



Research article

Effect of tillage systems and tillage direction on soil hydrological properties and soil suspended particle concentration in arable land in Uganda

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ABSTRACT

The 2030 Agenda for Sustainable Development addressing the issues of environmental degradation has been challenged by human developments and activities. Crop production systems and technologies (e.g. soil tillage) are among the leading factors causing environmental degradation. In this study, the effect of soil tillage systems (i.e. no-tillage (NT); stubble-mulching (SM); deep tillage (DT); and conventional tillage (CT)) on surface runoff volume (SRV), suspended sediment concentration (SSC), infiltration rate (IR), and soil moisture content (SMC) in the common bean (*Phaseolus vulgaris* L.) farms, Mukono District, Uganda was evaluated. The effect of soil tillage direction on SRV was also assessed. The SRV, SSC, IR, and SMC were monitored under Complete Randomized Block Design (CRBD) experiments with four soil tillage systems in Goma and Kimenyedde experimental sites during two wet seasons. The results showed that SRV, SSC, IR, and SMC were significantly ($p < 0.05$) influenced by the soil tillage system, season, and site. The highest total SRV was observed during the first season in Goma experimental site under CT with soil tillage along the slope (1071.3 mm). The lowest SRV was observed during the second season in Kimenyedde experimental site under NT (165.0 mm). The highest and lowest mean SSC was observed in the CT ($2.41 \pm 0.3 \text{ g L}^{-1}$) in Goma experimental site during the first season and NT ($0.43 \pm 0.1 \text{ g L}^{-1}$) in Kimenyedde experimental site during the second season, respectively. The SSL was highest under CT in both Goma ($147.17 \text{ kg ha}^{-1}\text{season}^{-1}$) and Kimenyedde ($114.93 \text{ kg ha}^{-1}\text{season}^{-1}$), and lowest under NT with the means of 11.25 and 9.19 $\text{kg ha}^{-1}\text{season}^{-1}$ in Goma and Kimenyedde experimental sites, respectively. Both SRV and SSC increased linearly with both rainfall amount (RF) and rainfall intensity at 10 min (RI_{10}). The highest and lowest IR and SMC were observed in the NT and CT treatments, respectively. No significant ($p > 0.05$) variations were observed in the SMC under the NT and SM treatments. Overall, soil tillage systems, soil type, and rainfall characteristics are among the key factors influencing the magnitudes of SRV and SSC in both time and space. This particular study suggests that NT and SM would help reduce the magnitudes of SRV and SSC, in agricultural fields.

1. Introduction

According to the 2015 international community, the 2030 Agenda for Sustainable Development, addressing the issues of environmental degradation has been challenged by human developments and activities. The increasing human-induced transformation of the global environment has tremendously caused environmental degradation through depletion of resources such as water and soil; ecosystem services; and pollution (Green et al., 2019; Jouanjan et al., 2014). Crop production systems and technologies are among the leading factors causing environmental degradation. Numerous indications have proven that current crop

production technologies are not sustainable (Takács-György et al., 2014). For instance, soil tillage being one of the crop production technologies is among the leading anthropogenic activities influencing the water and soil hydrological functioning, through regulating the water flow processes (Tapia-Vargas et al., 2001; Van de Giesen et al., 2011). In East Africa, the inappropriate soil tillage practices involving soil excavation, destruction of the soil green biomass cover, and unsuitable soil conservation measures have accelerated surface runoff and suspended sediment loads; and have raised ecological and hydrological concerns in the region (Guzha et al., 2018; Lundgren, 1980; Odada et al., 2004). Soil inversion and intensive monocultures have further interfered with the soil

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compaction, infiltration rates, and soil water-holding capacities (Baumhardt et al., 2017; Guzha et al., 2018; Mitchell et al., 2017; Nyamadzawo et al., 2012); which have further increased the magnitude of surface runoff and SSC.

The ecological and hydrological concerns are related to soil degradation and pollution of water reservoirs (Guzha et al., 2018; Odada et al., 2004). Surface runoff and sediment transportation are the primary causes of stream and lake damages in sub-Saharan Africa, particularly in the East African watersheds and large water bodies (Azanga, 2016; Hecky et al., 2003; Olago and Odada, 2007). This is because the surface runoff and SSC are loaded with substantial quantities of pollutants mainly from the urban areas, agricultural fields, and landfills. Besides, the surface runoff and SSC contribute to detachment of the soil particles from its parent tilth; thereby causing loss of the vital productive soils (Peng and Wang, 2012). However, soil/environmental degradation due to soil tillage systems/technologies could be strategically minimized. One of the potential ways in the reduction of soil/environmental degradation and contribute to the 2, 6, 14, and 15th SDGs could be transforming the agricultural sector, by switching from the conventional soil tillage which amplifies environmental degradation to conservation soil tillage systems which promote soil, water, and ecosystem health.

Several studies have been conducted to assess the effects of soil tillage systems on the surface runoff generation (Ahuja et al., 1998; Green et al., 2019) and SSC in different agro-ecosystems (Lefrançois et al., 2007; Steegen et al., 2000). Some studies reported that conservation tillage involving reduced soil tillage and minimal disturbances of the soil ecosystem, serves to enhance the reduction in surface runoff through improving the soil structure (Govaerts et al., 2007; Machado et al., 2015); increasing the soil aggregation and organic matter content (Mitchell et al., 2017); increasing storage of soil moisture (Baumhardt et al., 2017; Govaerts et al., 2007); and improving water infiltration rate (Kahlon et al., 2013; Mitchell et al., 2017; Roper et al., 2013). In contrast, related studies observed improved hydrological properties, particularly higher infiltration rate and surface runoff reduction in soils subjected to the conventional tillage practices than the conserved soils under NT and minimum tillage (MT) practices (Celik and Ersahin, 2011; Melero et al., 2011; Schwartz et al., 2010). However, it is only a few field-based studies that reported no noticeable differences in the surface runoff and infiltration rate between both the conventional and conservation tillage practices (Capowiez et al., 2009; McGarry et al., 2000).

Although many studies have been done to evaluate the influence of soil tillage systems on surface runoff generation and SSC in agricultural fields, such studies are deficient in East Africa, particularly in Uganda. Additionally, studies that assess the effect of soil tillage direction on the surface runoff are also lacking. Yet the magnitude of SRV and SSC vary in space and time depending on the environmental and climatic conditions. It is against this background that, the current study aimed to assess the effect of soil tillage systems on the soil hydrological parameters namely; IR, SMC, SRV, and SSC in Mukono District, Uganda. The effect of the soil tillage direction on the SRV was also assessed. This study also reports the correlational relationships between the rainfall amount and rainfall intensity with SRV and SSC in the common bean farm. It is hypothesized that soil inversion involving DT and CT is a major source of surface runoff generation and suspended sediments. The results of this study are relevant in identifying the soil tillage systems that enhance soil water conservation, improve the infiltration rate, reduce the surface runoff generation and suspended sediment load. The results also provide a new understanding of the dynamic paradigm of the soil tillage direction on the surface runoff generation in Uganda.

2. Materials and methods

2.1. Study site description

This study was conducted during two consecutive wet seasons from April to June 2019 and September to November 2019. The field

experiments were conducted at two study sites in Goma and Kimenyedde Sub-counties (Figure 1) in Mukono District (00°28'50.0"N; 32°46'14.0"E), Uganda. Mukono District is located between 1,000 to 1,300 m above sea level (m a.s.l). The topography of Mukono District is characterized by flatlands in the northern parts and sloping lands with undulations in the southern parts.

The climate of the study area is classified as a tropical climate with a mean annual precipitation of 1,100 mm Figure 2 shows the total precipitation and mean ambient temperature of the study sites for 14 years. The groundwater table remained at a depth of about 64 m. The mean monthly ambient temperature of the district range from 16 to 28 °C (UBOS, 2018).

2.2. Site management and experimental design

Goma and Kimenyedde experimental sites were selected based on their distinct variations in the soil texture differences. The site soils in Goma site are sandy clay loam with 51% sandy, 30% clay, and 19% silt, while that in Kimenyedde site are sandy loam with 65% sandy, 20% clay, and 15% silt. The mean slopes of Goma and Kimenyedde sites were 15 and 10%, respectively. Goma and Kimenyedde sites are elevated at 1121 and 1250 m a.s.l, respectively. The study site soils are classified as Lixic Ferralsols according to the protocols outlined by the Food and Agricultural Organization (FAO, 1998).

Two field-based experiments were conducted to assess the effect of soil tillage systems on the soil hydrological parameters (i.e. SRV, SSC, IR, and SMC) using a CRBD procedure with four replicates while following protocols described by Mead (2017). At each experimental site, a total of 16 experimental plots of 30 m long and 5 m wide were established for four soil tillage systems under natural rainfall. The four soil tillage systems, namely; NT, SM, DT, and CT were randomly assigned to the plots as the treatment variables. In the CRBD experimental setup, the soil tillage systems consisted of one crop type: common bean (*Phaseolus vulgaris* L.) of NABE 4 variety as the experimental blocking factor.

2.3. Description of the soil tillage systems and tillage direction

2.3.1. Soil tillage systems

The NT system involves the exclusive use of herbicides to control field weeds (Mrabet, 2002). A total weed control herbicide; Round-up (Glyphosate 360 g/L) with an application rate of 10 mL per litre of water was used. Specialized seed drills were employed to create narrow slots by cutting through the topsoil cover made of live mulches and crop residues in which seeds were placed. The NT is advantageous because it offers no or very minimal disturbance to the soil ecosystem during seedbed preparation (Morell et al., 2010; Mrabet, 2002). The SM involved soil tillage with a Huard plough with three frames, drawn by a Fiat tractor 980 DT 100 hp to the depth of 15 cm and covering the soil with the mulches and crop residues present in the same garden (Table 1). Like the NT system, the SM involved the use of herbicides (Glyphosate 360 g/L) to manage weeds at an application rate of 10 mL per litre of water. For both the CT and DT systems, a Huard plough with three frames, drawn by a Fiat tractor 980 DT 100 hp was used to prepare the seedbeds and the soils were tilled up to 15 and 40 cm in depth, respectively, and no crop residues and mulches were left on top of the seedbed (Table 1). For all the soil tillage systems, sowing and post-sowing agronomic practices such as seeding rate and weeding followed the traditional agronomic practices. Thus, the bean seeds were sowed at a spacing of 50 cm between rows and 10 cm within rows at a seeding rate of 82 kg/ha. Two seeds were planted in each hole.

2.3.2. Tillage direction

For all the tillage systems (except NT), two soil tillage directions were considered. The first soil tillage direction involved soil tillage down the slope/hill (TDS), while the second soil tillage direction involved soil tillage perpendicular to the direction of slope (TPS), i.e. contour tillage

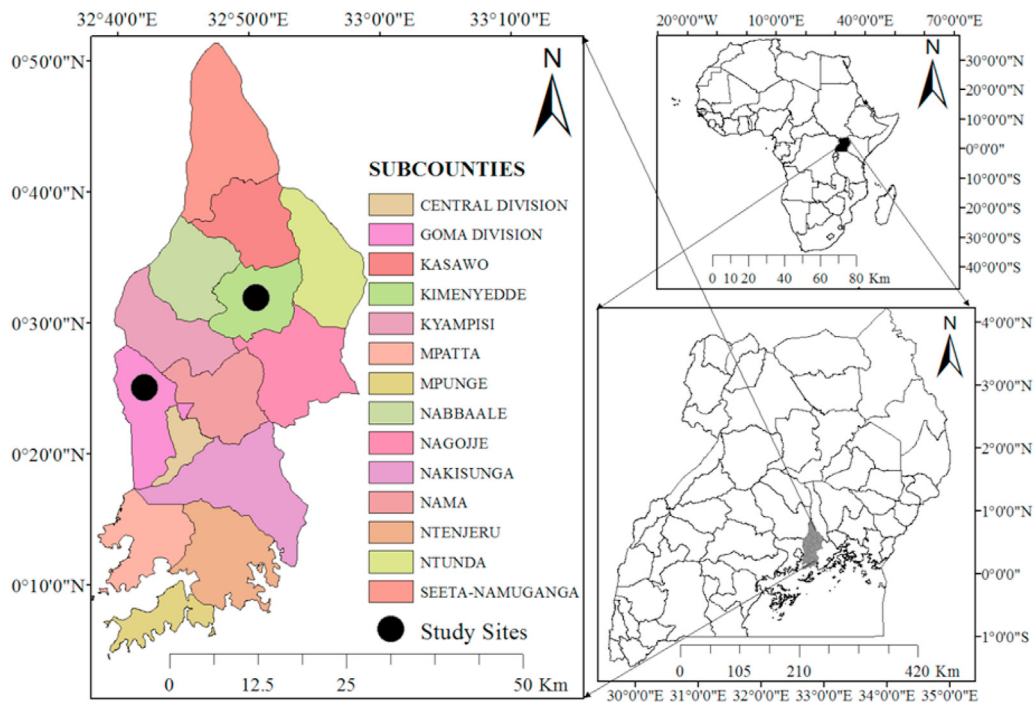


Figure 1. Map showing the study sites in Goma and Kimenyedde Sub-counties, Mukono District, Uganda: the map was developed using Arc-GIS software.

(Figure 3). Planting was done along the contour lines following the pattern of the ground.

2.4. Measurement of the surface runoff volume

A calibrated water collection tank was used to measure the SRV, following standard measurements and protocols outlined by Jeje and Agu (1990). The surface runoff from each plot was tapped into the 1000 L calibrated water collection tanks. To ensure that only the surface runoff from each plot enters the designated collection tanks, the plots were separated with galvanized iron sheets (Figure 4). These iron sheets were employed to retard entry of any in-coming rainfall into the water collection tank from the atmosphere; which was not part of the anticipated surface runoff. Due to the random occurrence of rainfall events and the difficulties in recording data in real-time especially during the heavy rainfall events, an automated data recording system of the water levels was installed in the water collection tanks. The installation procedures described by Joel et al. (2002) were followed when installing the recording devices in the tanks. The water collection tanks were emptied daily and total SRV measured (Swain, 2011). A Delta-T tipping-bucket rain gauge of 0.2 mm resolution was installed along with the water collection tanks, and this facilitated the automated recording of the rainfall data.

2.5. Measurement of suspended sediment concentration and suspended sediment load

About 1.4 L of water sample was taken off from the surface runoff collected from each runoff plot. The collected water samples were stored in polypropylene bottles (of volume: 1.5 L). The bottles were placed in a cool-box and taken to the Makerere University soil science laboratory for analysis of the SSC. The SSC was analysed by the filtration method following the protocols outlined by Shreve and Downs (2005). A 1000 mL of the sample from each runoff plot was filtrated through pre-weighed Whatman filter papers (Whatman, Little Chalfont, Buckinghamshire, UK); with a pore size of 0.45 μm and a diameter of 47 mm. The filtrate was dried at 105 °C for 24 h and re-weighed to measure the SSC. The suspended sediment load (SSL) was estimated using Eq. (1):

$$SSL\left(\frac{g}{ha}\right) = \frac{SR(l) \times SSC\left(\frac{g}{l}\right)}{0.015} \tag{Equation 1}$$

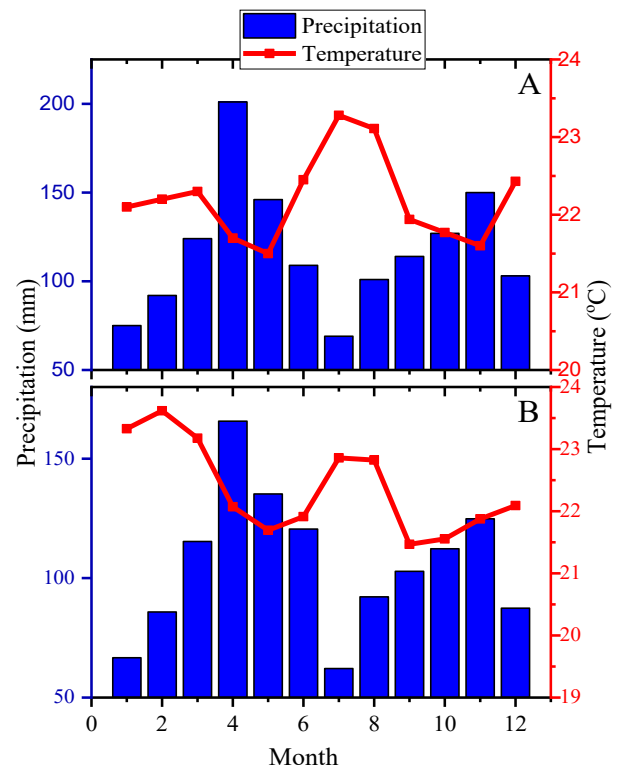


Figure 2. Average monthly precipitation and ambient temperature for Goma (A) and Kimenyedde (B) experimental sites from 2005-2018 (Data obtained from Climate Change Knowledge Portal; <https://climateknowledgeportal.worldbank.org/download-data>) (World Bank, 2018).

Table 1. Description of the different tillage systems and management practices.

Tillage system	Tillage depth (cm)	Tilling equipment	Tilling and planting direction	Crop residues	Mulches	Herbicides
NT	0	Disk openers	-	Yes	Yes	Roundup: Glyphosate 360 g/L
SM	15	Huard plough	TDS TPS	No	Yes	Roundup: Glyphosate 360 g/L
DT	40	Huard plough	TDS TPS	No	No	-
CT	15	Huard plough	TDS TPS	No	No	-

NT is for no-tillage; SM is for stubble-mulch; DT is for deep tillage; CT is for conventional tillage; TDS is for soil tillage down the slope; TPS is for soil tillage perpendicular to the slope.

Where SSL is the suspended sediment load; SR is the surface runoff; SSC is the suspended sediment concentration; 0.015 is the area in hectare.

$$SSL \left(\frac{kg}{ha} \right) = \frac{SSC \left(\frac{g}{ha} \right)}{1000} \tag{Equation 2}$$

The SSL (g/ha) was then converted to kg ha⁻¹ using Eq. (2):

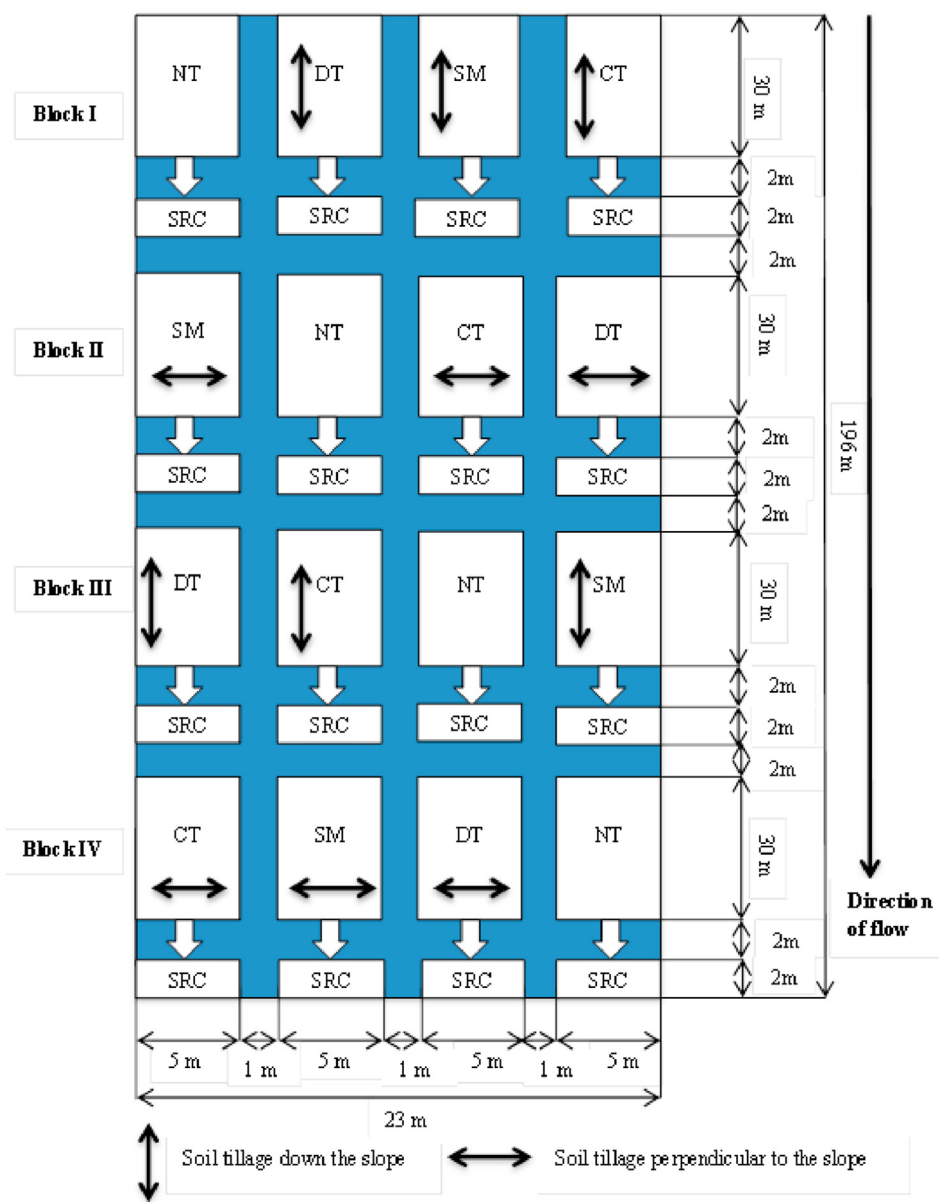


Figure 3. Schematic diagram showing the field layout. NT: no-tillage; DT: deep tillage; SM: stubble mulch; CT: conventional tillage; SRC: surface runoff collection tanks.



Figure 4. Surface runoff volume collection from the four tillage systems in the study sites.

2.6. Measurement of the soil moisture content and steady-state infiltration rate

To investigate the soil moisture dynamics under the different soil tillage systems, soil moisture sensors were installed at 0–15 cm depth in each study plot while following the standard protocols outlined by Temesgen et al. (2012). The EC-5 soil moisture sensors (PESSL INSTRUMENTS GmbH, Werksweg 107, A-8160 Weiz, Austria) with an accuracy of ±1–2% were used to measure the volumetric water content of the soils and were calibrated before installation using procedures suggested by Bogen et al. (2007) and Saito et al. (2009). The soil moisture sensors were externally linked with an EM50 data collector with 24 h acquisition time interval.

The steady-state infiltration rate was estimated by using a double-ring infiltrometer. The inner ring (diameter; 30 cm) was driven into the ground (10 cm depth) first followed by the outer ring (diameter; 60 cm), while taking care to ensure that the ring is driven into the ground at a uniform rate around the entire circumference of the ring. Water was poured to an initial level in both rings, and water level drop was recorded within the inner ring using a float and a ruler. A total of 48 infiltration rate tests were done during the experimental period. The double-ring

infiltrometer device was selected because it improves measurements by avoiding lateral flow (Chowdary et al., 2006; Hendriks, 2010).

2.7. Statistical analysis

Statistical Package for the Social Sciences (SPSS) version 20.0 (SPSS, Chicago, IL, USA) was used for statistical analyses. The data were tested for normal distribution before analysis and log₁₀-transformed. A three-way analysis of variance (ANOVA) was used to test the main effects of soil tillage system, season, experimental site, and their interactive effect on IR, SMC, SRV, and SSC. In case of significant ($p \leq 0.05$) values, multiple comparisons were done using Post-hoc Tukey's test. The Pearson correlation and simple regression analysis were used for relating the SRV and SSC with rainfall amount and rainfall intensity.

3. Results

3.1. Characteristics of rainfall in the study sites

The seasonal rainfall characteristics for both experimental sites are presented in Table 2. In Goma experimental site, the total rainfall amount was 2453 mm for the whole study period, with 1332 mm in the first season and 1121 mm in the second season. In Kimenyedde experimental site, the rainfall amount decreased from 1203 mm in the first season to 952 mm in the second season, with a total rainfall amount of 2155 mm for both seasons. The overall mean daily rainfall (R) was higher in Goma (10.1 mm) than in Kimenyedde (8.9 mm) experimental site (Table 2).

3.2. Effect of soil tillage systems and season on surface runoff volume

The results related to the total seasonal SRV in the two experimental sites are presented in Table 2. The SRV significantly varied between the soil tillage systems ($F = 242.40, p = 0.000$), experimental sites ($F = 132.33, p = 0.041$), and seasons ($F = 102.12, p = 0.031$). The interactions between experimental site \times season \times soil tillage systems also significantly ($F = 153.16, p = 0.030$) affected the SRV. Unsurprisingly, the CT depicts the highest SRV, while NT registered the lowest as illustrated in

Table 2. Rainfall characteristics, surface runoff volume (mm), and three-way ANOVA testing the effect of sites, seasons, soil tillage systems, and their interactions on the surface runoff volume from the common bean farms in Goma and Kimenyedde experimental sites in Mukono District, Uganda.

Site	Season	Rainfall characteristics				Surface runoff volume (mm)					
		TR	R	RD	NT	SM		DT		CT	
		(mm)	(mm)			TDS	TPS	TDS	TPS	TDS	TPS
Goma	One	1332	5.3	55	281.4	391.5	380.9	801.3	743.7	1071.3	1000.3
	Two	1121	4.8	48	214.8	249.5	246.0	612.4	564.8	781.3	748.5
	All seasons	2453	10.1	103	496.2	641	626.9	1413.7	1308.5	1852.6	1748.8
Kimenyedde	One	1203	5.1	50	245.4	252.2	246.4	689.4	608.1	912.6	801.6
	Two	952	3.8	46	165.0	178.2	172.1	470.9	416.2	574.3	525.4
	All seasons	2155	8.9	96	410.4	430.4	418.5	1160.3	1024.3	1486.9	1327
Factor						ANOVA for SRV					
						F-value			p-value		
Site						132.33			0.041		
Season						102.12			0.031		
Tillage system						242.40			0.000		
Site \times Season						91.00			0.046		
Site \times Tillage system						82.01			ns		
Tillage system \times Season						105.10			ns		
Site \times Season \times Tillage system						153.16			0.030		

TR: Total rainfall; R: Daily mean rainfall; RD: Number of rainy days, a rainy day is counted if rainfall exceeds 0.2 mm; NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage; TDS is for soil tillage down the slope; TPS is for soil tillage perpendicular to the slope. The p -values marked in bold are considered significant ($p < 0.05$); non-significant p -values are reported as "ns" in the ANOVA. $n = 360$.

Table 2. In Goma experimental site, 21.1% (281.4 mm) of the total rainfall (1332 mm) received in the first season was converted to surface runoff under NT, 29.4% (391.5 mm) under SM with soil tillage down the slope (SM-TDS), 28.6% (380.9 mm) under SM with soil tillage perpendicular to the slope (SM-TPS). In the same site and season, over 60% (801.3 mm) and 55.8% (743.7 mm) of the total rainfall was converted to surface runoff under DT with soil tillage down the slope (DT-TDS) and soil tillage perpendicular to the slope (DT-TPS), respectively. During the first season, the CT produced the highest surface runoff volume of 80.4% (1071.3 mm) and 75.1% (1000.3 mm) in the TDS and TPS plots, respectively. In the same site during the second season, 19.2% (214.8 mm) of the total received rainfall (1121 mm) was converted to surface runoff under NT. Similarly, 22.3% (249.5 mm) and 21.9% (246.0 mm) of the total rainfall was converted to surface runoff under SM-TDS and SM-TPS, respectively. Out of the total rainfall received in the second season, the SRV was 54.6% (612.4 mm) and 50.4% (564.8 mm) under DT-TDS and DT-TPS, respectively in Goma experimental site. Correspondingly, 69.7% (781.3 mm) and 66.8% (748.5 mm) of the total rainfall was converted to SRV under conventional tillage down the slope (CT-TDS) and conventional tillage perpendicular to the slope (CT-TPS), respectively during the second season in Goma experimental site (Table 2).

In Kimenyedde experimental site, 20.4% (245.4 mm) of the total received rainfall (1203 mm) in the first season was converted to surface runoff under NT, 21.0% (252.2 mm) under SM-TDS, and 20.5% (246.4 mm) under SM-TPS. In the same site and season, 57.3% (689.4 mm) and 50.4% (608.1 mm) of the total rainfall was converted to surface runoff under DT-TDS and DT-TPS, respectively. Around 75.9% (912.6 mm) and 66.6% (801.6 mm) of the total received rainfall in the first season was converted to surface runoff under CT-TDS and CT-TPS plots, respectively. In the same site during the second season, 17.4% (165.0 mm) of the total received rainfall (952 mm) was converted to surface runoff under NT, 18.7% (178.2 mm) and 18.1% (172.1 mm) under SM-TDS and SM-TPS, respectively. The SRV was 49.5% (470.9 mm) and 43.7% (416.2 mm) under DT-TDS and DT-TPS, respectively in Kimenyedde experimental site in the second season. Similarly, the TDS plots produced higher SRV than

TPS plots under CT, with 60.3% (574.3 mm) and 55.2% (525.4 mm) SRV, respectively (Table 2).

3.3. Soil tillage systems, seasons, suspended sediment concentration, and suspended sediment load

Results related to the mean values of SSC and the SSL in the two experimental sites are summarized in Table 3. The SSC varied significantly between the soil tillage systems ($F = 81.12, p = 0.000$), experimental sites ($F = 99.51, p = 0.020$), and seasons ($F = 201.01, p = 0.000$) (Table 3). In Goma experimental site, the highest mean values of the SSC was observed under CT ($2.41 \pm 0.3 \text{ g L}^{-1}$), followed by DT ($1.90 \pm 0.4 \text{ g L}^{-1}$), SM ($0.68 \pm 0.1 \text{ g L}^{-1}$), and NT ($0.65 \pm 0.1 \text{ g L}^{-1}$), with the suspended sediment load (SSL) of 171.41, 101.50, 17.75, and 12.19 kg ha^{-1} , respectively, during the first season. In the same site during the second season, slightly lower SSC than that of the first season was recorded under all the soil tillage systems with the mean SSC of $1.40 \pm 0.5, 1.21 \pm 0.4, 0.60 \pm 0.1$, and $0.58 \pm 0.1 \text{ g L}^{-1}$, in the CT, DT, SM, and NT, respectively. The SSL of 122.92, 85.40, 14.98, and 10.31 kg ha^{-1} were recorded in the CT, DT, SM, and NT, respectively.

In Kimenyedde experimental site, the SSC and SSL were lower than that in Goma experimental site under all the soil tillage systems (Table 3). During the first season in Kimenyedde experimental site, the mean SSC of 2.12, 1.53, 0.62, and 0.59 g L^{-1} , with the respective SSL of 128.98, 70.32, 10.42, and 9.65 kg ha^{-1} were recorded under the CT, DT, SM, and NT treatments. Similarly, the lowest mean SSC was observed under the NT during the second season ($0.43 \pm 0.1 \text{ g L}^{-1}$), for which no significant ($p > 0.05$) difference was observed with that under the SM ($0.44 \pm 0.1 \text{ g L}^{-1}$). More than nine and ten times higher SSC were recorded under the DT ($1.56 \pm 0.3 \text{ g L}^{-1}$) and CT ($1.59 \pm 0.4 \text{ g L}^{-1}$), respectively, than under NT. The SSL of 100.88, 58.97, 10.23, and 8.73 kg ha^{-1} were recorded under the CT, DT, SM, and NT, respectively during the second season in Kimenyedde experimental site (Table 3).

Table 3. Mean suspended sediment concentration (g L^{-1}), suspended sediment load ($\text{kg ha}^{-1}\text{season}^{-1}$), and three-way ANOVA testing the effect of sites, seasons, soil tillage systems, and their interactions on suspended sediment concentration from the common bean farms in Goma and Kimenyedde experimental sites in Mukono District, Uganda.

Site	Season	NT		SM		DT		CT	
		SSL (kg ha^{-1})	SSC (g L^{-1})	SSL (kg ha^{-1})	SSC (g L^{-1})	SSL (kg ha^{-1})	SSC (g L^{-1})	SSL (kg ha^{-1})	SSC (g L^{-1})
Goma	One	12.19	$0.65 \pm 0.1^{\text{a,c}}$	17.75	$0.68 \pm 0.1^{\text{c}}$	101.50	$1.90 \pm 0.4^{\text{b}}$	171.41	$2.41 \pm 0.3^{\text{a}}$
	Two	10.31	$0.58 \pm 0.1^{\text{b}}$	14.98	$0.60 \pm 0.1^{\text{b}}$	85.40	$1.21 \pm 0.4^{\text{a}}$	122.92	$1.40 \pm 0.5^{\text{a}}$
	All seasons	11.25	0.62 ± 0.1	16.37	0.64 ± 0.2	93.45	1.56 ± 0.3	147.17	1.91 ± 0.5
Kimenyedde	One	9.65	$0.59 \pm 0.1^{\text{c}}$	10.42	$0.62 \pm 0.1^{\text{c}}$	70.32	$1.53 \pm 0.4^{\text{b}}$	128.98	$2.12 \pm 0.3^{\text{a}}$
	Two	8.73	$0.43 \pm 0.1^{\text{b}}$	10.23	$0.44 \pm 0.1^{\text{b}}$	58.97	$1.56 \pm 0.3^{\text{a}}$	100.88	$1.59 \pm 0.4^{\text{a}}$
	All seasons	9.19	0.51 ± 0.1	10.33	0.53 ± 0.1	64.65	1.55 ± 0.4	114.93	1.86 ± 0.5
Factor	ANOVA for SSC								
		F-value		F-value		F-value		p-value	
Site		99.51		99.51		99.51		0.020	
Season		201.01		201.01		201.01		0.000	
Tillage system		81.12		81.12		81.12		0.000	
Site × Season		111.09		111.09		111.09		0.022	
Site × Tillage system		87.08		87.08		87.08		ns	
Tillage system × Season		74.34		74.34		74.34		ns	
Site × Season × Tillage system		72.53		72.53		72.53		0.042	

The superscript lower-case letters (a, b, and c) in the rows represent the significance at 5% for SSC. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage; SSL is for the total suspended load; and SSC is for suspended sediment concentration. The p-values marked in bold are considered significant ($p < 0.05$); non-significant p-values are reported as “ns” in the ANOVA. n = 360.

* Values are arithmetic means of SSC for soil tillage systems in Goma and Kimenyedde experimental sites in Mukono District, Uganda.

Table 4. Pearson correlation matrix between surface runoff volume and suspended sediment concentration with rainfall amount and rainfall intensity for no-tillage (NT), stubble-mulching (SM), deep tillage (DT) and conventional tillage (CT) in Goma (n = 360) and Kimenyedde (n = 360) experimental sites, Mukono District, Uganda.

Site	Season		NT		SM		DT		CT	
			RF	RI ₁₀	RF	RI ₁₀	RF	RI ₁₀	RF	RI ₁₀
Goma	One	SRV	0.86*	0.92*	0.71*	0.86*	0.84*	0.81*	0.63*	0.79*
		SSC	0.70*	0.79*	0.69*	0.77*	0.68*	0.73*	0.61*	0.70*
	Two	SRV	0.71*	0.65*	0.80*	0.85*	0.87**	0.84*	0.82**	0.70**
		SSC	0.077	0.45*	0.60*	0.66*	0.068	0.014	0.42*	0.062
	All seasons	SRV	0.85*	0.82*	0.73*	0.74*	0.76**	0.84**	0.70**	0.59**
		SSC	0.62*	0.64**	0.61*	0.74*	0.69*	0.79*	0.59*	0.61*
Kimenyedde	One	SRV	0.80*	0.85*	0.87*	0.82**	0.86**	0.72*	0.87*	0.81**
		SSC	0.75*	0.76*	0.72*	0.74*	0.71*	0.70*	0.71*	0.73*
	Two	SRV	0.89*	0.71*	0.68**	0.89**	0.51**	0.66**	0.76**	0.78**
		SSC	0.32	0.043	0.017	0.73*	0.68*	0.72**	0.65*	0.051
	All seasons	SRV	0.82*	0.70*	0.71*	0.89**	0.83**	0.68**	0.82**	0.77**
		SSC	0.75*	0.71*	0.72*	0.68*	0.76*	0.65*	0.72*	0.68**

** and * are correlations at 0.01 and 0.05 significant levels.

3.4. Relationships between surface runoff volume and suspended sediment concentration with rainfall characteristics

Table 4 presents the results of Pearson correlation analysis between the rainfall amount (RF) and rainfall intensity at 10 min (RI₁₀) with SRV and SSC for the four soil tillage systems for both experimental sites. In Goma experimental site, the correlation matrix (Table 4) shows that SRV positively associated with RF and RI₁₀ with the r-values ranging from 0.63 to 0.87 and 0.65 to 0.92, respectively across seasons. Correspondingly, the SSC positively associated with RF and RI₁₀ in Goma site. Although the r-values between SSC and RF were higher (>0.60) for most of soil tillage systems in both seasons, very weak correlations were observed between SSC and RF in the NT (r = 0.077) and DT (r = 0.068) during the second season. The RI₁₀ also showed some weak correlations with SSC under DT (r = 0.014) and CT (r = 0.062) in the second season (Table 4).

In Kimenyedde experimental site, the SRV positively correlated with RF and RI₁₀ with the r-values ranging from 0.51 to 0.89 and 0.66 to 0.89, respectively across seasons. Correspondingly, the SSC positively associated with RF with the r-values ranging from 0.32 to 0.75. Like in Goma experimental site, weak correlations were observed between SSC and RF under NT (r = 0.32) and SM (r = 0.017) during the second season. The RI₁₀ also showed weak correlations with SSC under NT (r = 0.043) and CT (r = 0.051) in the second season (Table 4).

3.5. Effect of soil tillage systems on steady-state infiltration rate

The IR was determined during two growing seasons in Goma and Kimenyedde experimental sites (Figure 5). Across sites, the IR reached a steady-state at 125, 102, 98, and 99 min under NT, SM, DT, and CT, respectively. The IR significantly (p < 0.05) varied between soil tillage systems (F = 96.34, p = 0.000) and experimental sites (F = 2.56, p = 0.029). The IR was lower in Goma than Kimenyedde experimental site under all the soil tillage systems (Figure 5). During the first season, the IR of 20.3, 20.1, 14.3, and 15.5 mm h⁻¹ were recorded under NT, SM, DT, and CT, respectively in Goma experimental site. During the same period, IR of 23.1, 22.9, 17.3, and 16.0 mm h⁻¹ were recorded under NT, SM, DT, and CT, respectively in Kimenyedde experimental site. Although no significant (p > 0.05) differences were observed in the IR during the first and second seasons, lower IR was recorded in the second season in both experimental sites under all the tillage systems. The IR was 20.2, 20.0, 14.3, and 14.9 mm h⁻¹ under NT, SM, DT, and CT, respectively in Goma experimental site during the second season. During the same season, significantly (p < 0.05) higher IR of 22.8, 22.7, 17.0, and 15.6 mm h⁻¹

under NT, SM, DT, and CT, respectively were recorded in Kimenyedde experimental site (Figure 5).

3.6. Effect of soil tillage systems and season on soil moisture content

Figure 6 shows the SMC for the soil tillage systems during the two seasons in Goma and Kimenyedde experimental sites. There were significant (p < 0.05) variations in the SMC between the soil tillage systems (F = 120.01, p = 0.000), experimental sites (F = 85.62, p = 0.032), and seasons (F = 72.35, p = 0.420). The SMC was higher in Goma than Kimenyedde experimental site under all the soil tillage systems (Figure 6). During the first season, the mean SMC of 69, 68, 56, and 54% were recorded under NT, SM, DT, and CT, respectively in Goma experimental site. During the same period, the mean SMC was 66, 65, 56, and 54% under NT, SM, DT, and CT, respectively in Kimenyedde experimental site. During the second season, lower SMC was recorded in both experimental sites. In Goma experimental site, the mean SMC of 64, 64,

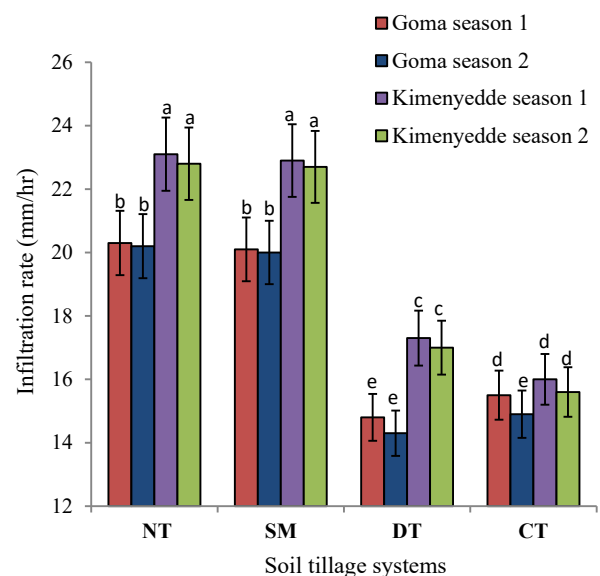


Figure 5. Steady-state infiltration rate for the soil tillage systems in Goma and Kimenyedde experimental sites in Mukono District, Uganda. The letters: a, b, c, d, and e represent significance at 5% significant level. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; and CT is for conventional tillage.

48, and 47% were recorded under NT, SM, DT, and CT, respectively. In Kimenyedde experimental site, SMC was slightly lower with mean of 58, 57, 46, and 46% under NT, SM, DT, and CT, respectively. No significant ($p > 0.05$) variations were observed in the SMC under NT and SM treatments (Figure 6).

4. Discussion

4.1. Soil tillage systems, seasons, and surface runoff volume

The SRV significantly varied between the soil tillage systems ($F = 242.40, p = 0.000$), with the highest SRV under CT, followed by DT, SM, and was lowest under NT (Table 2). The lower SRV observed under NT and SM indicated that the majority of the rainfall received infiltrated the soil (Figure 5). The current results are consistent with the findings of Yu et al. (2000), Armand (2004), Quinton and Catt (2004), Krutz et al. (2009), Truman et al. (2009), and Tiessen et al. (2010); who observed reduced SRV under conservation tillage systems (thus NT, SM, and reduced tillage) relative to the CT. As reported by Akinbile (2010), the magnitude of surface runoff greatly depends on the infiltration rate; which in turn is controlled by the inherent properties of the soil (Akinbile et al., 2016; Bhatt and Khara, 2006). The NT and SM systems are advantageous in SRV reduction over the DT and CT due to the availability of the crop residues, biomass, and mulches; which concurrently improve the soil properties (Armand et al., 2009; Kurothe et al., 2014; Leys et al., 2010; Mchunu et al., 2011). Thus, retention of crop residues and improvement in the soil properties increases the water infiltration and reduces surface runoff generation. Additionally, the crop residues reduce the impact of the raindrop on the soil surface; thereby improving soil porosity for infiltration and hence reducing the magnitude of surface runoff (Mchunu et al., 2011; Quinton and Catt, 2004).

Goma experimental site showed relatively higher SRV as opposed to Kimenyedde experimental site (Table 4), which could be attributed to the differences in the soil types and rainfall characteristics. As reported by Truman et al. (2011) and Inocencio et al. (2003), soil type influence surface runoff by affecting the infiltration rates and evaporation. In line

with the current observations, Inocencio et al. (2003) reported significantly lower surface runoff volume in soils with low clay content than soils with high clay content. Additionally, the slightly higher rainfall in Goma than Kimenyedde experimental site (Table 2) could have been the cause of the variations in SRV between the two sites.

The SRV was significantly ($t = 84.12; p < 0.05$) higher in the plots with soil tillage down the slope/hill (TDS) as opposed to the plots with soil tillage perpendicular to the direction of slope (TPS). The current observations were in good accord with the findings of Takken et al. (2001a), who reported less surface runoff in plots tilled across the slope. Although Souchere et al. (1998) and Takken et al. (2001b) noted that the flow of water in an agricultural field depends on tillage lines, the runoff pattern is often predicted by topography and slope gradient; which defines the sites for water collection (Takken et al., 2001a). In the current study, the reduction in the SRV under TPS plots could be attributable to the minimal surface runoff velocity, which allowed more available time for the water to infiltrate into the soil (Quinton and Catt, 2004).

4.2. Suspended sediment concentration/load and soil tillage systems

The soil tillage systems significantly influenced the SSC ($F = 81.12, p = 0.000$), with the lowest SSC recorded under NT and the highest under CT. Similarly, the SSL was highest under CT and DT than under NT and SM (Table 3). The current results are consistent with the findings of Tiessen et al. (2010), Truman et al. (2005), and Tapia-Vargas et al. (2001), who observed higher SSC under CT than under NT practices. The soil tillage systems with crop residues (NT and SM) significantly reduced SSC than the soil tillage system with no crop residues, similar to the findings of Tapia-Vargas et al. (2001). As noted by Didoné et al. (2014), Lamba et al. (2015), and Dagneu et al. (2017) SSC is influenced by soil and management practices; and disturbed ecosystems tend to produce more SSC than the natural and undisturbed ecosystems. In support, Bagagiolo et al. (2018) reported 2 to 4 times higher SSC under NT than under CT practices. Fawcett et al. (1994), Wauchope (1978), and Tiessen et al. (2010) reported 44–90% reduction in suspended sediments under conservation tillage practices relative to CT practices. Owens et al. (2002) and Pulley and Collins (2020) respectively recorded 2.2 and 5.4 times more SSL under the disturbed soils than under the undisturbed soils. The reduction in sediment losses under conservation tillage practices is considerably attributable to the increased residue on the soil surface; which is responsible for the decreased erosion (Tiessen et al., 2010). The SSC varied seasonally ($F = 201.01, p = 0.000$), probably because of the variations in the seasonal runoff which influence sediment transport capacity.

4.3. Effect of rainfall amount and intensity on surface runoff and suspended sediment concentration

Strong and significant ($p < 0.05$) correlations were observed between the SRV with rainfall amount (RF) and rainfall intensity at 10 min (RI₁₀) (Table 4). Jin et al. (2009) and Kleinman et al. (2006) also reported higher SRV at a higher rainfall intensity. From this point of view, the higher SRV under high rainfall intensity could be attributed to the soil infiltration excess. The variations in rainfall amount, duration, and intensity play an important role in the hydrological behavior (e.g., infiltration, soil moisture content, etc.) in agro-ecosystem catchments (Bronstert and Bárdossy, 2003); which affect the magnitude of the surface runoff. The SSC was strongly and positively influenced by both rainfall amount and rainfall intensity (Table 4). In the relatively dry soils with low rainfall amount and rainfall intensity, the suspended sediment response is often low and vice versa (Lana-Renault et al., 2007). The increase in SSC and SSL with precipitation amount (Table 4) was primarily due to the increase in SRV with the associated detachment of the soil from the surface.

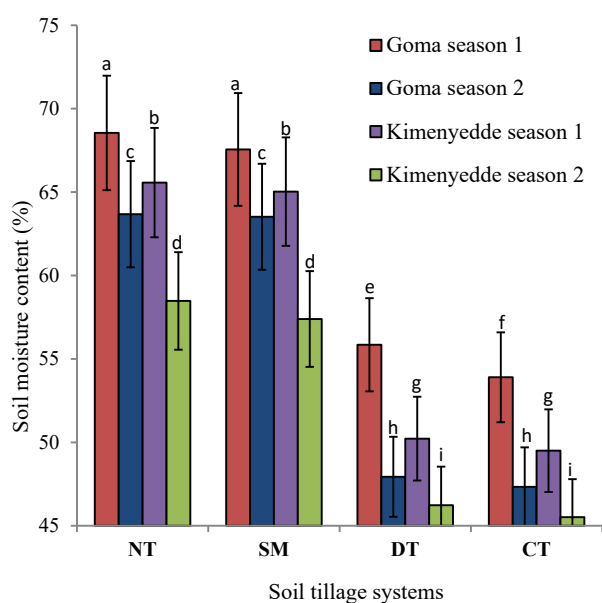


Figure 6. Soil moisture content for the soil tillage systems in Goma and Kimenyedde experimental sites in Mukono District, Uganda. The letters: a, b, c, d, e, f, g, h, and i represent significance at 5% significant level. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; and CT is for conventional tillage.

4.4. Infiltration rate and soil tillage systems

The IR significantly ($p < 0.05$) varied between soil tillage systems ($F = 96.34$, $p = 0.000$), with the lowest IR under CT and DT, and the highest under NT and SM. The current results are in line with the observations reported in the literature by Quincke et al. (2007), Asmamaw et al. (2012), Fan et al. (2013), Kahlon et al. (2013), and TerAvest et al. (2015); who observed lower IR under CT than under NT. He et al. (2009) observed over 100 % higher infiltration rates under NT (17.0 mm/min) compared with under CT (4.25 mm/min). Similarly, Fan et al. (2013) reported a 59.4 and 15.5 % higher infiltration rate under NT in 2007 and 2009, respectively compared with under CT. Wang et al. (2001) in northern China, reported a 1.5–1.6 times higher infiltration rate under NT than under CT for a period of 3 years. The lower IR under CT and DT could be attributed to the disruptions in the soil aggregate; which exposed the soil to the impact of the direct raindrops (Abu-Hamdeh et al., 2006; Glanville and Smith, 1988). Badalikova and Hrubý (2006) and Badalíková (2010) argued that soil tillage systems considerably affect soil permeability by changing the volume of pores, aggregate stability and soil structure, thus affecting the infiltration rate. Conversely, the conservation systems are advantageous in increasing the infiltration rate primarily due to the residue retention that provides enough time to the water before running off (Celik and Ersahin, 2011; Fan et al., 2013; Wang et al., 2001).

The IR significantly ($p < 0.05$) varied between the experimental sites ($F = 2.56$, $p = 0.029$), with higher IR observed in Kimenyedde experimental site than Goma site. These variations in the IR between experimental sites could be attributed to the differences in soil types. Kimenyedde experimental site had lighter textured soils (sandy loam) which might have allowed easy water permeability into the soil (Mamedov et al., 2001). The heavy textured soils (sandy clay loam) in Goma experimental site could have led to the seal formation on the soil surface; resulting in reduced water infiltration (Lado et al., 2004; Mamedov et al., 2001; Stern et al., 1991).

4.5. Soil moisture content and soil tillage systems

There were significant ($p < 0.05$) variations in the SMC between the soil tillage systems ($F = 120.01$, $p = 0.000$), with the highest SMC under NT and the lowest under the CT treatment. The current observations are in line with the findings of Kladvík (2001), Licht and Al-Kaisi (2005), and Wang et al. (2007); who observed higher SMC under the conservation tillage systems (i.e., NT and SM) than under the conventional tillage systems. Filho et al. (2013) reported 10.0 and 5.7, 6.7 and 5.7% increase in soil water storage at 0–5 and 5–10 cm depth under NT and reduced tillage, respectively compared with the CT. In Pampas region of Argentina, Alvarez and Steinbach (2009) observed 13–14% more soil water retention under no-tillage compared with the tilled plots. Soil water retention under NT and SM could be explained by the presence of the crop residues and mulches; which increased the water infiltration into the soil and reduced the evaporation rate (Šarauškus et al., 2009; Su et al., 2007). Additionally, Blanco-Canqui et al. (2017) and Filho et al. (2013) noted that the ability of the soil to retain water depends on the level of soil disturbances. Hence, the reduced SMC under the tilled systems (i.e., DT and CT) could have been due to the disturbances in the soil structure and aggregates; which exposed the soil surface to water loss via evaporation (Su et al., 2007).

Irrespective of the soil tillage systems, significantly ($p < 0.05$) higher SMC was observed in Goma than Kimenyedde experimental site (Figure 6). The variations in the soil types and rainfall amounts could have been the primary cause of the differences in the SMC in the experimental sites. Goma experimental site had sandy clay loam soils which might have enhanced soil moisture retention (Gong et al., 2003; Wang et al., 2016; Yahaya et al., 2011). Secondly, the differences in localized weather patterns in Goma and Kimenyedde experimental sites could considerably explain the variations in the SMC between the

experimental sites (Seneviratne et al., 2010; Wu et al., 2011). Goma experimental site received slightly higher rainfall and had more rain days (Table 2), which could have resulted in higher SMC.

5. Conclusion

In this study, the effect of soil tillage systems on SRV, SSC, IR, and SMC at a farm level was evaluated. The influence of the soil tillage direction on the SRV was also assessed. The correlational relationship between rainfall amount and rainfall intensity with SRV and SSC was also investigated. The results showed that SRV, SSC, IR, and SMC were significantly ($p < 0.05$) influenced by the soil tillage systems, tillage direction, seasons, and site. The CT treatment with TDS increased SRV by 2–6 fold compared with other tillage systems. The results of NT and SM for two seasons (6 months) indicate the advantage of NT and SM in reducing SRV and SSC, and improving IR and SMC in the common bean field. Application of NT and SM systems could help to reduce environmental degradation. Overall, soil tillage systems, soil type, and rainfall characteristics are among the key factors influencing the magnitudes of SRV and SSC in both time and space. Further research and long-termed experiments are essential in this area. In line with the SDG No. 2 (Zero hunger), future studies should also assess the economic performance of the crop under the different tillage systems in order to have a decisive decision on the best soil tillage system.

Declarations

Author contribution statement

N. Fatumah: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

S. A. Tilahun: Conceived and designed the experiments; contributed reagents, materials, analysis tools or data; Wrote the paper.

S. Mohammed: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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