a partition board dividing the tray into upslope and downslope compartments. The boundary wall size was designed to a height of 20 cm and a diameter of 20 cm to prevent splash-in from outside and splash-out from the cup. The cup slope was reduced to nearly 0° to prevent rainfall from entering the exposed soil area and to exclude runoff effects. Four splash cups were placed in each plot; in the inter row between potatoes and legumes for intercropping and between two potato rows for the sole potato plots. The soil particles detached by splashing were caught in the catch tray and were collected and freed from litter fall, and averaged for each plot after each rainfall event. About 20 g samples were oven-dried at 105 °C for 48 h and expressed as dry soil mass per square meter. The soil splash detachment rate (SD) was calculated using Eq. (10).

$$SD\ (g\ m^{-2}) = \left[1 - \exp\left(-\frac{\pi R}{2\Lambda}\right)\frac{2\Lambda}{\pi R}\mu\right] \tag{10}$$

where; R = cup radius (m); Λ = average soil splash length in m; μ = actual detachment rate in g m^{-2}.

The reduction coefficient for splash detachment under the crop canopy was calculated using Eq. (11).

$$\mathit{Reduction\ coefficient}\ (\%) = \frac{SDR_{BL} - SDR_{Crop}}{SDR_{BL}} * 100 \tag{11}$$

where SDR_{BL} is the splash detachment rate on bare soil (g m^{-2} h^{-1}), and SDR_{Crop} is the splash detachment rate under crop canopy (g m^{-2} h^{-1}).

2.9. Particle size separation

Aggregate size partitioning was used to separate the eroded sediment into size fractions (Cambardella and Elliot, 1992; Sohi et al., 2001) (Fig. 2). Briefly, 50 g of the sediment was dispersed by 50 ml of 5% sodium hexametaphosphate made to 250 ml using 200 ml deionized water. The sample was shaken overnight and passed through series of sieves of sizes 250–53 μm on a mechanical sieve shaker. Sand fractions were retained on sieves >50 μm while silt and clay fractions (<50 μm) were repeatedly siphoned off.

2.10. Determination of crop yield

The tuber and legume yields were estimated from the central 1.2 m^2 area of each plot, representing 20 potato plants and 20 legume plants. Tubers were dug out using fork hoe at 85–95 days after planting when the stems were completely dry, brushed and fresh weight taken. About 500 g of the samples from each plot were sliced and dried in an oven at 65 °C for 72 h and reweighed to determine tuber dry weight. Harvesting for climber bean and garden pea was done at 80–100 days after planting while that of lablab bean was done after 115–130 days after planting. The aboveground biomass estimations was done by cutting the plants at the soil surface using machetes. The dry mass was determined by oven-drying about 500 g samples at 65 °C to a constant mass. The yield (for tubers and legumes) was converted into potato equivalents (PEY) terms using Eq. (12). For lablab bean, the estimations considered grain and shoot biomass separately for this legume is used both as pulse and forage.

$$\begin{aligned} PEY\ \left(t\ ha^{-1}\right) &= PY\left(kg\ ha^{-1}\right) \\ &+ LY\ \left(kg\ ha^{-1}\right) * LP\ \left(US\frac{kg^{-1})}{PP\ \left(US\ kg^{-1}\right)}\right. \end{aligned} \tag{12}$$

Where PEY = potato equivalent yield, PY = potato yield, LY = legume yield, PP = market price of potato (0.35 US$ kg^{-1}) and LP = market price of the legume (1.60, 1.25, 0.05 and 1.70 US$ kg^{-1} for garden pea grain, climber bean grain, lablab bean forage and lablab bean grain respectively).

2.11. Statistical analysis

Data was subjected to analysis of variance (ANOVA) using Genstat 15th version. The statistical significance was determined at $p \le 0.05$, while means were separated using the Fischer's least significant difference (LSD) test. Pearson's correlation analysis was conducted to establish the relationship between sediment particle size and nutrient load in the eroded sediment. Paired *t*-test and General Linear Model (GLM) analyses were performed to determine the response of soil and nutrient losses to vegetal cover, rainfall kinetic energy, throughfall kinetic energy and their interactions.

3. Results

3.1. Rainfall characteristics during the study period

Fig. 2 presents the rainfall characteristics for the observation period between 3rd March 2015 and 20th August 2016 under which the soil erosion occurred. Over this period, 116 rainy days were observed with cumulative rainfall amount of 1620 mm. Soil erosion was generated by 27 rainfall events which recorded rainfall amounts ranging from 33 to 104 mm per event with maximum rainfall intensities between 10.9 and 58.4 mm h^{-1}. Largest sediments were produced by eight most intense rainstorms with maximum rainfall intensities between 48.9 and 58.4 mm h^{-1} and kinetic energy between 61.3 and 74.5 J m^{-2}, and

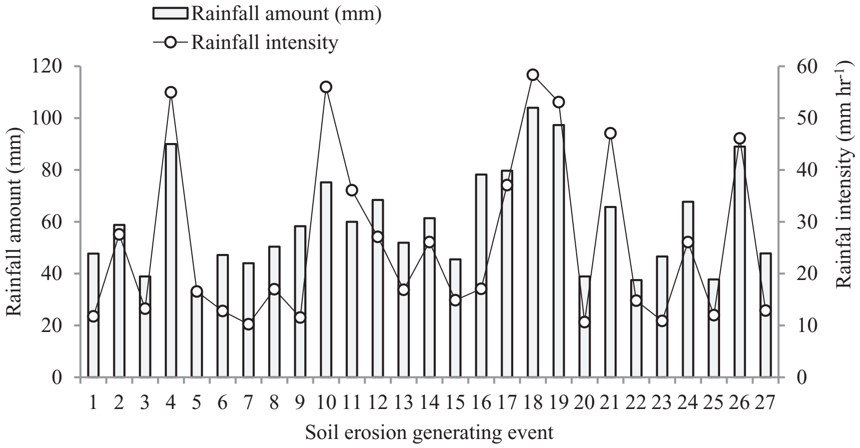

Fig. 2. Rainfall amounts and the corresponding rainfall intensity measured during each runoff event.

accounted for 80 to 95% of the total soil loss recorded during this study period. The greatest rainfall irrespective of the season, occurred at potato emergence stage.

3.2. Crop cover establishment by the different cropping systems

Crop cover development differed among the cropping systems and was on average highest in potato-lablab, followed by potato-climber bean, potato-garden pea and lowest in pure potato plots (Fig. 3). Cover development was higher in 2015/16 long rains than in the 2015 short rains. Compared to the intercrop plots which attained groundcover above 40% in 14–25 d after planting, the pure potato stands attained this coverage after 40–50 days after planting. Maximum canopy cover was attained at pre-flowering stage regardless of the treatment and season, and decreased progressively from tuber initiation to <10% after potato harvest, except in potato-lablab intercropping which maintained groundcover above 50% after potato harvest.

3.3. Temporal changes in soil surface roughness

Soil surface roughness generally decreased in height with progressive increase in cumulative rainfall, but exhibited a sharp increase (of 44–68%) at vegetative phase I and pre-flowering stages when hilling was performed, decreasing gradually thereafter (Fig. 4). Soil surface roughness of the bare plots however, increased by 20% at post-potato harvest of the 2016 long rains. Soil surface roughness of the pure potato stand decreased from the initial height at pre-flowering (second hilling) by 53–62%, on average, after receiving accumulative rainfall amount of between 250 and 300 mm. This was 13–60% higher compared to the decay under potato-lablab bean system. The decay of soil surface roughness under protective cover was significantly lower by 13–55% than when the soil was bare. Soil surface roughness taken immediately after land preparation in the subsequent seasons was 6–15% higher in bare plots than in plots under canopy.

3.4. Throughfall and splash detachment rate at different stages of potato growth

The throughfall intensity ranged between 5.8 mm h^{-1} in potato-lablab and 32.4 mm h^{-1} in pure potato stands with kinetic energy ranging between 8.8 J m^{-2} and 42.8 J m^{-2} (Table 2). Maximum values of throughfall intensity and kinetic energy were recorded at potato emergence stage regardless of the treatments. The splash detachment rates were on average lower under crop canopy by 109 to 500 g m^{-2} h^{-1} than in bare soil, representing a reduction of 27% to 88%. The average splash detachment coefficient increased with increasing leaf area index up to bulking stages and generally decreased with decreasing leaf extinction coefficient. Potato-lablab intercropping recorded markedly higher detachment coefficient at maturation and post-potato

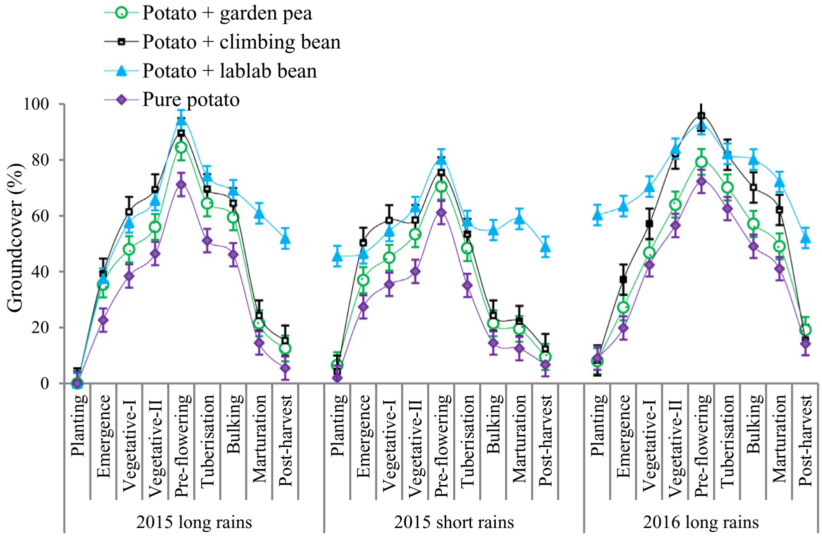

Fig. 3. Development of crop cover by different cropping systems during the study period (March 2015 to August 2016). Vertical bars indicate standard error of means.

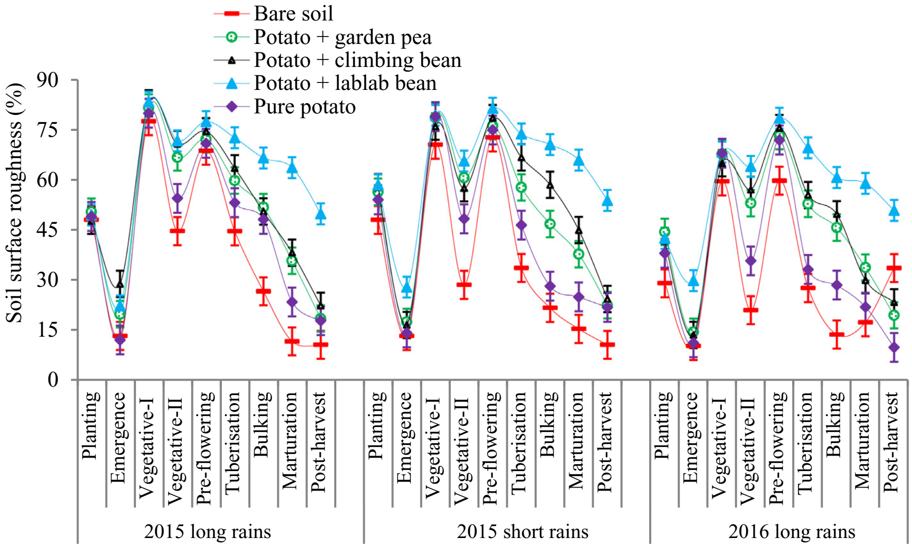

Fig. 4. Changes in soil surface roughness at different stages of potato growth during the study period (March, 2015 to August, 2016). Vertical bars indicate standard error of means.

harvest stages compared to other treatments. This represented 16% to 53% soil detachment reduction ability over pure potato.

3.5. Soil loss and runoff

Mean seasonal soil loss and runoff differed significantly among the treatments ($p < 0.05$) and were consistently highest in bare plots and lowest in potato + lablab intercropping plots (Table 3). Compared to the bare plots, cumulative soil loss reduced by 62% in potato + lablab bean intercropping and by 48% in potato + climber bean, while soil loss reduction was only 21% in pure potato stand. Cumulative runoff showed a similar trend reducing by 22 to 69% respectively in pure potato and in potato + lablab plots relative to the bare soil. There was no significant differences in runoff and soil loss between plots with potato + garden pea and potato + climber bean regardless of the season.

3.6. Nutrient export in eroded sediment

The rates of nutrient export by the eroded sediment were significantly greater for sole potato relative to intercropping and decreased in the order of potato + garden pea, potato + climber bean and potato + lablab bean (Fig. 5). Soil organic carbon export rates decreased from 39.5 kg C ha^{-1} yr^{-1} in pure potato stands to 16.6 kg C ha^{-1} yr^{-1} in potato + lablab bean representing a reduction of 44%. The pure potato stands however recorded significantly lower SOC export rates relative to the bare plots (54.6 kg C ha^{-1} yr^{-1}). The export rates of NPK were

Table 2
Throughfall and splash detachment rates as measured at different stages of potato growth.

Potato growth Stage	Treatment	LAI m^2 m^{-2}	Leaf extinction coefficient§	Throughfall intensity mm h^{-1}	Throughfal KE J m^{-2}	Splash detachment rate g m^{-2} h^{-1}	Splash Reduction coefficient. (%)
Emergence	Bare soil	§	§	§	§	789d	Base
	Pure potato stand	0.33a	0.61d	‡	‡	474c	56a
	Potato + garden pea	0.98b	0.56c	‡	‡	351b	53a
	Potato + climber bean	0.99b	0.51b	‡	‡	336b	57a
	Potato + lablab bean	1.81c	0.49ab	‡	‡	222a	59a
Vegetative	Bare soil	§	§	§	§	554d	Base
	Pure potato stand	3.08a	0.46b	32.4c	42.8c	234c	59a
	Potato + garden pea	3.41b	0.36a	22.9b	28.8b	184b	68b
	Potato + climber bean	3.67bc	0.35a	21.7b	24.8b	177b	69b
	Potato + lablab bean	3.79c	0.32a	15.5a	11.8a	69a	88c
Bulking	Bare soil	§	§	§	§	447d	Base
	Pure potato stand	2.19a	0.57b	19.8c	29.8c	201c	55a
	Potato + garden pea	2.85b	0.36a	9.8b	21.8b	169b	62c
	Potato + climber bean	3.09bc	0.38a	11.9b	28.8c	175b	61bc
	Potato + lablab bean	3.49c	0.35a	5.8a	8.8a	68a	84d
Maturation & postharvest	Bare soil	§	§	§	§	398d	Base
	Pure potato stand	0.11a	0.61c	11.9c	21.8b	289c	27a
	Potato + garden pea	0.96b	0.48b	7.8b	18.8bc	198b	50b
	Potato + climber bean	1.18b	0.47b	6.8ab	24.8c	201b	50b
	Potato + lablab bean	3.12c	0.35a	5.9a	9.8a	75a	81c

Means followed by different letters within a column denote significant differences at Fischer's $p \leq 0.05$. § indicates data not taken in bare plots due to lack of vegetal cover while ‡ denotes data not taken due to undeveloped canopy just after plant emergence. Values are presented as pooled means.

Table 3
Mean seasonal and cumulative soil loss and runoff at different stages of potato growth.

		Soil loss					Runoff				
		Bare soil	Pure potato	Potato + garden pea	Potato + climber bean	Potato + lablab	Bare soil	Pure potato	Potato + garden pea	Potato + climber bean	Potato + lablab
	Potato growth stage	(t ha^{-1})					mm				
Long rains 2016	Emergence	20.4a	17.7b	10.2c	9.2c	8.0c	13.2a	11.7a	6.7b	6.8b	6.0b
	Vegetative	16.1a	9.0b	8.8c	6.2c	3.8d	11.5a	8.5a	4.9b	4.2b	2.6b
	Tuber initiation	16.3a	11.7b	7.2c	6.8c	2.0d	9.5a	7.9a	4.8b	4.1b	1.2c
	Post-harvest	17.5a	16.7a	7.2b	5.2b	1.4c	8.5a	6.7a	3.9b	3.4b	1.4c
	Total	70.3a	55.1b	26.1c	27.4c	15.2d	42.7a	32.1a	20.3b	18.5b	12.6b
Long rains 2015	Emergence	24.8a	22.4b	8.7c	7.8c	6.0c	21.4a	20.7a	13.8b	13.2b	10.1b
	Vegetative	18.1a	12.0b	7.7c	7.3c	4.6c	12.2a	8.0b	3.1c	3.2c	2.8c
	Tuber initiation	14.5a	9.4b	8.6b	7.2b	2.1c	11.4a	6.4b	4.2c	3.1c	1.7d
	Post-harvest	20.5a	18.7a	6.1b	5.3b	3.0b	9.5a	8.9a	3.8b	3.2b	1.1c
	Total	77.9a	62.5b	31.0c	34.6c	17.6d	54.5a	43.8b	24.7b	22.7b	16.5b
Short rains 2015	Emergence	22.6a	20.4b	8.4c	8.2c	7.0c	18.9a	16.7a	11.4b	10.2b	8.8c
	Vegetative	14.6a	8.0b	5.5c	5.2c	4.8c	8.8a	5.2b	2.9c	2.6c	1.7d
	Tuber initiation	11.5a	9.7a	5.7b	5.2b	2.0c	7.3a	5.8b	4.9c	4.3c	1.4d
	Post-harvest	16.3a	13.2a	5.9b	5.5b	1.3c	8.5a	7.3a	3.8b	3.1b	2.0b
	Total	65.0a	51.3b	25.5c	25.1c	17.1d	43.5a	34.0b	23.0b	20.2b	13.9b
Cumulative		213a	169b	83c	82c	50d	141a	110b	68c	61c	43c
Reduction coefficient (%)		Base	21	45	48	62	Base	22	44	56	69

Means followed by different letters across the rows denote significant differences at Fischer's $p \leq 0.05$.

significantly greater in pure potato plots (29.8, 16.4, 14.6 kg ha^{-1} yr^{-1} respectively) than in bare soil (12.4, 39.87 kg ha^{-1} yr^{-1}) and lowest in potato-lablab intercropping. Intercropping with climber bean and garden pea generally exhibited statistically similar soil nutrient export rates irrespective of the nutrient element tested.

3.7. Response of soil and nutrient losses to vegetal cover and raindrop indices

Significant linear dependence of soil loss on rainfall kinetic energy ($p = 0.009$; $\beta = 0.137$), vegetal cover ($p = 0.012$; $\beta = -2.34$) and throughfall kinetic energy ($p = 0.023$; $\beta = 0.008$) was found (Table 4). Throughfall kinetic energy interacted with vegetal cover and rainfall kinetic energy ($p = 0.003$; $\beta = -0.642$) to influence soil loss. Nutrient loss significantly depended on vegetal cover ($p = 0.006$; $\beta = 1.727$) and rainfall kinetic energy ($p = 0.041$; $\beta = -0.053$).

3.8. Relationships between sediment particle size and nutrient enrichments

The highest positive coefficients ($r = 0.87$; $p < 0.001$) were exhibited by SOC and fine silt and clay particles (Table 5). Available P related significantly with silt plus clay particles and micro-aggregates, similar to exchangeable K and CEC. Soil pH related significantly with all the analyzed soil fractions.

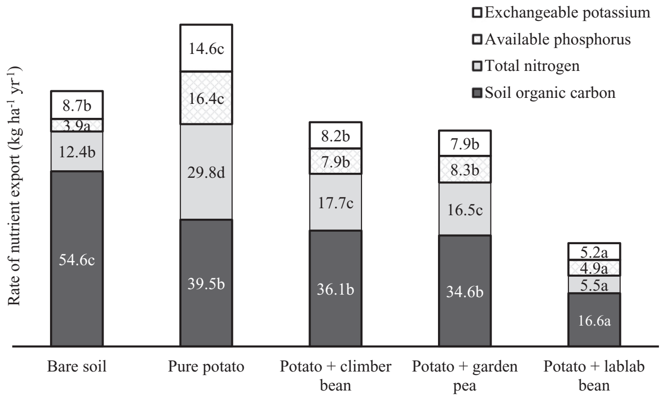

Fig. 5. Nutrient export rate as measured under different treatments. Data presented as pooled averages of the three seasons. Values with different letters for a given element are significantly different at $p \leq 0.05$ according to Fischer's LSD test.

3.9. Intercropping effect on potato yield

Potato equivalent yields (PEY) differed significantly between the treatments ranging between 6.7 t/ha in potato + climber bean and 17.6 t/ha in potato + lablab bean across the seasons (Fig. 6). Despite the lack of significant differences, the PEY were notably lower in potato + climber bean (6.7–8.6 t/ha) relative to sole potato stands (7.1–9.9 t/ha). For potato-garden pea intercropping (7.7–10.3 t/ha), the PEY was numerically higher compared to sole potato stands but indicated statistical similarities irrespective of the seasons. The PEY were significantly higher in the long rains than in the short rains.

4. Discussions

4.1. Temporal changes in crop cover development and soil surface roughness

The faster canopy development in intercropping was related to the faster germination and development of legumes compared to potato which took about two weeks to emerge. The generally high groundcover development by intercrop of potato and lablab bean was attributed to the rapid growth of lablab bean which enhanced canopy

Table 4
Response of soil and nutrient losses to vegetal cover and raindrop indices.

	Regression parameter	Coefficient	Standard error	t Stat	p
Soil loss	Vegetal cover (VC)	-2.340	0.936	-2.500	0.012
	Rainfall KE (KEr)	0.137	0.039	3.513	0.009
	Throughfall KE (KEth)	0.080	0.044	1.818	0.023
	VC*KEr*KEth	-0.642	0.274	-2.346	0.030
Nutrient loss	Vegetal cover (VC)	1.727	0.492	3.510	0.006
	Rainfall KE (KEr)	-0.053	0.024	-2.208	0.041
	Throughfall KE (KEth)	-0.124	0.043	-2.887	0.056
	VC*KEr*KEth	-0.513	0.112	-4.580	0.012

R square = 0.78 and 0.81 respectively for soil loss and nutrient loss.

Table 5
Relationships between sediment particle size and sediment nutrient contents.

	Aggregate size (um)		
	Macro-aggregates	Micro-aggregates	Fine silt-plus clay
	(2000–250)	(250–50)	(<50)
pH	0.41^{*}	0.51^{*}	0.55^{*}
Total SOC	0.42^{ns}	0.57^{*}	0.87^{**}
Total nitrogen	0.78^{*}	0.67^{**}	0.63^{*}
Available P	0.38^{ns}	0.88^{*}	0.89^{**}
Exchangeable K	0.48^{*}	0.50^{*}	0.54^{**}
CEC	0.38^{ns}	0.51^{*}	0.57^{*}

ns = not significant at $p \leq 0.05$; *, ** = p significant at Fischer's 1 and 5% respectively.

overlap between the crop components and closed the inter-row spacing. Further, lablab bean tolerated the drought conditions which were prevalent across the seasons. Garden peas delayed to establish and were chocked by potatoes, while climber bean was characterized by bushy canopy leaving bare spaces underneath.

The decline in groundcover at tuber initiation and bulking stages regardless of treatment could be explained by potato leaf senescence observed at these stages. This process was characterized by yellowing of the older leaves at the vine base followed by leaf fall and gradual death. This lowered the canopy integrity and the associated leaf area coverage. Mihovilovich et al. (2014) observed that tuber initiation triggers preferential partitioning of dry matter to tubers at the expense of stems and branches reducing canopy development. The ability of lablab bean to maintain groundcover above 50% after potato harvest was due to its indeterminate growth pattern and its ability to tolerate low moisture conditions prevalent during the off-seasons (Kokila et al., 2014; Nyawade, 2015). Climber bean and garden pea however attained physiological maturity and dried up 2 to 3 weeks after potato harvest leaving the ground bare.

The high leaf extinction coefficient observed in pure potato stands at all stages of potato growth was an indication of fewer vertical leaves in this system. It thus implies that potato had more curved leaves with increased propensity to converge raindrops. The leaf extinction coefficient was notably higher at potato emergence due to undeveloped foliage and at bulking and maturation stages due to the potato leaf senesces which lowered the crop leaf area index. Fleisher and Timlin (2006) showed that leaf senesces process modifies the potato leaf angle of inclination and leaf optical properties thus affecting the leaf orientations. The legume cover crops however contributed more vertical leaves which compensated for the leaf senesces occurring underneath potato canopy thus strengthening the dissipative effect of canopy on raindrop kinetic energy.

The better groundcover development in long rains than in the short rains was absolutely due to the high accumulative rainfall recorded in the former seasons that maintained the plants' demand for water. Potatoes grown in low moisture conditions often grow taller with longer internodes, reduced leaf numbers, and are characterized by leaves which are shorter and narrower (Struik et al., 1989). A decrease in canopy of potato grown in high ambient temperature conditions was also observed by Nyawade et al. (2018a) who suggested that such a reduction in cover offers a mechanism for potato plant to avoid heat stress. These authors alluded that the decrease in canopy development reduces the number of stomata per unit area, and consequently reduces transpiration.

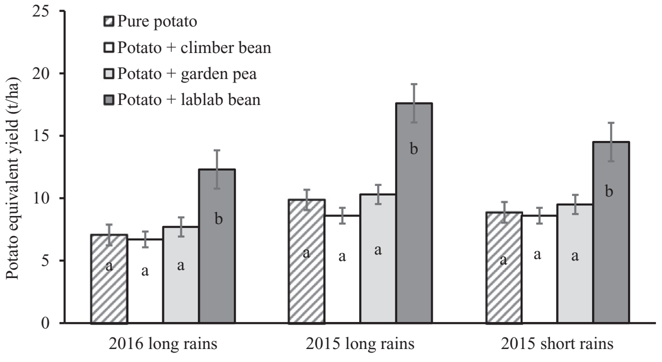

Fig. 6. Yields expressed as potato equivalent as recorded in the long rains of 2015/16 and 2015 short rains. Values in bars between treatments followed by the same letter within a given rainy season are not significantly different at $p \leq 0.05$ according to Fischer's LSD test. Error bars are standard error of means.

The decrease in soil surface roughness with progressive rainfall could be attributed to the fragmentation of larger clods that were formed following land cultivation. These clods were broken down by raindrop splash, generating finer homogenous soil particles which caused a decrease in soil surface roughness. Part of the disintegrated particles filled the surface depressions raising their height and leveling off the furrows between the potato mounds, thus decreasing the soil surface roughness. The concentrated surface runoff flow within the furrows also scoured the soil particles from the mound slopes, transporting the eroded sediment. This decreased the height of surface microrelief over time. Rosa et al. (2012) observed loss of cohesive forces between soil particles with increasing cumulative rainfall thus reducing surface micro-topography.

The observed increase in soil surface roughness in bare plots after potato harvest in 2016 long rains was due to the high-intensity rainfall exceeding the soil's infiltration capacity on bare soil following four consecutive heavy rainstorm events. This reduced the influence of soil surface roughness on runoff generation thus concentrating the surface runoff flow. This process increased the potential for runoff water to scour the soil leading to formation of rill network which created depressions that varied spatially and thus changed the soil surface configuration.

The sharp increase in soil surface roughness immediately after potato hilling is attributed to the till operations which led to formation of mounds and furrows, and to the semi-incorporated plant residues thus protecting the micro-relief from the raindrop effect. The rapid decay of soil surface roughness at potato emergence may be attributed to the low vegetal cover developed at this stage. Gómez and Nearing (2005) showed that in a bare soil, the depressions created during tillage are the areas where net deposition occur and act as temporary puddles before the retained water overflows. Sun et al. (2009) observed that early rainfall occurring soon after crop planting consolidates the loosely tilled soil upon drying, in which case, surface tension forces operate to achieve a suction effect and the shear strength of the soil is increased. This enhances soil particle fragmentation resulting into a more homogenous layer with low soil surface configuration. A similar observation was made by Longshan et al. (2014) who explained it by the sloughing of soil clod upon wetting during the early rainstorms forming a uniform soil layer with low variations in micro-relief heights.

The soil surface roughness decay rate was relatively slow at potato vegetative and pre-flowering stages due to the combination of well-developed crop canopy and lower rainfall intensity characterizing these periods. The protective cover intercepted the raindrop preventing its detachment effect on soil micro-topography. This ensured high capacity for temporary water storage in surface depressions prior to the connection of flow paths. An increase in crop cover in excess of 40% generally lowered the scouring of relief micro-topography thus preserving the soil surface roughness. This is consistent with observation by Khisa et al. (2002) who noted that an effective cover for soil erosion control is that which is >40%. At 40% coverage, the crops grown in this study were fully developed and functioned to intercept rainfall, reducing its ability to detach the loosened soil particles. With increasing crop growth and development, the disturbed soil from potato hilling activity were stabilized over time by crop roots and the natural processes (Xing et al., 2011). This might have enhanced water infiltration potential at later stages of potato growth thus reducing the adverse runoff effect on relief-micro topography.

The occurrence of low values of soil surface roughness in bare plots relative to cropped plots soon after land preparation was an indication of the plant residues effect on soil surface roughness. These residues created micro-relief that increased the local slope of the surface, resulting in a high anisotropy of splash droplets. Bertol et al. (2006) observed that the roughness formed by plant residues is more persistent in time, though it has less capacity to retain runoff water than the surface roughness caused by tillage. These residues when left on the soil surface can dissipate the kinetic energy of rain drops, preventing direct impact on the soil surface roughness (Castro et al., 2006).

4.2. Sediment yield

There was a remarkable increase in sediment yield immediately after potato hilling indicating that hilling played a significant role in soil loss. Potato hilling loosened the soil particles and increased its detachment capacity thus contributing to the higher soil losses. Soil loss was relatively high at emergence and postharvest stages when canopy cover was below 40%. This time constituted 65% of cumulative soil loss in pure potato plots indicating that vegetal cover had effect on soil detachment. Compared to pure potato plots, soil loss that occurred at emergence and post-harvest was 35 t/ha and 32.6 t/ha respectively lower in potato-lablab representing a reduction of 40–55%. Potato took about 2 weeks to sprout and up to 60 days to close the canopy while lablab bean emerged after 7 days and closed the canopy after 21 days. The canopy closure with lablab bean was extended up to about 2 months after potato harvest thus minimizing the offseason soil losses.

Regardless of treatments, the splash detachment rate was notably higher at potato emergence stage, a time that was characterized by high-intensity rainfall events and undeveloped plants. The higher rainfall kinetic energy easily sagged the weak leaf petioles, increasing the amount of bare soil between crop rows and weakening the dissipating effect of the canopy on splash detachment. The degree of leaf bending under splash effect has been found to differ with the type of plants with some leguminous crops being more prone under high kinetic energy of rainfall due to their wider and softer leaves (Ma et al., 2015). This may explain in part the variability in splash detachment rates between the different treatments.

Splash detachment coefficient increased in all the treatments at potato vegetative stage when the groundcover was on average above 60% in all the treatments. This observation could be ascribed to the reduced rainfall kinetic energy explained by the better canopy development at this stage of potato growth. As the crops grew, the increasing number of thicker leaves substantially increased. This enhanced canopy overlap which increased the capability of leaves to resist bending thus increasing the effective rain-receiving area. The notable decrease in splash detachment coefficients occurring soon after potato bulking could be explained by the general decline in the canopy coverage. This was indicated by the general decrease in the leaf area index across the treatments. The leaf senesces observed underneath the potato from bulking stage left considerable ground area exposed in the intervening space, leading to increased splash erosion in plots under canopy.

The higher splash reduction coefficient in potato-lablab bean intercropping compared to potato-garden pea and potato-climber bean intercropping at potato maturity and post-harvest stages suggests that as the lablab bean grew, the resistant effects of the canopy on splash erosion became stronger. Lablab bean contributed shorter, closed and more uniform canopy that lowered the falling distance of throughfall raindrops. On the contrary, as the climber beans grew, the plants became higher, reaching about 1.2 m when potato attained maturity. This significantly increased the throughfall height which meant that the renewed large drops had more erosion energy to produce more splash detachment. The vast majority of water collected by garden pea foliage fell as throughfall because of the velvety texture of garden pea leaves which easily sagged under stronger rainfall intensity, reducing ground coverage and increasing bare soil between rows, thereby increasing soil splash erosion.

While the roughness caused by hilling was important in retaining the eroded sediments and increasing infiltration rates of surface water, it caused soil disturbance which could induce soil erosion. The higher canopy cover contributed by lablab bean coupled with its continuity however, formed a protective layer over the disturbed soil which dissipated the raindrop reducing its splash effect. Additionally, the relatively higher residue mulch retained by lablab bean (data not presented) reduced the rainfall kinetic energy slowing down the degradation of potato mounds thus enabling the disturbed soil to stabilize. This caused a pronounced decrease in sediment yield and transport. Xing et al. (2011) observed that hilling when the soil is properly covered with the vegetation makes a ridge of soil which partially disconnects the lateral flow of surface soil water, while increasing aeration of the soil on the hill. Darboux and Huang (2004) however, observed that the larger depressions created in the inter-mounds can accumulate much water once runoff reaches a steady state, with either an increased or decreased sediment flux. This effect may persist until the roughness elements disappear causing a localized increase in soil erosion.

The interactive effect of splash detachment rate, throughfall intensity and vegetal cover on nutrient and soil loss indicated that these parameters had combined effect on splash erosion. The canopy heterogeneity under intercropping, contributed by differences in plant heights, generally intercepted and dispersed the raindrops at different levels. The first raindrops that hit the canopy were intercepted and dispersed by the intercrops due to their greater heights relative to potato canopy. These raindrops were further dissipated into even smaller drops when they landed on the low potato canopy, thus gradually weakening their erosion potential. Pure potato stands however, due to their low uniform canopy height, converged the smaller raindrops to bigger drops renewing their erosion potential. This arguement was supported by the observed higher potato leaf extinction coefficient implying that potato leaves were more bent and thus enhanced dripping of rain splash on the leaf tips and edges. This feature led to formation of more drastic throughfall and subsequent splash erosion. Finney (1984) observed a similar result and attributed it to the smooth leaf edge exhibited by potato which easily converged the raindrops, producing throughfalls with renewed energy.

4.3. Soil pH, soil texture and nutrient export in eroded sediment

The highest contents of NPK were recorded in sole potato plots as potato delayed to establish protective cover and left the soil highly exposed to erosion. A substantial amount of the applied fertilizer may have been washed from these plots following the runoff events that occurred in the first few weeks after planting. Growth of legumes was however rapid and provided protective soil cover which significantly minimized the nutrient losses. Potato-lablab bean intercrop recorded lower contents of nutrients in eroded sediments because lablab bean maintained effective groundcover during the transitional period between the seasons and at the onset of the seasons which significantly controlled soil erosion.

The nutrient export rates in eroded sediment were high for phosphorus irrespective of the treatment because this element is usually adsorbed and fixed as iron phosphates in acidic soils (Quinton et al., 2001) and is therefore mobilized with the eroded sediment. The result thus implies that a slight soil loss through erosion may lead to a greater loss of phosphorus. The export rates of exchangeable potassium in the eroded sediment however showed little variations between the treatments because this element is uniformly distributed within the soil profile (Khisa et al., 2002). Though not fertilized, the eroded sediment from control bare soils exported marked contents of total nitrogen, available phosphorus and exchangeable potassium probably due to the high mobilization of these elements in their inherent organic and inorganic forms.

The values of soil pH in eroded sediment was higher than that of the original soil irrespective of the treatment (data not presented) suggesting that the eroded soil material was enriched in bases and may lead to Ca, Mg, K and Na deficiency. The highest export rates occurred for SOC indicating that most of the eroded sediment was enriched in soil organic matter. This suggests the preferential transport of soil organic matter in sediments probably due to its low density. Rainfall splash effect may have peeled the soil aggregates exposing their outer layers which have higher SOM concentration (Ghadiri and Rose, 1991). This effect was greater in the sole potato and in the bare soils that were characterized by low groundcover protection. Similarly, the contents of clay and silt were greater in the eroded sediment relative to the source soil irrespective of the treatments, indicating that the erosion process was selective, carrying with it the lighter material (clay and silt) and leaving the heavier material in the plots. This is due to the fact that the energy required to entrain and transport silt and clay particles is comparatively lower than that of the coarser sand-sized aggregates (Boix-Fayos et al., 2009).

The highest positive coefficients were exhibited by SOC and fine silt and clay particles indicating a non-homogeneous distribution of SOC within the soil aggregates. Nyawade et al. (2018b) observed that losses of SOC due to soil erosion occur mainly in silt and clay. These soil particles adsorb SOC making it mobilized as whole by the surface runoff water. Stronger associations of phosphorus and total nitrogen was found with the micro-aggregates (250–50 μm) than with the macro-aggregates (250–50 μm) pointing to the different degree of nutrient mobilization and distribution within the aggregates. Phosphorus is usually adsorbed and locked up within the clay colloids (Bertol et al., 2007) and thus was wholly entrained in the eroded sediment. The non-significant association of soil particles with exchangeable potassium could be ascribed to the uniform distribution of this element (Khisa et al., 2002). The observed positive relationship between soil pH with all soil fractions indicates that the eroded sediment was uniformly enriched in H^+, calcium, magnesium and potassium ions. This was further demonstrated by the positive association between CEC and the micro aggregates as well as silt plus clay particles.

4.4. Potato yields under different cropping systems

Intercropping potato with lablab bean increased potato equivalent yield (PEY), an observation that was associated with either increase in forage yield or increase in numbers of tubers per hill. Gitari et al. (2018b) related the increase in PEY to increase in soil water content under high canopy cover establishment by lablab bean. This is consistent with this study that found significantly higher groundcover with potato-lablab bean intercropping relative to pure potato stands. In addition, the ability of lablab bean to confer shade thus lowering soil temperatures and increasing PEY has been reported by Gitari et al., (2018a). This effect is mediated in part by the deep root system of lablab bean making it capable of drawing soil water reserved in deep profile layers. In a study conducted by Randeni and Caesar (1986), heating the soil to 28 °C reduced flow of assimilates to tubers. Similarly, Krauss and Marschner (1984) observed cessation of starch accumulation when developing tubers were subjected to soil temperature of 30 °C. It may therefore be possible that allocation of assimilated carbon into non-structural and structural carbon was altered by the high soil temperature that likely characterized the pure potato stands (Arai-Sanoh et al., 2010).

The invariably lower potato equivalent yield recorded under climber bean intercropping is largely due to the shading effect caused by the bushy canopy of this legume. The quality of light in terms of the ratio of light intercepted to total solar radiation reaching the potato crop was thus compromised. Burke (2017) noted that shading prolongs the stolon elongation period and delays tuberisation. When shading reduced radiation by approximately 50% during the period of tuber initiation, tuber numbers decreased by 20%. The low PEY with climber bean intercrop was further adduced to the exclusion of shoot biomass in yield computation as this crop retained no biomass that a farmer would use for forage. This case was similar for garden pea that was considered primarily for pulse. Additionally, the low PEY by garden pea was caused by the bird pests that ate up a greater portion of the grains.

The observed seasonal yield differences are primarily due to variations in the amount and distribution of rainfall in relation to the potential demand for water. The larger amount and better distribution of rainfall observed during the long rains growing period led to more soil moisture content in the soil profile which in turn favored early establishment and growth of crops. On the contrary, potato suffered from severe moisture stress conditions during flowering and tuber filling stages which greatly contributed to low vegetative growth and yield decreases during the short rains.

5. Conclusion

These results suggest the benefit of a more diversified crop mixture on soil erosion control and thus affirm intercropping as an alternative strategy to sustainably control nutrient export in smallholder potato farming systems. Soil erosion occurred mainly at potato emergence and after potato harvest when soil was left bare. Thus cumulative sediment yield and seasonal nutrient losses were greatest in pure potato plots than in plots with legume intercrops that exhibited rapid and extended groundcover establishment. The yield expressed as potato equivalents were greatest in potato-lablab intercropping indicating that this system may be preferred by the smallholder potato farmers. Even though we could not directly relate the increase in potato equivalent yields to reduced soil and nutrient losses, it was apparent that this advantage would occur in the long-term with legume intercropping. Compatibility and resource productivity of such intercropping systems should be examined across wide range of agro-ecological zones.

Conflict of interest

The authors declare that they have no competing interests in this paper and the study as a whole.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.geodrs.2019.e00225. These data include the Google map of the most important areas described in this article.

References

Anderson, J.M., Ingram, J.S.I., 1998. Tropical Soil Biology and Fertility. A Hand Book of Methods. 2nd edition. .

Arai-Sanoh, Y., Tsutomu, I., Akihiro, O., Motohiko, K., 2010. Effects of soil temperature on growth and root function in Rice. Plant Prod. Sci. 13 (3), 235–242.

Athanase, N., 2013. Effects of different limes on soil properties and yield of Irish potatoes (*Solanum tuberosum.* L) in Burera District, Rwanda. Master's Thesis, Department of Agricultural Resource Management. Kenyatta University, Kenya.

Barber, R.G., Moore, T.R., Thomas, D.B., 1979. The erodibilty of two soils from Kenya. J. Soil Sci. 30, 579–591.

Berry, L., 2003. Land Degradation in Ethiopia: Its Extent and Impact. World Bank, Washington, p. 23.

Bertol, I., Amaral, A.J., Vazquez, E.V., Gonzalez, A.P., Barbosa, F.T., Brignoni, L.F., 2006. Relations of soil surface roughness with the rainfall volume and water aggregate stability. Rev Bras Cieˆnc Solo 30, 543–553.

Bertol, I., Engel, F.L., Mafra, A.L., Bertol, O.J., Ritter, S.R., 2007. Phosphorus, potassium and organic carbon concentrations in runoff water and sediments under different soil tillage systems during soybean growth. Soil Tillage Res. 94, 142–150.

Boix-Fayos, C., Vente, J., Albaladejo, J., Martinez-Mena, M., 2009. Soil carbon erosion and stock as affected by land use changes at the catchment scale in Mediterranean ecosystems. Agric. Ecosyst. Environ. 133, 75–85.

Burke, J.J., 2017. Growing the Potato Crop. Vita, Equity House. Upper Ormond Quay, Dublin 7, Ireland.

Cambardella, C.A., Elliot, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56, 777–783.

Castro, L.G., Cogo, N.P., Volk, L.B.D., 2006. Alterations in soil surface roughness by tillage and rainfall in relation to water erosion. Rev. Bras. Cieˆnc. Solo. 30, 339–352.

Coxson, D.S., Looney, J.H.H., 1986. Point frame method of crop cover determination. Can. J. Bot. 64, 2464–2475.

Darboux, J.M., Reichert Huang, C., 2004. Soil roughness effects on runoff and sediment production. 2004-13th International Soil Conservation Organisation Conference -Brisbane. Conserving Soil and Water for Society: Sharing Solutions. Paper no. 116.

EARO, 2002. Soil and Water Research Program Annual Research Report. EARO, Addis Abeba, Ethiopia.

FAO, 2012. Harmonized World Soil Database (Version 1.2). Food Agriculture Organization, Rome, Italy and IIASA, Laxenburg, Austria. http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ (Accessed 14th September, 2018).

Finney, H.J., 1984. The effect of crop covers on rainfall characteristics and splash detachment. J. Agric. Eng. Res. 29, 337–343.

Fleisher, D.H., Timlin, D., 2006. Modeling expansion of individual leaves in the potato canopy. Agric. For. Meteorol. 139, 84–93.

Gachene, C.K.K., 1989. Soils of the Erosion research farm, Kabete campus, University of Nairobi. Soil Sci. Soc. Am. J. 61, 565–569.

Gachene, C.K.K., Jarvis, N.J., Mbuvi, J.P., 1997. Soil erosion effects on soil properties in a highland area of Central Kenya. Soil Sci. Soc. Am. J. 61, 559–564.

Gachene, C.K.K., Linner, H., Jarvis, N.J., Mbuvi, J.P., 1998. Soil organic carbon and phosphorus losses in eroded sediments from runoff plots on a clay soil in Kenya. Appl Plant Sci 12 (3), 72–76.

Ghadiri, H., Rose, C.W., 1991. Sorbed chemical-transport in overland-flow: enrichment ratio variation with erosion processes. Environ Qual 20 (3), 634–641.

Gitari, H.I., Gachene, C.K.K., Karanja, N.N., Kamau, S., Nyawade, S., Sharma, K., Schulte-Geldermann, E., 2018a. Optimizing yield and economic returns of rain-fed potato (*Solanum tuberosum* L.) through water conservation under potato-legume intercropping systems. Agric. Water Manag. 208, 59–66.

Gitari, H.I., Karanja, N.N., Gachene, C.K.K., Kamau , S., Sharma, K., Schulte-Geldermann, E., 2018b. Nitrogen and phosphorous uptake by potato (*Solanum tuberosum* L.) and their use efficiency under potato-legume intercropping systems. Field Crop Res. 222, 78–84.

Gitari, H.I., Gachene, C.K.K., Karanja, N.N., Kamau, S., Nyawade, S., Schulte-Geldermann, E., 2019. Potato-Legume Intercropping on a Sloping Terrain and its Effects on Soil Physico-Chemical Properties. Plant Soil https://doi.org/10.1007/s11104-019-04036-7 In press.

Gómez, J.A., Nearing, M.A., 2005. Runoff and sediment losses from rough and smooth soil surfaces in a laboratory experiment. Catena. 59, 253–266.

Han, X.K., Wu, B.Z., An, T.X., He, J., 2010. Advance of research for splash erosion. ISWCR. 17 (4), 46–51.

Farm management handbook of Kenya. In: Jaetzold, R., Hornetz, B., Shisanya, C.A., Schmidt, H. (Eds.), Vol. I-IV (Western, Central, Eastern, Nyanza, Southern Rift Valley, Northern Rift Valley, Coast), Nairobi Available at:. https://www.uni-trier.de/index.php?id=58581 (Accessed 20th September, 2018).

Khisa, P., Gachene, C.K.K., Karanja, N.K., Mureithi, J.G., 2002. The effect of post-harvest crop cover on soil erosion in a maize-legume based cropping system in Gatanga. Kenya JARTS 103, 17–28.

Kokila, S., Myrene, R.D., Varadahalli, R., Devaraj, 2014. Response of Lablab purpureus (hyacinth bean) cultivars to drought stress. Asian J Plant Sci Res 4 (5), 48–55.

Krauss, A., Marschner, H., 1984. Growth rate and carbohydrate metabolism of potato tubers exposed to high temperatures. Potato Res. 27, 297–303.

Kuipers, H., 1957. A relief meter for soil cultivation studies. NJAS 5, 255–262.

Lal, R., 1995. Erosion – crop productivity relationships for soils in Africa. Soil Sci. Soc. Am. J. 59 (3), 661–667.

Lal, R., 1998. Soil Erosion impact on agronomic productivity and environment quality. Crit. Rev. Plant Sci. 17, 319–464.

Lal, R., 2001. Soil degradation by erosion. Land Degrad. Dev. 12, 519–539.

Landon, J.R., 1991. Booker Tropical Soil Manual: A Handbook for soil survey and agricultural land evaluation in the tropics Longman Scientific and Technical. Booker Tate Ltd, UK, pp. 112–140.

Longshan, Z., Xinlan, L., Faqi, W., 2014. Soil surface roughness change and its effect on runoff and erosion on the loess plateau of China. JAL 6 (4), 400–409.

Ma, B., Yuxin, L., Xiaojun, L., Fan, M., Faqi, W., Zhanbin, L., 2015. Soil splash detachment and its spatial distribution under corn and soybean cover. Catena 127, 142–151.

Mihovilovich, E., Carli, C., de Mendiburu, F., Hualla, V., Bonierbale, M., 2014. Protocol Tuber Bulking Maturity Assessment of Elite and Advanced Potato Clones CIP Lima Peru. p. 43.

Mitiku, H., Karl, H., Brigitta, S., 2006. Sustainable Land Management –a New Approach to Soil and Water Conservation in Ethiopia. p. 269.

Morgan, R.P.C., 1978. Field studies of rainsplash erosion. Earth Surf. Process. Landf. 3, 295–299.

Muchena, F.N., Gachene, C.K.K., 1988. Soils of the Highland and mountainous areas of Kenya with special emphasis on agricultural soils. IMS 8, 183–191.

Mulder, J.P.M., 1985. Simulating interception loss using standard meteorological data. In: Hutchison, B., Hicks, B. (Eds.), The Forest-Atmosphere Interaction. D. Reidel, pp. 177–196.

Nanko, K., Hotta, N., Suzuki, M., 2006. Evaluating the influence of canopy species and meteorological factors on throughfall drop size distribution. J. Hydrol. 329, 422–431.

Nanko, K., Shigeru, M., Yuichi, O., 2008. Estimation of soil splash detachment rates on the forest floor of an unmanaged Japanese cypress plantation based on field measurements of throughfall drop sizes and velocities. Catena 72, 348–361.

Nyawade, O.S., 2015. Effect of Potato (*Solanum tuberosum* L.) Cropping Systems on Soil and Nutrient Losses through Run-off in a Humic Nitisol. MSc. Thesis. University of Nairobi, Kenya.

Nyawade, S., Karanja, N., Gachene, C.K.K., Schulte-Geldermann, E., Parker, M., 2018a. Effect of potato hilling on soil temperature, soil moisture distribution and sediment yield on a sloping terrain. Soil Tillage Res. 184, 24–36.

Nyawade, S., Karanja, N., Gachene, C., Parker, M., Schulte-Geldermann, E., 2018b. Susceptibility of soil organic matter fractions to soil erosion under potato-legume intercropping systems in central Kenya. J. Soil Water Conserv. 73, 568–577.

Nyawade, S., Gachene, C., Karanja, N., Gitari, H., Schulte-Geldermann, E., Parker, M., 2019. Short-term dynamics of soil organic matter fractions and microbial activity in smallholder legume intercropping systems. Appl. Soil Ecol. https://doi.org/10.1016/j.apsoil.2019.04.015.

Okalebo, J.R., Gathua, K.W., Woomer, P.L., 2002. Laboratory methods for soil and plant analysis: A working manual. TSBF. Nairobi.

Pender, J., Berhanu, G., Mitiku, H., 2002. Livelihood strategies and land management practices in the highlands of tigray. Policies for Sustainable Land Management in the East African Highlands. IFPRI and ILRI. Summary of Papers and Conference Proceedings. Addis Ababa.

Polyakov, V., Lal, R., 2004. Modeling soil organic matter dynamics as affected by soil water erosion. Environ. Int. 30 (4), 547–556.

Quinton, J.N., Catt, J.A., Hess, T.M., 2001. Selective removal of phosphorus from soil: is event size important? J. Environ. Qual. 30, 538–545.

Randeni, G., Caesar, K., 1986. Effects of soil temperature on the carbohydrate status in in the potato plant (*S. tuberosum* L.). J. Agron. Crop Sci. 154 (4), 217–224.

Rosa, J.D., Miguel, C., Carlos, M., 2012. Soil roughness evolution in different tillage systems under simulated rainfall using a semivariogram-based index. Soil Tillage Res. 124, 226–232.

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C- saturation of soils. Plant Soil 241, 155–176.

Sohi, S.P., Mahieu, N., Arah, J.R.M., Powlson, D.S., Madari, B., Gaunt, J.L., 2001. A procedure for isolating soil organic matter fractions suitable for modeling. Soil Sci. Soc. Am. J. 65, 1121–1128.

Struik, P.C., Geertsema, J., Custers, C.H.M.G., 1989. Effects of shoot, root and stolon temperature on the development of potato (*Solanum tuberosum* L.) plant. Development of tubers. Potato Res. 32, 151–158.

Sun, Y., Lin, J., Lammers, P., Damerow, L., Hueging, H., Zhang, H., Sun, W., 2009. Predicting surface porosity using a fine-scale index of roughness in a cultivated field. Soil Tillage Res. 103 (1), 57–64.

Swift, M.J., Seward, P.D., Frost, P.G.H., Qureshi, J.N., Muchena, F.N., 1994. Long-term experiments in Africa: developing a data-base for sustainable land use under global change. In: Leigh, R.A., Johnson, A.E. (Eds.), Long-Term Experiments in Agricultural and Ecological Sciences. CAB International, Wallingford, pp. 229–251.

Tongi, E.R.M., 1990. The Effect of Soil Erosion on Soil Productivity of Humic Nitisols, Kabete. MSc. Thesis. Department of Soil Science, University of Nairobi.

UNDP, 2002. World Development Report. Oxford University Press.

Wendelaar, F.E., Purkins, A.N., 1979. Recording soil loss and runoff from Erosion Research Field Plots. Research Bulletins No. 24, Department of Conservation and Extension, Salisburry, Rhodesia.

Wischmeier, W.H., Smith, D.D., 1958. Rainfall energy and its relationship to soil loss EOS. Transactions American Geophysical Union 39, 285–291.

Xing, Z., Lien, C., Herb, W., Rees, F.M., Monteith, J., Stevens, L., 2011. A comparison of effects of one-pass and conventional potato hilling on water runoff and soil erosion under simulated rainfall. Can. J. Soil Sci. 91, 279–290.

Zheng, Z.C., He, S.Q., Wu, F.Q., 2009. Splash erosion effects of tillage practices on soil surface roughness under different rainfall. Trans CSAE 25 (11), 103–108.

Zobisch, M., Richter, C., Heiligtag Schlott, B.R., 1993. Nutrient losses from cropland in the central highlands of Kenya due to surface runoff and erosion soil. Till.Res. 33, 109–116.