



# Enhancing Climate Resilience of Rain-Fed Potato Through Legume Intercropping and Silicon Application

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## OPEN ACCESS

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### Specialty section:

This article was submitted to  
Crop Biology and Sustainability,  
a section of the journal  
Frontiers in Sustainable Food Systems

**Received:** 27 May 2020

**Accepted:** 28 September 2020

**Published:** 06 November 2020

### Citation:

Nyawade S, Gitari HI, Karanja NN,  
Gachene CKK,  
Schulte-Geldermann E, Sharma K and  
Parker ML (2020) Enhancing Climate  
Resilience of Rain-Fed Potato Through  
Legume Intercropping and Silicon  
Application.  
Front. Sustain. Food Syst. 4:566345.  
doi: 10.3389/fsufs.2020.566345

A large portion of sub-Saharan Africa is situated in belts of uncertain rainfall and are characterized by low soil fertility with limited capacity to adapt to and mitigate the impacts of climate change. A field study was conducted in the semi-humid potato-growing belt of Kenya to test the effect of legume intercropping and water soluble silicon (orthosilicic acid) on soil erosion, and use efficiency of light and water. Potato (*Solanum tuberosum* L.) was grown singly and intercropped with dolichos (*Lablab purpureus* L.) or hairy vetch (*Vicia sativa* L.). Each cropping system was subjected to granular water-soluble silicon (Si) amendment at two rates [2.5 kg Si ha<sup>-1</sup> (+Si) vs. 0 kg Si ha<sup>-1</sup> (-Si)]. Plants receiving Si maintained significantly higher ( $p < 0.05$ ) percent relative leaf water content (62–89% vs. 52–72% in controls) and exhibited higher concentrations of proline (1.99–2.91 vs. 1–1.19  $\mu\text{mol g}^{-1}$ ), soluble carbohydrates (28–59 vs. 10–28  $\mu\text{mol g}^{-1}$ ) and electrolyte conductance (1,409–3,903 vs. 746–2,307  $\text{mS cm}^{-1}$ ). Legume intercropping enhanced groundcover establishment and reduced soil and nutrient losses by 45–80% compared with sole potato. Crop yields were 2–3-fold greater in intercropping relative to sole potato and were significantly greater in treatments subjected to Si application. Land equivalent ratios were above unity in intercropping but less than unity in sole potato, and were 8–20% increased by Si application. Use efficiency of water (5.99–9.09  $\text{Kg ha}^{-1} \text{m}^{-3}$ ) and light (1.98–2.98  $\text{g MJ}^{-1}$ ) were significantly greater under legume intercropping compared with sole potato (1.13–3.23  $\text{Kg ha}^{-1} \text{m}^{-3}$  and 0.77–0.98  $\text{g MJ}^{-1}$ , respectively) and increased with Si application. Integrative use of Si and legume intercropping presents the smallholder farmers an opportunity to increase productivity of potato while enhancing resource use efficiency and soil fertility in the semi-humid tropics.

**Keywords:** climate change adaptation, crop water productivity, legume intercropping, silicon, smallholder potato farmers, soil conservation

## INTRODUCTION

Declining soil productivity and potato yield in sub-Saharan Africa (SSA) presents the need to develop more sustainable production systems. The average potato yield in this region is only  $13 \text{ t ha}^{-1}$  against potential yield of  $40 \text{ t ha}^{-1}$  (FAOSTAT, 2017; Gitari et al., 2018a). This situation is expected to deteriorate as climatic change is projected to lead to warmer and drier conditions with more variable and extreme weather events (Meehl et al., 2007). Declining rainfall and rising temperatures, which are associated with this change will have a direct negative effect on vegetation cover, which in turn will contribute to soil degradation because of the exposure of the soil surface to wind and water erosion. Consequently, SSA is projected to lose about 14% of cultivable land and about 20% of its pasture production potential by 2080 (Shah et al., 2008).

Potato is vulnerable to water deficit because of its fibrous root systems, which are concentrated in the upper (0–0.3 m) soil profile (Gitari et al., 2018a,b; Nyawade et al., 2018; Gitari et al., 2020b). Appreciable decrease in tuber yield occurs if a balance between soil temperature, soil moisture content, and crop nutrient uptake is not attained (Ferreira and Gonçalves, 2007; Nyawade et al., 2019b, 2020). High temperatures within the ridges at tuber initiation cause fluctuations in soil moisture, resulting in tuber malformation and tuber growth cracks (Polgar et al., 2017). Below soil water content of 20%, the matric potential of the ridges and furrows decline rapidly, slowing the redistribution of water within the soil profile (Nyawade et al., 2018). This impairs the nutrient uptake potential of potato leading to irregular plant growth.

There is therefore a growing need to provide farmers with practical and sustainable solutions to maintain potato yields under more challenging conditions while using water, nutrients, and soil resources more efficiently. Legume intercropping is one of such climate-smart cropping practices suitable to smallholder farmers. This is due to its potential to achieve multiple benefits that relate to climate mitigation and adaptation and general risk aversion via diversification (Gitari et al., 2019a,b; Nyawade and Gitari, 2020). Intercropping that includes forage legumes improves quality of forage while improving soil structure (Nyawade et al., 2018). This in turn increases water infiltration and air circulation, thus improving soil water-holding capacity.

The effectiveness of intercropping technology may be enhanced by use of silicon (Crusciol et al., 2009; Farhad et al., 2011; Pilon et al., 2014). Silicon is absorbed by plants mainly as orthosilicic acid ( $\text{H}_4\text{SiO}_4$ ) also known as monosilicic or silicic acid (Mitani and Ma, 2005). At  $\text{pH} > 9$ , orthosilicic acid occurs in ionized form ( $\text{H}_3\text{SiO}_4/\text{H}_2\text{SiO}_4$ ) (Knight and Kinrade, 2001). Most soils with  $\text{pH} < 9$  thus contain Si as undissociated silicic acid over concentrations range of 0.1–0.6 mM and is in equilibrium with soil  $\text{SiO}_2$  at  $\text{pH} 3$  (Tubaña and Heckman, 2015). At low soil pH, Si may reduce soil phosphorus sorption by increasing the soil pH or by competing for Mn, Fe, and Al ions for the active sites thereby enhancing P availability for plant uptake (Pilon et al., 2014).

Nevertheless, little research has been conducted to assess the effect of Si application on nutrient availability and crop

water productivity. This information is needed for identification of climate-smart management practices that would sustainably increase the productivity of soil in the current and future climatic scenario. Therefore, the present work was designed to test the hypothesis that potato-legume intercropping interacts with silicon application to increase light and water productivity, and minimize the high soil erosion rates in the semi-humid sloppy terrains of Kenya.

## MATERIALS AND METHODS

### Study Area

This study was conducted at Upper Kabete Research Farm of University of Nairobi, Kenya during the 5 rainy seasons commencing in 2016 long rains and running to 2018 short rains. The farm is located at latitude  $1^\circ 14' 45.00''\text{S}$  and longitude  $36^\circ 44' 19.51''\text{E}$  (Figure 1). The region is characterized by semi-humid climatic conditions and lies in agro-ecological region II, which receives an average rainfall amount of 1,000 mm per annum. These rains come in two seasons with the wet season occurring between March and August, and dry season between September and December. The area has an annual mean temperature of  $20.4^\circ\text{C}$  and is dominated by semi-intensive farming system where potato production accounts for more than half of the total cropped area (Jaetzold et al., 2006; Kibunja et al., 2018). The soils in Kabete are dark red friable clay classified as Humic Nitisol (Jaetzold et al., 2006). Details of the measured soil properties (0–0.3 m depth) before and after the experiment are provided in Table 1.

### Experimental Design and Crop Husbandry

A split-plot randomized complete block study design was implemented in runoff plots measuring 5.8 m long by 2.4 m wide and were separated from each other by 1 m path with four replicates (blocks). Cropping system was considered a whole-plot factor and Si application as subplot factor. Each cropping system was subjected to granular water-soluble silicon (Si) amendment at rates of  $2.5 \text{ kg ha}^{-1}$  (+Si) and  $0 \text{ kg ha}^{-1}$  Si (–Si, the controls). The water-soluble Si was in the form of orthosilicic acid (OSA) with 0.4% Si and 5% fulvic acid (Privi Nutrifight-Privi Life Sciences PVT.LTD).

The cropping system consisted of potato (*Solanum tuberosum* L.) grown singly and intercropped with hairy vetch (*Vicia sativa* L.) or dolichos (*Lablab purpureus* L.), and the respective single crop of the legumes. The “Unica” (CIP 392797.22) potato cultivar used in this study is locally used for chips, crisp and boiling. This cultivar is heat and water stress tolerant making it well-adapted to wide range of agro-ecological conditions [National Potato Council of Kenya (NPCK), 2017; Rukundo et al., 2019]. The Rongai cultivar of dolichos (KT 003) used has a high biomass production with high crude protein content. This cultivar is used both as forage and as pulse and is a popular choice in the midlands and lowlands as a cover crop on infertile, acidic soils, and because of its high tolerance to drought. Vetch is not commonly grown by the farmers in this study area, but has great capacity to supplement the pasture and conserve the soil against erosion.

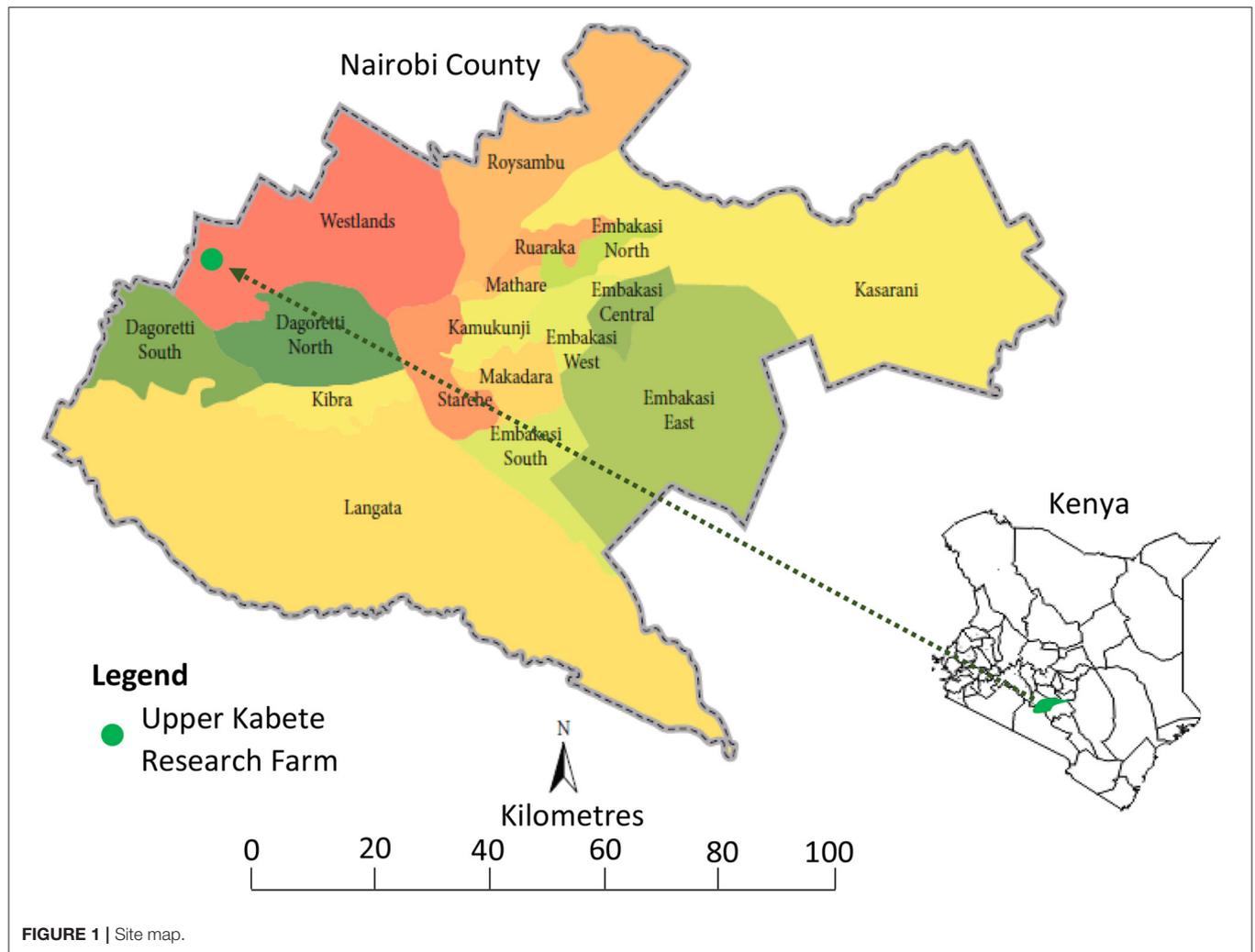
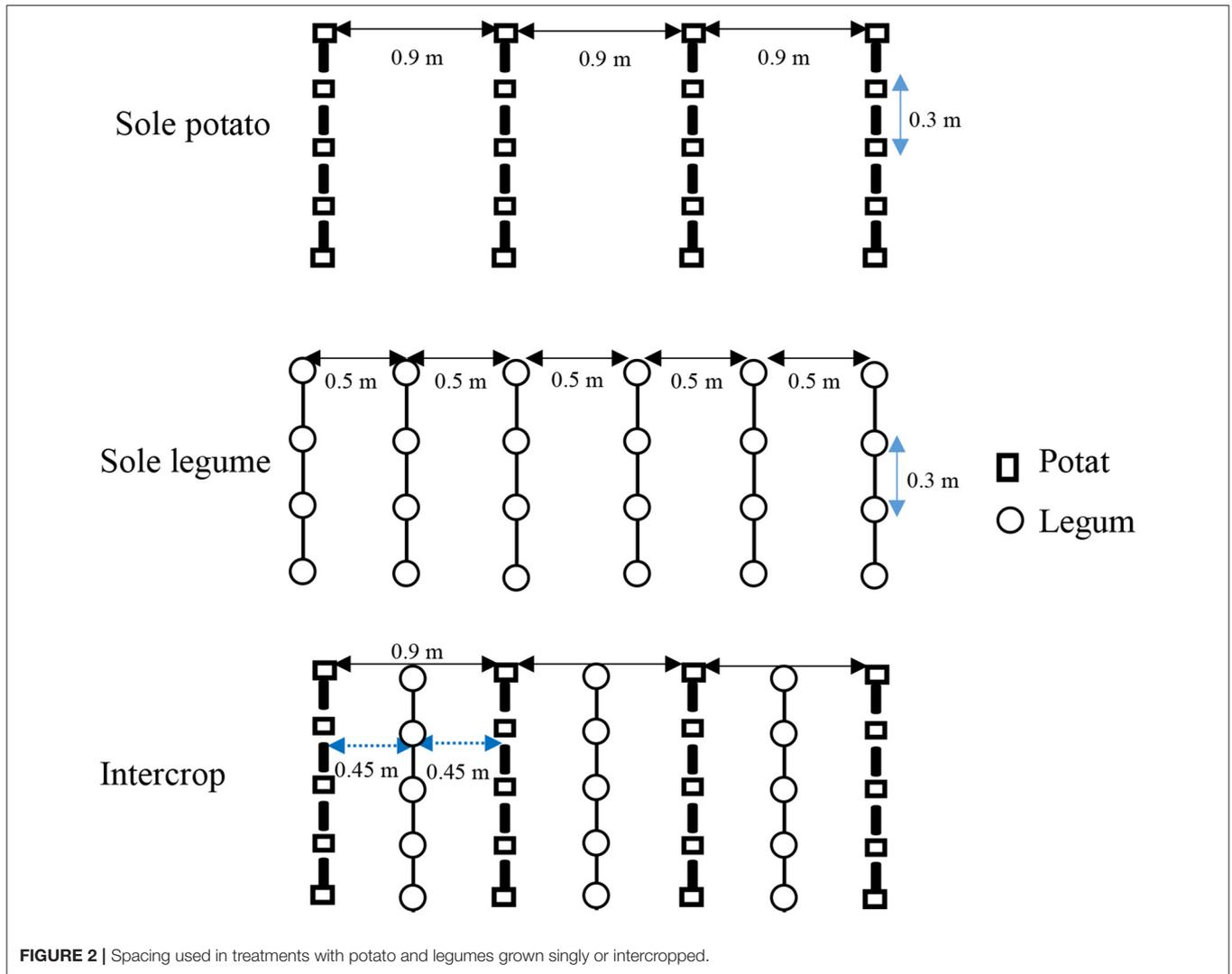


FIGURE 1 | Site map.

TABLE 1 | Soil properties measured before and after the experiment.

	Soil depth	Clay	Silt	Sand	Texture	pb	θfc	Si	Fe	Mn	pH	SOC	N	P	K
	m	%				gcm <sup>-3</sup>	cm cm <sup>-3</sup>		mg dm <sup>-3</sup>			%	%	ppm	Cmol (+) kg <sup>-1</sup>
Before	0–0.15	24.5	33.3	42.2	Clay loam	1.19	0.11	16.8	34.9	9.1	5.19	2.12	0.23	33.30	1.23
	0.15–0.3	24.2	36.9	38.9	Clay loam	1.24	0.09	17.7	31.9	8.2	5.19	1.34	0.23	23.40	1.33
	0.3–0.6	28.9	29.8	41.3	Clay loam	1.34	0.15	12.7	30.1	7.4	5.13	1.08	0.19	24.40	1.19
	0.6–0.9	23.8	32.4	43.8	Clay loam	1.35	0.18	18.9	28.5	9.1	5.12	0.83	0.10	20.20	1.09
After	0–0.15	25.2	32.2	42.6	Clay loam	0.99	0.28	37.1	33.8	10.2	5.22	2.45	0.25	44.40	1.33
	0.15–0.3	25.7	38.9	38.4	Clay loam	1.04	0.27	32.3	24.8	6.9	5.34	1.56	0.26	48.20	1.36
	0.3–0.6	27.9	27.8	44.3	Clay loam	1.14	0.26	33.2	23.8	6.7	5.36	1.57	0.25	43.70	1.31
	0.6–0.9	28.5	31.4	40.1	Clay loam	1.19	0.28	18.9	28.9	7.6	5.30	1.09	0.19	35.60	1.30

pb is soil bulk density, θwp, θfc, θs indicate soil water content at permanent wilting point, field capacity and saturation, respectively, Ks is saturated hydraulic conductivity.



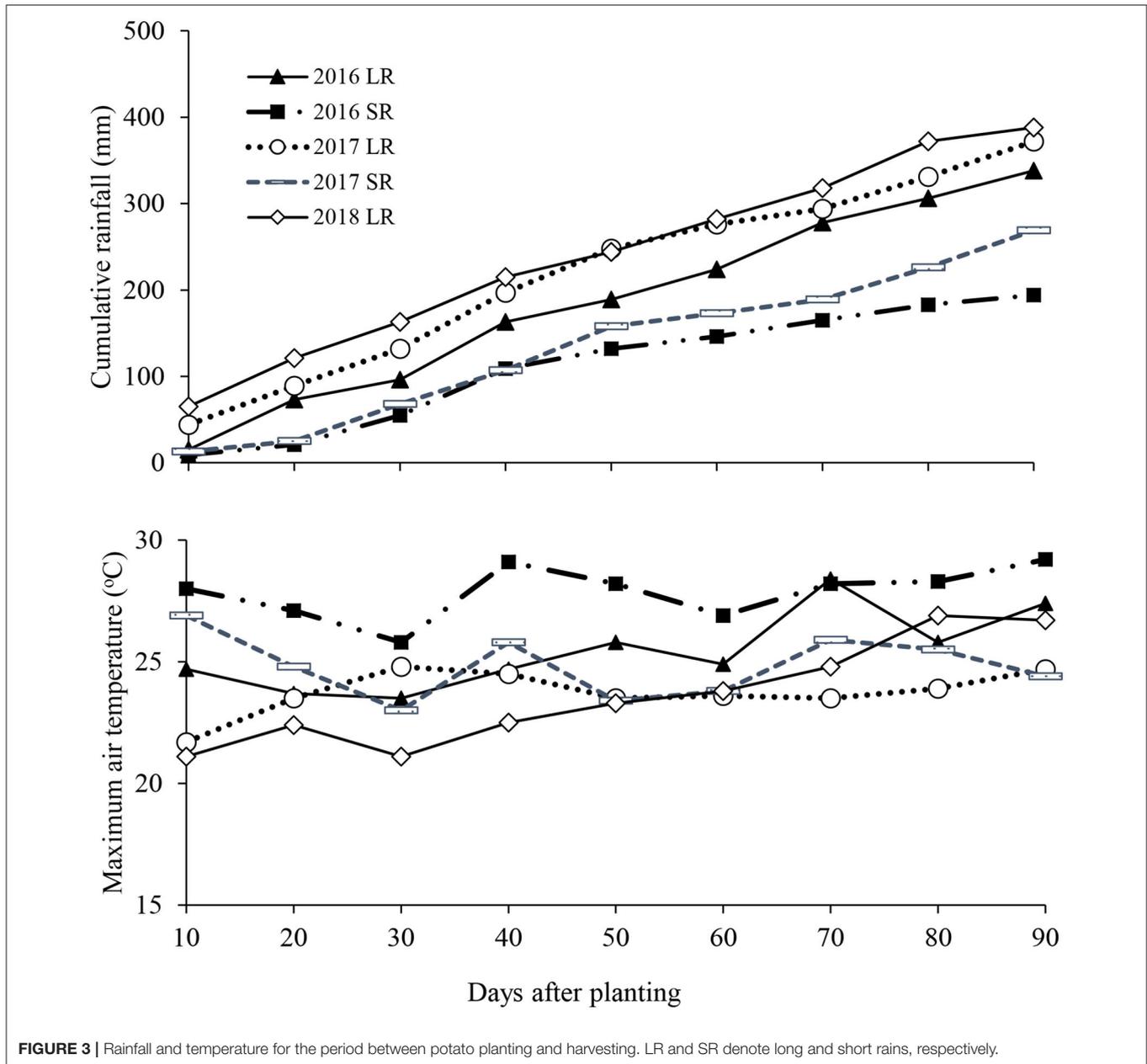
**FIGURE 2** | Spacing used in treatments with potato and legumes grown singly or intercropped.

Sole potato rows were spaced 0.9 m with an interplant spacing of 0.3 m giving a plant population of 37,037 per ha. Sole legumes were spaced 0.5 m between rows and 0.3 m within rows giving plant population of 66,667 per ha. Intercropping was done in the inter-rows of potato spaced at 0.9 m, at  $\sim 0.45$  m from potato to the legume with interplant spacing of 0.3 m (Figure 2). This gave a plant population of 101,074 plants per ha. All the potato treatments received basal fertilization at a rate of 50 kg N ha<sup>-1</sup>, 90 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub>, 100 kg ha<sup>-1</sup> of K<sub>2</sub>O and topdress of 40 kg N ha<sup>-1</sup>. Legumes received only basal phosphorus (46% triple super phosphate) applications at a rate of 20 kg ha<sup>-1</sup>. Weeding and hilling were performed at 14–21 days after crop emergence by hand hoeing. The legumes were sprayed with Duduthrin 1.7 EC (Lambda-cyhalothrin 17.5 g L<sup>-1</sup>) alternating with Bestox 100 EC (Alpha-cypermethrin 50 g L<sup>-1</sup>) to control aphids while potatoes were sprayed alternately with Ridomil Gold MZ 68WG (Mefenoxam 40 g kg<sup>-1</sup> + Mancozeb 640 g kg<sup>-1</sup>) and Agriphite-600 (phosphonate) to control potato blight disease. Potatoes were harvested at maturity by digging out the tubers using hand hoes

while dolichos were harvested by plucking out the pods and retaining the residues, which together with hairy vetch biomass were incorporated back into the soil.

### Soil Sampling and Soil Physico-Chemical Analyses

Soil samples were taken from each plot at 0–0.3 m depths just before planting and at the end of each season using soil auger. For each plot, the soil samples were drawn from the inner rows and bulked to give one composite sample. The soils were passed through 2 mm sieve, analyzed for gravimetric moisture content, and stored at 4°C. Soil pH was measured in 1:2.5 soil to water suspensions, soil texture by the hydrometer method (Gee and Bauder, 1986), total N by modified Kjeldahl method (Bremner and Mulvaney, 1982) and organic carbon by modified Walkley and Black method (Nelson and Sommers, 1996). Extraction of soil samples for analysis of available P and extractable K was done using Mehlich 1 procedures (Mylavarapu et al., 2002) and determined using UV-vis spectrophotometer



**FIGURE 3** | Rainfall and temperature for the period between potato planting and harvesting. LR and SR denote long and short rains, respectively.

(Murphy et al., 1998) and flame photometry (Jackson, 1967) methods, respectively.

**Climatic Data**

Rainfall amount was recorded after every rainfall event using an onsite rain gauge. Air temperature were obtained from the onsite HOBO temperature sensors. Micro-lysimeters installed to a depth of 0.3 m were used to estimate the soil evaporation. The cumulative seasonal rainfall amounts received during the potato-growing period of 2016 long rains, 2016 short rains, 2017 long rains, 2017 short rains and 2018 long rains were 338, 194, 269, 372, and 388 mm, respectively (Figure 3). These rains occurred mainly at potato sprout development and at

tuber initiation regardless of the season. The corresponding mean maximum air temperatures were 26.3, 21.2, 22.9, 22.3, and 21.2°C, respectively.

**Soil Temperature, Soil Water Content, and Soil Water Retention**

Tensiometers (0–100 kPa) installed at 0.3 m were used to measure the soil water contents and soil water potential. The tensiometers located at radial distances of 0.15 and 0.3 m represented ridge and furrow positions in the potato plots. Soil temperature were recorded by automatic Onset HOBO USeries, UX120-006 M data-logging equipment at 1 h common step.

## Estimation of Root Length Density

Root samples were taken separately at 0–0.3 and 0.3–0.9 m soil depths to establish the spatial complementarity exerted by legume intercropping. The roots were extracted using 0.15 m × 0.1 m × 0.1 m metal cores directly driven under the plant rhizosphere (Bohm, 1979; Nyawade et al., 2018). Soil cores containing the roots were placed in a bucket of water and gently agitated to break down larger soil particles, and to remove the debris and dead roots. This mixture was sieved through 2 mm mesh placed in a shallow tub of water to wash away fine soil particles attached to the roots. The roots were floated on shallow water placed in a tray and scanned using Epson Expression 1680 Scanner (Seiko Epson Corp., Tokyo, Japan). Root length density analysis was done using WinRHIZO Root Analyzer System (Regent Instruments Inc., Quebec, Canada) (Equation 1).

$$\text{Root length density (cm cm}^{-3}\text{)} = \frac{\text{Root length (cm)}}{\text{Soil volume of corresponding depth (cm}^3\text{)}} \quad (1)$$

## Assessment of Leaf Water Content

Four plants (potato and legumes) were harvested at 40 days after emergence for determination of leaf water content (LWC). Five leaves sampled from the fifth fully expanded leaf (from the plant apex) of the four plants were used (Barr and Weatherley, 1962). Sampling was done from the center of the leaves avoiding the veins and immediately weighed to prevent water loss, and to obtain the fresh weight (FW). The leaves were placed in petri dishes and soaked in deionized water for 12 h in the dark to attain saturation. The leaf samples were wiped with paper towels to remove the excess water and weighed again to get the turgid weight (TW). The samples were oven dried at 65°C for 24 h and placed in a desiccator for 30 min to reach ambient temperature. The leaves were weighed to obtain dry weight (DW) and the LWC computed using Equation (2).

$$\text{LWC} = \left[ \frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}} \right] * 100 \quad (2)$$

## Physiological and Biochemical Processes

Canopy temperature and stomatal conductance were measured by a portable photosynthesis system (LI-6400, LI-COR, Lincoln, NE, USA) at vegetative phase of potato growth. Nine plants from each experimental plot were randomly selected and the measurements were conducted on the fourth petiole and averaged. All the measurements were done on a sunny day.

Computations of proline contents was done at 40 days after emergence (beginning of tuber bulking stage) (Pilon et al., 2014). The leaf samples used were obtained from the fourth leaf of the plant apex, which were wrapped in aluminum foil, immersed in liquid N and stored in a freezer (−80°C) for subsequent biochemical analysis. The leaf samples (1 g) were extracted with 3% sulphosalicylic acid and 2 mL of the extract added to 1 mL acid ninhydrin and 1 mL glacial acetic acid (Bates et al., 1973). The mixture was held in a water bath for 1 h before a 2 mL toluene was added. The proline concentrations were measured with a spectrophotometer (Shimadzu UVmini-1240, Shimadzu Corp.,

Kyoto, Japan) at a wavelength of 520 nm and calculated against a standard proline (Pilon et al., 2014).

For total soluble carbohydrates, leaves from 4 randomly sampled plants (both potato and the legumes) were placed in oven with forced air circulation at 70°C for 72 h. Upon drying, the leaves were ground to powdery and the powder stored in a glass container in the dark at 15°C until biochemical analyses. About 20 mg of the leaf powder was incubated with 2.0 μL of 80% ethanol at 95°C for 20 min and centrifuged for 5 min at 20°C. A 100 μL supernatant sample was carefully decanted and added to a solution containing 1.25 μL of 100% H<sub>2</sub>SO<sub>4</sub>, 70 μL of 15% phenol, and 580 μL H<sub>2</sub>O before the soluble carbohydrate contents were measured at 490 nm using glucose as a standard (Dubois et al., 1956).

Leaf electrolyte conductance was measured at stolon and tuber formation stage of potato growth using procedure adapted from Hirashima et al. (2009). The uppermost fully expanded leaf trifoliolate, both for potato and legumes was selected. The three leaflets, excluding the petioles were cut, placed in 50 ml eppendorf plastic tubes and covered to minimize water loss. About 20 mL of deionized water was added to 50 ml eppendorf plastic tubes, covered with lids and shaken for 2 h on an orbital shaker at 144 revolutions per minute (rpm). Initial conductance was measured using a conductivity meter (Model WTWCond3110 fitted with a tetracon 325 electrode; WTW 82362 Wellheim, Germany). This measurement indicated free leaf electrolytes outside the leaf cell membrane (apoplast). The leaf segments were boiled by placing the tubes on a 100°C water bath for 15 min followed by centrifuging at 144 rpm for another 2 h. The conductance of the boiled leaf tissues was measured after cooling down to a room temperature. This conductance indicated electrolyte status of electrolytes in the apoplast and electrolytes, which were previously bound within the leaf cell membrane (symplast) before being released because of aggravated membrane damage arising from exposure of the leaf segments to the hot water bath. To allow for direct comparison of apoplast, symplast and total leaf electrolyte status of the potato and legume species evaluated, the leaf segments were oven-dried to a constant weight at 85°C for 24 h.

## Chlorophyll Content, Light Interception, Crop Yield and Radiation Use Efficiency

At 60 days after potato emergence (middle period of the tuber bulking stage), two leaf samples from the third leaf were collected for determination of chlorophyll content (Moran and Porath, 1980). The leaf samples were placed in 1.5 mL of dimethylformamide for 48 h and then incubated. The chlorophyll readings were taken using a spectrophotometer at wavelengths of 480, 646.8, and 663.8 nm.

Radiation interception of photosynthetically active radiation (PAR) and leaf area index (LAI) were measured from 14 days after potato emergence and progressively at 14–16 days interval until physiological maturity using a Sunfleck Ceptometer-LP-80 (Decagon Devices, Pullman, WA, USA). Measurements were taken only under blue-sky conditions with no or minimum clouds between 1130 and 0130 h (local time), and during a period

of constant incident solar radiation. For each measurement, nine above and below canopy readings were taken perpendicularly to the crop rows to ensure that more leaf area was exposed to the light sensors. Corresponding LAI values were read upon averaging the above and below canopy readings. Plot values were computed from the average of four successive middle row readings. The PAR intercepted was calculated using Equations (3–5) (Koocheki et al., 2016).

$$PAR_{intercrop} = PAR_o [1 - \exp((-λ_{potato} * LAI_{potato}) + (-λ_{legume} * LAI_{legume}))] \quad (3)$$

$$PAR_{potato} = \frac{λ_{potato} * LAI_{potato}}{(λ_{potato} * LAI_{potato}) + (λ_{legume} * LAI_{legume})} \quad (4)$$

$$PAR_{legume} = PAR_{intercrop} - PAR_{potato} \quad (5)$$

Where PAR = photosynthetically active radiation (400–700 nm); LAI = leaf area index,  $λ$  = light extinction coefficient;  $PAR_o$  = PAR incident equal to half the daily global radiation (Monteith and Unsworth, 1990). Daily global radiation was estimated from the daily sunny hours recorded from the adjacent meteorological station. The light extinction coefficient ( $λ$ ) was determined from the slope of the linear regression between the natural logarithm of radiation transmission and leaf area index (Monteith, 1965).

The tuber and legume yields were estimated from the central 1.2 m<sup>2</sup> area of each plot. About 500 g of tuber harvested from each plot were sliced and dried in an oven at 65°C for 72 h and reweighed to determine the tuber dry weight. For the legumes, the shoot biomass estimations was done by cutting the plants at the soil line using machetes. The dry mass was determined by oven-drying about 500 g samples at 65°C to a constant mass. The yields were converted into potato equivalent (PEY) using Equation (6) (Gitari et al., 2018a, 2020a). For dolichos, the estimations considered grain and shoot biomass separately as this legume is used as both pulse and forage.

$$PEY \left( t \text{ ha}^{-1} \right) = PY \left( kg \text{ ha}^{-1} \right) + \frac{LY \left( kg \text{ ha}^{-1} \right) * LP \left( US\$ \text{ kg}^{-1} \right)}{PP \left( US\$ \text{ kg}^{-1} \right)} \quad (6)$$

Where PEY = potato equivalent yield, PY = potato yield, LY = legume yield, PP = market price of potato (0.38 US\$ kg<sup>-1</sup>) and LP = market price of the legume (0.51, 0.28, and 1.15 US\$ kg<sup>-1</sup> for vetch forage, dolichos forage, and dolichos grain, respectively).

Radiation use efficiency (RUE) (g MJ<sup>-1</sup>) was estimated by fitting a linear regression (least square) to the cumulative amount of radiation absorption (MJ m<sup>-2</sup>) and dry matter accumulation from successive harvests (g m<sup>-2</sup>) (Monteith, 1994). The slope of each regression was taken as the RUE for each treatment.

## Estimation of Soil Water Balance and Crop Water Productivity

The topsoil (0–0.3 m) water balance was estimated at the end of each season according to procedures outlined by Allen et al. (1998) (Equation 7).

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I - CR_i + ET_i + DP_i + \Delta SWC_i \quad (7)$$

where  $D_{r,i}$  and  $D_{r,i-1}$  are the cumulative depth of evaporation (root-zone moisture depletion) following complete wetting from the exposed and wetted fraction of the topsoil at the end of time  $i$  and time  $i-1$ , respectively,  $P$  is precipitation,  $RO$  is runoff from the soil surface,  $I$  is net irrigation depth that infiltrates into the soil,  $CR$  is capillary rise from the groundwater table,  $ET$  is the actual crop evapotranspiration, and  $Dp$  is deep percolation beyond the root-zone,  $\Delta SW$  = change in soil water storage in root zone between planting and harvesting ( $\Delta SW$ ). All terms are expressed in mm relative to time  $i$ , that is, start of season and harvest. Capillary rise was assumed negligible because the groundwater table was more than 25 m below the soil surface (Karuku et al., 2014). The total amount of surface runoff was quantified from the runoff plots, soil evaporation by micro-lysimeters installed in each plot. Deep percolation ( $Dp$ ) was estimated as residual term of potato root-zone water balance (Bethune et al., 2008). No irrigation water was applied throughout the growing period, similar to what the farmers in this area do.

Crop water productivity (CWP) was computed using Equation (8) (Pereira et al., 2012).

$$CWP = \frac{PEY}{P + CR + \Delta SW + I - RO} \quad (8)$$

Where PEY = potato equivalent yield;  $P$  = precipitation;  $CR$  = capillary rise of water;  $\Delta SW$  = change in soil water storage in root zone between planting and harvesting period ( $\Delta SW$ ) and  $I$  = irrigation ( $I$ );  $R$  = runoff.

## Quantification of Soil Loss and Runoff

Eroded sediment was quantified 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 Equation (9).

$$\text{Soil loss (g)} = \text{total runoff (l)} * \text{sediment conc. (g l}^{-1}\text{)} \quad (9)$$

Runoff from each plot was converted into mm depth using Equation (10).

$$\text{Runoff (mm)} = \frac{\text{Total runoff volume (m}^3\text{)}}{\text{Plot area}} \quad (10)$$

Nutrient loss was expressed as enrichment ratio, the ratio of nutrient element in the eroded sediment to that in the source soil (Polyakov and Lal, 2008).

## Assessment of Intercrop Productivity

The land equivalent ratio (LER) (Mead and Willey, 1980) was used to evaluate the productivity of intercrops over sole cropping (Equation 11) while the system productivity index (SPI) (Odo,

**TABLE 2 |** Effect of silicon application and legume intercropping on soil, soil temperature, soil evaporation, and soil water balance.

Cropping system		Root zone volumetric water	Matric potential	Soil temperature	Soil evaporation	Soil water balance
		cm <sup>3</sup> cm <sup>-3</sup>	cmH <sub>2</sub> O	°C	mm	
+Si	Sole potato	0.15 ± 0.02bc	-85 ± 3.12b	23.1 ± 1.12d	92.2 ± 4.21g	5.1 ± 0.11b
	Sole dolichos	0.30 ± 0.04g	-31 ± 2.05f	18.8 ± 2.05a	42.2 ± 3.32a	14.2 ± 1.21g
	Sole vetch	0.27 ± 0.02f	-48 ± 3.12de	20.8 ± 2.12bc	53.3 ± 3.12b	9.3 ± 1.17de
	Potato + dolichos	0.24 ± 0.01e	-44 ± 3.94e	20.9 ± 1.94bc	61.1 ± 3.43bc	11.1 ± 1.41f
	Potato + vetch	0.20 ± 0.01d	-51 ± 3.01cd	21.4 ± 2.11b	70.9 ± 3.94de	9.9 ± 0.51def
-Si	Sole potato	0.08 ± 0.01a	-99 ± 4.12a	27.1 ± 1.12	101.3 ± 3.87h	3.3 ± 0.07a
	Sole dolichos	0.24 ± 0.02e	-42 ± 2.05e	20.6 ± 2.05b	53.3 ± 3.27b	10.1 ± 1.07e
	Sole vetch	0.21 ± 0.04d	-54 ± 2.34cd	22.9 ± 2.34d	64.5 ± 4.42c	6.5 ± 1.01bc
	Potato + dolichos	0.17 ± 0.03c	-56 ± 4.03cd	22.5 ± 2.03cd	76.9 ± 3.54e	7.7 ± 1.09c
	Potato + Vetch	0.14 ± 0.01b	-59 ± 3.06c	23.1 ± 2.06d	81.1 ± 3.64f	5.2 ± 0.31b
Silicon		*	ns	ns	ns	*
Cropping system		*	*	**	**	*
Silicon*cropping system		**	*	*	*	**
Season		**	**	**	**	**

\*Significant at the 0.05 probability level; \*\*Significant at the 0.01 probability level; ns, not significant at the 0.05 probability level; +Si, silicon application; -Si, zero silicon application. Different letters indicate significant differences for means between the cropping systems and Si applications at  $p \leq 0.05$  by Tukey's HSD test. Values (means ± standard error) are 4 replicates expressed as averages over five seasons.

1991) was used to assess the stability of the intercropping systems (Equation 12).

$$LER = \frac{Y_{il}}{Y_{sl}} + \frac{Y_{ip}}{Y_{sp}} \tag{11}$$

Where  $Y_{il}$  and  $Y_{ip}$  are intercrop yields of legume and potato, respectively, while  $Y_{sl}$  and  $Y_{sp}$  are the sole yields of legume and potato.  $LER > 1$  indicates a production advantage;  $LER = 1$  indicates no production advantage; and  $LER < 1$  indicates a production disadvantage of the crop system.

$$SPI = Y_{pi} + \left( \frac{Y_{ps}}{Y_{ls}} \right) * Y_{li} \tag{12}$$

Where  $Y_{pi}$  and  $Y_{li}$  depict the economic yield of potato and legume under intercropping, respectively, whereas  $Y_{ps}$  and  $Y_{ls}$  represents the respective yields under pure stands.

### Data Analysis

The statistical analyses were performed in R software, version 3.4.2 (R Core Team, 2017) using linear mixed model analysis of variance (ANOVA). The datasets explored were soil temperature, soil moisture, canopy temperature, leaf water content, stomatal conductance, proline contents, total soluble carbohydrates, leaf electrolyte conductance, root length density, chlorophyll content, light interception, crop yield, radiation use efficiency, crop water productivity, soil loss, and runoff. The mixed-models were defined with the R-package lme4 (Bates et al., 2015) using likelihood based inference (Demidenko, 2013). Treatments and their interactions were considered as fixed factors while season and blocks (replications) were regarded as random factors because the study objective was to compute the variability

of treatment differences across different seasons. Significant interactions between fixed factors were detected using likelihood ratio tests for generalized linear mixed models. Whenever treatment effects were significant, the response variable was subjected to Tukey's Honest Significant Difference (HSD) test ( $p \leq 0.05$ ) for multiple mean comparisons with the agricolae package. Differences between treatments are indicated by different lower-case letters in figures and tables. Mean values are reported with standard errors, except for soil loss, runoff, and enrichment ratios where estimates are reported with 95% confidence intervals. Whenever necessary, data were either log transformed or an unequal variance model used to meet assumptions of normality and equal variance. Substitutive design was used to hold the total density of the intercrop constant and vary the ratio among the intercrop species.

## RESULTS

### Changes in Soil Moisture and Soil Temperature

There were significant differences ( $p \leq 0.05$ ) in the mean volumetric soil water contents (SWCs) measured between the different cropping systems and Si applications (Table 2). Compared with the sole potato stands, which recorded the lowest SWC (0.08–0.15 cm<sup>3</sup> cm<sup>-3</sup>), the highest SWC in the surface soil layer (0–0.3 m) was measured under potato-dolichos intercropping (0.17–0.24 cm<sup>3</sup> cm<sup>-3</sup>) irrespective of Si application. The soil moisture content were influenced by Si application irrespective of the cropping system. The corresponding matric potential values varied among the treatments and were significantly higher ( $p \leq 0.05$ ) in

**TABLE 3** | Effect of silicon application and legume intercropping on leaf area index, leaf orientation, leaf nitrogen, stomatal conductance, and chlorophyll content.

Cropping system		Leaf area index	Extinction coefficient	Specific leaf nitrogen	Stomatal conductance	Chlorophyll content
				g N m <sup>-2</sup> leaf	molm <sup>-2</sup> s <sup>-2</sup>	ug m <sup>-2</sup>
+Si	Sole potato	2.8 ± 0.21bc	0.53 ± 0.02e	1.63 ± 0.11b	0.36 ± 0.04b	4.93 ± 0.33b
	Sole dolichos	4.1 ± 0.02fg	0.38 ± 0.01a	2.13 ± 0.05h	0.69 ± 0.04g	8.45 ± 0.47e
	Sole vetch	3.4 ± 0.02cd	0.41 ± 0.04b	2.02 ± 0.12g	0.55 ± 0.06ef	7.56 ± 0.12e
	Potato + dolichos	4.5 ± 0.15g	0.41 ± 0.02b	2.84 ± 0.94j	0.55 ± 0.08ef	8.30 ± 0.28e
	Potato + vetch	3.9 ± 0.05ef	0.45 ± 0.01c	2.43 ± 0.14i	0.51 ± 0.07de	7.61 ± 1.04e
-Si	Sole potato	2.1 ± 0.04a	0.59 ± 0.02d	1.13 ± 0.08a	0.21 ± 0.01a	3.12 ± 0.11a
	Sole dolichos	3.4 ± 0.07c	0.40 ± 0.05b	1.97 ± 0.05fg	0.56 ± 0.03f	5.34 ± 0.27cd
	Sole vetch	2.9 ± 0.12bc	0.43 ± 0.02bc	1.76 ± 0.33c	0.43 ± 0.03c	4.78 ± 0.03b
	Potato + dolichos	3.7 ± 0.13def	0.42 ± 0.03b	1.94 ± 0.12efg	0.50 ± 0.05d	5.82 ± 0.49cd
	Potato + vetch	3.3 ± 0.04cde	0.45 ± 0.06c	1.88 ± 0.07d	0.48 ± 0.02cd	5.52 ± 1.01d
F statistics						
Silicon		*	*	*	ns	ns
Cropping system		*	*	Ns	*	*
Silicon*cropping system		*	*	*	**	*
Season		*	*	Ns	**	ns

\*Significant at the 0.05 probability level; \*\*Significant at the 0.01 probability level; ns, not significant at the 0.05 probability level, +Si, silicon application; -Si, zero silicon application. Different letters indicate significant differences for means between the cropping systems and Si applications at  $p \leq 0.05$  by Tukey's HSD test. Values (means ± standard error) are 4 replicates expressed as averages over five seasons.



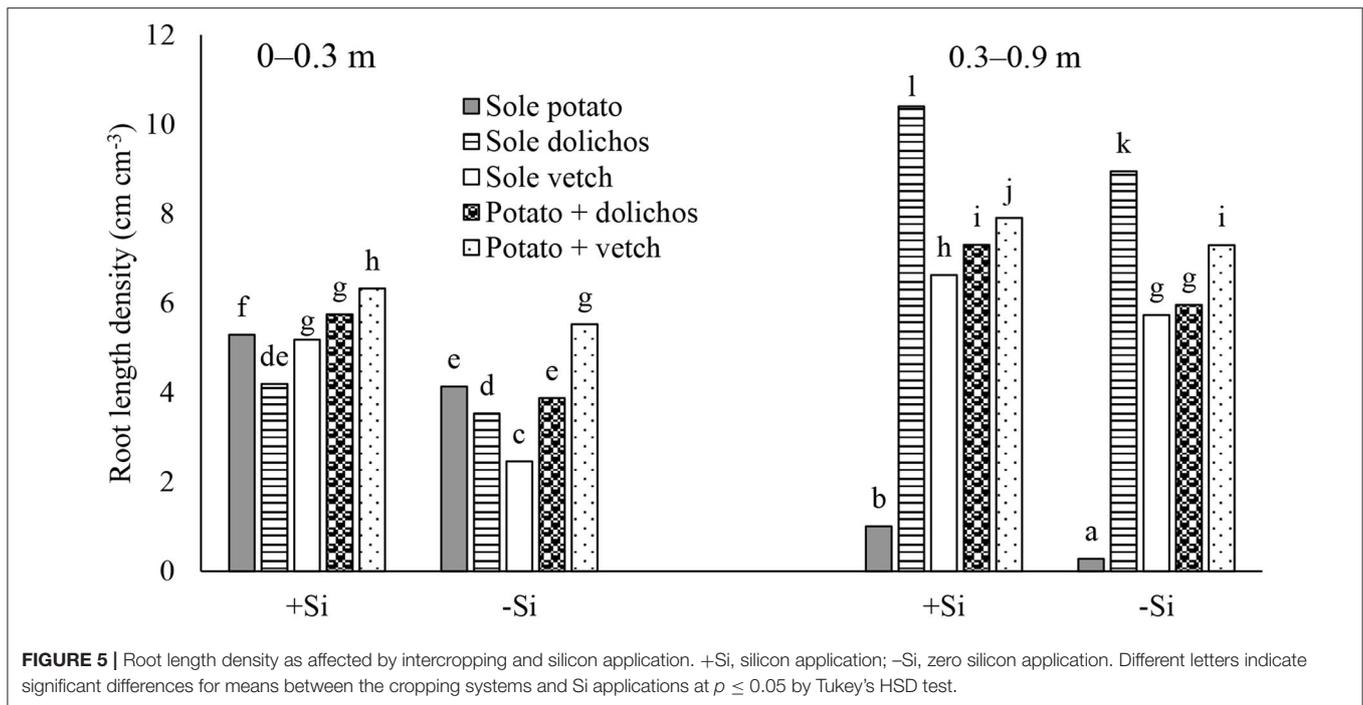
**FIGURE 4** | Effect of Si application and legume intercropping on crop growth. (a,b) sole potato, (c,d) sole dolichos, (e,f) potato-dolichos intercrop, (g,h) sole vetch, (i,j) potato-vetch intercrop, with Si (+Si) and without Si (-Si) applications, respectively.

intercrops (-44–59 cmH<sub>2</sub>O) relative to sole potato (-85–99 cmH<sub>2</sub>O) and increased with Si application. Mean soil temperatures (23.1–27.1°C) were higher in sole potato plots than in potato-legume intercropping (20.9–23.1°C). Similarly, soil evaporation was significantly greater under sole potato (92.2–101.3 mm) than under intercrops (61.1–81.1 mm) and were significantly influenced by Si application ( $p \leq 0.01$ ). The soil water balance was greatest under sole legumes (6.5–14.2 mm) followed by intercrops (5.2–11.1 mm) and lowest in sole potato (3.3–5.1 mm). Dolichos recorded higher soil

water balance compared with vetch. Seasons, and interaction of Si and cropping system had significant effect on soil water balance ( $p \leq 0.05$ ).

### Intercropping and Silicon Application Effects on Crop Growth

Intercropping and Si interaction exhibited significant effect on crop growth and leaf nitrogen content (Table 3; Figure 4). Leaf area index was significantly greater in intercrops (3.3–4.5) followed by sole stands of legumes (3.3–4.1) and was lowest in



pure potato stands (2.1–2.8). Leaf area index increased by 18–33% with Si application. Intercropping significantly ( $p \leq 0.05$ ) lowered the leaf extinction coefficient of both legumes and potato with mean value of 0.56 in sole potato compared with 0.41 in intercrops. Specific leaf nitrogen ranged from 1.13–1.63 g N m<sup>-2</sup> leaf in sole potato compared with 1.88–2.84 g N m<sup>-2</sup> leaf in intercrops and were up to 51% increased by Si application. Stomatal conductance ranged from 0.21–0.36 molm<sup>-2</sup> s<sup>-2</sup> in sole potato compared with 0.48–0.55 molm<sup>-2</sup> s<sup>-2</sup> in intercropping, and significantly increased with Si application. Chlorophyll contents were similarly higher ( $p < 0.01$ ) in intercrops (5.52–8.30  $\mu\text{g m}^{-2}$ ) relative to sole potato treatments (3.12–4.93  $\mu\text{g m}^{-2}$ ) and increased with Si application. The LAI, chlorophyll content, stomatal conductance, and specific leaf nitrogen content responded significantly to Si application and to Si by cropping system interaction ( $p \leq 0.05$ ). Season had significant effect on LAI, leaf extinction coefficient, and stomatal conductance.

Root length density (RLD) increased from 4.13–5.29 cm cm<sup>-3</sup> in sole potato to 5.52–6.32 cm cm<sup>-3</sup> in intercrops. The potato plants subjected to Si application exhibited significantly higher RLD both in the 0–0.3 and 0.3–0.9 m depths (Figure 5). In the 0.3–0.9 m depth, sole legumes exhibited significantly higher RLD (8.94–10.40 cm cm<sup>-3</sup>) followed by intercrops (5.96–7.90 cm cm<sup>-3</sup>) and lowest in sole potato (0.28–1.01 cm cm<sup>-3</sup>). Dolichos generally showed significant higher RLD density ( $p \leq 0.05$ ) in relation to vetch irrespective of cropping system and Si application.

## Canopy Temperature and Biochemical Processes

Intercropping significantly ( $p \leq 0.05$ ) lowered the canopy temperature from 25.6 to 27.8°C in sole potato to 18.7–21.8°C,

the effect of which increased with Si application (Table 4). The percent leaf water content was significantly higher ( $p \leq 0.05$ ) in the plants subjected to combined application of Si and intercropping (75.2–78.5%) compared with the -Si treatments (62.9–63.3%). Leaf electrolyte conductance ranged from 746–1,409 mS cm<sup>-1</sup> in sole potato compared with 1,423–3,107 mS cm<sup>-1</sup> in intercropping and were increased by 36–111% with Si application. Silicon application increased the contents of total soluble carbohydrates from 28 to 59  $\mu\text{mol g}^{-1}$  (110%). Similarly, Si application increased the contents of proline from 1.0 to 2.9  $\mu\text{mol g}^{-1}$  in sole potato (191%), 1.12–2.3  $\mu\text{mol g}^{-1}$  (104%) in potato-dolichos intercropping and 1.08 to 2.32  $\mu\text{mol g}^{-1}$  (115%) in potato-vetch intercropping. A significant effect of Si cropping system, season and Si by cropping system interaction was found on canopy temperature, leaf water content, proline content, total soluble carbohydrates and leaf electrolyte conductance.

## Soil Erosion and Nutrient Loss

Cumulative soil loss and runoff differed significantly among the treatments ( $p \leq 0.05$ ) and were consistently highest in sole potato plots (198–221 t ha<sup>-1</sup> and 88–108 mm) and lowest in potato-dolichos intercrop (79–99 t ha<sup>-1</sup> and 42–52 mm) plots, respectively (Table 5). Enrichment ratios of the measured parameters were above unity irrespective of treatments and differed significantly among the treatments ( $p \leq 0.05$ ) except for the sand fractions. The highest values of enrichment ratios for NPK were recorded in sole potato plots (1.87–3.09) and lowest in sole dolichos plots (1.21–1.39). Even though an observable reduction in the enrichment ratio was observed due to Si application, these values were not significantly different from the controls (-Si treatments).

**TABLE 4** | Silicon and intercropping effects on canopy temperature, leaf water content, and crop biochemical processes.

Cropping system	Canopy temperature	Leaf water content	Leaf electrolyte conductance	Total soluble carbohydrates	Proline content	
	°C	%	mS cm <sup>-1</sup>	umol g <sup>-1</sup>		
+Si	Sole potato	25.6 ± 2.12de	62.4 ± 3.17b	1,409 ± 23b	59.3 ± 2.32e	2.91 ± 0.33d
	Sole dolichos	20.7 ± 1.87bc	89.1 ± 3.34e	3,903 ± 29e	31.3 ± 2.21c	2.45 ± 0.41c
	Sole vetch	19.9 ± 1.78ab	71.7 ± 3.65d	2,401 ± 19c	28.9 ± 2.12c	1.99 ± 0.12b
	Potato + dolichos	18.9 ± 1.43a	78.7 ± 3.22cd	3,107 ± 31d	42.2 ± 2.76d	2.30 ± 0.28c
	Potato + vetch	18.7 ± 1.45a	75.2 ± 3.05cd	3,003 ± 27d	38.9 ± 2.88d	2.32 ± 0.17c
-Si	Sole potato	27.8 ± 1.54f	52.2 ± 3.14a	746 ± 17a	28.2 ± 2.12c	1.00 ± 0.01a
	Sole dolichos	23.6 ± 1.45d	72.3 ± 3.04c	2,307 ± 23c	18.1 ± 1.09b	1.19 ± 0.02a
	Sole vetch	24.4 ± 1.76e	60.3 ± 3.87b	1,764 ± 19b	10.3 ± 2.24a	1.14 ± 0.07a
	Potato + dolichos	21.8 ± 1.67c	62.9 ± 3.18b	1,654 ± 28b	18.1 ± 1.83b	1.12 ± 0.09a
	Potato + vetch	21.6 ± 1.89c	63.3 ± 3.76b	1,423 ± 24b	16.2 ± 1.32b	1.08 ± 0.03a
F statistics						
Silicon	*	ns	**	**	**	
Cropping system	*	*	*	ns	ns	
Silicon*cropping system	**	*	*	*	**	
Season	**	*	ns	ns	**	

\*Significant at the 0.05 probability level; \*\*Significant at the 0.01 probability level; ns, not significant at the 0.05 probability level; +Si, silicon application; -Si, zero silicon application. Different letters indicate significant differences for means between the cropping systems and Si applications at  $p \leq 0.05$  by Tukey's HSD test. Values (means ± standard error) are 4 replicates expressed as averages over five seasons.

**TABLE 5** | Intercropping and silicon effects on soil erosion and soil nutrient loss.

Cropping system	Cumulative soil loss	Cumulative runoff	Enrichment ratio									
	t ha <sup>-1</sup>	mm	pH	SOC	N	P	K	CEC	Sand	Silt	Clay	
+Si	Sole potato	198f	88g	1.08a	1.98h	1.87h	2.78h	1.89c	1.19b	0.98a	1.15a	1.17a
	Sole dolichos	48a	31a	1.03a	1.03a	1.11ab	1.23a	1.04a	1.07a	0.87a	1.13a	1.15a
	Sole vetch	72b	33a	1.01a	1.22d	1.32ef	1.43de	1.06a	1.08a	0.88a	1.14a	1.15a
	Potato + dolichos	79b	42bc	1.01a	1.45f	1.21cd	1.31b	1.34b	1.08a	0.89a	1.15a	1.16a
	Potato + vetch	98d	55ef	1.03a	1.54g	1.43g	1.46ef	1.38b	1.09a	0.87a	1.14a	1.16a
-Si	Sole potato	221g	108g	1.09a	2.09	1.92h	3.09i	1.92c	1.21b	0.99a	1.19a	1.19a
	Sole dolichos	78bc	35a	1.05a	1.13b	1.17bc	1.34bc	1.05a	1.09a	0.87a	1.17a	1.16a
	Sole vetch	92cd	48cd	1.04a	1.32e	1.38f	1.49fg	1.09a	1.08a	0.89a	1.15a	1.15a
	Potato + dolichos	99d	52de	1.03a	1.51cd	1.25de	1.39cd	1.36b	1.09a	0.88a	1.16a	1.17a
	Potato + vetch	123e	59f	1.04a	1.61c	1.46g	1.51g	1.38b	1.10a	0.89a	1.17a	1.18a
F statistics												
Silicon	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cropping system	**	*	ns	**	**	*	ns	*	ns	ns	ns	ns
Silicon*cropping system	*	*	*	*	ns	**	ns	*	ns	ns	ns	ns
Season	*	*	ns	ns	ns	ns	ns	*	ns	ns	ns	ns

\*Significant at the 0.05 probability level; \*\*Significant at the 0.01 probability level; ns, not significant at the 0.05 probability level; +Si, silicon application; -Si, zero silicon application. Different letters indicate significant differences for means between the cropping systems and Si applications at  $p \leq 0.05$  by Tukey's HSD test. Values are 4 replicates expressed as averages over five seasons.

## Intercropping Productivity

Cumulative biomass was significantly greater in intercrops (8.8–15.8 t ha<sup>-1</sup>) than in sole potato stands (1.9–2.1 t ha<sup>-1</sup>) and increased significantly with Si application (Table 6). Highest

potato equivalent yields were recorded by intercrops relative to sole crop of potato, vetch, or dolichos. Potato equivalent yields for potato-dolichos system subjected to Si application was 14.5 t ha<sup>-1</sup> greater than that of sole dolichos, and 23.3 t ha<sup>-1</sup> than

**TABLE 6** | Silicon and legume intercropping effect on biomass yield, potato yield, and resource use efficiency.

Cropping system	Cumulative biomass	PEY	fPAR	RUE	CWP	LER	SPI	
	t ha <sup>-1</sup>	t ha <sup>-1</sup>		g MJ <sup>-1</sup>	Kg ha <sup>-1</sup> m <sup>-3</sup>		Kg ha <sup>-1</sup>	
+Si	Sole potato	2.1 ± 0.12a	13.9 ± 1.09b	0.43 ± 0.03b	0.98 ± 0.09b	3.23 ± 0.12b	0.89 ± 0.01b	2923 ± 21a
	Sole dolichos	18.8 ± 2.05e	25.2 ± 3.01e	0.76 ± 0.06f	2.03 ± 0.05ef	6.78 ± 1.03e	0.98 ± 0.04c	3223 ± 28a
	Sole vetch	10.2 ± 1.12bc	20.9 ± 2.09d	0.67 ± 0.07de	1.94 ± 0.13d	5.98 ± 1.12cd	0.97 ± 0.03c	3098 ± 34a
	Potato + dolichos	15.8 ± 1.34d	32.2 ± 3.00f	0.87 ± 0.05g	2.98 ± 0.08h	9.09 ± 1.04g	1.29 ± 0.08f	3987 ± 32b
	Potato + vetch	8.9 ± 1.01b	24.9 ± 2.12e	0.72 ± 0.01ef	2.56 ± 0.02g	7.38 ± 1.01ef	1.21 ± 0.07e	3765 ± 29b
-Si	Sole potato	1.9 ± 0.01a	8.9 ± 0.76a	0.31 ± 0.012a	0.77 ± 0.11a	1.13 ± 0.12a	0.74 ± 0.03a	2421 ± 19a
	Sole dolichos	14.9 ± 1.03d	17.7 ± 2.01c	0.65 ± 0.06d	1.89 ± 0.05d	4.78 ± 0.08c	0.91 ± 0.07b	3018 ± 23b
	Sole vetch	8.8 ± 1.04b	13.3 ± 0.09bc	0.54 ± 0.12c	1.78 ± 0.10c	4.34 ± 0.34c	0.89 ± 0.03b	2967 ± 28b
	Potato + dolichos	11.8 ± 1.13c	25.1 ± 2.03e	0.77 ± 0.03f	2.09 ± 0.08f	6.89 ± 0.03e	1.12 ± 0.09d	3661 ± 27c
	Potato + vetch	8.8 ± 0.04b	17.3 ± 1.64c	0.65 ± 0.06d	1.98 ± 0.02de	5.99 ± 0.06cd	1.09 ± 0.05d	3587 ± 20c
Silicon (Si)	ns	**	*	*	ns	ns	*	
Cropping system (CS)	*	*	*	**	*	**	**	
Si* CS	**	**	**	**	*	*	*	
Season	**	**	*	**	*	ns	ns	

\*Significant at the 0.05 probability level; \*\*Significant at the 0.01 probability level; ns, not significant at the 0.05 probability level; +Si, silicon application; -Si, zero silicon application; fPAR, fraction of photosynthetically active radiation intercepted; PEY, potato equivalent yield; CWP, crop water productivity; RUE, radiation use efficiency; LER, land equivalent ratio; SPI, System productivity index. Different letters indicate significant differences for means between the cropping systems and Si applications at  $p \leq 0.05$  by Tukey's HSD test. Values (means  $\pm$  standard error) are 4 replicates expressed as averages over five seasons.

that of sole potato. Yield increase due to vetch intercropping was 11.6 and 16 t ha<sup>-1</sup> greater than that of sole vetch and sole potato respectively. Irrespective of the Si application, crop water productivity was 3–8-fold greater in intercrop relative to sole potato. Fractions of light intercepted were consistently greatest in intercrops (0.67–0.87) than in sole legumes (0.54–0.76) and lowest in the sole potato stand (0.31–0.43) ( $p \leq 0.05$ ). Intercrop of potato and dolichos subjected to Si application recorded the highest significant RUE, which was 3-fold greater than that of sole potato.

Land equivalent ratios were greater than unity in intercrops compared with sole cropping system of potato, which recorded LER values below unity. Regardless of the cropping system, application of Si significantly increased the crop water productivity, radiation use efficiency, and light interception (PAR). Silicon and intercropping interaction had significant effect on land productivity as measured by LER. System productivity index (SPI) was significantly ( $p \leq 0.05$ ) influenced by potato-legume intercropping systems. The index increased with Si application.

## DISCUSSIONS

### Intercropping and Silicon Effect on Soil Moisture and Soil Temperature

The significantly higher soil water content within the potato root-zone in intercropped plots indicated long-term moisture accumulation. The greater rooting system by potato grown in intercropping increased the capacity of crops to extract water by increasing the size of the water reservoir. While potato crop was characterized by roots that rarely exceeded a vertical depth of

0.3 m, dolichos and vetch roots colonized the 0.3–0.9 m depth. Legumes could therefore access soil water to deeper subsurface layers than the potato crop, allowing potato to draw the soil moisture in the 0–0.3 m depth. Giller (2015) highlighted that legumes have prolonged water uptake from deep soil layers. This helps the plants to improve their leaf water status and to maintain transpiration rates and dry matter production. As legume intercropping enhanced canopy formation and overlap, this meant a high groundcover that considerably reduced soil evaporation and increased soil water storage.

Soil temperatures were lower in intercropping due to the shade created by the canopy overlap between the intercrop components. The higher soil water content under intercropping further enhanced the soil cooling. Generally, a dry soil has lower heat capacity than a wet soil (Li et al., 2017). For the sole potato plots, heat from the topsoil was easily lost to the atmosphere through the intervening bare soil. Silicon application enhanced soil cooling due to its indirect effect on soil temperature as this amendment facilitated potato and legume growth thus enhancing canopy formation and subsequent shading of the soil (see the photo on Figure 4).

### Effect of Silicon Application on Potato Growth, Physiology and Biochemical Composition

The greater LAI due to intercropping could be explained by the differences that existed in the vertical foliage arrangement and canopy architecture of the different crop varieties. Potato canopy was generally characterized by bare surfaces between the crop rows. While vetch provided low-density canopy, which closed the bare spaces between potato rows, the effective canopy

overlap by dolichos bridged the inter-row spacing thus enhancing the LAI development. Nyawade et al. (2019a) observed that the larger and nearly vertical leaves exhibited by dolichos provided complementarity to the slender and more bent leaves of potato thus increasing the LAI. Even though the full canopy closure of potato occurred only after 40–45 days followed by rapid decline after physiological maturity, the legume components conferred a complimentary canopy that kept LAI relatively high during these periods. The higher leaf extinction coefficient (above 0.5) observed in pure potato stand was an indication of sagged leaves with increased propensity to converge solar radiation.

Plant growth and photosynthesis capacity were influenced by Si application. Silicon strengthened the plant tissues, an observation reflected in the relatively lower leaf extinction coefficient. This observation was supported by the measured high leaf water content in plants receiving Si relative to the controls. These plants were thus able to provide more leaf area toward light, thereby enhancing light interception. In addition, silicon increased the specific leaf nitrogen content, which is a major component of plant chlorophyll. Similar results have been found in a related study (Albiski et al., 2012). The increase in root length density due to Si application implies that Si promoted maintenance of root growth at the expense of shoot growth, a factor which has been shown to contribute to drought tolerance (Jefferies, 1993).

Both Si and legume intercropping significantly lowered the canopy temperatures and thus conferred an effective cooling mechanism to potato plants. This improved the plant tolerance to water deficit and to the high heat stress. Meunier et al. (2017) reported that Si stimulates the formation of plant-silicified structures, which offset leaf heat-load in plants. As was reflected in its additive effect on proline accumulations, Si altered the biochemical composition of potato tissues making the plant more resistant to heat stress under water deficit conditions. This is in agreement with the previous work, which demonstrated the role of proline in offsetting the adverse effects of water deficit thereby conferring stress tolerance (Sapre and Vakharia, 2016). Other studies have verified that proline concentrations in potato leaves increase with increase in Si concentrations under water-deficit conditions, which indicates that silicon may be associated with plant osmotic adjustment (Crusciol et al., 2009; Farhad et al., 2011; Pilon et al., 2014). This argument is supported by the fact that proline represents a water loss regulatory mechanism that reduces cell water potential (Fumis and Pedras, 2002), and is a biochemical marker of metabolic alterations generated by different types of stress (Lima et al., 2004). High proline levels enable potato plants to maintain cell turgidity, a fact attributed to the more negative osmotic potential of the cells and consequently alleviating the effects of water deficit (Moussa and Abdel-Aziz, 2008).

The increase in total leaf electrolyte conductance by treatments subjected to Si was possibly a consequence of Si-induced osmotic adjustment process that according to previous studies triggers accumulation of compatible solutes including sugars, ions, and amino acids in response to water deficit and heat stress (Crusciol et al., 2009; Farhad et al., 2011; Pilon et al., 2014). Accordingly, these plants had significantly higher total

soluble carbohydrates content compared with the plants not subjected to Si application. The increased accumulation of solutes was a strategy meant to lower leaf osmotic potential and allow movement of water into the leaf cells, thereby maintaining turgor potential (Midega et al., 2017). This consequently increased plant tissue tolerance to low soil water conditions. According to Chaves et al. (2003), the accumulated solutes sequester water molecules and protect the cell membranes and protein complexes, thus allowing continued cell metabolic functioning. Leaf electrolyte conductance and total carbohydrate content of potato grown in intercrop without Si application were similar to those of sole potato receiving Si. This suggests that intercropping caused the potato plants to maintain their leaf cell membrane stability, which not only enhanced retention of water but also enabled accumulation of electrolytes within the symplast during exposure to heat and water deficit stress. This observation was attributed to the enhanced soil water content caused by decreased soil evaporation under higher ground cover contributed by legume intercrops.

### Intercropping Effect on Soil Erosion

Compared with pure potato plots, soil loss was significantly reduced by intercropping relative to sole potato cropping. These losses were generally higher in the wet seasons, at emergence and after crop senescence when canopy cover was below 40%. This time constituted 60% of the cumulative soil loss in pure potato plots indicating that vegetal cover had effect on soil detachment. Seasonal effect was due mainly to the rainfall amounts, which were higher in the wet seasons. Potato took about 2 weeks to sprout and up to 45 days to close the canopy while dolichos emerged after 7 days and closed the canopy in only 21 days. The canopy closure with vetch occurred at 28 days after planting and was characterized by low dense cover with slender leaves and high propensity to control soil erosion. The canopy closure with dolichos was extended up to 1 month after potato harvest thus minimizing the off-season soil losses. The higher kinetic energy of rainfall that occurred early in the season sagged the weak leaf petioles, increasing the amount of bare soil between the potato rows and weakening the dissipating effect of the canopy on energy. 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, thus gradually weakening their erosion potential. Ma et al. (2015) noted that the degree of leaf bending under splash effect differs with the type of plants with some leguminous crops being more prone to bending under high kinetic energy of rainfall due to their wider and softer leaves.

The highest values of enrichment ratio for total nitrogen, available phosphorus, extractable potassium, magnesium, and calcium were recorded in pure potato plots pointing to the high nutrient losses under pure potato stands. Potato delayed to establish protective cover and left the soil highly exposed to erosion, thus causing a substantial loss to the applied fertilizer. These losses occurred mainly in the first few weeks after planting when heavy rainstorms caused substantial soil erosion. Compared with vetch, growth of dolichos was more rapid and

provided protective soil cover, which significantly minimized the nutrient losses. The enrichment ratio was particularly high for phosphorus 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 enrichment ratio for exchangeable potassium was lower than that of total nitrogen and phosphorus because phosphorus is uniformly distributed within the soil profile (Nyawade, 2015).

Across the treatments, the enrichment ratio of total soil organic carbon was above unity 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 SOC concentration compared with the inner core resulting into SOC ratios above unity (Ghadiri and Rose, 1991). The soil pH enrichment ratio was above unity suggesting that the eroded soil material was enriched in bases relative to the source soil and may lead to Ca, Mg, K, and Na deficiency. This was asserted by the enrichment ratio of CEC, which was above unity in all the plots indicating that the eroded soil materials had higher positive charges relative to the source soil material. The enrichment ratio for clay and silt were greater than one, but that for sand was less than unity, 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 because 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).

## Intercropping and Silicon Effect on Crop Yield and Resource Productivity

Intercropping increased biomass yield, an observation that was associated with either increase in numbers of tubers per hill or increase in individual tuber weight. The yields were greater in the wet seasons due to the greater rainfall amounts. The intercropping effect on soil temperature was of great importance in explaining the yield variability between the treatments. In a study conducted by Radeni 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 could also be possible that allocation of assimilated carbon into non-structural and structural carbon was altered by the high soil temperature (Arai-Sanoh et al., 2010). For the legumes, the effects of high soil temperature were mediated in part by the deep roots coupled with their good adaptations to high temperatures.

Synergistic interaction between silicon application and intercropping on crop biomass accumulation under water deficit conditions was evident. Silicon enhanced the production of photoassimilates as was shown by the greater accumulation of total soluble carbohydrates. Further, the Si-mediated increase of water uptake under water deficit conditions enabled the potato plants to tolerate short periods of water stress, minimizing its detrimental effects on tuber yield. For the sole potato plots not

applied with Si, water stress not only restrained the potato foliage and plant development but also limited the number of leaves. Potato plants with few leaves are unable to produce large number of tubers and therefore exhibit lower yields (Obidiegwu et al., 2015).

The potato plants supplied with Si in intercropping recorded higher LAI and number of leaves, which enhanced light interception and biomass accumulation. In addition, potato intercrop exhibited greater root length density, which enhanced the crop's capacity to absorb soil water. The adverse effect of water shortage altered chlorophyll contents of the potato plants, decreased the leaf stomatal conductance and inhibited their net photosynthesis. These plants had limited capacity to mobilize the photosynthates to tubers leading to less dry matter formed per amount of water used.

The increased solar radiation interception and use efficiency by intercropping relative to monocropping was asserted to the increased canopy size and duration. The intercrops generally attained maximum canopy above 3, a value that corresponds to full groundcover by a typical potato cropping system (Burke, 2017). This was partly attributed to the increased number of leaves forming on lateral branches of potato grown in intercrops. Plants in intercropping systems were thus able to occupy all the empty niches thus contributing strongly to canopy size and radiation interception. Vetch put short, dense canopy with many slender leaves relative to dolichos, which established tall, broad dense crown with fewer interior leaves, which allowed more light to pass directly through the canopy. Unlike legumes, which indicated progressive growth with little response to prevailing heat stress, potato crop responded by developing leaves showing downward curvatures. This mechanism greatly reduced leaf area exposure to solar radiation and thus reduced radiation interception. When the crops suffered longer heat stress, potato leaves drooped followed by wilting that started from the lower strata leaves. Only leaves that exhibited some level of greenness recovered turgor and finalized their production cycle. These leaves however had limited capacity to absorb solar radiation, an observation affirmed by the proportional decrease of LAI with increasing soil and ambient temperatures.

The land equivalent ratios recorded under intercropping systems were greater than one, an indication that integration of legumes into potato-based cropping systems favored growth and yield of the companion crops grown in mixtures. The system productivity index of intercrops were greater than that of the sole potato, which was an indication that interspecific facilitation was greater than interspecific competition (Gitari et al., 2020a). This implies that intercropping resulted in greater land-use efficiency and resource productivity (Wahla et al., 2009; Machiani et al., 2018). This ability was enhanced by Si application as was indicated by the higher LER and SPI values. Seasonal effects on LER and SPI were due to fluctuating rainfall amounts, which were generally greater in the wet seasons.

## CONCLUSION

This study demonstrated the beneficial effect of legume intercropping and silicon application on resource productivity, potato yield, and risk aversion in the semi-humid tropics.

For silicon to be fully integrated into potato cropping, the element should be considered essential for higher plants and should form part of soil amendment. Silicate fertilizer should be processed from the complex silicate minerals dominating in the tropics and be available in the local markets. As this study did not integrate an open participatory learning approach, it lacked the farmer-researcher interactions necessary for enhanced adoption. To bridge this gap, close connections with the farming sector, including the farmers, extension services, and fertilizer blending companies is necessary during scaling up. Where possible, crowdsourcing applications can be adopted to provide inputs that meet the researchers' needs and help in closing the knowledge dissemination loop between researchers and practitioners and foster farmer-to-farmer interactions.

## DATA AVAILABILITY STATEMENT

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

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## AUTHOR CONTRIBUTIONS

SN conceptualized the idea, took part in the design of study, and drafted and proofread the manuscript. HG, NK, CG, KS, ES-G, and MP took part in synthesis of idea, design of the manuscript, and manuscript review and proofreading. All authors contributed to the article and approved the submitted version.

## ACKNOWLEDGMENTS

This work was implemented as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from CGIAR Fund Donors and through bilateral funding agreements. For details, please visit <https://ccaafs.cgiar.org/donors>. The authors greatly acknowledge Privi Life Sciences Private Limited for providing the orthocilicic acid amendment. The views expressed in this document cannot be taken to reflect the official opinions of these organizations.

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

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