



Research article

Water use efficiency, grain yield, and economic benefits of common beans (*Phaseolus vulgaris* L.) under four soil tillage systems in Mukono District, Uganda



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ABSTRACT

With the increasing climate change impacts and variabilities, water is becoming a limiting factor for rainfed crop production in Uganda. Conservation tillage practices could improve soil and water conservation in croplands. Field experiments were conducted for three consecutive seasons from April 2019 to June 2020. The experiments evaluated the effect of soil tillage treatments on soil water storage, water use efficiency, grain yield, and economic benefits of the common beans (*Phaseolus vulgaris* L.) in two sub-counties of Mukono District, central Uganda. The soil tillage treatments were: no-tillage, stubble-mulching, deep tillage, and conventional tillage. The no-tillage and stubble-mulching improved soil water storage by 46 and 45%, respectively, compared with the conventional tillage in the 0–100 cm soil depth over the 14 months. Soil tillage treatments significantly ($p < 0.05$) affected the water use efficiency, with water use efficiency values generally higher under no-tillage and stubble-mulching than under deep tillage and conventional tillage treatments. The grain yield was highest under no-tillage and stubble-mulching than deep tillage and conventional tillage treatments, with over 5, 38, and 43% higher grain yield under no-tillage than under stubble-mulching, deep tillage, and conventional tillage treatments, respectively. Although no-tillage and stubble-mulching improved soil water storage and grain yield, seasonal precipitation distribution had a greater influence on the final grain yield, soil water storage, and water use efficiency. The net profit was 3 and 5 times higher under no-tillage than under conventional tillage and deep tillage treatments, respectively. The overall results showed that no-tillage and stubble-mulching were the optimum tillage treatments for increasing soil water storage and common bean yield, enhancing water use efficiency, and improving economic returns in central Uganda.

1. Introduction

Common beans are among the world's largest cultivated crops used for direct human consumption (FAO, 2016). In the Ugandan context, over 90% of the population depends on common beans for protein and income (Department for International Development (DFID), 2020). In 2018, Uganda produced about 1.039 Tg of common beans (FAOSTAT, 2018). Despite the importance of common beans as a food and cash crop for Uganda, its productivity has declined over the recent past, partly due to unsustainable management practices; low soil fertility; and adverse climate change impacts that cause moisture deficits and erratic precipitation (Mubiru et al., 2012, 2018). The growing seasons are increasingly

subjected to prolonged dry spells, sustained droughts, and low green water use efficiency (WUE-grain), resulting in moisture deficits (Mubiru et al., 2018). To date, the dry spells considerably reduce crop yields and sometimes cause total crop failure (Berhane et al., 2013; Sabiiti et al., 2018). In response, many commercial farmers in Uganda have resorted to irrigation to sustain bean productivity. Nonetheless, sole dependency on irrigation is slowly affecting the water tables, increasingly leading to over-exploitation of the groundwater resources (Swain, 2011). Besides, over 72% of Uganda's agriculture is carried out by subsistence farmers who cannot afford the irrigation technologies and costs (Uganda Bureau of Statistic (UBOS), 2017). Therefore, more sustainable farming practices, approaches, and technologies that increase soil water availability,

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maintain balanced soil moisture, and optimize crop water use throughout the crop growing season are required (Kagoya et al., 2018; Turinawe, 2019). One of such sustainable farming practices is conservation tillage approaches.

Conservation tillage practices, namely; reduced tillage (RT), no-tillage (NT), stubble-mulching (SM), subsoiling (SS), and tied-ridge, provide instant benefits to farmers such as increasing rainwater harvesting, improved soil water storage (SWS) (Kargas et al., 2012; TerAvest et al., 2015), WUE (Miriti et al., 2012), and crop yields (Blanco-Canqui et al., 2017; Hosseini et al., 2016). In Kenya, a 4-year study by Miriti et al. (2012) reported up to 9.1 and 31.7% increase in cowpeas grain yield and WUE, respectively under tied-ridge when compared with conventional tillage (CT). Related long-term studies in Kenya, Malawi, Ghana, and Zambia reported that conservation tillage practices improved SWS, crop yield, and economic benefits by 35, 31, and 25%, respectively, relative to CT (Buah et al., 2017; TerAvest et al., 2015; Thierfelder et al., 2013). In Malawi, conservation tillage practices increased SWS up to 37.5%, maize grain yield by 10.6%, and WUE by 11.1% compared with CT (TerAvest et al., 2015). Hosseini et al. (2016) also reported a 16.0–24.6% increase in soybean grain yield under NT than CT.

However, the effectiveness of the different conservation tillage practices in improving SWS, WUE, and yields could depend on the seasonal agronomic and environmental factors, including rainfall distribution and amount and soil type (Hemmat and Eskandari, 2004). Some soil hydrological properties such as increased infiltration, low evapotranspiration, and low surface runoff are enhanced by conservation tillage practices (Fatumah et al., 2020), which in turn improve the SWS and WUE. With SWS and WUE being among the factors limiting crop production in Uganda (Adhikari et al., 2015), studies and data relating SWS and WUE to the traditional tillage practices are a pre-requisite to

sustainably improved crop production. Therefore, this study compared the effect of the conservation and intensive tillage practices on SWS, WUE, grain yield, and economic benefits under common bean fields in central Uganda. The study hypothesized that under Ugandan weather conditions, the traditional conservation tillage practices could improve the SWS, WUE, sustain crop productivity, and improve economic benefits/returns.

2. Materials and methods

2.1. Study area location and description

The study was conducted in Goma and Kimenyedde experimental sites in Mukono District, Uganda, elevated at 1121 and 1250 m a.s.l, respectively. Goma and Kimenyedde experimental sites are located at 00°25'0"N; 32°42'0"E and 00°32'0"N; 32°50'0"E, respectively (Figure 1). The soils in the study areas are Lixic Ferralsols, according to the Food and Agriculture Organization (FAO, 1998). The soils in Goma are sandy clay loam with 51% sandy, 30% clay, and 19% silt. The initial soil pH was 6.5, while OC was 5.2%, N was 0.5%, available Phosphorous (Av. P) was 12.12 mg kg⁻¹, and available Potassium (Av. K) was 0.96 mg kg⁻¹. At Kimenyedde experimental site, the soils were sandy loam with 65% sandy, 20% clay, and 15% silt. The soil pH was 6.3, OC was 4.9%, N was 0.6%, Av. P was 11.23 mg kg⁻¹ and Av. K was 0.88 mg kg⁻¹. The topography of the study sites is characterized by sloping lands with undulations.

The climate of the study areas is classified as a tropical climate with a mean annual precipitation of 1,100 and 1000 mm for Goma and Kimenyedde sites, respectively. The average long-term (2005–2018) seasonal

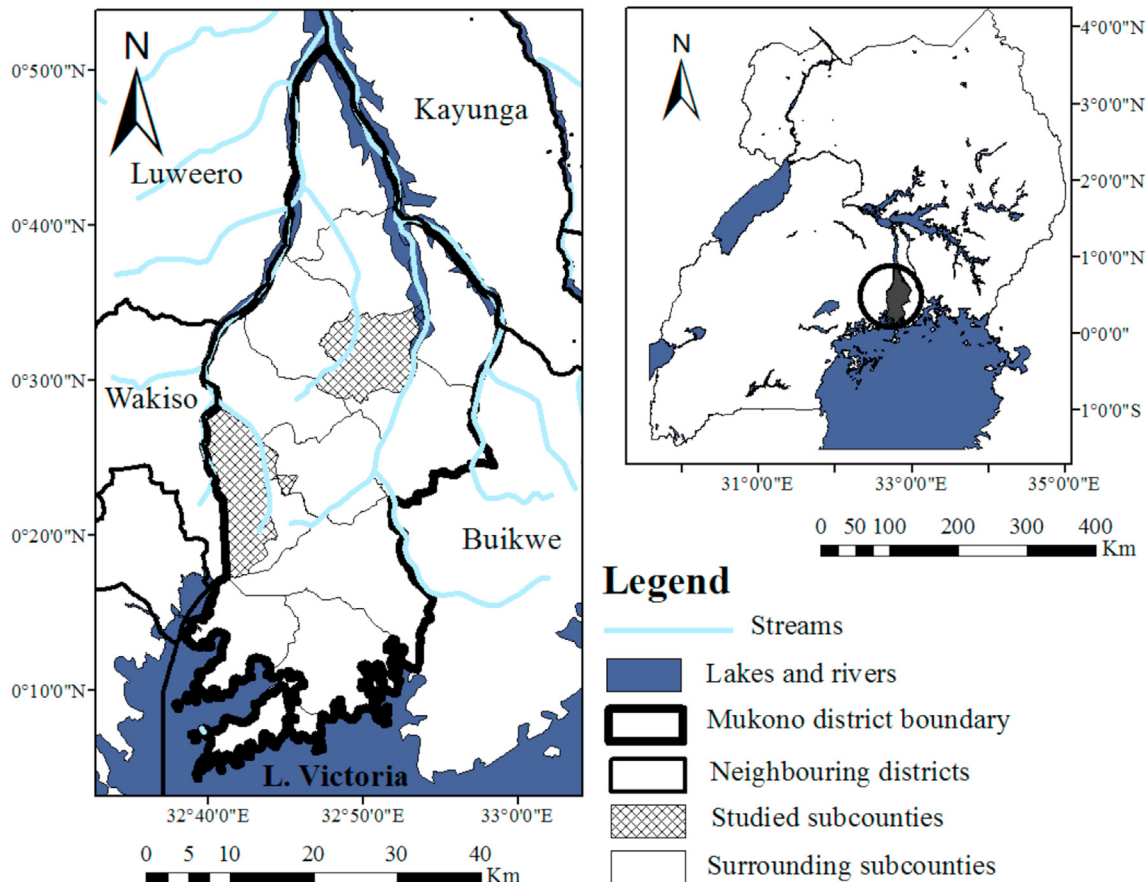


Figure 1. Map of the study area showing sites where the experiments were conducted: the map was developed using Arc-GIS software.

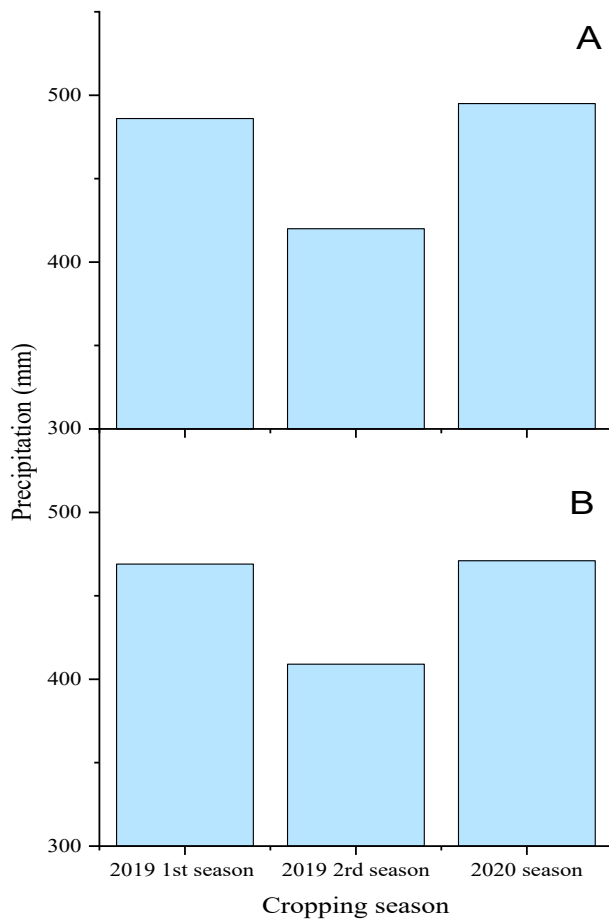


Figure 2. Average long-term (2005–2018) seasonal precipitation for Goma (A) and Kimenyedde (B) experimental sites for the three seasons (Data obtained from Climate Change Knowledge Portal; <https://climateknowledgeportal.worldbank.org/download-data>) (World Bank, 2018).

precipitation for Goma (A) and Kimenyedde (B) experimental sites for the three seasons is presented in Figure 2.

2.2. Experimental design and soil tillage treatment description

Experiments with common beans were started in April 2019 to June 2020 and covered three consecutive growing seasons at Goma and Kimenyedde experimental sites. The seeds of common bean cultivar “NABE 4” were obtained from the National Agricultural Research Organisation (NARO), Uganda. Plots of 30 m by 5 m were laid down in a completely randomized design (CRD) with four tillage treatments to assess their effect on SWS, WUE, grain yield, and economic benefits. Each treatment was replicated two times, making eight plots at each experimental site. The soil tillage treatments included: NT, SM, deep tillage (DT), and CT.

- **NT:** The land surface was covered with crop residues and mulches (8 Mg ha⁻¹). Disk openers were used to create narrow slots through the topsoil without disturbing the soil. The seeds were then planted in the narrow slots. Round-up (glyphosate 360 g L⁻¹) herbicide at an application rate of 10 ml L⁻¹ of water making 6 L ha⁻¹ was used to control the weeds. The plots were previously used for maize (*Zea mays*) production but have been under two years fallow before the current experimentation.
- **SM:** It involved soil excavation up to a depth of 15 cm using a Huard plough with three frames, drawn by a Fiat 980 DT 100 hp tractor. After ploughing, the soil surface was then covered with mulches

(8 Mg ha⁻¹) and crop residues from the previous season. The weeds were also controlled using glyphosate 360 g L⁻¹ herbicides at the same application rate as NT.

- **DT and CT:** Both DT and CT involved soil tillage up to a depth of 0–40 and 0–15 cm, respectively, using a Huard plough with three frames, drawn by a Fiat 980 DT 100 hp tractor. No soil covering was done, and weeds were controlled by regular weeding with a hand hoe.

The common bean seeds were sowed at a spacing of 50 cm between rows and 10 cm within rows, making 90 kg ha⁻¹ during each season. The detailed information on planting and harvesting data is presented in Figure 3. No fertilization application was done for all seasons.

2.3. Soil sampling and analysis

Soil samples were collected at 0–20, 20–40, 40–60, 60–80, 80–100 cm depth from each tillage treatment using a soil auger in a zig-zag pattern as described by Rayment and Higginson (1992).

A 1:2.5 wet-soil-to-extract-volume ratio method was used to determine the soil pH (Rayment and Higginson, 1992). Organic carbon (OC) and Nitrogen (N) content in % were analysed using the dry combustion procedures with a C/N analyser following the guidelines of Nelson and Sommers (1996). Av. P was determined using the phosphorous analysis procedures of Olsen et al. (1982), while Av. K was measured using the ammonium acetate (C₂H₇NO₂) buffer-extraction method described by Rayment and Higginson (1992). The bulk density (BD) was determined by using a core method (Blake, 1965).

2.4. Determination of soil water storage and evapotranspiration

The SWS was determined by excavating soil samples from 10 cm to 100 cm soil depth in three replicates, using the cutting ring method following the protocols described by Dam et al. (2005). The soil samples were collected from each soil tillage treatment at planting and maturity time (80–86 days after sowing). The SWS for each soil layer at each growing period was then determined using Eq. (1) as described by Liu et al. (2016):

$$SWS = \frac{BD}{\rho_w} \times SWC \times D \quad (1)$$

where SWS is the soil water storage (mm); BD is the bulk density (g dry soil cm⁻³); ρ_w is the water density (1 g cm⁻³); SWC is the soil water content (g water g⁻¹ dry soil); D is the depth of the soil profile (mm). The BD and SWC were determined by the oven-drying technique, as described by Blake (1965).

The soil water balance method was used to determine the ET using Eq. (2) (Bodner et al., 2007):

$$ET = P + W - D_R - R_O \pm \Delta SWS \quad (2)$$

where ET (mm) is the Evapotranspiration; P (mm) is the precipitation, W is an upward capillary rise in the root zone, R_O is the surface runoff, D_R is drainage, and ΔSWS (mm) is the changes in SWS from planting to harvesting at 0–100 cm depth. The P and R_O were measured directly in the field. The P was measured with automatic-weather-station instruments (model: JL-03-Q4; Shandong, China), while the R_O was measured with calibrated water collection tanks following the protocols described by Jeje and Agu (1990). W was not considered since the groundwater table was deep (64 m) (Boukhari et al., 2015; Su et al., 2007). D_R was calculated as the surplus of water P exceeding the total soil water availability (Mastrorilli et al., 1998).

2.5. Determination of the grain yield

A plot of 1 m × 1 m was established in the middle of each experimental treatment plot to determine the grain yield. At physiological

	Season	2019									2020				
		March	Apr	May	Jun	Aug	Sept	Oct	Nov	Feb	March	Apr	May	Jun	
Goma	One	12 th -20 th	9 th			29 th									
	Two					15 th -20 th	2 nd				23 rd				
	2020- season											20 th -27 th	18 th		13 th
Kimenyedde	One	21 th -27 th	11 th			30 th									
	Two					18 th -25 th	7 th				29 th				
	2020- season											15 th -22 nd	18 th		17 th

Legend Land preparation Crop management
 Sowing Harvesting

Figure 3. Common bean calendar from April 2019 to June 2020.

maturity, pods were harvested, air dried, and hand threshed. The grain weight was taken after oven drying the grains at 60 °C for 24 h until reaching an average moisture content of 13%.

2.6. Determination of crop water use efficiency

The WUE-grain of the common bean crops under different soil tillage treatments was determined as described by Xu and Hsiao (2004) and Payero et al. (2008) using Eq. (3).

$$WUE = \frac{\text{Grain yield}}{ET} \tag{3}$$

Where WUE-grain (kg ha⁻¹ mm⁻¹) is the WUE of the grain yield and ET (mm) is the growing season actual ET calculated from Eq. (2).

2.7. Economic benefits and benefit-cost ratio (BCR) estimation

The economic benefits of the different soil tillage treatments was estimated using simple economic analyses. The net profit for each treatment was computed following Eq. (4).

$$\text{Net profit (USD)} = (\text{Grain yield} \times P) - \text{Gross cost} \tag{4}$$

Where the grain yields (kg ha⁻¹) are from the 30 m × 5 m plots, P is the selling price of the common beans at harvest (USD/kg), and gross cost included the cost of land rent, cost for tillage, machinery, seeds, mulches, herbicide, insecticide, labor, harvesting, etc. in USD/ha. The market selling price of the common beans was Ugshs.3800/ = , which was equivalent to USD1.03/kg.

The BCR was then calculated from Eq. (5)

$$BCR = \frac{\text{Net profit}}{\text{Gross cost}} \tag{5}$$

2.8. Statistical data analysis

The data were checked for normality distribution in Statistical Package for the Social Sciences (SPSS) version 19.0 (IBM Corp., Chicago, IL, USA), using the Shapiro–Wilk test for goodness of fit. The homoscedasticity was evaluated by using Levene's test for equality of variances. The grain yield, ET, and SWS were not normally distributed. The grain yield and ET were Log₁₀-transformed, while SWS was square-root-transformed. An analysis of variance (ANOVA) was used to test the effect of soil tillage treatments, seasons, and experimental sites on grain yield, ET, and WUE-grain. Differences among means were determined using Post-hoc Tukey's test at a 5% confidence interval.

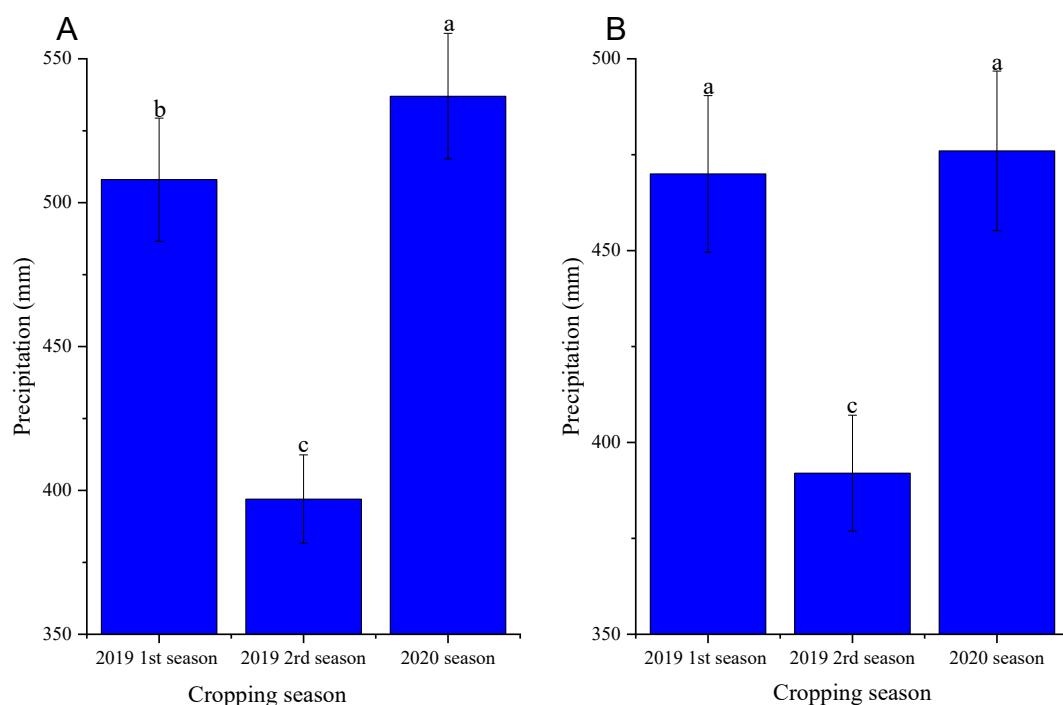


Figure 4. Mean seasonal precipitation distribution at Goma (A) and Kimenyedde (B) experimental sites for the three growing seasons. Bars above the mean indicate the standard error.

3. Results

3.1. Precipitation during the experimental period

The seasonal precipitation during the first season of 2019 (508 mm) and the 2020 growing-season (537 mm) (Figure 4) was higher than the average long-term seasonal precipitation (486 mm) at Goma site (2005–2018) (Figure 2). During the second season of 2019, the seasonal precipitation (397 mm) was 89 mm less than the average long-term precipitation. At Kimenyedde experimental site, the seasonal precipitation was 470 and 476 mm during the first season of 2019 and 2020 growing-season, respectively, which were close to the long-term seasonal precipitation (Figure 2) of Kimenyedde site. Like Goma site, Kimenyedde site received the lowest precipitation amount (392 mm) in the second season of 2019 (Figure 4).

3.2. Soil characteristics

Table 1 shows the soil characteristics under the NT, SM, DT, and CT treatments at both Goma and Kimenyedde experimental sites. The soils at both experimental sites were neutral to slightly alkaline, with pH-values ranging from 5.1 to 7.1 (Table 1). The soil tillage treatments significantly affected OC with the respective OC of 3.11, 3.12, 2.23, and 2.01% under NT, SM, DT, and CT. The OC decreased down the soil profile. The greatest OC was observed in the 0–20 cm (3.87%), followed by 20–40 cm

(3.25%), 40–60 cm (2.71%), 60–80 cm (1.94%), and 80–100 cm (1.44%). Similarly, the N content varied between the soil tillage treatments and decreased with an increase in soil depth. The highest N content was observed under the NT (0.26%) and SM (0.26%), whilst DT (0.16%) and CT (0.17%) had the lowest N content. The 0–20 cm (0.26%) and 20–40 cm (0.25%) layers had the highest N content, while the lowest N content was observed in the 80–100 cm layer (0.14%). Av. P (mg kg⁻¹) was 7.87, 5.95, 4.69, and 3.56 under NT, SM, DT, and CT, respectively. Av. K (cmol kg⁻¹) was 0.63, 0.64, 0.48, and 0.51 under NT, SM, DT, and CT, respectively. Both Av. P and Av. K decreased with soil depth. The BD (g cm⁻³) also varied between the soil tillage treatments and increased with soil depth (Table 1).

3.3. Soil water storage dynamics

The SWS varied seasonally and between the soil tillage treatments (Figure 5a and b). The mean SWS (averaged across soil tillage treatments and sites) in the 100 cm soil profile at planting was highest during the 2020 growing-season (54.98 mm), followed by the first season of 2019 (55.22 mm), and lowest during the second season of 2019 (51.22 mm). A similar trend was recorded at harvesting, with the 2020 growing-season (23.60 mm) having the greatest SWS, followed by the first season of 2019 (22.97 mm) and then the second season of 2019 (22.00 mm). The effect of soil tillage treatments on SWS was significant at planting with the highest SWS under NT (56.65 mm) and SM (55.52 mm) than DT (50.66

Table 1. Soil characteristics at 0–100 cm depth in Goma and Kimenyedde experimental sites in Mukono District, Uganda.

Tillage treatment	Goma Site					Kimenyedde Site				
	0–20	20–40	40–60	60–80	80–100	0–20	20–40	40–60	60–80	80–100
pH										
NT	7.1 ± 0.1	6.9 ± 0.1	6.5 ± 0.2	5.8 ± 0.2	6.8 ± 0.1	6.8 ± 0.2	6.6 ± 0.1	6.2 ± 0.1	5.5 ± 0.2	6.5 ± 0.1
SM	6.7 ± 0.1	6.5 ± 0.1	6.7 ± 0.1	5.9 ± 0.1	6.4 ± 0.1	6.4 ± 0.1	6.2 ± 0.1	6.4 ± 0.1	5.6 ± 0.2	6.1 ± 0.1
DT	6.2 ± 0.1	6.0 ± 0.1	5.6 ± 0.1	5.6 ± 0.1	5.9 ± 0.1	5.9 ± 0.1	5.7 ± 0.1	5.3 ± 0.1	5.3 ± 0.1	5.6 ± 0.1
CT	5.9 ± 0.1	5.7 ± 0.1	5.4 ± 0.1	5.5 ± 0.1	5.6 ± 0.1	5.6 ± 0.1	5.4 ± 0.1	5.1 ± 0.1	5.2 ± 0.1	5.3 ± 0.1
OC (%)										
NT	4.54 ± 0.2	4.24 ± 0.2	3.07 ± 0.1	2.18 ± 0.1	2.02 ± 0.1	4.34 ± 0.2	4.04 ± 0.2	2.87 ± 0.1	1.98 ± 0.1	1.82 ± 0.1
SM	4.45 ± 0.2	4.38 ± 0.1	3.02 ± 0.1	2.22 ± 0.1	2.02 ± 0.1	4.25 ± 0.2	4.18 ± 0.2	2.82 ± 0.1	2.02 ± 0.1	1.82 ± 0.1
DT	3.85 ± 0.2	2.75 ± 0.1	2.49 ± 0.1	1.91 ± 0.1	1.10 ± 0.1	3.65 ± 0.2	2.55 ± 0.2	2.29 ± 0.1	1.71 ± 0.1	0.90 ± 0.1
CT	3.02 ± 0.1	2.02 ± 0.1	2.66 ± 0.1	1.85 ± 0.1	1.02 ± 0.1	2.82 ± 0.2	1.82 ± 0.2	2.46 ± 0.1	1.65 ± 0.1	0.82 ± 0.1
N (%)										
NT	0.32 ± 0.2	0.30 ± 0.2	0.28 ± 0.1	0.21 ± 0.1	0.15 ± 0.2	0.31 ± 0.2	0.30 ± 0.0	0.24 ± 0.1	0.25 ± 0.1	0.19 ± 0.1
SM	0.31 ± 0.1	0.31 ± 0.1	0.29 ± 0.2	0.22 ± 0.0	0.13 ± 0.2	0.33 ± 0.1	0.29 ± 0.1	0.26 ± 0.1	0.23 ± 0.0	0.18 ± 0.1
DT	0.21 ± 0.1	0.19 ± 0.0	0.16 ± 0.2	0.15 ± 0.1	0.10 ± 0.2	0.22 ± 0.1	0.18 ± 0.0	0.15 ± 0.1	0.15 ± 0.1	0.13 ± 0.2
CT	0.20 ± 0.1	0.19 ± 0.1	0.17 ± 0.1	0.23 ± 0.1	0.12 ± 0.1	0.20 ± 0.0	0.21 ± 0.0	0.16 ± 0.1	0.14 ± 0.1	0.12 ± 0.1
Available P (mg kg⁻¹)										
NT	9.40 ± 0.2	10.71 ± 0.2	6.65 ± 0.2	6.21 ± 0.2	5.91 ± 0.2	9.55 ± 0.2	9.40 ± 0.2	8.28 ± 0.2	6.80 ± 0.2	5.82 ± 0.2
SM	7.41 ± 0.3	7.40 ± 0.2	5.61 ± 0.2	4.42 ± 0.2	3.94 ± 0.2	8.22 ± 0.2	7.11 ± 0.3	5.66 ± 0.1	5.21 ± 0.2	4.52 ± 0.1
DT	5.38 ± 0.2	5.11 ± 0.3	4.93 ± 0.2	5.22 ± 0.2	3.33 ± 0.3	6.67 ± 0.3	5.63 ± 0.2	4.27 ± 0.1	4.20 ± 0.1	2.20 ± 0.1
CT	5.12 ± 0.2	4.17 ± 0.2	4.12 ± 0.1	3.70 ± 0.3	2.80 ± 0.2	4.56 ± 0.3	3.38 ± 0.1	3.11 ± 0.1	2.30 ± 0.1	2.33 ± 0.1
Available K (cmol kg⁻¹)										
NT	0.91 ± 0.01	0.70 ± 0.02	0.53 ± 0.02	0.52 ± 0.02	0.41 ± 0.01	0.88 ± 0.01	0.84 ± 0.02	0.61 ± 0.03	0.58 ± 0.01	0.32 ± 0.02
SM	0.85 ± 0.01	0.80 ± 0.02	0.62 ± 0.01	0.44 ± 0.01	0.31 ± 0.01	0.90 ± 0.01	0.74 ± 0.01	0.76 ± 0.02	0.51 ± 0.02	0.47 ± 0.01
DT	0.71 ± 0.02	0.51 ± 0.01	0.50 ± 0.01	0.42 ± 0.01	0.23 ± 0.01	0.62 ± 0.03	0.53 ± 0.03	0.52 ± 0.01	0.48 ± 0.01	0.26 ± 0.01
CT	0.70 ± 0.02	0.65 ± 0.01	0.53 ± 0.01	0.43 ± 0.02	0.32 ± 0.01	0.73 ± 0.03	0.54 ± 0.03	0.51 ± 0.02	0.36 ± 0.01	0.29 ± 0.01
BD (g cm⁻³)										
NT	1.45 ± 0.01	1.51 ± 0.01	1.52 ± 0.01	1.56 ± 0.01	1.56 ± 0.01	1.25 ± 0.01	1.31 ± 0.01	1.32 ± 0.01	1.36 ± 0.01	1.36 ± 0.01
SM	1.46 ± 0.01	1.52 ± 0.01	1.50 ± 0.01	1.51 ± 0.02	1.53 ± 0.02	1.26 ± 0.01	1.32 ± 0.01	1.30 ± 0.01	1.31 ± 0.01	1.33 ± 0.01
DT	1.10 ± 0.02	1.22 ± 0.01	1.35 ± 0.01	1.48 ± 0.01	1.54 ± 0.01	0.90 ± 0.01	1.02 ± 0.01	1.15 ± 0.01	1.28 ± 0.01	1.34 ± 0.01
CT	1.40 ± 0.02	1.51 ± 0.01	1.50 ± 0.01	1.49 ± 0.01	1.49 ± 0.01	1.21 ± 0.01	1.31 ± 0.01	1.30 ± 0.01	1.29 ± 0.01	1.29 ± 0.01

OC is for organic carbon; N is for nitrogen content; P is for Phosphorous; K is for potassium; BD is for bulk density; NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; and CT is for conventional tillage.

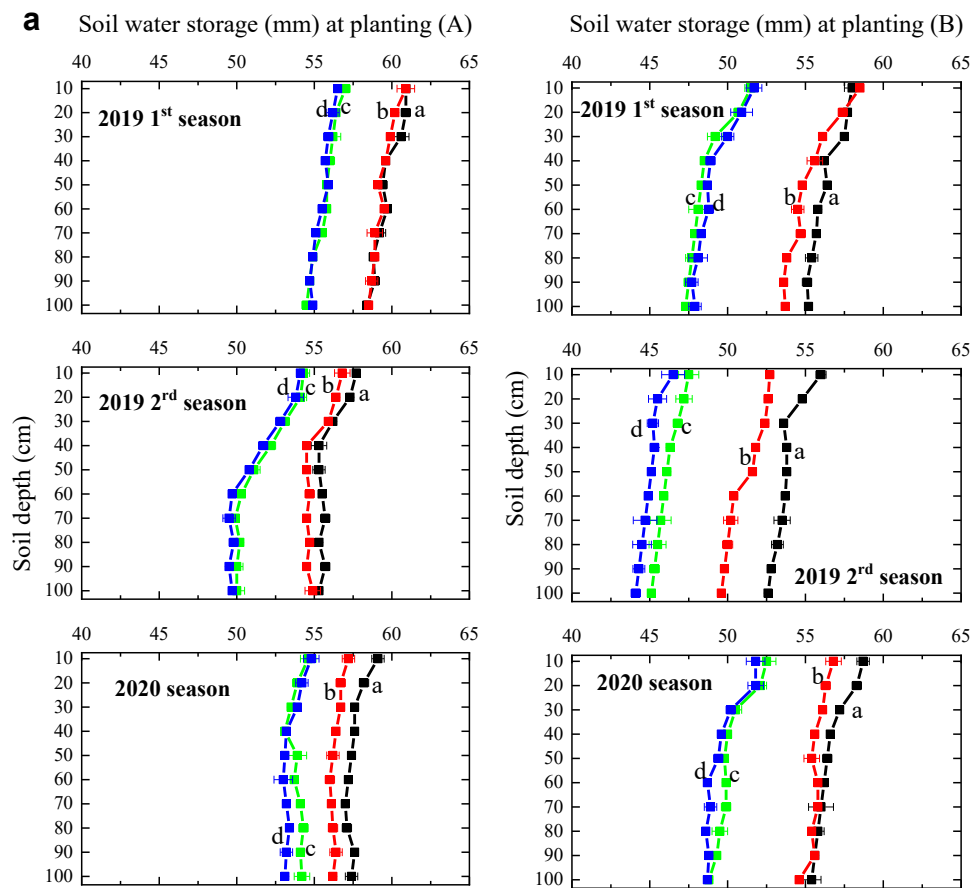


Figure 5a. Soil water storage at 0–100 cm soil depth under NT (a), SM (b), DT (c), and CT (d) at a time of common bean planting at Goma (A) and Kimenyedde (B) experimental sites.

mm) and CT (51.03 mm). A similar trend was observed at harvesting with the greatest SWS under NT (27.06 mm) and SM (26.82 mm) than DT (19.05 mm) and CT (18.50 mm).

The effect of soil depth on SWS was not significant at planting, but SWS declined with soil depth with 55.25 mm at 0–10 cm, 54.73 mm at 10–20 cm, 54.05 at 20–30 cm, 53.46 mm at 30–40 cm, 53.26 mm, at 40–50 cm, 53.05 mm at 50–60 cm, 52.92 mm at 60–70 cm, 52.75 mm at 70–80 cm, 52.64 mm at 80–90 cm, and 52.50 mm at 90–100 cm. At harvesting, the soil water change was 10% between 0–40 cm, 4% between the 40–80 cm, and 1% in the 80–100 cm. The effect of experimental site on SWS was not significant, but Goma site (23.36 mm) preserved more soil water than Kimenyedde site (22.35 mm).

3.4. Common bean grain yield

The grain yield under the soil tillage treatments during the three seasons in the two experimental sites are presented in Figure 6. The grain yield was considerably affected by seasons, soil tillage treatments, and experimental sites. Seasonally, the grain yield was highest during the 2020-growing season (1545 kg ha⁻¹), followed by the first season of 2019 (1418 kg ha⁻¹), and lowest in the second season of 2019 (1335 kg ha⁻¹). Averaged across seasons and experimental sites, the grain yield decreased from NT (1842.5 kg ha⁻¹) to SM (1794.5 kg ha⁻¹), DT (1083.3 kg ha⁻¹), and then to CT (1010.0 kg ha⁻¹). On average, NT increased grain yield by 3, 41, and 45% compared with SM, DT, and CT treatments, respectively. When the grain yield was compared between experimental sites, Goma site (1506 kg ha⁻¹) produced 11% more yield than Kimenyedde site (1359 kg ha⁻¹).

3.5. Evapotranspiration and water use efficiency

Table 2 presents ET and WUE-grain under the different soil tillage treatments in the three growing seasons at Goma and Kimenyedde experimental sites. The ET significantly ($p < 0.05$) varied between the soil tillage treatments, but no statistical differences in ET were observed between seasons and experimental sites. The interactions between soil tillage treatment × experimental site and soil tillage treatment × season were also significant. Averaged across soil tillage treatments and experimental sites, the ET was highest in the second season of 2019 (141.60 mm), followed by the first season of 2019 (130.98 mm), and lowest in the 2020 growing-season (129.42 mm). The highest ET was recorded under CT (170.79 mm) and DT (168.14 mm), while NT (98.03 mm) and SM (99.05 mm) had the lowest ET. Averaged across all seasons, Goma site (133.46 mm) had a slightly lower evaporative demand than Kimenyedde site (144.55 mm).

The WUE-grain significantly ($p < 0.05$) varied between seasons and soil tillage treatments. The interaction between experimental sites × season, experimental sites × soil tillage treatments, and soil tillage treatment × season was also significant. Averaged across soil tillage treatments and experimental sites, the WUE-grain was highest during the 2020 growing-season (1.42 kg m⁻³), followed by the first season of 2019 (1.39 kg m⁻³), and lowest in the second season of 2019 (1.00 kg m⁻³). The differences between soil tillage treatments on WUE-grain were highly appreciable, with the greatest WUE-grain under NT (1.99 kg m⁻³) and SM (1.86 kg m⁻³) and lowest under DT (0.75 kg m⁻³) and CT (0.71 kg m⁻³). Though no considerable variations were observed in the WUE-

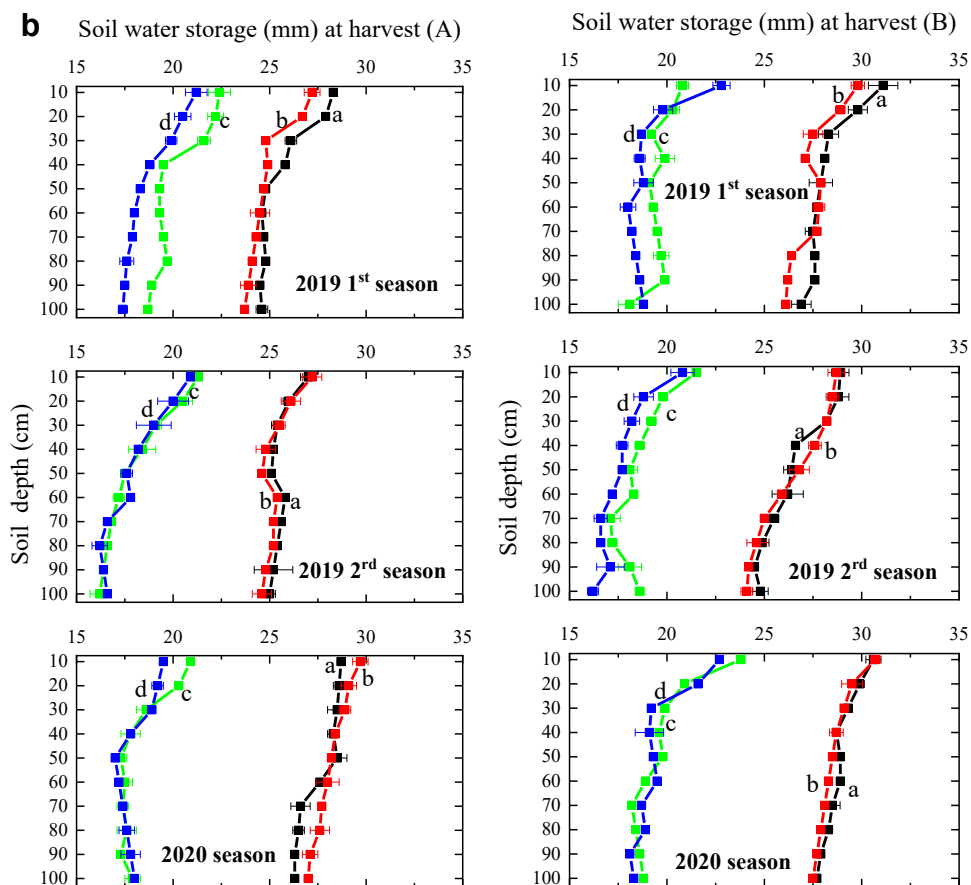


Figure 5b. Soil water storage at 0–100 cm soil depth under NT (a), SM (b), DT (c), and CT (d) at a time of common bean harvesting at Goma (A) and Kimenyedde (B) experimental sites.

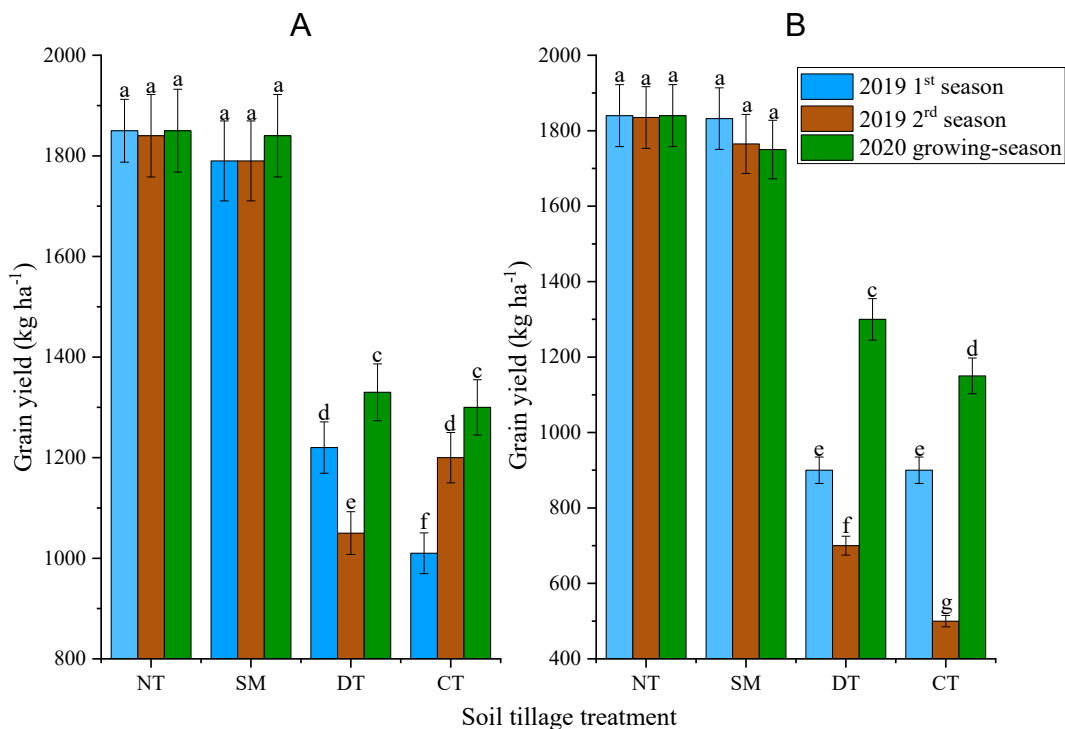


Figure 6. Effect of soil tillage treatments and seasons on common bean grain yield at Goma (A) and Kimenyedde (B) experimental sites. Bars over the mean indicate the standard errors, and the lower case letters indicate significance at 0.05. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage.

Table 2. Mean values of ET and WUE-grain for the common beans for the soil tillage treatments and ANOVA testing the effect of experimental sites, seasons, soil tillage treatments, and their interactions on the ET and WUE-grain during three growing seasons at Goma and Kimenyedde experimental sites in Mukono District, Uganda.

Site	Season	ET (mm)				WUE-grain (kg m ⁻³)			
		NT	SM	DT	CT	NT	SM	DT	CT
Goma	2019 1 st season	95.27 ^b	96.17 ^b	158.27 ^a	160.75 ^a	1.94 ^a	1.69 ^b	0.77 ^c	0.62 ^c
	2019 2 nd season	99.84 ^b	100.12 ^b	170.57 ^a	173.29 ^a	1.80 ^a	1.69 ^b	0.65 ^c	0.71 ^c
	2020 growing-season	96.17 ^b	96.77 ^b	152.17 ^a	155.15 ^a	1.92 ^a	1.89 ^a	0.84 ^b	0.81 ^b
Kimenyedde	2019 1 st season	95.29 ^b	97.01 ^b	160.75 ^a	164.36 ^a	1.76 ^a	1.65 ^b	0.56 ^c	0.55 ^c
	2019 2 nd season	105.89 ^b	107.30 ^b	177.65 ^a	178.11 ^a	1.68 ^a	1.43 ^b	0.39 ^c	0.28 ^d
	2020 growing-season	95.69 ^b	96.91 ^b	159.45 ^a	163.06 ^a	1.78 ^a	1.73 ^a	0.82 ^b	0.77 ^b

Factor	ANOVA-table			
	ET (mm)		WUE-grain (kg m ⁻³)	
	F-value	p-value	F-value	p-value
Experimental site	86.21	ns	98.30	ns
Season	129.84	ns	202.51	0.048
Soil tillage treatment	76.22	0.001	68.54	0.003
Experimental site × Season	100.71	ns	99.05	0.042
Experimental site × Soil tillage treatment	86.06	0.041	112.33	0.041
Soil tillage treatment × Season	89.43	0.038	184.68	0.032
Experimental site × Season × Soil tillage treatment	109.44	ns	100.09	ns

NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; and CT is for conventional tillage; ET is for evapotranspiration; WUE-grain is for grain yield water use efficiency. Values with the same superscript letters within a row are not significantly different at $p = 0.05$, and “ns” in the ANOVA table is for not significant.

Table 3. Gross cost, gross revenue, net profit, and benefit-cost ratio for common beans under no-tillage, stubble-mulching, deep tillage, and conventional tillage systems for 14 months.

Tillage system	Gross cost (USD ha ⁻¹)	Gross revenue (USD ha ⁻¹)	Net profit (USD ha ⁻¹)	Benefit-cost ratio
NT	642.44 ^c	2471.17 ^a	1828.73 ^a	2.85 ^a
SM	1172.67 ^a	2351.71 ^a	1179.04 ^b	1.01 ^b
DT	1180.57 ^a	1522.52 ^b	341.95 ^d	0.29 ^d
CT	786.86 ^b	1419.46 ^c	632.60 ^c	0.80 ^c

NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; and CT is for conventional tillage. Values with the same superscript letters (a, b, c, and d) within a column are not significantly different at $p = 0.05$.

grain between experimental sites, Goma site (1.28 kg m⁻³) had slightly higher WUE-grain than Kimenyedde site (1.12 kg m⁻³).

3.6. Gross cost, net profit, and benefit-cost ratio

The cost of production/gross cost and the economic benefits/net profit of the common beans under the soil tillage treatments in Goma and Kimenyedde experimental sites are shown in Table 3. The gross cost varied significantly ($p < 0.05$) between the soil tillage treatments, with DT having 2 and 1.5 times higher gross cost than NT and CT, respectively. The gross cost for DT and SM were indistinguishable. The net profit was 5 and 3 times higher under NT treatment compared with DT and CT treatments, respectively. The BCR was greater than one under NT and SM and less than one under DT and CT (Table 3).

4. Discussion

4.1. Soil characteristics and soil tillage treatments

The soil tillage treatments influenced soil OC, N content, and soil BD (Table 1). Soil tillage practices have been reported to affect the soil characteristics, especially in the superficial soil layer (Martínez et al., 2008; Pareja-Sánchez et al., 2017). Slightly higher soil pH-values were observed under NT and SM than under DT and CT [Table 1; Rahman et al. (2008)]. The higher soil pH-values under NT and SM could be attributed to the decomposition of the organic matter [Table 1; Rhoton (2000)], which increased electrolytes concentration (McCauley et al., 2017;

Rahman et al., 2008) under NT and SM treatments. Consistent with the current study, Blanco-Canqui and Lal (2007) observed higher OC under stubble plots than plots without stubble. In a meta-study, Alvarez (2005) reported a 14% higher OC under NT and RT than CT in the top 30 cm depth. The increase in OC in conservation tillage practices seems to happen in the top layer [Table 1; Baker et al. (2007)] and is primarily attributable to the crop residues and mulches that decompose, hence releasing organic matter (Fuentes et al., 2009; Stone and Schlegel, 2010). The N content was higher under NT and SM than under DT and CT treatments (Table 1), which could considerably be attributed to retention of the crop residue on the soil surface (Al-Kaisi et al., 2005; Alam et al., 2014). In line with the current results, Jin et al. (2007) reported 0.41 g/cm³ higher BD under NT than CT practice. Husnjak et al. (2002) concluded that minimal soil disturbances improve soil chemical and physical properties than the intensive tillage systems.

4.2. Seasonal variations in soil water storage between the soil tillage treatments and experimental sites

The highest values of SWS were recorded during the 2020 growing-season and first season of 2019. Probably, during the 2020 growing-season and the first season of 2019, the higher precipitation amount (Figure 4) improved the hydraulic properties and increased the SWS. Precipitation amount and distribution can significantly influence the SWS both in space and time (Semalulu et al., 2015).

The influence of the soil tillage treatments on the SWS was highly significant at harvesting than at planting. The SWS decreased as soil

tillage intensity increased (Figure 5a and b). The effect of the soil tillage treatments on the SWS often varies depending on soil and environmental conditions. Smith et al. (2001) and Semalulu et al. (2015) noted that SWS depends on the amount and distribution of rainfall, soil texture, structure, depth, and compaction. The highest SWS was recorded under NT and SM. Similar findings were reported by Ngigi et al. (2006) in Kenya, where a 25% increase in SWS was observed under the conservation tillage compared to CT. The indistinguishable SWS under NT and SM signifies that the retention of a considerable amount of crop residues and mulches over the soil can considerably increase SWS even under conditions of high evaporative demand (Fuentes et al., 2009; Govaerts et al., 2009); hence conserving soil water.

Differences between seasons on SWS were appreciable at Kimenyedde and negligible at Goma experimental site. Kimenyedde experimental site showed lower SWS due to the higher evaporative demand and lower precipitation amount (Figure 4; Table 2). Therefore, mechanisms that reduce evapotranspiration (such as mulch-tillage) would be vital in Kimenyedde experimental site to increase water retention and water availability to the crops.

4.3. Common bean grain yield

Concerning the estimated potential common bean yields of 2.5–3.5 t ha⁻¹ by the Uganda Bureau of Statistic (UBOS) (2010), low grain yields (<2.0 t ha⁻¹) were obtained under all the soil tillage treatments. Although the current precipitation amount (392–538 mm) was within the range (300–500 mm) of precipitation suitable for common bean production (Beebe et al., 2011), uneven precipitation distribution and dry spells were common during the growing seasons. These dry spells (which occurred for about ten days at the flowering stage) could have affected the grain yield in the current study. Mubiru et al. (2018) noted that the low crop productivity in Sub-Saharan Africa under the rainfed agricultural systems is primarily due to uneven distribution of the precipitation across the growing seasons than low annual precipitation.

When averaged across soil tillage treatments and experimental sites, the grain yield produced in the 2020 growing-season (1545 kg ha⁻¹) and the first season of 2019 (1418 kg ha⁻¹) was significantly higher than the grain yield produced in the second season of 2019 (1295 kg ha⁻¹), primarily due to the differences in precipitation distribution. The low grain yield in the second season of 2019 was due to the dry conditions during grain filling due to a dry spell of 12 days. According to Hong-ling et al. (2008) and Alvarez and Steinbach (2009), short episodes of water stress that occur during water-sensitive development stages of the crop often cause substantial adverse effects on the grain yields.

Conservation tillage practices of reducing/eliminating tillage and retaining crop residues and mulches significantly impacted the grain yield in this study. Consistent with the current findings, Buah et al. (2017) in Ghana reported up to 51% increase in soya bean grain yield under NT plots when compared with CT. Miriti et al. (2012) and Munyao et al. (2019) in Kenya observed a 24 and 15% increase in common bean and cowpeas grain yield, respectively under NT when compared with CT and Hosseini et al. (2016) in Iran also observed a 9% increase in soya bean grain yield under NT when compared with CT. The increase in the grain yield under NT could be attributed to better weed control and water conservation than under CT (Ngwira et al., 2012). In the current study, water conservation was improved with NT and SM due to the crop residues and mulches that were retained in these soil tillage treatments. The DT and CT significantly lost water in the form of evapotranspiration through frequent weeding (Table 2). Additionally, the crop residues and mulches under NT and SM could have improved nutrient supply to the crops under these treatments (Table 1), which improved the grain yield. Both Mrabet (2000) and Cantero-Martínez et al. (2007) concluded that the higher yield under NT than CT is credited to the better soil moisture conditions and nutrient supply under NT, due to the retained crop residues.

Under DT and CT, the grain yield varied between seasons and experimental sites. The low and variable grain yield under DT and CT at Goma and Kimenyedde experimental sites was primarily due to the spatial differences in precipitation distribution [Figure 4; Uganda National Meteorological Authority (UNMA) (2019)]. Averaged across seasons and soil tillage treatments, Goma site had a higher grain yield than Kimenyedde experimental site. The higher grain yield at Goma was not only because of the higher precipitation but also because the precipitation was evenly distributed (i.e. less than five consecutive dry days) than that of Kimenyedde, which had a dry spell of twelve days.

4.4. Water use efficiency

Averaged across soil tillage treatments and experimental sites, the WUE-grain was highest during the 2020 growing-season, followed by the first season of 2019 and least in the second season of 2019 (Table 2). The WUE-grain was most remarkable in the 2020 growing-season and the first season of 2019 because of the better precipitation distribution and crop yield in these seasons. Lower WUE-grain was observed in the second season of 2019 due to the higher evaporative demand in this season (Table 2) and lower grain yield that resulted from poor rainfall distribution. The second season of 2019 had the least amount of precipitation and the lowest WUE-grain, demonstrating the direct influence of both precipitation amount and distribution on WUE-grain (Miriti et al., 2012). Similar findings were reported in Kenya by Johnson et al. (2018), who observed low WUE-grain in the common bean field during the season with short and erratic precipitation.

The WUE-grain was highest under NT and SM and lowest under DT and CT treatments (Table 2). The smaller quantities of grain yield and higher ET under DT and CT were responsible for the lower WUE-grain in these soil tillage treatments relative to the NT and SM treatments. The current findings align with Miriti et al. (2012) that cowpea WUE-grain significantly differed between conservation tillage practices and CT. Mbava et al. (2020) reviewed the effect of grain yield on WUE-grain for various crops and reported a correlation (*r*) of 0.834 between grain yield and WUE-grain. Additionally, the variations in the SWS between the soil tillage treatments could be responsible for the considerably high variations of the WUE-grain in these tillage treatments. Studies by Angadi et al. (2008) and Mbava et al. (2020) also reported higher WUE-grain under well-watered soils than water-stressed soils.

The WUE-grain was higher at Goma than Kimenyedde experimental site, probably due to the higher grain yield at Goma experimental site. Additionally, the higher precipitation amount at Goma than Kimenyedde experimental site could be attributable to the higher WUE-grain at Goma than Kimenyedde experimental site. Similar observations were reported by Mbava et al. (2020), who reported a correlation coefficient (*r*) of 0.52 between WUE-grain with precipitation amount.

4.5. Soil tillage treatments, gross cost, and economic benefits

The gross cost varied significantly (*p* < 0.05) between the soil tillage treatments (Table 3) and increased in the order of NT, CT, SM, and DT. The current results are consistent with Micheni et al. (2014) and Otieno et al. (2019) in the common bean fields, who reported higher gross costs under CT than conservation tillage practices. The reduced gross cost under NT could primarily be attributable to the less labor that was required for management practices such as cultivation, machinery, and weeding since weeds were controlled using herbicides. Additionally, the crop residues and mulches under NT helped to suppress the weeds, which reduced the cost of herbicide and labor, hence further lowering the gross cost (Lal et al., 2003). The DT, CT, and SM treatments involved land tilling, which required lots of fuel, labor, and machinery, resulting in higher gross cost (Pannell et al., 2014; Su et al., 2007). Conversely, tilling of the land during seedbed preparation and constant weeding episodes increased the gross cost under CT and DT (Mloza-Banda and Nanthambwe, 2011).

The economic benefits (in terms of net profit) varied significantly ($p < 0.05$) between the soil tillage treatments, with the highest net profit under NT and the lowest under DT (Table 3). In line with the current observations, Fischer et al. (2002) and Bueno et al. (2007) reported higher net profit under conservation tillage practices (NT and RT) than CT, mainly due to the lower operating costs and better economic returns (Su et al., 2007). Moreover, the lower net profit under DT and CT could be attributable to the lower quantities of grain yield under these soil tillage treatments than under the NT and SM treatments. Franke et al. (2014) reported that low quantities of grain yield significantly reduce profitability in the eastern Africa region. The argument seems to be necessary, as Kihara et al. (2011) also reported that the net profit from a given soil tillage practice is often based on the quantities of yield from that particular soil tillage practice.

Additionally, the BCR was greater than one under NT and SM and less than one under DT and CT (Table 3). Similar observations were reported by Jabran and Aulakh (2015) in the wheat field, where NT produced a higher BCR than DT. The current study indicates that NT and SM are economically feasible for common bean production in central Uganda due to their higher economic returns.

5. Conclusion

The current study investigated the effect of soil tillage treatments, seasons, and locality on SWS, WUE-grain, grain yield, and economic returns in the common bean fields. The findings indicated that NT and SM improved soil water conservation and WUE-grain, saving about 44 and 42% of soil water than CT treatment. However, our study suggested that the ability of these conservation tillage practices to conserve water depends mainly on the soil physical properties and weather conditions (i.e. precipitation amount vs. evaporative demand). Although NT and SM improved SWS and grain yield, seasonal precipitation distribution had a greater influence on the final grain yield. The higher grain yield and lower ET under NT and SM also contributed to the higher WUE-grain in these soil tillage treatments.

Water scarcity and moisture deficiency are increasingly affecting Uganda's crop production sector. Numerous soil and water management technologies, including conservation tillage practices, are increasingly being demonstrated in Uganda. Some conservation tillage practices are costly, others are labor-intensive, and their suitability varies for different areas. Adoption of a particular soil tillage practice in a given locality must, therefore, be economically justified. In our study, the net profit was 3 and 5 times higher under NT than under CT and DT treatments, respectively, indicating that NT is economically feasible for common bean production in central Uganda due to its higher economic returns.

However, crop farming systems and soil tillage practices are complex in agro-ecological and sociopolitical aspects, and the implementation of these tillage practices across geographies is challenging. Since the current study was case-specific, further studies are needed to generalize the findings to other regions over long-term comparisons.

Declarations

Author contribution statement

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

Seifu A. Tilahun; Ssemwanga Mohammed: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

- Adhikari, U., Nejadhashemi, A.P., Woznicki, S.A., 2015. Climate change and eastern Africa: a review of the impact on major crops. *Food Energy Sec.* 4 (2), 110–132.
- Al-Kaisi, M.M., Yin, X., Licht, M.A., 2005. Soil carbon and nitrogen changes as affected by tillage system and crop biomass in a corn-soybean rotation. *Appl. Soil Ecol.* 30 (3), 174–191.
- Alam, M., Islam, M., Salahin, N., Hasanuzzaman, M., 2014. Effect of tillage practices on soil properties and crop productivity in wheat-mungbean-rice cropping system under subtropical climatic conditions. *Sci. World J.* 10, 40–55.
- Alvarez, R., 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. *Soil Use Manag.* 21 (1), 38–52.
- Alvarez, R., Steinbach, H.S., 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. *Soil Tillage Res.* 104 (1), 1–15.
- Angadi, S., McConkey, B., Cutforth, H., Miller, P., Ulrich, D., Selles, F., Volkmar, K., Entz, M., Brandt, S., 2008. Adaptation of alternative pulse and oilseed crops to the semi-arid Canadian Prairie: seed yield and water use efficiency. *Can. J. Plant Sci.* 88 (3), 425–438.
- Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration—what do we really know? *Agric. Ecosyst. Environ.* 118 (1–4), 1–5.
- Beebe, E.S., Ramirez, J., Jarvis, A., Rao, M.I., Mosquera, G., Bueno, M.J., Blair, W.M., 2011. Genetic improvement of common beans and the challenges of climate change. In: Yadav, S.S., Redden, J.R., Hatfield, L.J., Lotze-Campen, H., Hall, E.A. (Eds.), *Crop Adaptation to Climate Change*. Blackwell Publishing Ltd, Cali, Colombia, pp. 356–369.
- Berhane, G., Mworozzi, E., Kibaya, P., Majaliwa, M., Mfitumukiza, D., 2013. Enhancing Adaptive Capacity of Communities to Climate Change-Induced Water Challenges Using ICT in Uganda: Second Interim Technical Report. Kampala, Uganda.
- Blake, G., 1965. Bulk density. In: Black, C.A. (Ed.), *Methods of Soil Analysis, Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling*, 1. American Society of Agronomy, Madison, WI, USA, p. 770.
- Blanco-Canqui, H., Lal, R., 2007. Impacts of long-term wheat straw management on soil hydraulic properties under no-tillage. *Soil Sci. Soc. Am. J.* 71 (4), 1166–1173.
- Blanco-Canqui, H., Wienhold, B.J., Jin, V.L., Schmer, M.R., Kibet, L.C., 2017. Long-term tillage impact on soil hydraulic properties. *Soil Tillage Res.* 170, 38–42.
- Bodner, G., Loiskandl, W., Kaul, H.-P., 2007. Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation. *Agric. Water Manag.* 93 (3), 85–98.
- Boukhari, K., Fakir, Y., Stigter, T., Hajhouji, Y., Boulet, G., 2015. Origin of recharge and salinity and their role on management issues of a large alluvial aquifer system in the semi-arid Haouz plain, Morocco. *Environ. Earth Sci.* 73 (10), 6195–6212.
- Buah, S.S.J., Ibrahim, H., Derigubah, M., Kuzie, M., Segtaa, J.V., Bayala, J., Zougmore, R., Ouedraogo, M., 2017. Tillage and fertilizer effect on maize and soybean yields in the Guinea savanna zone of Ghana. *Agric. Food Secur.* 6 (1), 17.
- Bueno, J., Amiama, C., Hernanz, J., 2007. No-tillage drilling of Italian ryegrass (*Lolium multiflorum* L.): crop residue effects, yields and economic benefits. *Soil Tillage Res.* 95 (1–2), 61–68.
- Cantero-Martínez, C., Angás, P., Lampurlanés, J., 2007. Long-term yield and water use efficiency under various tillage systems in Mediterranean rainfed conditions. *Ann. Appl. Biol.* 150 (3), 293–305.
- Dam, R., Mehdi, B., Burgess, M., Madramootoo, C., Mehuys, G., Callum, I., 2005. Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. *Soil Tillage Res.* 84 (1), 41–53.
- Department for International Development (DFID), 2020. Beans sector strategy – Uganda. In: *Commercial Agriculture for Smallholders and Agribusiness Uganda Country Team*. <https://www.casaprogramme.com/wp-content/uploads/CASA-Uganda-BeansSector-analysis-report.pdf>. (Accessed 14 December 2020).
- FAO, 1998. World Reference Base for Soil Resources. Food and Agriculture Organization of the United Nations, Rome, Italy.
- FAO, 2016. Phaseolus Bean post-harvest Operations. *Post-harvest Compendium*.
- FAOSTAT, 2018. FAO Statistics Online Database. Production/crops – 'beans, Dry', Year 2018. Food and Agriculture Organization (2018). <http://www.fao.org/faostat/en/#data/QC>. (Accessed 14 December 2020).

- Fatumah, N., Tilahun, S.A., Mohammed, S., 2020. Effect of tillage systems and tillage direction on soil hydrological properties and soil suspended particle concentration in arable land in Uganda. *Heliyon* 6 (12), e05616.
- Fischer, R., Santiveri, F., Vidal, I., 2002. Crop rotation, tillage and crop residue management for wheat and maize in the sub-humid tropical highlands: I. Wheat and legume performance. *Field Crop. Res.* 79 (2-3), 107–122.
- Franke, A., Van Den Brand, G., Giller, K., 2014. Which farmers benefit most from sustainable intensification? An ex-ante impact assessment of expanding grain legume production in Malawi. *Eur. J. Agron.* 58, 28–38.
- Fuentes, M., Govaerts, B., De León, F., Hidalgo, C., Dendooven, L., Sayre, K.D., Etchevers, J., 2009. Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on physical and chemical soil quality. *Eur. J. Agron.* 30 (3), 228–237.
- Govaerts, B., Sayre, K.D., Goudeseune, B., De Corte, P., Lichter, K., Dendooven, L., Deckers, J., 2009. Conservation agriculture as a sustainable option for the central Mexican highlands. *Soil Tillage Res.* 103 (2), 222–230.
- Hemmat, A., Eskandari, I., 2004. Conservation tillage practices for winter wheat-fallow farming in the temperate continental climate of northwestern Iran. *Field Crop. Res.* 89 (1), 123–133.
- Hong-ling, Q., Gao, W.S., Li, M.A., Yin, C.M., Zhe, C., Chunlan, C., 2008. Effects of subsoiling on soil moisture under no-tillage for two years. *Agric. Sci. China* 7 (1), 88–95.
- Hosseini, S.Z., Firouzi, S., Aminpanah, H., Sadeghnejhad, H.R., 2016. Effect of tillage system on yield and weed populations of soybean (*Glycine Max L.*). *An Acad. Bras Ciências* 88 (1), 377–384.
- Husnjak, S., Filipovic, D., Kosutic, S., 2002. Influence of different tillage systems on soil physical properties and crop yield. *Rostl. Vyroba* 48, 249–254.
- Jabran, A., Aulakh, A., 2015. Higher yield and economic benefits for wheat planted in conservation till systems. *Yüzüncü Yıl Üniversitesi Tarım Bilimleri Dergisi* 25 (1), 78–83.
- Jeje, L.K., Agu, A.N., 1990. Runoff from bounded plots in Alakowe in southwestern Nigeria. *Appl. Geogr.* 10 (1), 63–74.
- Jin, H., Hongwen, L., Xiaoyan, W., McHugh, A., Wenyang, L., Huanwen, G., Kuhn, N., 2007. The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. *Soil Tillage Res.* 94 (2), 493–502.
- Johnson, Y.K., Ayuke, F.O., Kinama, J.M., Sijali, I.V., 2018. Effects of tillage practices on water use efficiency and yield of different drought-tolerant common bean varieties in Machakos county, Eastern Kenya. *Am. Sci. Res. J. Eng. Technol. Sci. (ASRJETS)* 40 (1), 217–234.
- Kagoya, S., Paudel, K., Daniel, N., 2018. Awareness and adoption of soil and water conservation technologies in a developing country: a case of Nabajuzi watershed in Central Uganda. *Environ. Manag.* 61 (2), 188–196.
- Kargas, G., Kerkides, P., Poulouvassilis, A., 2012. Infiltration of rainwater in semi-arid areas under three land surface treatments. *Soil Tillage Res.* 120, 15–24.
- Kihara, J., Martius, C., Bationo, A., Vlek, P.L., 2011. Effects of tillage and crop residue application on soybean nitrogen fixation in a tropical ferralsol. *Agriculture* 1 (1), 22–37.
- Lal, R., Follett, R., Kimble, J., 2003. Achieving soil carbon sequestration in the United States: a challenge to the policymakers. *Soil Sci.* 168 (12), 827–845.
- Liu, Y., Zhao, W., Zhang, X., Fang, X., 2016. Soil water storage changes within deep profiles under introduced shrubs during the growing season: evidence from semiarid Loess Plateau, China. *Water* 8 (10), 475.
- Martínez, E., Fuentes, J.-P., Silva, P., Valle, S., Acevedo, E., 2008. Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile. *Soil Tillage Res.* 99 (2), 232–244.
- Mastorilli, M., Katerji, N., Rana, G., Nouna, B.B., 1998. Daily actual evapotranspiration measured with TDR technique in Mediterranean conditions. *Agric. For. Meteorol.* 90 (1-2), 81–89.
- Mbava, N., Mutema, M., Zengeni, R., Shimelis, H., Chaplot, V., 2020. Factors affecting crop water use efficiency: a worldwide meta-analysis. *Agric. Water Manag.* 228, 105878.
- McCaughey, A., Jones, C., Olson-Rutz, K., 2017. Soil pH and Organic Matter. Nutrient Management Module No. 8. Montana State University, Bozeman.
- Micheni, A., Ouma, J., Kanampiu, F., Mburu, D., Mugai, N., 2014. Maize-bean Farming System under Conservation Agriculture: Assessing Productivity and Sustainability in Eastern Kenya, 2012–2014. <http://www.ctic.org>.
- Miriti, J., Kironchi, G., Esilaba, A., Heng, L., Gachene, C., Mwangi, D., 2012. Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya. *Agric. Water Manag.* 115, 148–155.
- Mloza-Banda, H., Nanthambwe, S., 2011. Conservation agriculture program and projects in Malawi: impacts and lessons. In: National Conservation Agriculture Task Force Secretariat Land Resources Conservation Department. Lilongwe. <http://hdl.handle.net/10919/69913>.
- Mrabet, R., 2000. Differential response of wheat to tillage management systems in a semiarid area of Morocco. *Field Crop. Res.* 66 (2), 165–174.
- Mubiru, D.N., Komutunga, E., Agona, A., Apok, A., Ngara, T., 2012. Characterising agrometeorological climate risks and uncertainties: crop production in Uganda. *South Afr. J. Sci.* 108 (3-4), 108–118.
- Mubiru, D.N., Radeny, M., Kyazze, F.B., Zziwa, A., Lwasa, J., Kinyangi, J., Mungai, C., 2018. Climate trends, risks and coping strategies in smallholder farming systems in Uganda. *Clim. Risk Manag.* 22, 4–21.
- Munyao, J.K., Gathaara, M.H., Micheni, A.N., 2019. Effects of conservation tillage on maize (*Zea mays L.*) and beans (*Phaseolus vulgaris L.*) chlorophyll, sugars and yields in humic nitisols soils of Embu County, Kenya. *Afr. J. Agric. Res.* 14 (29), 1272–1278.
- Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), *Methods of Soil Analysis. Part 3—Chemical Methods*; Madison: SSSA Book Ser. 5, 1996. Soil Science Society of America, American Society of Agronomy, Madison, WI, USA, pp. 961–1010.
- Ngigi, S.N., Rockström, J., Savenije, H.H.G., 2006. Assessment of rainwater retention in agricultural land and crop yield increase due to conservation tillage in Ewaso Ng'iro river basin, Kenya. *Phys. Chem. Earth, Parts A/B/C* 31 (15), 910–918.
- Ngwira, A.R., Aune, J.B., Mkwinda, S., 2012. On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. *Field Crop. Res.* 132, 149–157.
- Olsen, S., Sommers, L., Page, A., 1982. *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties of phosphorus*. Agronomy Monograph, 9. American Society of Agronomy/Academic Press, Madison, pp. 403–430.
- Otieno, H.M.O., Chemining'wa, G.N., Gachene, C.K., Zingore, S., 2019. Economics of maize and bean production: why Farmers need to shift to conservation agriculture for sustainable production. *Turk. J. Agric. Food Sci. Technol.* 7 (10), 1548–1553.
- Pannell, D.J., Llewellyn, R.S., Corbeels, M., 2014. The farm-level economics of conservation agriculture for resource-poor farmers. *Agric. Ecosyst. Environ.* 187, 52–64.
- Pareja-Sánchez, E., Plaza-Bonilla, D., Ramos, M.C., Lampurlán, J., Álvaro-Fuentes, J., Cantero-Martínez, C., 2017. Long-term no-till as a means to maintain soil surface structure in an agroecosystem transformed into irrigation. *Soil Tillage Res.* 174, 221–230.
- Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D., Petersen, J.L., 2008. Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. *Agric. Water Manag.* 95 (8), 895–908.
- Rahman, M.H., Okubo, A., Sugiyama, S., Mayland, H., 2008. Physical, chemical and microbiological properties of an Andisol as related to land use and tillage practice. *Soil Tillage Res.* 101 (1-2), 10–19.
- Rayment, G.E., Higginson, F.R., 1992. Soil survey standard test method for electrical conductivity. Australian Laboratory Handbook of Soil and Water Chemical Methods; Australian Soil L. Surv. Handbooks. Inkata Press, Melbourne, Australian.
- Rhoton, F., 2000. Influence of time on soil response to no-till practices. *Soil Sci. Soc. Am. J.* 64 (2), 700–709.
- Sabiiti, G., Ininda, J.M., Ogallo, L.A., Ouma, J., Artan, G., Basalirwa, C., Opjiah, F., Nimusiima, A., Ddumba, S.D., Mwesigwa, J.B., 2018. Adapting Agriculture to Climate Change: Suitability of Banana Crop Production to Future Climate Change over Uganda *Limits To Climate Change Adaptation*. Springer, pp. 175–190.
- Semalulu, O., Kaizzi, K., Komutunga, E., Mubiru, D., Magunda, M., 2015. Conserving Soils: Water-Smart Agriculture through Integrated Soil and Water Management: the Uganda Experience. International Water Management Institute (IWMI).
- Smith, C.W., Johnston, M.A., Lorentz, S.A., 2001. The effect of soil compaction on the water retention characteristics of soils in forest plantations. *S. Afr. J. Plant Soil* 18 (3), 87–97.
- Stone, L.R., Schlegel, A.J., 2010. Tillage and crop rotation phase effects on soil physical properties in the west-central Great Plains. *Agron. J.* 102 (2), 483–491.
- Su, Z., Zhang, J., Wu, W., Cai, D., Lv, J., Jiang, G., Huang, J., Gao, J., Hartmann, R., Gabriels, D., 2007. Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on the Loess Plateau, China. *Agric. Water Manag.* 87 (3), 307–314.
- Swain, A., 2011. Challenges for water sharing in the Nile basin: changing geopolitics and changing climate. *Hydrol. Sci. J.* 56 (4), 687–702.
- TerAvest, D., Carpenter-Boggs, L., Thierfelder, C., Reganold, J.P., 2015. Crop production and soil water management in conservation agriculture, no-till, and conventional tillage systems in Malawi. *Agric. Ecosyst. Environ.* 212, 285–296.
- Thierfelder, C., Mwila, M., Rusinamhodzi, L., 2013. Conservation agriculture in eastern and southern provinces of Zambia: long-term effects on soil quality and maize productivity. *Soil Tillage Res.* 126, 246–258.
- Turinawe, A., 2019. Impact of soil and water conservation technology adoption on smallholder farms in South-Western Uganda. *J. Dev. Agric. Econ.* 11 (9), 217–233.
- Uganda Bureau of Statistic (UBOS), 2010. Uganda Census of Agriculture 2008/2009, IV. Crop area and production report, p. 178.
- Uganda Bureau of Statistic (UBOS), 2017. Statistical Abstract UBOS, 2017. Kampala, Uganda.
- Uganda National Meteorological Authority (UNMA), 2019. 2019 seasonal rainfall outlook over Uganda. Available at: <https://unma.go.ug/>.
- World Bank, 2018. *Climate Change Knowledge Portal (CCKP)*, World Bank Groups accessed on 01 April 2020. <https://climateknowledgeportal.worldbank.org/country/uganda/download-data>.
- Xu, L.-K., Hsiao, T.C., 2004. Predicted versus measured photosynthetic water-use efficiency of crop stands under dynamically changing field environments. *J. Exp. Bot.* 55 (407), 2395–2411.