AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

# EFFECT OF SOIL TILLAGE SYSTEMS ON SOIL HYDROLOGICAL PROCESSES IN COMMON BEAN (*Phaseolus vulgaris* L.) FARMS IN MUKONO DISTRICT, UGANDA

**By**

**NAKIGULI FATUMAH**

A PhD dissertation submitted to the Africa Center of Excellence for Water Management, the School of Graduate Studies of Addis Ababa University in partial fulfilment of the requirements for The Degree of Doctor of Philosophy in Water Management (Hydrology and Water Resource Management)

JULY 2021

Addis Ababa, Ethiopia

Africa Center of Excellence for Water Management

Addis Ababa University

School of Graduate Studies

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# DECLARATION

I, Nakiguli Fatumah (ACEWM/GSR/7789/10), hereby declare that this research Dissertation titled *"Effect of soil tillage systems on soil hydrological processes in common bean (Phaseolus vulgaris* L.) *Farms in Mukono District, Uganda"* has been developed by me and has not been submitted to any other institution for the award of any academic qualification. The content of the dissertation has not been plagiarized, and where works of other researchers have been used, they have been appropriately cited.

| | | |
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| Nakiguli Fatumah | NFatumah | 07/06/2021 |
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**AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT**

**ADDIS ABABA UNIVERSITY**

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A PhD DISSERTATION SUBMITTED
TO
AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT
ADDIS ABABA UNIVERSITY

APPROVED BY BOARD OF EXAMINERS

This is to certify that we have read this PhD research proposal and that, in our opinion, it is fully adequate, in scope and quality, as a PhD dissertation for The Degree of Doctor of Philosophy in Water Management (Hydrology and Water Resources Management).

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# DEDICATION

***To my lovely Twins***

*“Nashwiha & Nasheem”*

*Leaving you at 2-years of age for this PhD study was heartbreaking*

*I have no excuse for leaving you at such a tender age, but sincerely apologies for not being around when you needed me most.*

*But I honestly assure you that I did this PhD for you, and it is because of you; I was encouraged to strive to the end.*

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# LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| AET | Actual evapotranspiration |
| APEX | Agricultural Policy/Environmental eXtender |
| Av. K | Available Potassium |
| Av. P | Available Phosphorus |
| BCR | Benefit-cost Ratio |
| BD | Bulk Density |
| CBD | Complete Block Design |
| $CN_2$ | Curve Number |
| CNIC | Curve Number Index Coefficient |
| CT | Conventional Tillage |
| DDS | Dynamically Dimensioned Search |
| DT | Deep Tillage |
| FAO | Food and Agriculture Organization |
| IR | Infiltration Rate |
| ITCZ | Inter-Tropical Convergence Zone |
| MP | Mould-board Ploughing |
| MT | Minimum Tillage |
| N | Nitrogen |
| NARO | National Agricultural Research Organization |
| NRCS | Natural Resources Conservation Service |
| NT | No-Tillage |
| OC | Organic carbon |
| PET | Potential evapotranspiration |
| PT | Plow tillage |
| RT | Reduced Tillage |
| SM | Stubble-Mulching |
| SMC | Soil Moisture Content |
| SRV | Surface Runoff Volume |
| SSA | Sub-Saharan Africa |

| | |
|---|---|
| SSC | Suspended Sediment Concentration |
| SWS | Soil Water Storage |
| SY | Sediment Yield |
| TDS | Tillage Down the Slope |
| TPS | Tillage Perpendicular to the Slope |
| UBOS | Uganda Bureau of Statistics |
| UN | United Nations |
| UNDIC | United Nations Development International Community |
| UNMA | Uganda National Meteorological Agency |
| USDA | United States Department of Agriculture |
| WUE | Water Use Efficiency |

# ABSTRACT

Goal 15 of the United Nations 2030 Agenda for Sustainable Development addresses the protection, restoration, and promotion of sustainable use of terrestrial ecosystems by halting and reversing land degradation. Soil tillage is one of the main factors causing land degradation in sub Saharan Africa. In this study, the effect of soil tillage systems on infiltration rate, soil moisture content, soil water storage, surface runoff volume, suspended sediment concentration, and sediment yield in common bean (*Phaseolus Vulgaris* L.) farms, at Goma and Kimenyedde experimental sites in Mukono District, Uganda was evaluated. The study also assessed the effect of soil tillage systems on grain yields, water use efficiency, and economic returns of the common beans. The study further evaluated the performance of the Agricultural Policy/Environmental eXtender model in the simulation of surface runoff volume and sediment yield. The soil tillage systems were: no-tillage, stubble-mulching, deep tillage, and conventional tillage. Field experiments were arranged in Complete Block Design under four soil tillage systems, consisting of two tillage directions: tillage down the slope and tillage perpendicular to the direction of slope during three wet seasons. The results showed the highest and lowest infiltration rate and soil moisture content under no-tillage and conventional tillage, respectively. No-tillage and stubble-mulching improved soil water storage by 46 and 45%, respectively, compared with conventional tillage in the 0-100 cm soil depth over the 16 months. The highest surface runoff volume was observed during the third season at Goma site under conventional tillage with tillage down the slope (1082 mm), while the lowest surface runoff volume was observed during the second season in Kimenyedde site under no-tillage (165 mm). Tillage perpendicular to the direction of slope reduced surface runoff volume by the range of 5-15%, relative to tillage down the slope. The highest and lowest suspended sediment concentration were observed under conventional tillage ($2.65 \pm 0.5$ g $L^{-1}$) at Goma site during the third season and no-tillage ($0.43 \pm 0.1$ g $L^{-1}$) at Kimenyedde site in the second season, respectively. Sediment yield was highest under conventional tillage at Goma (183.01 kg $ha^{-1}$) during the third season and lowest under no-tillage (9.19 kg $ha^{-1}$) at Kimenyedde site, during the second season. Soil tillage systems significantly ($p < 0.05$) affected water use efficiency, with water use efficiency values generally greater under no-tillage and stubble-mulching than under deep tillage and conventional tillage. Grain yield was highest under no-tillage and stubble-mulching than deep tillage and conventional tillage, with over 5, 38, and 43% higher grain yield under no-tillage than under stubble-mulching, deep tillage, and conventional tillage, respectively. Seasonal precipitation distribution considerably influenced crop yield, soil water storage, and water use efficiency. The net profit was three and five times higher under no-tillage than under conventional tillage and deep tillage, respectively. No-tillage and stubble-mulching were the optimum soil tillage systems for increasing infiltration rate, soil water storage, enhancing water use efficiency, improving grain yield and economic returns in central Uganda. Evaluation of Agricultural Policy/Environmental eXtender model performance for surface runoff volume and sediment yield simulation provided good results. For both calibration and validation periods, Nash-Sutcliffe efficiency values were > 0.5, coefficient of determination > 0.6, and percent bias values were within ±20% for surface runoff volume and sediment yield. The Agricultural Policy/Environmental eXtender model can be a useful tool for evaluating surface runoff volume and sediment yield for different management practices in Mukono District. Adopting no-tillage and stubble-mulching would be efficient strategies for controlling excessive surface runoff and sediment in the region.

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of the Problem

The rapidly growing population in developing countries has caused environmental degradation by depleting resources such as water and soil; ecosystem services; and pollution (Green *et al.*, 2019; Jouanjean *et al.*, 2014). The need to increase food to feed the growing population has led to unsustainable crop production technologies and practices that involve extensive land disturbances and use of synthetic, inorganic agro-inputs such as fertilizers and herbicides. Numerous indications have proven that the current crop production technologies are not sustainable (Takács-György *et al.*, 2014). For instance, soil tillage, one of the crop production technologies, is among the leading anthropogenic activities regulating water flow processes, thereby influencing soil hydrological functioning (Tapia-Vargas *et al.*, 2001; Van de Giesen *et al.*, 2011). Intensive soil tillage systems interfere with soil compaction, infiltration rates (IR), and soil water-holding capacities (soil moisture content [SMC] and soil water storage [SWS]) (Baumhardt *et al.*, 2017; Guzha *et al.*, 2018; Mitchell *et al.*, 2017; Nyamadzawo *et al.*, 2012); which is likely to increase the magnitude of surface runoff volume (SRV), suspended sediment concentration (SSC), and sediment yield (SY).

Several studies have been conducted to assess the effect of soil tillage systems on soil hydrology, SSC, and SY in different agro-ecosystems (Ahuja *et al.*, 1998; Green *et al.*, 2019; Lefrançois *et al.*, 2007; Steegen *et al.*, 2000). Some studies reported improved soil hydrological functioning under conservation tillage practices due to: improved soil structure (Govaerts *et al.*, 2007; Machado *et al.*, 2015); (ii) increased soil aggregation (Mitchell *et al.*, 2017); (iii) increased SWS (Baumhardt *et al.*, 2017; Govaerts *et al.*, 2007); and (iv) improved IR (Kahlon *et al.*, 2013; Mitchell *et al.*, 2017; Roper *et al.*, 2013). In contrast, related studies observed improved soil hydrological properties, notably higher IR and SRV reduction under conventional tillage (CT) practices than under no-tillage (NT) and minimum tillage (MT) practices (Celik & Ersahin, 2011; Melero *et al.*, 2011; Schwartz *et al.*, 2010). Limited field-based studies reported no noticeable differences in soil hydrological processes between CT and conservation tillage practices (Capowiez *et al.*, 2009; McGarry *et al.*, 2000).

Nonetheless, the effectiveness of conservation tillage practices in improving soil hydrological processes depends on agronomic practices and environmental factors, including rainfall amount, distribution, and soil types (Hemmat & Eskandari, 2004). Efforts should be made towards understanding and adapting sustainable cropping/soil tillage technologies in Uganda and Sub-Saharan Africa (SSA) countries to reduce environmental degradation.

## 1.2 Statement of the Problem

The SSA countries, Uganda in particular, are challenged by unprecedented environmental degradation due to unsustainable crop production systems (Adenle & Agboola, 2011). Approximately 65% of agricultural land in SSA countries is affected by land degradation, mainly soil erosion and soil acidification resulting from unsustainable crop production systems such as intensive soil tillage practices (Zingore *et al.*, 2015). These unsustainable crop production technologies such as intensive soil tillage affect the ecosystem services (Nkonya *et al.*, 2008), which has raised several ecological and hydrological concerns in the SSA region (Guzha *et al.*, 2018; Lundgren, 1980; Odada *et al.*, 2004).

The ecological and hydrological concerns are related to soil erosion, surface runoff, and sedimentation (Guzha *et al.*, 2018; Odada *et al.*, 2004). Surface runoff and sediment transportation are the primary causes of stream and lake damages in SSA, particularly in the East African watersheds and large water bodies (Azanga, 2016; Hecky *et al.*, 2003; Olago & Odada, 2007). This is because surface runoff is loaded with substantial pollutants, mainly from agricultural fields and landfills. Besides, surface runoff contributes to the detachment of the soil particles from their parent tilth, thereby causing loss of the vital productive soils (Peng & Wang, 2012). However, adopting appropriate soil tillage/cropping technologies could strategically minimize environmental degradation in SSA. One of the potential ways to reduce environmental degradation and contribute to the United Nations' Sustainable Development Goals (UN-SDGs) number 2, 6, 14, and 15, namely; zero hunger, clean water and sanitation, life below water, life on land, respectively, could be transforming the agricultural sector by switching from intensive tillage practices to conservation tillage practices that could promote soil, water, and ecosystem health.

Furthermore, over 95% of the cultivated crops in Uganda are rain-fed (Recha *et al.*, 2012; Sridharan *et al.*, 2019). With the increasing climate change impacts, the growing seasons are subjected to prolonged dry spells, sustained droughts, and low green water use efficiency (WUE-grain), resulting in moisture deficits (Mubiru *et al.*, 2018; Roudier *et al.*, 2011). To date, 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 crop productivity. Nonetheless, over 72% of Uganda's agriculture is carried out by subsistence farmers who cannot afford irrigation technologies and costs (Uganda Bureau of Statistic [UBOS], 2017). Therefore, more sustainable farming practices, approaches, and technologies that increase soil water availability, maintain balanced soil moisture, and optimize crop water use throughout the crop growing season are required (Kagoya *et al.*, 2018; Turinawe, 2019).

Besides, studies assessing soil hydrology are often field-based. But performing field-based experiments across all climates and management practices is excessively costly and time-demanding (Benli *et al.*, 2006). However, using computer simulation models such as Agricultural Policy/Environmental eXtender (APEX) could help explain complex data; predict spatial and temporal impacts of cropping/soil tillage systems on soil hydrology at a precisely lower cost. In East Africa and Uganda, there are limited studies relating soil tillage systems and soil hydrology in the cultivated fields. Additionally, studies comparing field-based hydrological data to computer-simulated data are lacking.

## 1.3 Significance of the Study

This study intended to inform soil-water conservation practices, reduce environmental degradation, and improve bean crop productivity in Uganda. The study addresses the following knowledge gaps:

The land and water management strategies that combine short-term techniques for climate variability (periodic floods and droughts) and long-term strategy for climate change are needed (Mukheibir, 2010). Liu *et al.* (2013) and Liu *et al.* (2016a) noted that optimizing soil tillage technologies could help conserve soil structures, soil biota, and soil moisture content while simultaneously conserving soil hydrological regime. This study reveals valuable information that can help to identify appropriate soil tillage technologies that optimize crop yield, soil productivity, and soil-water conservation.

Secondly, in East Africa, and Uganda in particular, dry spells and droughts are considerably reducing crop yields (Berhane *et al.*, 2013; Sabiiti *et al.*, 2018). Building resilience by bridging the dry spells that are increasingly occurring during the rainy seasons and decreasing vulnerability to climate change's adverse effects is inevitable. This study provides valuable information on soil-water management practices to the smallholder farmers: how to manage the inter-seasonal dry spells, improve SWS, and increase adaptability to the scarce water in this era of climate change.

Water is increasingly becoming scarce in SSA countries (Ashton & Turton, 2009). Building resilience by engaging in agricultural conservation techniques could help to increase yield per unit of water (Adhikari *et al.*, 2015), which would reduce the amount of water used in irrigation. This study comes in as a solution to this problem by comparing water use efficiencies under different soil tillage systems.

In SSA countries, documented studies on sediment yield (SY) from agricultural soils are very limited. Yet innovative cropping practices and technologies that reduce sedimentation while improving productivity can address water quality issues (Lefrançois *et al.*, 2007). This study provides essential information on SY from agriculture fields, which would be necessary for selecting appropriate soil tillage systems primarily for the farmers near water bodies.

Like most SSA countries, data on soil tillage technologies and their impacts on ecosystem services, particularly soil hydrology, are limited in Uganda. The deficiency of hydrological data associated with land-use systems, particularly crop production, widens the knowledge gap and consequently impedes the decision-making process towards selecting more appropriate soil-water conservation technologies and practices in the crop production sector.

Lastly, comparative assessment of field-based and APEX simulated data can provide answers to environmental problems such as water scarcity and areas where sedimentation is of primary importance in Uganda.

Henceforth, the current study seeks to assess the *“Effect of soil tillage systems on soil hydrology in common bean farms in Mukono District, Central Uganda”*. The proposed research was based on the recommendations of Connor *et al.* (2011), which identified the need for designing appropriate cropping technologies, which account for environmental sustainability, conservation of soil hydrological regimes while simultaneously optimizing crop productivity to ensure long-term sustainability.

## 1.4 Research Objectives

### 1.4.1 General Objective

The study's main objective was to assess the effect of soil tillage systems on soil hydrology in a plot-scale in an event-based period in Mukono District, Uganda.

### 1.4.2 Specific Objectives

The specific objectives of the study are to;

i) Assess the effect of soil tillage systems on surface runoff volume, infiltration, soil moisture content, soil water storage, and soil suspended particle concentration in arable land in Uganda,

ii) Determine the effect of soil tillage systems on grain yields, water use efficiency, and economic return of the common beans,

iii) and test the performance of the APEX Model in surface runoff volume and sediment yield simulation in Central Uganda.

## 1.5 Research Questions

The research questions of the study are;

i) Can the surface runoff volume, suspended sediment concentration, and sediment yield differ in the different soil tillage systems?

ii) Is there any significant difference in surface runoff volume collected from the plots tilled along the slope and that tilled perpendicular to the slope?

iii) Do soil tillage systems influence the infiltration rate, soil moisture content, and soil water storage?

iv) Does water use efficiency of the common bean crop depend on the soil tillage system/technology?

v) Do grain yields and economic returns of the common beans vary with soil tillage systems/technology?

vi) Does the APEX model's performance in the simulation of surface runoff volume or sediment yield depend on the soil tillage system/technology?

vii) Can the APEX model provide excellent or satisfactory results in simulation for surface runoff volume and sediment yield in central Uganda?

## 1.6 Delimitation of the Study

This study is quantitative in nature and focused on assessing the influence of selected soil tillage systems/technologies on soil hydrological processes in Mukono District of Uganda. The study was limited to SRV, IR, SMC, and SWS assessment in smallholder farms in Uganda. The study also evaluated the effect of soil tillage systems on SSC and SY. The study also assessed the effect of soil tillage systems on grain yield, WUE of grain yield, and economic returns for the common beans. Lastly, the study evaluated the ability of the APEX model in simulation of SRV and SY in central Uganda. The study was restricted to four major soil tillage systems (NT, stubble-mulching (SM), deep tillage (DT), and CT) in Goma and Kimenyedde Sub counties of Mukono District.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Definition of Terms

### 2.1.1 Soil Tillage Systems

Soil tillage can be defined as a method of "working" the soil either physically, chemically, mechanically or biologically to create suitable conditions for seedling germination, establishment and growth (Food and Agriculture Organization [FAO], 2011). Soil tillage systems make an ideal seedbed condition for plant emergence, developments and un-impeded root growth (Licht & Al-Kaisi, 2005). The soil tillage systems can be categorised based on their soil tillage depth, and the proportion of crop biomass residues left after seedbed preparation (Mrabet, 2002). Nevertheless, soil tillage systems are primarily classified into two major categories: conservation and CT, depending on the equipment used, tillage depth, and soil surface coverage.

### 2.1.2 Conservation Tillage

Conservation tillage systems are primarily based on reducing soil disturbance by restricting land preparation activities to a shallow depth and eliminating soil inversion while conserving and managing crop residues (Cunningham *et al.*, 2004). Conservation tillage practices include but not limited to zero tillage or NT, MT or reduced tillage (RT), mulch-tillage, ridge tillage, contour tillage, and subsoiling (Busari *et al.*, 2015; Wang *et al.*, 2003). Conservation tillage aims to leave at least 30% of the previous crop residues on the soil surface, whereas CT leaves less than 15% (Busari *et al.*, 2015; Uri, 1999).

#### (i) No-Tillage (NT)

The NT involves direct drilling of the land to open up the soil during sowing (Mrabet, 2002). In NT, no intensive tillage is done, and crop residues from the previous cropping season on the soil surface are required (Lal, 2004). The soil is only manipulated at the moment of planting when a groove is opened in the soil in order to deposit seeds and fertilizers (Busari *et al.*, 2015; Telles *et al.*, 2018). Under NT, herbicides are used to control weeds, and seed drills are used to open up the seedbed, and nearly 90 to 100% of the initial crop biomass is left uninterrupted during land preparation (Morell *et al*., 2010).

### (ii) Reduced Tillage (RT)

The RT involves a reduced level of soil manipulation during ploughing using primary tillage implements (Busari *et al.*, 2015). This tillage system involves a narrow soil exaction below 10 cm depth using a hand - hoe, oxen or disc plough leaving between 15 and 30% of the biomass residue as a soil cover (Zanin *et al*., 1997). The RT is mainly used during crop rotation operations (Zanin *et al*., 1997).

### (iii) Mulch Tillage

Mulch-tillage involves soil preparation or tillage so that the plant residues or other materials are left to cover the surface to a maximum extent (Busari *et al.*, 2015).

### (iv) Subsoiling

Subsoiling refers to the breaking up the dense soil layer using subsoiler without disturbing the soil (Miriti *et al.*, 2012; Qin *et al.*, 2008). The subsoiler breaks up compacted soil layers, loosens the soil and deepens the topsoil without inverting it (Huang *et al.*, 2006).

### (v) Ridge Tillage and Contour Tillage

Ridge tillage involves planting crops in rows either along both sides or on top of the ridges which are prepared at the commencement of the cropping season. When tillage is at right angles to the direction of the slope, it is referred to as contour tillage (Busari *et al.*, 2015).

## 2.1.3 Conventional Tillage

The CT typically involves inversion tillage, disturbs the soil to a depth of >20 cm, redistributes soil layers, and exposes subsurface horizons to oxidation (Shepherd *et al.,* 2001). It involves ploughing (soil inversion), followed by one or two harrowing events to produce a suitable layer for plant establishment and the removal of most of the plant residues derived from the previous cropping season. The CT system embraces primary cultivation practices based on ploughing or soil inversion and secondary operations directed at land preparation and sowing. The CT may include deep tillage (DT), mould-board plough (MP) etc.

Most farmers do not use a single system but instead find it convenient to use more than one soil tillage systems on their farms, depending on crop types, soil types, and seasons. The current technological developments have resulted in creating effective machines that can operate in different systems, making it simple for the farmers to combine ploughing and RT (Mrabet, 2002; Zanin *et al*., 1997).

## 2.2 Soil Tillage Systems and Infiltration Rate

Soil infiltration is a process by which water moves downwards through the soil surface into the soil (Dingman, 2008; Warrick, 2003). Several factors, including; vegetation, slope, rainfall regime, soil texture, soil structure, can influence the IR (Mishra *et al.*, 2003). In the current section, the effect of soil tillage systems in the IR was reviewed. Soil tillage systems considerably affect soil permeability (Badalíková, 2010), by changing the volume of pores, aggregate stability and soil structure, thus affecting the IR (Badalikova & Hrubý, 2006; Díaz-Zorita *et al.*, 2004). Table 1 presents data from literature regarding IR under different soil tillage systems.

In Ethiopia, Asmamaw *et al.* (2012) studied steady-state IR under two soil tillage systems: subsoiling and traditional tillage. The authors observed a 100% increase in IR under subsoiling (0.1 mm/min) than the traditional tillage system (0.05 mm/min). Misbah *et al.* (2019) also studied steady-state IR in maize (*Zea mays* L.) field under NT, DT, and CT for two years. The authors reported a reduction in IR by 17 and 5% under NT than CT in 2015 and 2016, respectively and reported the highest IR under DT for 2015 (3.7 mm/min) and 2016 (4.4 mm/min). In southwestern Nigeria, Busari and Salako (2012) observed a higher IR under CT (1.6 mm/min) and MT (1.9 mm/min) than NT (1.4 mm/min) at the end of the first year of their study (Table 1). At the end of the second year, NT (1.23 mm/min) had higher IR than CT (1.18 mm/min). The authors attributed the higher IR under CT than NT in the first year to the fast draining macro-pores created by CT; which reduced with time as a result of repackaging of soil aggregates (Martínez *et al.*, 2008).

In China, He *et al.* (2009) and Boukhari *et al.* (2015) studied steady-state IR under NT and MP for a period of 15 and 2 years, respectively. He *et al.* (2009) observed over 100% higher IR under NT (17.0 mm/min) compared with under MP (4.25 mm/min). On the other hand, Boukhari *et al.* (2015) reported a 59 and 16% higher IR under NT in 2007 and 2009, respectively, than under MP (Table 1). Similarly, in northern China, Wang *et al.* (2001) reported a 1.5-1.6 times higher steady-state IR under NT than under MP for three years. They simultaneously attributed the higher IR under NT to the residue retention.

In a review by Alvarez and Steinbach (2009) in Argentine, steady-state IR was significantly higher under NT and RT than under plow tillage (PT). In Ohio, U.S.A, Kahlon *et al.* (2013) studied steady-state IR under NT, ridge tillage, and PT for twenty-two years. The authors observed over 100% higher IR under NT than under PT. Although the tillage depth was the same (20 cm) for both PT and ridge tillage, 50-100% higher IR was observed under ridge tillage than under PT. The authors concluded that the multiple MP under PT disturbed the soil aggregate more than the single MP under ridge tillage, which lowered IR under PT. A similar study by Schwartz *et al.* (2010) in Washington State compared steady-state IR under NT and PT and reported a 69% lower IR under NT than under PT (Table 1).

Similarly, Celik and Ersahin (2011) in Turkey compared steady-state IR under NT, RT, and MP, all with crop residues shredding for three years. The authors observed 81 and 80% lower IR under NT (0.5 mm/min) and RT (0.6 mm/min) than under MP (2.9 mm/min). They concluded that NT is advantageous in increasing the IR only because of crop residue retention. Their argument was confirmed by Gangwar *et al.* (2006) in India who carried out a comparative study of steady-state IR under NT, RT, and CT (all with 5 Mg ha$^{-1}$ of mulches) for three years. The authors observed a 53 and 34% lower IR under NT (0.15 mm/min) and RT (0.21 mm/min), respectively, compared with CT (0.32 mm/min). Similar observations were reported by Lhomme and Katerji (1991) in Poland and Kahlon *et al.* (2013) in Ohio, where IR was highly influenced by crop residues and mulches than soil tillage systems. Kahlon *et al.* (2013) reported that IR increased from 0.5 to 0.8, 0.4 to 0.6, and 0.2 to 0.4 under NT, ridge tillage, and PT, respectively, with an increase in mulch rate from 0 to 16 Mg ha$^{-1}$. Blanco-Canqui *et al.* (2017) and Basche and DeLonge (2019) also noted that IR in the soil tillage systems is largely influenced by residue management. Besides, the effect of soil tillage systems on IR is site-specific (Stone & Schlegel, 2010). Nevertheless, limited studies on IR and soil tillage systems have been conducted in Africa and East Africa, in particular. A targeted effort to understand IR under East African soils is necessary to accurately understand their runoff capacity, SWS, among other factors.

**Table 1:** Effect of Soil Tillage Systems on the Steady-state Infiltration Rate

| *Soil tillage system* | *Tillage depth (cm)* | *Crop residue/mulch application* | *Steady-state IR (mm/min)* | *Impact on IR* | *% increase /decrease compared to CT* | *Country: Reference* |
|---|---|---|---|---|---|---|
| Subsoiling | * | * | 0.1 | + | 100% | Ethiopia: Asmamaw *et al.* (2012) |
| Traditional tillage | * | * | 0.05 | | | |
| NT | 0 | * | 1.9 (2015); 1.9 (2016) | - | 17% (2015); 5% (2016) | Ethiopia: Misbah *et al.* (2019) |
| DT | 60 | * | 3.7 (2015); 4.4 (2016) | + | 61% (2015); over 100% (2016) | |
| CT | 15 | * | 2.3(2015); 2.0 (2016) | | | |
| NT | 0 | * | 1.4 (2008); 1.23 (2009) | -(2008); +(2009) | -13% (2008); + 4% (2009) | Nigeria: Busari and Salako (2012) |
| MP | * | * | 1.9 (2008); 1.30 (2009) | + | 19% (2008); 10% (2009) | |
| CT | * | * | 1.6 (2008); 1.18 (2009) | | | |
| Continuous NT | 0 | Crop residues shredding | 1.4 (Nkhotakota); 0.8 (Dowa) | + | Over 100% | Malawi: TerAvest *et al.* (2015) |
| Conservation agriculture rotation | 0 | Crop residues shredding | 0.9 (Nkhotakota); 0.5 (Dowa) | + | 80% (Nkhotakota); 25% (Dowa) | |
| CT rotation | 30 | Crop residues removed | 0.5 (Nkhotakota); 0.4 (Dowa) | | | |
| NT-mulching | 0 | * | 12.3(2007);14.4 (2009) | + | 59% (2007); 16% (2009) | China: Boukhari *et al.* (2015) |
| MP | | * | 7.7 (2007); 12.5 (2009) | | | |
| NT-mulching | 0 | * | * | + | * | Argentine: Alvarez and Steinbach (2009) |
| RT | * | * | * | + | * | |
| PT | * | * | * | | | |
| NT-mulching | 0 | Mulch treatments (0 to 8 to 16 Mg ha$^{-1}$) | 0.5; 0.7; 0.8 | + | Over 100% | Ohio, U.S.A: Kahlon *et al.* (2013) |
| Ridge tillage-single MP | 20 | Mulch treatments (0 to 8 to 16 Mg ha$^{-1}$) | 0.4; 0.5; 0.6 | + | 100; 67; 50% | |
| PT-multiple MP | 20 | Mulch treatments (0 to 8 to 16 Mg ha$^{-1}$) | 0.2; 0.3; 0.4 | | | |
| NT | 0 | Residue retention | 17.0 | + | Over 100% | China: He *et al.* (2009) |
| MP | 30 | Residue removal | 4.25 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| NT | 0 | Mulch treatments (5 Mg ha$^{-1}$) | 0.15 | - | 53% | India: Gangwar *et al.* (2006) |
| RT | * | Mulch treatments (5 Mg ha$^{-1}$) | 0.21 | - | 34% | |
| CT | * | Mulch treatments (5 Mg ha$^{-1}$) | 0.32 | | | |
| NT | 0 | * | 1.1 | - | 61% | Poland: Lhomme and Katerji (1991) |
| CT | 20 | * | 2.8 | | | |
| NT | 0 | * | * | - | 69% | Washington state, USA: Schwartz *et al.* (2010) |
| PT | * | * | * | | | |
| NT | 0 | Crop residues shredding | 0.5 | - | 81% | Turkey: Celik and Ersahin (2011) |
| RT | * | Crop residues shredding | 0.6 | - | 81% | |
| MP | * | Crop residues shredding | 2.9 | | | |

+ and - represents an increase and decrease in the steady-state IR, respectively. * indicates that no data was provided. NT is for no-tillage; MP is for mould-board ploughing; CT is for conventional tillage; RT is for reduced tillage; PT is for plow tillage

## 2.3 Soil Tillage Systems, Soil Water Storage, and Soil Moisture Content

Soil tillage systems can significantly influence soil water dynamics (SMC and SWS). Varying results have been reported regarding the effect of soil tillage systems on soil water dynamics (Table 2). Blanco-Canqui *et al.* (2017) studied the influence of three soil tillage systems: NT-crop residues, disk plow, and MP on SMC for thirty-five years. The authors observed a 6 and 12% higher SMC under NT (1.35 mm) than MP (1.27 mm). They concluded that the ability of the soil to retain water depends on the level of soil disturbances. In the USA, Filho *et al.* (2013) compared the effect of NT, RT, and CT on SWS over forty-six years. The authors reported an increase in SWS with a reduction in soil disturbances: 10 and 6%; 7 and 6% higher SWS were recorded in the NT and RT at 0-5 and 5-10 cm depth, respectively, compared with CT. Similarly, Su *et al.* (2007) in China studied SWS (0-200 cm depth) under NT with mulching, RT without mulching, subsoiling with mulching, and CT without mulching for seven years (Table 2). The authors observed a 17 and 16% higher SWS under NT with mulching (176 mm) and subsoiling with mulching (175 mm), and a 8% lower SWS under RT without mulching (139 mm) relative to CT without mulching (151 mm). They concluded that the ability of the soil to retain soil water primarily depends on residue and mulching management than on the soil disturbances.

Martínez *et al.* (2011) in central Chile studied SMC under NT with mulching, NT with contour plowing, NT with barrier hedge, NT with subsoiling, and CT. They observed 33 and 5% higher SMC under NT with mulching, NT with contour plowing and 15 and 35% lower SMC under NT with barrier hedge, and NT with subsoiling, respectively, compared with CT. In a review by Wang *et al.* (2007) in China, 3-50% higher available soil water was observed under conservation tillage than under CT systems. In the Pampas region of Argentina, Alvarez and Steinbach (2009) observed 13-14% more SWS under NT than under tilled plots. Kahlon and Chawla (2017) also reported maximum volumetric soil moisture under NT systems with residue, followed by NT without residue, CT, and DT. The authors also observed that volumetric soil moisture decreased with an increase in soil disturbance through frequent tilling.

Schwartz *et al.* (2010) studied the effect of soil tillage practices on SWS in a semiarid environment. They found that CT significantly decreased SWS about a depth of 30 cm than NT in a dry period. They concluded that the presence of crop residues and mulches on the soil surface moderated the soil evaporation and improved the physical properties of the soil; there by increasing water retention. On the other hand, CT forms a seal on topsoil with the first rainfall, thereby reducing water infiltration (Munodawafa & Zhou, 2008).

**Table 2:** Effect of Soil Tillage Systems on Soil Water Storage and Soil Moisture Content

| *Soil tillage system* | *Tillage depth (cm)* | *Sampling depth (cm)* | *Amount of SWS/SMC* | *Units* | *Impact on SWS[1]/SMC[2]* | *% change with respect to CT* | *Country* | *Reference* |
|---|---|---|---|---|---|---|---|---|
| NT- crop residues shredding | 0 | 0-20 | 0.22(Nkhotakota); 0.22 (Dowa) | m$^3$ m$^{-3}$ | ↑ | 38% (Nkhotakota)<br>16% (Dowa) | Malawi | TerAvest *et al.* (2015)[2] |
| Conservation agriculture - crop residues | 0 | | 0.21(Nkhotakota);0.22 (Dowa) | | ↑ | 32% (Nkhotakota)<br>16% (Dowa) | | |
| CT rotation- crop residues removed | 30 | | 0.16(Nkhotakota);0.19 (Dowa) | | | | | |
| NT-crop residues | 0 | 0-30 | 1.35 | Mm | ↑ | 6% | United Kingdom | Blanco-Canqui *et al.* (2017)[2] |
| MP | * | | 1.27 | | | | | |
| NT | 0 | 0-5; 5-10 | 0.33; 0.37 | Mm | ↑ | 10; 6% | USA | Filho *et al.* (2013)[1] |
| RT | * | | 0.32; 0.37 | | ↑ | 7; 6% | | |
| CT | * | | 0.30; 0.35 | | | | | |
| NT-mulching | 0 | 0-200 | 176 | Mm | ↑ | 17% | China | Su *et al.* (2007)[1] |
| RT | 20 | | 139 | | ↓ | 8% | | |
| Subsoiling-mulching | * | | 175 | | ↑ | 16% | | |
| CT | 20 | | 151 | | | | | |
| NT –mulching | 0 | 10-30 | 32.30 | % | ↑ | 33% | Central Chile | Martínez *et al.* (2011)[2] |
| NT + contour plowing | * | | 25.40 | | ↑ | 5% | | |
| NT + barrier hedge | * | * | 20.65 | | ↓ | 15% | | |
| NT + subsoiling | 40 | | 15.83 | | ↓ | 35% | | |
| CT | * | | 24.28 | | | | | |
| NT | * | | * | * | ↑ | 3-50% | China | Wang *et al.* (2007)[1] |
| CT | * | | * | | | | | |
| NT | * | | * | * | ↑ | 13-14% | Argentina | Alvarez and Steinbach (2009)[1] |
| Tilled plots | * | | * | | | | | |
| NT-mulching (5 Mg ha$^{-1}$) | 0 | * | 25.3 | % | ↑ | 8% | India | Gangwar *et al.* (2006)[2] |
| RT -mulching (5 Mg ha$^{-1}$) | * | | 25.1 | | ↑ | 7% | | |
| CT -mulching (5 Mg ha$^{-1}$) | * | | 23.5 | | | | | |
| NT | 0 | | 87 | Mm | ↑ | 24% | Agramunt, Spain | Lampurlanés *et al.* (2016)[1] |
| Subsoiling | 50 | | 82 | | ↑ | 17% | | |
| Chisel | 20 | | 84 | | ↑ | 20% | | |
| MP | 30-35 | | 70 | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| NT | 0 | 104 | ↑ | 8% | Selvanera, |
| MT | 10-15 | 99 | ↑ | 3% | Spain |
| Subsoiling-25 | 25 | 97 | | | |
| Subsoiling-50 | 50 | 96 | | | |
| NT | 0 | 84 | ↑ | 1% | El-Canós, |
| MT | 10-15 | 83 | ↑ | 1% | Spain |
| Subsoiling-50 | 50 | 83 | | | |

↑ and ↓ represents an increase and decrease in the soil water storage/soil moisture content over time. * indicates that no data was provided. 1 and 2 represent soil water storage and soil moisture content, respectively. NT is for no-tillage; MP is for mould-board ploughing; CT is for conventional tillage; RT is for reduced tillage; MT is for minimum tillage

## 2.4 Surface Runoff

Surface runoff, also known as overland flow, is a two-dimensional flow of water over the ground surface (Guo *et al.*, 2019). Runoff generation is widely based on two primary forms: (i) the infiltration excess runoff and (ii) the saturation excess runoff (Rumynin, 2015). The infiltration excess runoff occurs when rainfall intensity exceeds the local infiltration capacity of the soil for a sufficient period (Horton, 1940), while saturation excess runoff occurs when the land surface is highly permeable, and precipitation is always less than the infiltration capacity (Dunne, 1978).

Several meteorological factors (i.e. rainfall intensity, amount, duration, distribution, antecedent precipitation, evapotranspiration, temperature, wind, relative humidity); and physical characteristics (i.e. land-use, soil type, drainage area, elevation, topography, drainage network patterns etc.) can significantly influence surface runoff generation (Akinbile, 2010; Akinbile *et al.*, 2016; Bhatt & Khera, 2006). However, in this section, the effect of soil tillage systems on SRV was reviewed.

### 2.4.1 Variation of Surface Runoff under Different Soil Tillage Systems

Table 3 presents pieces of literature comparing surface runoff from conservation tillage practices and CT practices. Averaged across studies, surface runoff was higher under CT systems than conservation tillage systems. However, in different crop and soil types, the surface runoff exhibited various responses to tillage systems (Table 3).

Yu *et al.* (2000), Meyer *et al.* (1999), and Tebrügge and Düring (1999) compared surface runoff under conservation and CT systems in various agro-ecosystems. Yu *et al.* (2000) observed a 14 and 73% reduction in SRV under conservation tillage of subsoiling (8 ± 1 mm/event) and NT (3 ± 0 mm/event), respectively, compared with CT of MP (9 ± 1 mm/event). Similarly, Meyer et al. (1999) observed an 11% reduction in SRV under NT than CT with chiseling in a soybean field under loamy soil.

Tebrügge and Düring (1999) performed their experiment under simulated rainfall (1 h, 63 mm) in a wheat field under loamy soil. They compared SRV from NT and MP. The authors observed a 39% reduction in SRV under NT compared with MP. A similar study was conducted by

Armand (2004) in a maize agroecosystem under loamy soil for two years. The author observed SRV of 2.12 ± 1.3 mm/event under MP and 0.26 ± 0.3 mm/event under NT. Therefore, an 88% reduction in SRV under NT compared with MP was observed. Quinton and Catt (2004) also assessed SRV under NT and MP, in a winter crop field, under sandy soil on a large scale (875 $m^2$) for ten years. The authors observed a 24% reduction in SRV under NT (62 ± 31 mm/year) compared to MP (82 ± 23 mm/year). Shipitalo *et al.* (2000) compared SRV from MP and NT systems in a maize field with loamy soil under natural rainfall for four years on a large scale. In their study, they observed 99% SRV reduction under NT (2 ± 3 mm/year) compared with MP (178 ± 93 mm/year) (Table 3).

Wuest *et al.* (2008) studied the effect of NT and inversion (tilled) systems on SRV for four years in a winter wheat field. Their observations showed higher SRV under the inversion plots (0.05 inches/year) than under NT plots (< 0.01 inches/year). In Henan province, China, Yao *et al.* (2004) studied SRV in three conservation tillage systems, i.e., NT, RT, and subsoiling. The authors' observations showed almost no runoff (100% reduction in runoff) under the NT system, while RT and subsoiling systems reduced runoff by up to 54 and 90%, respectively. Furthermore, Sun *et al.* (2015) indicated that the NT system effectively controlled runoff under plots with crop residue retention, while slightly higher runoff was recorded under the NT plots, without crop residues.

On the contrary, some studies reported an increase in SRV under conservation tillage systems than CT systems. For example, Kwaad *et al.* (1998) assessed SRV under NT and CT (i.e. mulch-spring plough) in a maize field under loamy soil for two years. The authors observed a 35% increase in SRV under NT (16 ± 5 mm) than under CT (10 ± 7 mm). They concluded that crop residues under CT could have led to the lower runoff in these plots. Wilson *et al.* (2004) performed their experiment under simulated rainfall (1 h, 65 mm) in areas of 40 $m^2$ in a maize field under loamy soil. They observed a 6 and 19% increase in SRV under NT with residue and NT without residues, respectively, compared with CT (chiseling) with residues (Table 3). Based on the current review, the magnitude of surface runoff under soil tillage systems is mainly influenced by soil covering. The ability of conservation tillage practices to reduce SRV can be attributed to surface crop residue retention that improves soil properties (Armand *et al.*, 2009; Kurothe *et al.*, 2014; Leys *et al.*, 2010; Mchunu *et al.*, 2011).

Although studies have been conducted to assess the effect of soil tillage systems on SRV, such studies are lacking in East Africa, yet the magnitude of surface runoff is always site-specific depending on several meteorological and environmental factors.

**Table 3:** Observed Surface Runoff in Conventional and Conservation Tillage Systems

| *Soil tillage system* | *Crop* | *Soil type* | *Rainfall type* | *No. of years* | *Runoff volume* | *Runoff generation compared with CT (%)* | *Reference* |
|---|---|---|---|---|---|---|---|
| MP (CT) | Winter crops | Sandy | Natural | 10 | 82 ± 23 mm/year | | Quinton and Catt (2004) |
| Shallow tillage | Winter crops | Sandy | Natural | 10 | 62 ± 31 mm/year | -24 | |
| Mulch-spring plough (CT) | Maize | Loamy | Natural | 2 | 10 ± 7 mm | | |
| NT on winter wheat | Maize | Loamy | Natural | 2 | 13 ± 13 mm | +35 | |
| Winter plough: NT | Maize | Loamy | Natural | 2 | 16 ± 14 mm | +7 | Kwaad *et al*. (1998) |
| Chiseling (CT) | Soybean | Loamy | Natural | 6 | 256 mm/year | | Meyer *et al*. (1999) |
| NT | Soybean | Loamy | Natural | 6 | 202 mm/year | -11 | |
| MP (CT) | Maize | Loamy | Natural | 2 | 2 ± 1 mm/event | | Armand (2004) |
| NT | Maize | Loamy | Natural | 2 | 0.26 ± 0.3 mm/event | -88 | |
| MP (CT) | Roselle | Silty sand | Natural | 3 | 9 ± 1 mm/event | | |
| Subsoiling | Roselle | Silty sand | Natural | 3 | 8 ± 1 mm/event | -14 | Yu *et al*. (2000) |
| NT | Roselle | Silty sand | Natural | 3 | 3 ± 0.4 mm/event | -73 | |
| MP (CT) | Wheat | Loamy | Simulated (1 h, 63 mm) | No data | 39 mm | | Tebrügge and Düring (1999) |
| NT | Wheat | Loamy | Simulated (1 h, 63 mm) | No data | 24 mm | -39 | |
| Chiseling (CT) | Maize | Loamy | Simulated (1 h, 65 mm) | No data | 53 mm/h (max) | | Wilson *et al*. (2004) |
| NT | Maize | Loamy | Simulated (1 h, 65 mm) | No data | 56 mm/h (max) | +6 | |
| NT without residues | Maize | Loamy | Simulated (1 h, 65 mm) | No data | 63 mm/h (max) | +19 | |

NT is for no-tillage; MP is for mould-board ploughing; CT is for conventional tillage

## 2.5 Comparison of Suspended Sediment Concentration/Sediment Yields in Agricultural Fields and other Land-use Systems

Several studies have reported the impact of crop production on SSC and SY (Lamba *et al.*, 2015; Russell *et al.*, 2001; Steegen *et al.*, 2000; Wu *et al.*, 2004). Most of the comparative studies (on crop production with other land-use systems) single out crop production as a significant source of SY relative to other land-use systems (Mahmoudzadeh *et al.*, 2002). For example, Lamba *et al.* (2015) compared SY from cropland, stream banks, and woodland in four sites. Across sites, they reported crop production as an important source of SY with contributions of between 15 to 100%, while stream banks and woodland had contributions of between 0 to 85 and 0 to 57%, respectively. In a study by Kroese *et al.* (2020) in Kenya, agricultural land was estimated to contribute 80 Mg km$^{-2}$ year$^{-1}$ of SY, while channel banks, tracks, and gullies were estimated to contribute 22 Mg km$^{-2}$ year$^{-1}$, 3 Mg km$^{-2}$ year$^{-1}$, and 1 Mg km$^{-2}$ year$^{-1}$, respectively. In Australia, Mahmoudzadeh *et al.* (2002) reported SY of 0.8 Mg ha$^{-1}$yr$^{-1}$ (range: 0.2-1.5; n = 3) under forests, 2.2 Mg ha$^{-1}$yr$^{-1}$ (range: 1.6-3.6; n = 6) under pasture, and 3.1 Mg ha$^{-1}$yr$^{-1}$ (range 2.7-3.5; n = 3) under crop lands. They concluded that the high SY under croplands was mainly due to the disturbances in the soil aggregates.

A study by Dagnew *et al.* (2017) in Ethiopia on SSC under croplands and grasslands showed that croplands (range 3.1 to 4.3 g L$^{-1}$) produced higher SSC than grass lands (range 2.3 to 3.7 g L$^{-1}$). In a similar study in China, Kang *et al.* (2001) compared SY under bare soil, croplands, and grasslands for three years. The authors observed a 33% reduction in SY under grasslands (1513.8 kg/m$^2$ × 10$^{-5}$) compared to croplands (2265.8 kg/m$^2$ × 10$^{-5}$). On the other hand, the bare soil produced the highest SY of 5279.2 kg/m$^2$ × 10$^{-5}$. They concluded that leaving the soil open increases soil loss which amplifies SY.

## 2.6 Effect of Soil tillage Systems on Suspended Sediment Concentration and Sediment Yield

Very few studies have been conducted to assess the effect of management practices such as fertilizer application, soil tillage systems, and irrigation on SSC and SY. Studies evaluating the effect of soil tillage systems on SSC and SY (Table 4) suggest the potential of conservation tillage in reducing SY. For example, in England, Pulley and Collins (2020) studied SY before and after ploughing for over five years. They observed 5.4 times more SY after ploughing (3.13 Mg ha$^{-1}$ yr$^{-1}$) than the post-ploughing period (0.58 Mg ha$^{-1}$ yr$^{-1}$). In a fifteen-year study by Owens *et al.* (2002) in North America, comparing different conservation tillage systems, sediment loss of 532, 828, and 1152 kg ha$^{-1}$ yr$^{-1}$ were observed under the NT system, chisel-plow, and disk plow, respectively. Bagagiolo *et al.* (2018) in Italy compared SSC under NT with mulching and CT system, and observed 2.2-3.6 times more SSC under the CT (5.74 g L$^{-1}$ at Vezzolano site; 9.51 g L$^{-1}$ at Cannona site) than under NT (2.59 g L$^{-1}$ at Vezzolano site; 2.62 g L$^{-1}$ at Cannona site). Several other studies, e.g. Fawcett *et al.* (1994), Wauchope (1978), and Tiessen *et al.* (2010), reported a 44 to 90% reduction in SY under conservation tillage practices relative to CT practices. They concluded that the decline in sediment losses under conservation tillage practices is attributable to the increased residue on the soil surface, which is responsible for the decreased erosion (Tiessen *et al.*, 2010).

On the contrary, in Minnesota, USA, Hansen *et al.* (2000) studied SSC under three soil tillage systems (i.e. ridge-till, chisel, and MP). They observed 1.8 and 3.6 times higher SSC under ridge-till (0.15 mg ha$^{-1}$) and chisel (0.29 mg ha$^{-1}$), respectively, compared with MP (0.08 mg ha$^{-1}$). In Ethiopia, Misbah *et al.* (2019) compared SSC under NT, CT, and DT in a maize field for two years. They reported 1.6 and 1.3 times higher SSC under DT in 2015 and 2016, respectively, compared with NT and CT combined (Table 4).

Generally, agriculture and crop production increase sediments and nutrients in streams, causing eutrophication and sedimentation of streams (Adela & Behn, 2015). The magnitude of SY from agriculture depends on the soil type, agronomic practices such as soil tillage and fertilizer application. Nevertheless, studies that assess SSC, SY or loads from agriculture and the associated management practices are lacking in Africa and East Africa in particular. But to reduce water body and reservoir pollution and eutrophication in Africa, quantification of SY from crop production is essential.

**Table 4:** Suspended Sediment Concentration and Sediment Yield from Different Land-use Systems and Soil Tillage Systems

| *Land-use systems* | *Amount of SSC$^{1}$, SY$^{2}$ or % contribution of the land use system to suspended sediment$^{3}$* | *Country* | *Reference* |
|---|---|---|---|
| Cropland; stream banks; woodland | 15 to 100; 0 to 85; 0 to 57% | **USA** | Lamba *et al.* (2015)$^{3}$ |
| Agricultural land; channel banks; tracks; gullies | 80; 22; 3; 1 Mg km$^{-2}$ year$^{-1}$ | **Kenya** | Kroese *et al.* (2020)$^{2}$ |
| Crop land; forest; pasture | 3.1; 2.2; 0.8 Mg ha$^{-1}$year$^{-1}$ | **Australia** | Mahmoudzadeh *et al.* (2002)$^{2}$ |
| Cropland and grassland | 3.1 to 4.3 and 2.3 to 3.7 g L$^{-1}$ | **Ethiopia** | Dagnew *et al.* (2017)$^{1}$ |
| Bare soil; cropland; grassland | 5279.2; 2265.8; 1513.8 kg/m$^{2}$ × 10$^{-5}$ | **China** | Kang *et al.* (2001)$^{2}$ |

| *Soil tillage system* | *Amount of SSC$^{1}$/SY$^{2}$* | *Unit* | *Impact SSC/SY* | *Number of times* | *Country* | *Reference* |
|---|---|---|---|---|---|---|
| Ridge tillage | 0.15 | Mg ha$^{-1}$ | ↑ | 1.8 | **Minnesota, USA** | Hansen *et al.* (2000)$^{1}$ |
| Chisel plow | 0.29 | | ↑ | 3.6 | | |
| MP | 0.08 | | | | | |
| NT + CT | 0.51 (2015); 1.2 (2016) | g L$^{-1}$ | ↑ | 1.6-1.3 | **Ethiopia** | Misbah *et al.* (2019)$^{1}$ |
| DT | 0.81 (2015); 1.5 (2016) | | | | | |
| Post-plough | 0.58 | Mg ha$^{-1}$ yr$^{-1}$ | ↓ | 5.4 | **England** | Pulley and Collins (2020)$^{2}$ |
| After ploughing | 3.13 | | | | | |
| NT (no soil disturbance) | 532 | Kg ha$^{-1}$ yr$^{-1}$ | ↓ | 2.2 | **North America** | Owens *et al.* (2002)$^{2}$ |
| Chisel plow (minimal soil disturbance) | 828 | | ↓ | 1.4 | | |
| Disk plow (minimal soil disturbance) | 1152 | | | | | |
| NT-mulching | 2.59 (Vezzolano); 2.62 (Cannona) | g L$^{-1}$ | ↓ | 2.2-3.6 | **Italy** | Bagagiolo *et al.* (2018)$^{1}$ |
| CT | 5.74 (Vezzolano); 9.51 (Cannona) | | | | | |
| NT | 25.3 | Mg L$^{-1}$ | ↓ | 4 | **Canada** | Tiessen *et al.* (2010)$^{2}$ |
| CT | 100.4 | | | | | |
| NT | * | Mg L$^{-1}$ | ↓ | 4 | **United States** | Truman *et al.* (2005)$^{2}$ |
| CT | * | | | | | |

SSC is for suspended sediment concentration; SY is for sediment yield. ↑ and ↓ indicate an increase and decrease in either SSC or SY with respect to CT/tilled plots. 1 and 2 represent SSC and SY, respectively

## 2.7 Effect of Soil Tillage Systems on Crop Yields and Water Use Efficiency

Varying results have been reported regarding the effect of soil tillage systems on grain yields and WUE (Table 5). While some studied report a positive effect of conservation tillage systems on grain yields (Gangwar *et al.*, 2006; Hosseini *et al.*, 2016) and WUE (Miriti *et al.*, 2012; Su *et al.*, 2007), others report a negative effect (Misbah *et al.*, 2019; Sun *et al.*, 2018).

For example, in Kenya, Miriti *et al.* (2012) studied the effect of tied-ridge, subsoiling-ripping, and conventional-ox-plough on cowpeas grain yields for four years. They observed a 9% increase in cowpeas grain yields under tied-ridge (0.60 Mg $ha^{-1}$) and a 15% reduction in cowpeas grain yields under subsoiling-ripping (0.47 Mg $ha^{-1}$) compared with conventional-ox-plough (0.55 Mg $ha^{-1}$). In the same study, WUE increased by 32 and 5% under tied-ridge (0.54 kg $m^{-3}$) and subsoiling-ripping (0.43 kg $m^{-3}$), respectively relative to conventional-ox-plough (0.41 kg $m^{-3}$).

Hosseini *et al.* (2016) compared soybean grain yields under two conservation tillage practices (i.e. no-till row crop seeding and no-till seed drilling) with CT practices (tillage-disc harrow and tillage-chisel packer) for one year in Iran. The authors observed that the conservation tillage practices increased soybean grain yields by 16-25% compared with CT (tillage-chisel packer). They attributed the higher yield under NT to the improved soil structure and surface residue retention; which enhance root growth and reduce soil water losses.

Gangwar *et al.* (2006) in India studied wheat grain yields under NT, RT, and CT for four years. At the end of the four years, they observed a 11 and 3% increase in the wheat grain yields under NT (5.10 Mg $ha^{-1}$) and RT (4.75 Mg $ha^{-1}$) compared with the CT (4.60 Mg $ha^{-1}$) (Table 5). The authors concluded that retaining crop residues cover could significantly increase wheat grain yields over a long term-scale by increasing water stable aggregates and porosity; which enhance crop growth and contribute to the higher yield. In China and the USA, Su *et al.* (2007) and Lenssen *et al.* (2007) reported a 13-15% increase in the wheat grain yields under not compared to CT. In the same studies, 3-8% higher WUE was observed under NT relative to CT.

In Malawi, TerAvest *et al.* (2015) compared maize grain yields and WUE under NT, conservation agriculture, and CT for one year. The authors observed a 24% reduction in maize grain yields under NT (3.87 Mg ha$^{-1}$) and an 11% increase in maize grain yields under conservation agriculture (5.65 Mg ha$^{-1}$) compared with CT (5.11 Mg ha$^{-1}$). In the same study, the WUE followed a similar trend with the highest WUE was observed under conservation agriculture (6.0 kg mm$^{-1}$), then CT (5.4 kg mm$^{-1}$), and NT (4.1 kg mm$^{-1}$). Similar studies by Sun *et al.* (2018) and Misbah *et al.* (2019) reported lower grain yields of wheat and maize, respectively, under NT than under the CT system. Sun *et al.* (2018) also observed a 10% lower WUE under NT than CT for over seven years.

## **Table 5:** Effect of Soil Tillage Systems on Grain Yields and Water Use Efficiency

| ***Soil tillage system*** | ***Crop*** | ***Fertilizer kg ha$^{-1}$*** | ***Years*** | ***GY Mg ha$^{-1}$*** | ***% change in GY with respect to CT*** | ***WUE*** | ***Units*** | ***% change in WUE with respect to CT*** | ***County & Reference*** |
|---|---|---|---|---|---|---|---|---|---|
| NT row crop seeding | Soybean | N = 25<br>P = 25<br>K = 50 | 1 | 3.84 | +25 | * | * | * | Iran: Hosseini *et al.* (2016) |
| NT seed drilling | | | | 3.57 | +16 | * | * | * | |
| Tillage-disc harrow and drill planting | | | | 3.14 | +2 | * | * | * | |
| Tillage-chisel packer and drill planting | | | | 3.08 | | * | * | * | |
| Tied-ridge | Cowpeas | $P_2O_5$ = 40 | 4 | 0.60 | +9 | 0.54 | kg m$^{-3}$ | +32 | Kenya: Miriti *et al.* (2012) |
| Subsoiling-ripping | | N = 20 | | 0.47 | -15 | 0.43 | | +5 | |
| Conventional-ox-plough | | | | 0.55 | | 0.41 | | | |
| NT | Wheat | * | 4 | 5.10 | +11 | * | * | * | India: Gangwar *et al.* (2006) |
| RT | | | | 4.75 | +3 | * | * | * | |
| CT | | | | 4.60 | | * | * | * | |
| NT | Maize | N = 34 | 1 | 3.87 | -24 | 4.1 | kg mm$^{-1}$ | -24 | Malawi: TerAvest *et al.* (2015) |
| Conservation agriculture | | P = 31 | | 5.65 | +11 | 6.0 | | +11 | |
| CT | | | | 5.11 | | 5.4 | | | |
| NT-mulching | Winter wheat | N = 150 | 6 | 4.679 | +13 | 1.216 | kg m$^{-3}$ | +8 | China: Su *et al.* (2007) |
| RT | | $P_2O_5$ =105 | | 3.937 | -4.6 | 1.110 | | -2 | |
| Subsoiling-mulching | | $K_2O$ = 45 | | 4.892 | +19 | 1.280 | | +13 | |
| CT | | | | 4.125 | | 1.130 | | | |
| NT | Wheat | N = 118 | 4 | 0.79 | +15 | 5.38 | kg ha$^{-1}$ mm$^{-1}$ | +3 | USA: Lenssen *et al.* (2007) |
| CT | | | | 0.69 | | 5.25 | | | |
| NT | Cowpeas | | | 0.74 | +12 | 9.9 | | +48 | |
| CT | | | | 0.66 | | 6.7 | | | |
| NT | Lentil | | | 0.13 | -54 | 0.9 | | -31 | |
| CT | | | | 0.28 | | 1.3 | | | |
| NT | Chickpea | | | 0.41 | +64 | 2.4 | | +60 | |
| CT | | | | 0.25 | | 1.5 | | | |
| NT | Wheat | N = 150 | 7 | 3.42 | -24 | 9.9 | | -11 | China: Sun *et al.* (2018) |
| Subsoiling | | $P_2O_5$ = 38 | | 4.30 | -4 | 11.0 | | -1 | |
| DT | | $K_2O$ = 75 | | 4.47 | | 11.1 | | | |
| NT | Maize | DAP = 200 | 2 | 3.10 | -22 | * | * | * | Ethiopia: Misbah *et al.* (2019) |
| DT | | Urea = 200 | | 4.35 | +10 | * | | * | |
| CT | | | | 3.95 | | * | | * | |

*Indicates no data provided

## 2.8 Effect of Soil Tillage Systems on Economic Returns

The decision to undertake any soil tillage technology is determined by several factors; among them is the profitability of production. Varying results have been reported regarding the effect of soil tillage systems on production cost and net/economic returns (Table 6). Most experiments, which compare production cost in soil tillage systems, have given inconsistent results. Some studies showed that CT and inversion tillage practices have higher production cost and lower net profit returns than conservation tillage practices (Gangwar *et al.*, 2006; Su *et al.*, 2007), while others have shown conflicting results (Panasiewicz *et al.*, 2020).

For example, in Poland, Panasiewicz *et al.* (2020) compared the profitability of production under RT and NT with CT in wheat fields for four years. The authors reported 7 and 15% lower production cost under RT and NT, respectively, compared to CT. The net profit was 17 and 34% lower under RT and NT, respectively, relative to CT. The authors attributed the lower net profit under RT and NT to the lower yields compared to CT. In a 3 year study by Gangwar *et al.* (2006) on the profitability of production under RT, NT, and CT in a wheat field in India, 8 and 22% less production cost was reported under RT and NT, respectively, relative to CT. A 5 and 8% higher net profit under RT and NT, respectively, compared to CT, was reported. The authors concluded that the lower production cost under RT and NT was due to the machinery used in these two systems that required less labour and fuel.

In China, Su *et al.* (2007) studied the profitability of production in a wheat field under four tillage systems, i.e. RT, subsoil tillage with mulching (ST), NT, and CT. The authors reported 10, 28, and 48% lower production cost under RT, ST, and NT than under CT. Similarly, net profit increased by 4, 90, and 108% under RT, ST, and NT, compared with CT. The authors attributed these variations to the significantly higher yields and lower costs of labor and machinery under ST and NT than CT. Al-Kaisi and Yin (2004) studied the profitability of corn-soybean rotation under NT and CT at different locations (Nashua and Sutherland) in the USA. The authors reported \$39 ha$^{-1}$ (27%) greater economic return under NT than CT at Nashua. At Sutherland, no significant difference in economic return was observed between NT and CT.

In a 3 year study by Sharma *et al.* (2011), remarkably higher net returns (€202 ha$^{-1}$) under MT relative to CT were observed. The MT showed a 26 and 61% increase in net returns and BCR compared to CT. A 36% higher net profit and 1.61 times higher BCR were recorded under NT compared to CT. In another study, Jabran and Aulahk (2015) assessed profitability of production for a wheat field under four tillage systems, i.e. CT, DT, RT, and NT in Pakistan. The authors reported a 2% higher production cost under DT (\$631 ha$^{-1}$) relative to CT (\$616 ha$^{-1}$). However, RT (\$571 ha$^{-1}$) and NT (\$548 ha$^{-1}$) had 7 and 11%, respectively lesser production cost than CT (\$616 ha$^{-1}$). The net profit was 14, 20, and 25% higher under DT (\$508 ha$^{-1}$), RT (\$535 ha$^{-1}$), and NT (\$558 ha$^{-1}$), respectively, relative to CT (\$445 ha$^{-1}$). The authors concluded that the higher yields under DT, RT, and NT than CT were responsible for the high net profit in these systems than under CT.

In Kenya, Otieno *et al.* (2019) compared the profitability of production for maize and dry beans under CT and NT for two years. The authors observed lower production cost under NT than CT for both maize and dry beans. About 18 and 32% lower production cost was observed under NT in maize and dry beans, respectively, compared to CT. The net profit increased by 25 and 45% under NT in maize and dry beans, respectively, compared to CT. Two factors were attributed to the lower production cost and higher net profit under NT than CT: (i) reduced number of days required for cultivation and weed control under NT compared to CT and (ii) Not carrying out pre-cultivation activities under NT.

In Ghana, Buah *et al.* (2017) studied the profitability of maize and dry beans under NT and CT. The authors reported 28 and 24% lower production cost under NT in maize and dry bean fields, respectively, compared to CT. The net profit was tremendously higher under NT (\$1883 ha$^{-1}$) than under CT (\$733 ha$^{-1}$) in a maize field. Similarly, higher net profit was observed under NT (\$1719 ha$^{-1}$) than under CT (\$772 ha$^{-1}$) in a dry beans field. In another similar study, Mosquera *et al.* (2019) studied the net benefit under MT and CT for two seasons. The authors reported 17 and 24% higher net benefit in the first and second seasons, respectively, under MT compared to CT.

Minimal studies have been conducted assessing the profitability of production under different tillage systems, especially in Africa. However, measures to address food insecurity and conserving the environment in Africa would require detailed information on the production cost, net profit, and BCR. Adequate soil tillage systems, which would increase profitability while conserving the soil health and the environment, are required.

**Table 6:** Production Cost, Net profit, and Benefit-cost Ratio under different Soil Tillage Systems *ha$^{-1}$

| *Tillage systems* | *Crop type* | *Cost of production* | *% increase in Production cost of conservation tillage relative to CT* | *Net profit/ benefit* | *% increase in net profit of conservation tillage relative to CT* | *BCR* | *Currency* | *Source* |
|---|---|---|---|---|---|---|---|---|
| CT | Wheat | 1091 | | 370 | | * | € | Panasiewicz *et al.* (2020) |
| RT | | 1020 | -7 | 308 | -17 | * | | |
| NT | | 925 | -15 | 242 | -34 | * | | |
| CT | Wheat | 273 | | 648 | | 3.38 | $ | Gangwar *et al.* (2006) |
| RT | | 252 | -8 | 682 | +5 | 4.26 | | |
| NT | | 212 | -22 | 701 | +8 | 4.32 | | |
| CT | Wheat | 385 | | 250 | | * | $ | Su *et al.* (2007) |
| RT | | 347 | -10 | 260 | +4 | * | | |
| ST | | 277 | -28 | 476 | +90 | * | | |
| NT | | 200 | -48 | 520 | +108 | * | | |
| CT | Maize | | * | * | | * | € | Sharma *et al.* (2011) |
| MT | | | * | * | +26 | 0.71 | | |
| NT | | | * | * | +36 | * | | |
| CT | Wheat | 616 | | 445 | | 1.72 | $ | Jabran and Aulahk (2015) |
| DT | | 631 | +2 | 508 | +14 | 1.81 | | |
| RT | | 571 | -7 | 535 | +20 | 1.94 | | |
| NT | | 548 | -11 | 558 | +25 | 2.02 | | |
| CT | Maize | 68,096 | | 108,605 | | 2.91 | Kenya Shs. | Otieno *et al.* (2019) |
| NT | | 55,553 | -18 | 135,740 | +25 | 4.06 | | |
| CT | Dry beans | 31,600 | | 49,325 | | 2.72 | | |
| NT | | 21,425 | -32 | 71,695 | +45 | 4.00 | | |
| CT | Maize | 1805 | | 733 | | * | $ | Buah *et al.* (2017) |
| NT | | 1294 | -28 | 1883 | +157 | * | | |
| CT | Dry beans | 1958 | | 772 | | * | | |
| NT | | 1481 | -24 | 1719 | +123 | * | | |
| CT (I) | Potato | * | | * | | | $ | Mosquera *et al.* (2019) |
| MT | | * | | * | +17 | | | |
| CT (II) | | * | | * | | | | |
| MT | | * | | * | +24 | | | |

CT is for conventional tillage; RT is for reduced tillage; MT is for minimum tillage; ST is for subsoil tillage with mulching; NT is for no-tillage. * indicates that no data was provided

## 2.9 APEX Model Overview

APEX model is a physically-based, daily time-step model that was developed to evaluate the effects of various land management practices on hydrological components, water supply and quality, SY, and crop growth (Radcliffe *et al.*, 2015; Wang *et al.*, 2014). The model was developed as an extension of the Environmental Policy Integrated Climate (EPIC) model (Williams, 1995). APEX model has an open-source code written in Fortran (Steglich & Williams, 2013). APEX can predict data in large farms or small watersheds. The farm/watershed may have homogenous characteristics or may have heterogeneous subareas based on climate, soil, management, topography, and routing reach characteristics (Williams *et al.*, 2006).

The main components of the APEX model include; Climate, hydrology, water and wind erosion, crop growth, livestock grazing, pesticide fate, manure erosion, routing component, phosphorous cycling and losses, nitrogen cycling and losses, carbon cycling, and economics component (Fig. 1; Wang *et al.* (2011)). In this section, the runoff subcomponent under the hydrological and routing components will be discussed. The hydrology component is responsible for the simulation of runoff, percolation, lateral subsurface flow, evaporation, and snow melt (Wang *et al.*, 2011). The APEX model provide two methods for the simulation of runoff: the modified soil conservation service (SCS) curve number (CN) (United States Department of Agriculture [USDA]-Natural Resources Conservation Service [NRCS], 2004) and the Green and Ampt infiltration method (Green & Ampt, 1911). The routing component was developed to predict water and sediment yield through channels and flood plains; organic N and P, and pesticide transported with sediment (Williams & Izaurralde, 2006). The APEX model provides seven options for simulation of sediment yield: MUST MUSL Theoretical, AOF Onstad-Foster, USLE Universal Soil Loss Equation, MUSS Small Watershed MUSLE, MUSL Modified USLE, MUSI MUSLE with input parameters (See BUS(1)), RUSLE Revised USLE, and RUSLE 2 Revised USLE (Williams *et al.*, 2006).

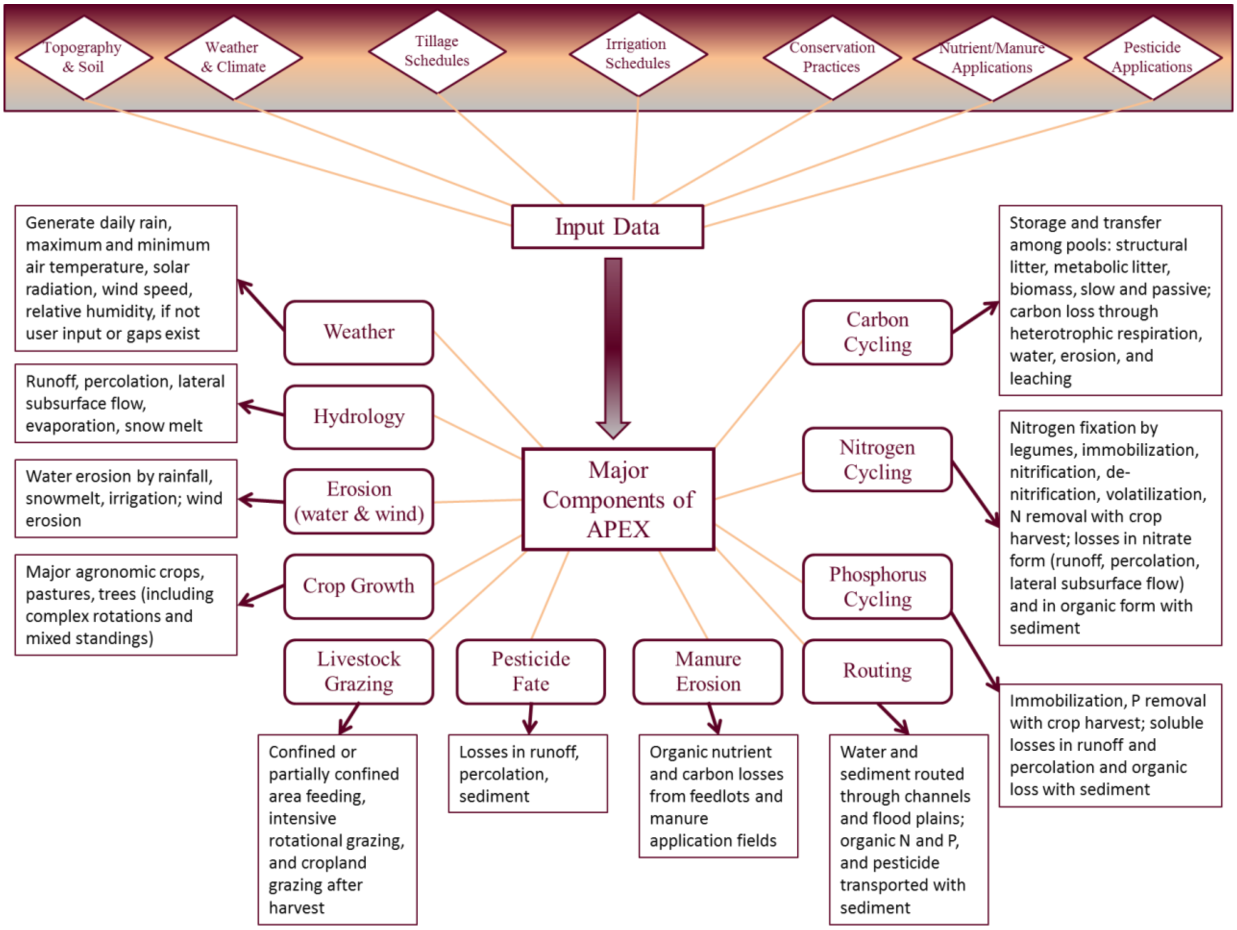


**Figure 1:** Inputs and Main Components of APEX Model [adopted from Wang *et al.* (2011)].

## 2.10 APEX Model Studies in Surface Runoff and Sediment Yield Simulation

Hydrological models can be important in understanding the impact of crop production technologies on the environment. Many studies have been conducted to evaluate the applicability of the APEX model in assessing human impacts on the environment (Gassman *et al.*, 2010; Le, 2017; Tuppad *et al.*, 2010; Wang *et al.*, 2008). A few of them that evaluated the applicability of the APEX model in the simulation of SRV and SY under different soil tillage systems are presented in Table 7.

Francesconi *et al.* (2014) assessed the ability of the APEX model in predicting SRV under two soil tillage systems (NT and RT) under silty loam soils in northeast Indiana. The authors reported that APEX could predict SRV under both soil tillage systems with satisfactory scores of coefficient of determination ($R^2$) = 0.87, NSE = 0.65 under NT, and $R^2$ = 0.76, NSE = 0.74 for

RT under the calibration period. Validation of the model also gave satisfactory scores of $R^2$ = 0.76, NSE = 0.76 for NT, and $R^2$ = 0.74, NSE = 0.74 for RT.

In another study by Wang *et al.* (2009), SRV and SY were simulated using the APEX model in the farmland before conservation practices (Pre-BMPs) and after application of conservation practices (Post-BMPs). Results from model calibration and validation confirmed that APEX was able to convincingly approximate SRV and SY for both management practices, with $R^2$-values ranging from 0.60 to 0.80 and Nash-Sutcliffe efficiency (NSE)-values ranging from 0.58 to 0.77. A similar study by Assefa *et al.* (2018) involved the application of the APEX model to simulated flow under CT and conservation practices at Dangishita in Ethiopia. The authors observed good calibration/validation ($R^2$ > 0.80; NSE > 0.70) results under both management practices.

Wang *et al.* (2008) simulated SRV and SY using the APEX model under CT and ridge-till in the Typic Hapludolls soil. The model provided satisfactory calibration/validation results for SRV under both CT ($R^2$ = 0.51/0.41) and ridge-till ($R^2$ = 0.38/0.35). The NSE-value also met the criteria (> 0.6) of their study. Model calibration/validation for SY gave NSE-values of 0.36/0.62 and $R^2$ from 0.43/0.63 under CT and NSE-values of 0.32/0.41 and $R^2$ from 0.35 to 0.41 for monthly comparisons. The authors concluded that predicted SRV was in good agreement with observed values for the studied management systems.

In a study by Ramirez-Avila *et al.* (2017), event-based SRV and SY were compared for field and APEX simulations under CT and RT management practices (Table 7). The calibrated APEX models satisfactorily predicted SRV under all management practices (NSE > 0.47, percent bias (PBIAS) < 34) except in the grazing lands (NSE < 0.11, PBIAS < 50). The SY under RT was the only one that produced satisfactory results for calibration/validation periods (NSE = 0.48/0.49; PBIAS = 22/−12%). The authors concluded that field and plot scale erosion models have difficulty predicting small-scale events.

In a nutshell, the APEX model can recognize the variations in SRV and SY under different soil tillage systems. But, studies on evaluation of the performance of APEX model in simulation of SRV and SY under different soil tillage systems are limited worldwide and lacking in Africa. Nonetheless, understanding appropriate environmental conservation measures at lower costs in terms of time and monetary resources is vital.

**Table 7:** Studies on Surface Runoff and Sediment Yield Calibration and Validation using APEX Model

| ***Management*** | ***$R^2$*** | | ***NSE*** | | ***Reference*** |
|---|---|---|---|---|---|
| | **Calibration** | **Validation** | **Calibration** | **Validation** | |
| **Surface Runoff** | | | | | |
| NT | 0.87 | 076 | 0.65 | 0.76 | Francesconi *et al.* (2014) |
| RT | 0.76 | 0.74 | 0.74 | 0.74 | |
| Pre-BMPs | 0.76 | 0.60 | 0.73 | 0.33 | Wang *et al.* (2009) |
| Post-BMPs | 0.78 | 0.77 | 0.61 | 0.75 | |
| CT | 0.89 | 0.90 | 0.85 | 0.77 | Assefa *et al.* (2018) |
| CT | 0.51 | 0.68 | 0.41 | 0.62 | Wang *et al.* (2008) |
| Ridge-till | 0.38 | 0.76 | 0.35 | 0.72 | |
| CT | 0.73 | 0.69 | 0.47 | 0.52 | Ramirez-Avila *et al.* (2017) |
| RT | 0.76 | 0.92 | 0.72 | 0.97 | |
| Grazing | 0.67 | 0.77 | -0.10 | 0.11 | |
| **Sediment Yield** | | | | | |
| Pre-BMPs | 0.80 | 0.62 | 0.77 | 0.61 | Wang *et al.* (2009) |
| Post-BMPs | 0.64 | 0.61 | 0.63 | 0.58 | |
| CT | 0.43 | 0.63 | 0.36 | 0.62 | Wang *et al.* (2008) |
| Ridge-till | 0.35 | 0.41 | 0.32 | 0.41 | |
| CT | 0.50 | 0.69 | 0.02 | -25.66 | Ramirez-Avila *et al.* (2017) |
| RT | 0.61 | 0.49 | 0.48 | 0.49 | |
| Grazing | 0.50 | 0.59 | -0.28 | -0.01 | |

NT if for no-tillage; RT is for reduced tillage; CT is for conventional tillage; Pre-BMPs is for prior to conservation practices; Post-BMPs is for after conservation practices

## CHAPTER THREE

## MATERIALS AND METHODS

### 3.1 Study Area Description

### 3.1.1 Study Area Location

The study was conducted in Goma and Kimenyedde experimental sites located in Mukono District, central Uganda. Mukono District is bordered by Luweero District to the north-west, Kayunga District to the north, Kalangala District to the south-west, Wakiso District to the west, and Buikwe District to the east (Fig. 2). Goma and Kimenyedde experimental sites in Mukono District are located at 00°25'0"N; 32°42'0"E and 00°32'0"N; 32°50'0"E, respectively. The elevations of Goma and Kimenyedde experimental sites are 1121 and 1250 meters above sea level (m a.s.l), respectively.

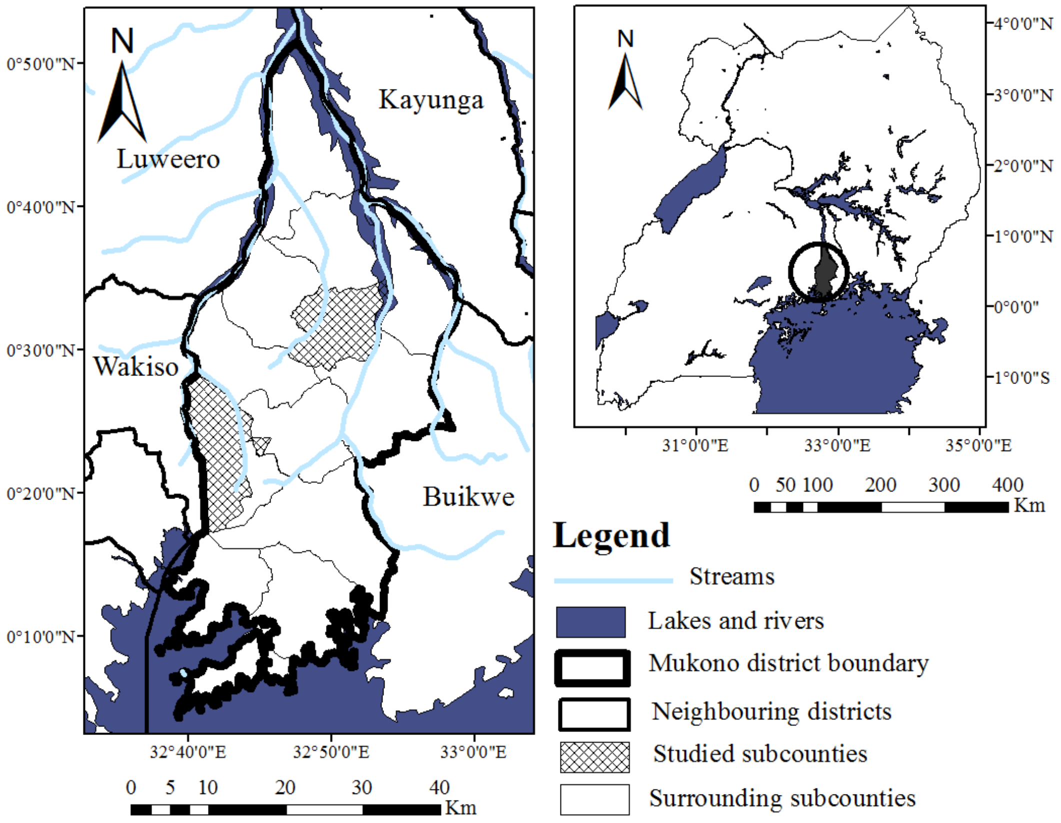


**Figure 2:** Map Showing the Study sites in Central Uganda: the Map was Developed Using Arc-GIS Software

### 3.1.2 Climate of the Study Area

The climate of Mukono District is classified as a tropical climate. Seasonal precipitation is driven mainly by the Inter-Tropical Convergence Zone (ITCZ) migration, a relatively narrow belt of shallow pressure and heavy rainfall that form near the Earth's equator. The position of ITCZ changes over the year. It migrates southwards from September to December through Uganda, and returning northwards in March to May, causing a bi-modal rainfall pattern. Fig. 3 shows the total precipitation and mean ambient temperature of the study areas for 14 years. The study area receives the "short" rains from September to November and the "long" rains from March to June. The mean annual precipitation of Goma and Kimenyedde experimental sites are 1,100 mm and 1,000 mm, respectively. The mean monthly air temperature for both Goma and Kimenyedde experimental sites range from 16 to 28 °C (UBOS, 2018).

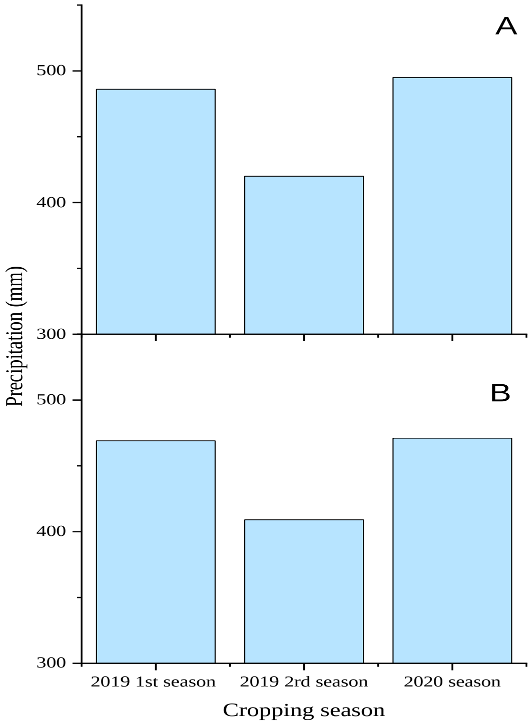


**Figure 3:** Average Monthly Precipitation and Ambient Temperature for Goma (A) and Kimenyedde (B) Experimental Sites from 2005-2018 (Data obtained from Climate Change Knowledge Portal; https://climateknowledgeportal.worldbank.org/download-data) (World Bank, 2018)

### 3.1.3 Soils and Geology of the Study Area

According to the Food and Agriculture Organization, the soils in the study areas are Lixic Ferralsols (FAO, 1998). The soils in Goma experimental site are sandy clay loam with 51% sandy, 30% clay, and 19% silt, while those in Kimenyedde experimental site are sandy loam with 65% sandy, 20% clay, and 15% silt.

Mukono District is dominated by Pre-Cambrian gneiss-granite composite rock (NERC, 2001). The southern part of the district consists of metamorphic rocks, mainly gneiss, hornblende, and phyllite. Quaternary sediments also line Sezibwa Swamp and the north shore of Lake Victoria (Taylor & Howard, 1995).

### 3.1.4 Vegetation of the Study Area

The study area has forest/savannah mosaic characterized by patches of dense forest in the South and scattered trees, shrubs and grassland in the Northern parts. The wetlands constitute mainly hyparrhenia, miscanthus, typha, and convolvulaceae species. The area also has swamp forest with *Pseudospondias microcarpa*, *Mitrogyra spp.*, and *bridelia micrautha* etc.

## 3.2 Experimental Design

The experiment with common beans was started in April 2019 to June 2020, covering 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 Organization (NARO), Uganda. Plots of 30 m long and 5 m width were laid down in a Complete Block Design (CBD) (Fig. 4), with four soil tillage systems to assess their effect on the soil hydrological processes (i.e. SRV, IR, SMC, and SWS), WUE, grain yield, and economic returns. Each soil tillage system was replicated three times, making 12 plots at each experimental site.

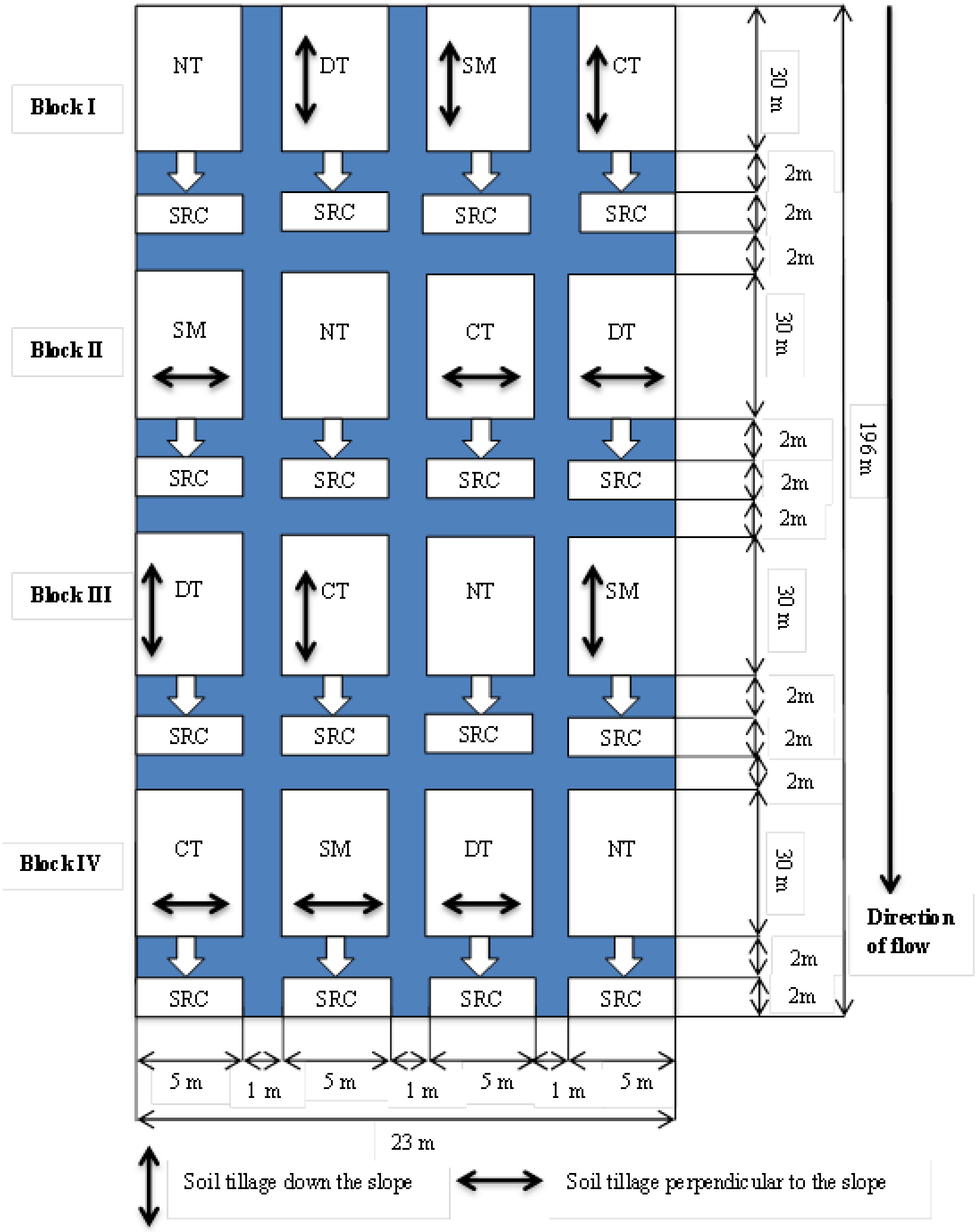


**Figure 4:** Schematic Diagram Showing Field Layout. NT is for no-tillage; DT is for deep tillage; SM is for stubble-mulching; CT is for conventional tillage; SRC is for surface runoff collection tanks

## 3.3 Soil Tillage Systems and Tillage Direction

### 3.3.1 Description of Soil Tillage Systems

The soil tillage systems included: NT, SM, DT, and CT (Table 8; Appendix 1).

#### (i) No-tillage

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.

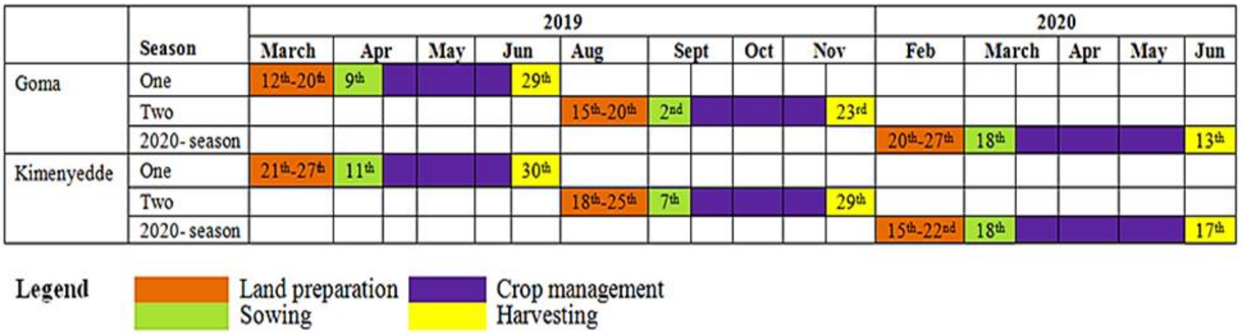
#### (ii) Stubble-Mulching

It involved soil digging up to a depth of 15 cm using a Huard plough (Model: Huard 570, Huard, United Kingdom) 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.

#### (iii) Deep Tillage and Conventional Tillage

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 Fig. 5. No fertilization application was made for all seasons.



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

Legend
🟧 Land preparation
🟩 Sowing
🟪 Crop management
🟨 Harvesting

**Figure 5:** Common Bean Calendar from April 2019 to June 2020

### 3.3.2 Description of Soil Tillage Direction

For all the soil tillage systems (except NT), two soil tillage directions were considered. The first soil tillage direction involved soil tillage down the slope/hill (TDS). In contrast, the second soil tillage direction involved soil tillage perpendicular to the direction of slope (TPS), i.e. contour tillage (Fig. 4). Planting was done along the contour lines following the pattern of the ground.

**Table 8:** Description of the Different Soil Tillage Systems and Management Practices

| Tillage system | Tillage depth (cm) | Tilling equipment | Tilling and planting direction | Crop residues | Mulches | Weed control |
|---|---|---|---|---|---|---|
| NT | 0 | Disk openers | - | Yes | Yes | Roundup: Glyphosate 360G/L |
| SM | 0-15 | Huard plough | TDS<br>TPS | Yes | Yes | Roundup: Glyphosate 360G/L |
| DT | 0-40 | Huard plough | TDS<br>TPS | No | No | Regular weeding (hand-hoe) |
| CT | 0-15 | Huard plough | TDS<br>TPS | No | No | Regular weeding (hand-hoe) |

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

## 3.4 Meteorological and Soil Data Collection

### 3.4.1 Measurement of Meteorological

Observed on-farm weather parameters, namely; temperature, relative humidity, and rainfall, air pressure, wind speed *etc.*, were collected using an automated-weather-stations-instrument which was installed on-site. The automated-weather-stations-instrument recorded weather parameters in every five min-intervals. Supplementary data at the same spatial resolutions were obtained from Uganda National Meteorological Agency (UNMA), regional stations for cross-validation.

### 3.4.2 Soil Sampling and Analysis

Soil samples were collected at 0-20, 20-40, 40-60, 60-80, 80-100 cm depth from each soil tillage system 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 soil pH (Rayment & Higginson, 1992). Organic carbon (OC) and Nitrogen (N) content in percentage were analysed using the dry combustion procedures with a C/N analyser following the guidelines of Nelson and Sommers (1996). The Av. P was determined using the phosphorous analysis procedures of Olsen *et al.* (1982), while Av. K was measured using the ammonium acetate ($C_2H_7NO_2$) buffer-extraction method described by Rayment and Higginson (1992). The bulk density (BD) was determined using a core method (Blake, 1965).

## 3.5 Collection of Hydrological Data

### 3.5.1 Measurement of Infiltration Rate

The IR was estimated by using a double-ring infiltrometer (Appendix 2). 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 IR 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).

### 3.5.2 Measurement of Soil Moisture Content

To investigate soil moisture dynamics in 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 to 2% were used to measure the volumetric water content of the soils and were calibrated before installation using procedures suggested by Bogena *et al.* (2007) and Saito *et al.* (2009). The soil moisture sensors were externally linked with an EM50 data collector with 24 hours acquisition time interval.

### 3.5.3 Determination of Soil Water Storage

The SWS was determined by digging soil samples after every 10 cm depths from a 1m soil depth using the cutting ring method following the protocols described by Dam *et al.* (2005). The soil samples were collected from each soil tillage system at planting and maturity time. The SWS for each soil layer at each growing period was then determined using equation 1 as described by Liu *et al.* (2016b):

$$SWS = \frac{BD}{\rho w} \times \text{ SMC } \times \text{D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Equation\ 1$$

Where SWS is the soil water storage (mm); BD is the bulk density (g dry soil cm$^{-3}$); ρw is the water density (1 g cm$^{-3}$); SMC is the soil moisture content (g water g$^{-1}$ dry soil); D is the depth of the soil profile (mm). The BD and SMC were determined by the oven-drying technique as described by Blake (1965).

### 3.5.4 Determination of Evapotranspiration

The actual evapotranspiration (AET) was determined using the soil water balance method using equation 2 (Bodner *et al.*, 2007), while the potential evapotranspiration (PET) was estimated using the Hargreaves method following equation 3 (Hargreaves & Samani, 1982).

$$EAT = P + W - D_R - R_O \pm \varDelta SWS \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 2$$

Where A$ET$ (mm) is the Evapotranspiration; $P$ (mm) is the precipitation; $W$ is an upward capillary rise in the root zone, $R_O$ is surface runoff, $D_R$ is drainage, and $\varDelta SWS$ (mm) is the changes in SWS from planting to harvest at 1 m depth. The $P$ and $R_O$ were measured directly in the field. $W$ was neglected since the groundwater table was deep (64 m) (Boukhari *et al.*, 2015; Su *et al.*, 2007). $D_R$ was neglected because daily $P$ never exceeded soil water capacity (Holmes, 1984; Lhomme & Katerji, 1991) and deep percolation was not considered due to the insignificant difference in the soil water storage down the soil profile (section 4.4).

$$ET_{HS} = K_{RS} R_a (T_{max} - T_{min})^{HE} \left( \frac{T_{max} + T_{min}}{2} + HT \right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \, Equation\ 3$$

Where $\boldsymbol{ET_{HS}}$ is daily PET (mm day$^{-1}$); $\boldsymbol{R_a}$ is extraterrestrial radiation (mm day$^{-1}$); $\boldsymbol{T_{max}}$ and $\boldsymbol{T_{min}}$ are daily maximum and minimum air temperature (°C), respectively; $\boldsymbol{K_{RS}}$ is the empirical radiation adjustment coefficient, set at 0.0023; *HE* is the empirical Hargreaves exponent, set at 0.5; and *HT* is the empirical temperature coefficient, set at 17.8 (Hargreaves, 1994).

### 3.5.5 Measurement of 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 liter 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 (Fig. 6). 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 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).

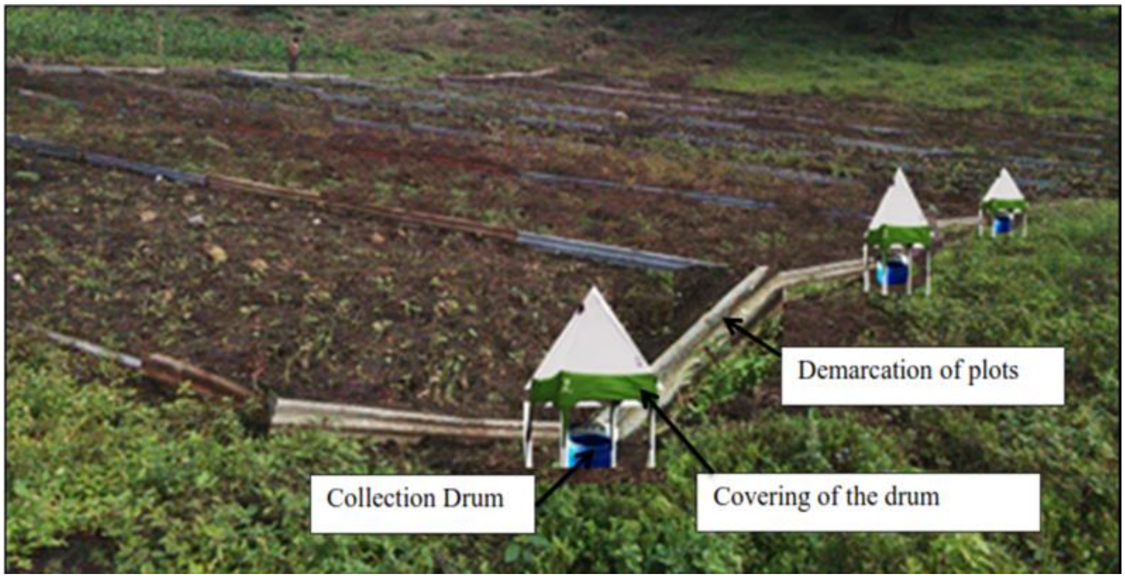


**Figure 6:** Surface Runoff Collection from the Four Soil Tillage Technologies in the Study Sites

### 3.6 Determination of Suspended Sediment Concentration and Sediment Yield

About 1.4 litres 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 litres). The bottles were placed in a cool box, and the samples were 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 SY was estimated using equation 4:

$$SY\left(\frac{g}{ha}\right) = \frac{SRV\ (l) \times SSC\ \left(\frac{g}{l}\right)}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Equation\ 4$$

Where SY is the sediment yield; SRV is the surface runoff volume; SSC is the suspended sediment concentration; A = 150 $m^2$.

### 3.7 Determination of Grain Yield

In each plot, a 2 m × 2 m plot was established in the middle of each treatment plot. At physiological maturity, pods were harvested, air dried, and hand threshed. The grain weight was taken after all seeds were oven-dried at 60 °C for 24 h.

### 3.8 Determination of Crop Water Use Efficiency

The grain yield (GY) water use efficiency (WUE-yield) of the common bean crops under different soil tillage systems was determined as described by Xu and Hsiao (2004) and Payero *et al.* (2008) using equation 5.

$$WUE = \frac{GY}{AET} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 5$$

Where WUE-yield (kg $ha^{-1}$ $mm^{-1}$) is the grain yield water use efficiency, GY (kg $ha^{-1}$) are the grain yields, and AET (mm) is the growing season actual evapotranspiration calculated from equation 2.

### 3.9 Economic Benefits and Benefit-cost Ratio (BCR) Estimation

The economic benefit/net profit of different soil tillage systems was estimated using simple economic analyses. The net profit for each soil tillage system was computed following equation 6.

$$Net\ profit\ (USD) = (Grain\ yield \times P) - Gross\ cost \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 6$$

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

The BCR was then calculated from equation 7

$$BCR = \frac{Net\ profit}{Gross\ cost} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 7$$

## 3.10 APEX Model Development

The APEX model was developed based on the required input and parameters. The weather input data for APEX included daily precipitation, maximum and minimum temperature, relative humidity, wind speed, and solar radiation (Williams *et al.*, 2006). The precipitation data was measured on-site using automated-weather-station instruments (model: JL-03-Q4; Shandong, China), and the other weather data were obtained from the nearest weather stations (15 km) to the sites. The soil data used in the development of the model are listed in Table 9. Soil properties that were not measured on-site site (e.g., Cation exchange capacity, saturated hydraulic conductivity, and wilting point) were estimated using the Soil Water Characteristics software (Table 9). Management operations (i.e. soil tillage systems, weeding, and herbicide application) are presented in Table 8 and Fig. 5. The simulation process was plot-based, where each soil tillage system was run independently.

**Table 9:** Soil Input Variables to the Model for Goma and Kimenyedde Experimental Sites

| ***Experimental site*** | ***NT*** | | ***SM*** | | ***DT*** | | ***CT*** | | ***Source*** |
|---|---|---|---|---|---|---|---|---|---|
| **Goma Site** | | | | | | | | | |
| Layers | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | Lab |
| Depth (m) | 0.5 | 1 | 0.5 | 1 | 0.5 | 1 | 0.5 | 1 | |
| Soil PH | 6.8 | 6.4 | 6.6 | 6.3 | 5.9 | 5.7 | 5.7 | 5.5 | |
| Bulk density (g $cm^{-3}$) | 1.49 | 1.55 | 1.25 | 1.51 | 1.22 | 1.46 | 1.47 | 1.49 | |
| Sand (%) | 51 | 52 | 52 | 51 | 50 | 51 | 52 | 52 | |
| Silt (%) | 19 | 18 | 17 | 20 | 20 | 19 | 18 | 19 | |
| Organic carbon (%) | 3.97 | 2.42 | 3.95 | 2.56 | 3.03 | 1.83 | 2.57 | 1.89 | |
| Wilting point (m $m^{-1}$) | 0.23 | 0.22 | 0.27 | 0.22 | 0.27 | 0.23 | 0.23 | 0.23 | Soil Water |
| Field capacity (m $m^{-1}$) | 0.34 | 0.32 | 0.40 | 0.33 | 0.41 | 0.34 | 0.34 | 0.34 | Characteristics |
| Saturated conductivity (mm $h^{-1}$) | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.27 | (Version 6.02.74) |
| **Kimenyedde Site** | | | | | | | | | |
| Soil PH | 6.5 | 6.1 | 6.3 | 6 | 5.6 | 5.4 | 5.4 | 5.2 | Lab |
| Bulk density (g $cm^{-3}$) | 1.29 | 1.35 | 1.29 | 1.31 | 1.02 | 1.26 | 1.27 | 1.29 | |
| Sand (%) | 65 | 64 | 65 | 63 | 63 | 62 | 65 | 62 | |
| Silt (%) | 15 | 17 | 15 | 18 | 18 | 18 | 15 | 19 | |
| Organic carbon (%) | 3.75 | 2.22 | 3.69 | 2.28 | 2.83 | 1.64 | 2.37 | 1.69 | |
| Wilting point (m $m^{-1}$) | 0.25 | 0.25 | 0.25 | 0.26 | 0.33 | 0.27 | 0.26 | 0.26 | Soil Water |
| Field capacity (m $m^{-1}$) | 0.39 | 0.37 | 0.39 | 0.38 | 0.49 | 0.40 | 0.40 | 0.39 | Characteristics |
| Saturated conductivity (mm $h^{-1}$) | 0.79 | 0.87 | 0.79 | 0.86 | 0.86 | 0.77 | 0.79 | 0.85 | (Version 6.02.74) |

NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage, and CT is for conventional tillage

APEX model provides two options for simulation of runoff volume: the modified soil conservation service (SCS) curve number (CN) (USDA-NRCS, 2004) and the Green and Ampt infiltration method (Green & Ampt, 1911). The SCS-CN (equation 8) was used in the estimation of SRV in this study due to its wide range of applicability, with satisfactory to good results (Assefa *et al.*, 2018; Wang *et al.*, 2008).

$$Q = \begin{cases} 0 & for\ P \leq I_a \\ \frac{(P-I_a)^2}{P-I_a+S} & for\ P > I_a \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 8}$$

Where Q is runoff (mm), P is rainfall (mm), S is potential maximum soil moisture retention after runoff begins (mm), $I_a$ is the initial abstraction (mm). $I_a$ is always considered to be $I_a = 0.2S$. The S retention parameter was calculated as a function of soil moisture parameters following the description of Williams (2008) in equation 9.

$$S = \frac{25400}{CN} - 254 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 9$$

The CN value was determined by looking up in the SCS handbook of Hydrology (NEH-4), section-4 (USDA, 1972).

The APEX model offers seven options for predicting sediment yield (details in section 2.9). Due to the nature of the current study (small plots: 150 m$^2$), the Modified Universal Soil Loss Equation for Small Watersheds (MUSLE) (Williams, 1975) was used to simulate SY following equation 10:

$$SY = 11.8 \times \left(Q \times q_p\right)^{0.56} \times K \times LS \times C \times P \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 10$$

Where $SY$ is the sediment yield (metric tons), $Q$ is the surface runoff volume (m$^3$), $q_p$ is the peak runoff rate (m$^3$ s$^{-1}$), $K$ is the soil erodibility factor (Mg MJ$^{-1}$ mm$^{-1}$), $LS$ is the slope length and slope steepness (dimensionless), $C$ is the crop management factor (dimensionless), P is the erosion control practice (dimensionless).

## 3.11 APEX Model Calibration and Validation

The APEX monthly SRV and SY calibrations were performed for April-December 2019 under four soil tillage systems for both Goma and Kimenyedde experimental sites. An auto-calibration of the APEX model was done using the APEX-CUTE tool (version 2.0) under the Dynamically

Dimensioned Search (DDS). The DDS optimization algorithm is a stochastic neighborhood search algorithm that focuses on finding preferred parameter combinations within the user-specified maximum number of model runs (Tolson & Shoemaker, 2007).

Adjustment in the most sensitive model parameters, i.e. initial input of condition 2 curve number ($CN_2$) and curve number index coefficient (CNIC) for SRV, was done (Wang *et al.*, 2005; Wang *et al.*, 2006). For the SY component, RUSLE C factor exponential residue coefficient (RCFC) (Wang *et al.*, 2006), height coefficient (RCF), erosion control practice factor (PEC), and peak runoff rate-rainfall energy adjustment factor (APM) were adjusted. Calibration was first done on SRV, then SY, because runoff is a controlling factor in the SY estimates (Williams & Izaurralde, 2006).

The multi-objective functions were used, which included; Nash-Sutcliffe efficiency (NSE) (Nash & Sutcliffe, 1970), coefficient of determination ($R^2$), and percent bias (PBIAS) (Legates & McCabe Jr, 1999). APEX model validation was performed for seven months (January-July, 2020) without any further changes in the model parameters.

### 3.12 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. Data transformation was done using either $Log_{10}$ or square root when the data were not normally distributed. 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, SSC, ET, WUE, and grain yield. Differences among means were determined using Fisher's least significant difference (LSD) at a 5% confidence interval. The Pearson correlation and simple regression analysis were used for relating the SRV and SSC with rainfall amount and rainfall intensity.

The PBIAS, NSE, and $R^2$ statistics were used to evaluate the performance of the APEX model. A model can be considered satisfactory if the values of NSE is $> 0.3$ and $R^2 > 0.5$ (Chung *et al.*, 2002). With guidance from previous studies, the current study considered the model satisfactory if NSE-values were > 0.5, $R^2 > 0.6$, and PBIAS-values were within 20 and 45% for SRV and SY, respectively.

# CHAPTER FOUR

# RESULTS

## 4.1 Precipitation and Soil Characteristics

### 4.1.1 Precipitation

Seasonal precipitation during the first season of 2019 (508 mm) and 2020 growing season (537 mm) (Fig. 7) was higher than the average long-term seasonal precipitation (486 mm: 2005-2018) at Goma site (Fig. 3). During the second season of 2019, seasonal precipitation (397 mm) was 89 mm less than the average long-term precipitation. At Kimenyedde experimental site, 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 (Fig. 3) of Kimenyedde site. The 2019 second season received the lowest precipitation amount (392 mm) (Fig. 7).

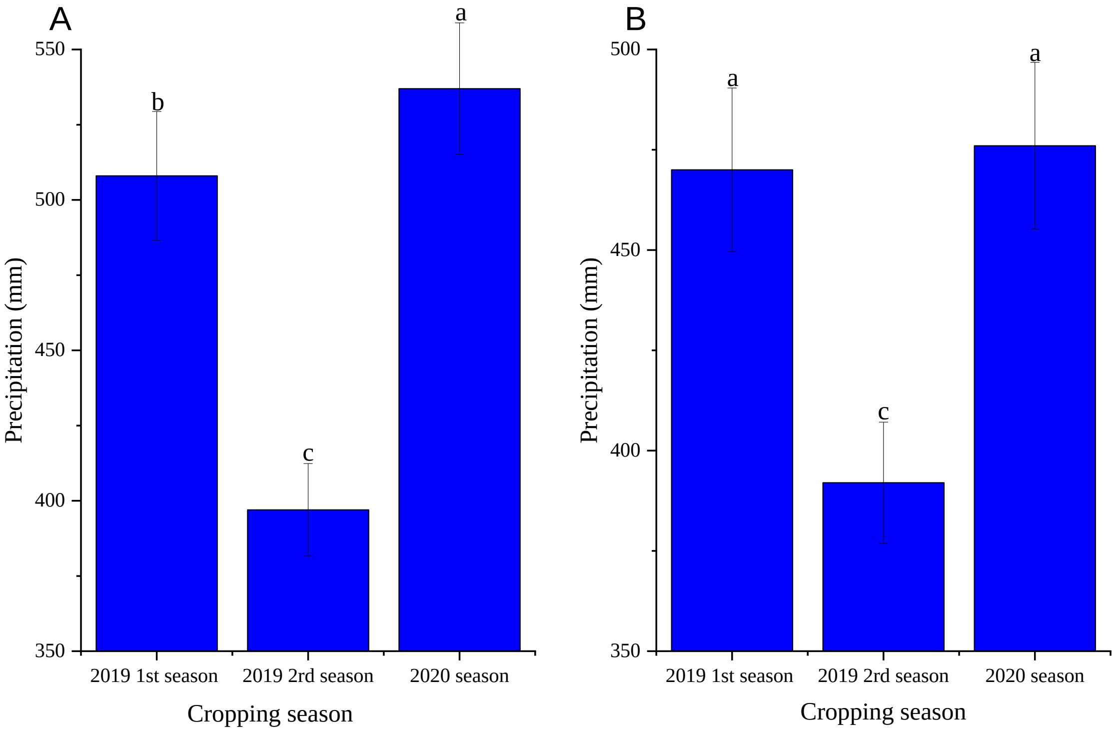


**Figure 7:** Mean Seasonal Precipitation Distribution at Goma (A) and Kimenyedde (B) Experimental Sites for the Three Growing Seasons. Bars Above the Mean Indicate the Standard Error

### 4.1.2 Soil Characteristics

Table 10 shows soil characteristics under NT, SM, DT, and CT systems 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 10). Soil tillage systems significantly ($p < 0.05$) affected OC with mean values of 3.11, 3.12, 2.23, and 2.01% under NT, SM, DT, and CT, respectively. 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, N content varied among soil tillage systems and decreased with an increase in soil depth. The highest N content was observed under 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. Soil BD (g $cm^{-3}$) varied among the different soil tillage systems and increased with soil depth (Table 10).

**Table 10:** Soil Characteristics at 0-100 cm depth at Goma and Kimenyedde Experimental Sites in Mukono District, Uganda

| **Tillage system** | **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±01 | 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; 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

## 4.2 Effect of Soil Tillage Systems on Steady-state Infiltration Rates

The steady-state IR was determined during three growing seasons at Goma and Kimenyedde experimental sites (Fig. 8). Across sites, IR reached a steady-state at 125, 102, 98, and 99 minutes under NT, SM, DT, and CT, respectively. The steady-state IR significantly ($p < 0.05$) varied among the soil tillage systems ($p = 0.000$, F = 96.34) and experimental sites ($p = 0.029$, F = 2.56). The steady-state IR was lower at Goma than Kimenyedde experimental site under all soil tillage systems (Fig. 8). During the first season, steady-state IR of 20.3, 20.1, 14.3, and 15.5 mm $h^{-1}$ were recorded under NT, SM, DT, and CT, respectively, at Goma experimental site. During the same period, steady-state IR of 23.1, 22.9, 17.3, and 16.0 mm $h^{-1}$ were recorded under NT, SM, DT, and CT, respectively, at Kimenyedde experimental site.

Although no significant ($p > 0.05$) differences were observed in steady-state IR during the first and second seasons, lower steady-state IR was recorded in the second season at both experimental sites under all soil tillage systems. The steady-state IR was 20.2, 20.0, 14.3, and 14.9 mm $h^{-1}$ under NT, SM, DT, and CT, respectively, at Goma experimental site during the second season. During the same season, significantly ($p < 0.05$) higher steady-state IR of 22.8, 22.7, 17.0, and 15.6 mm $h^{-1}$ under NT, SM, DT, and CT, respectively, were recorded at Kimenyedde experimental site.

The steady-state IR was 20.3, 20, 14.1, and 14.8 $h^{-1}$ under NT, SM, DT, and CT, respectively, at Goma experimental site during the third season. During the same season, significantly ($p < 0.05$) higher steady-state IR of 23.2, 22.9, 16.4, 15.5 mm $h^{-1}$ under NT, SM, DT, and CT, respectively, were recorded at Kimenyedde experimental site (Fig. 8).

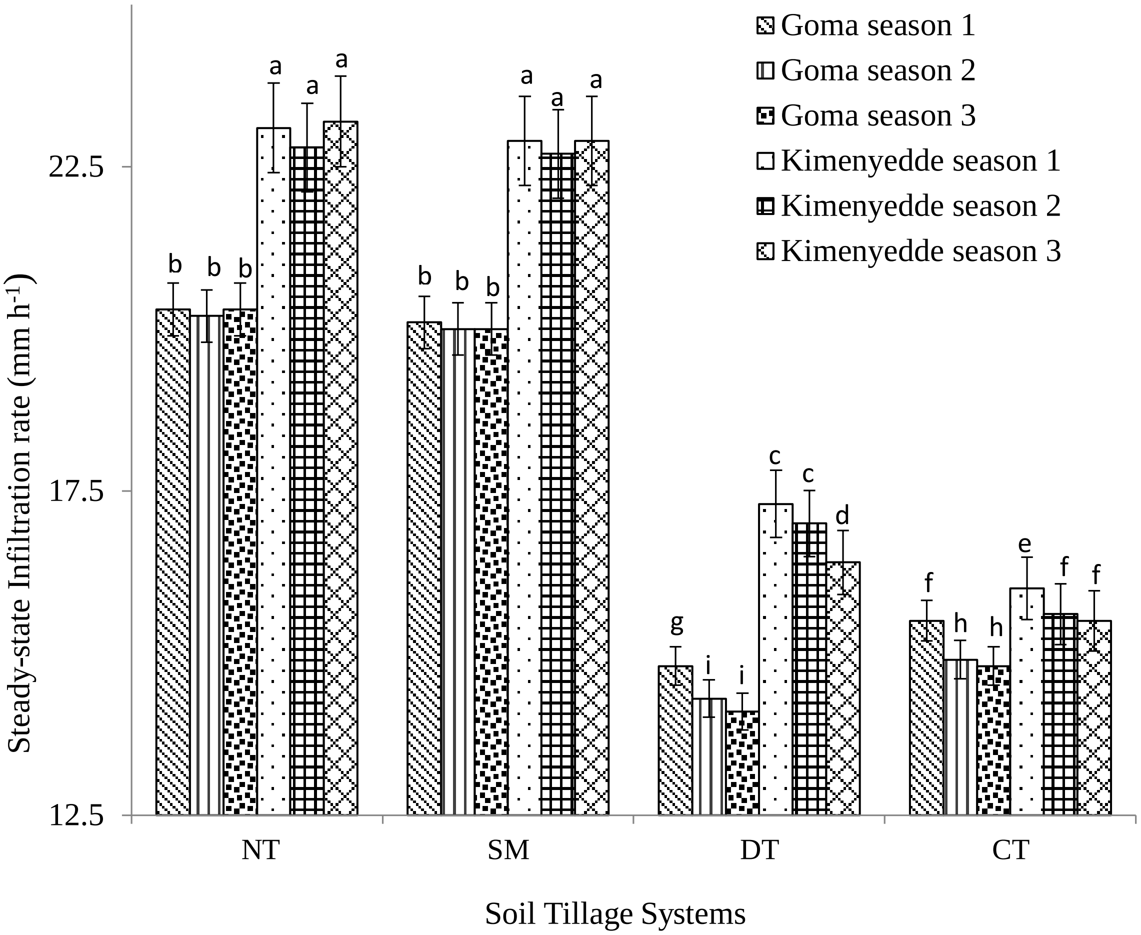


**Figure 8:** Steady-state Infiltration Rate under Different Soil Tillage Systems at Goma and Kimenyedde Experimental Sites in Mukono District, Uganda. The lower case letters: a, b, c, d, and e, represent significance at a 5% significant level. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage

### 4.3 Effect of Soil Tillage Systems and Season on Soil Moisture Content

Figure 9 shows the SMC under four different soil tillage systems during three seasons at two experimental sites. There were significant ($p < 0.05$) variations in SMC among soil tillage systems ($p = 0.000$, F= 120.01), experimental sites ($p = 0.032$, F = 85.62), and seasons ($p = 0.420$, F = 72.35). The SMC was higher at Goma than Kimenyedde experimental site under all soil tillage systems (Fig. 9). During the first season, mean SMC of 69, 68, 56, and 54 mm were recorded under NT, SM, DT, and CT, respectively, at Goma experimental site. During the same period, mean SMC was 66, 65, 56, and 54 mm under NT, SM, DT, and CT, respectively, at Kimenyedde experimental site.

During the second season, lower SMC was recorded at both experimental sites. At Goma experimental site, mean SMC of 64, 64, 48, and 47 mm were recorded under NT, SM, DT, and CT, respectively. At Kimenyedde experimental site, SMC was slightly lower with means of 58, 57, 46, and 46 mm under NT, SM, DT, and CT, respectively. No significant ($p > 0.05$) variations were observed in SMC under NT and SM systems.

The highest SMC was recorded during the third season. The mean SMC was 71, 70, 58, and 57 mm under NT, SM, DT, and CT, respectively at Goma experimental site. At Kimenyedde experimental site, the mean SMC was 67, 66, 50, and 53 mm under NT, SM, DT, and CT, respectively for the third season (Fig. 9).

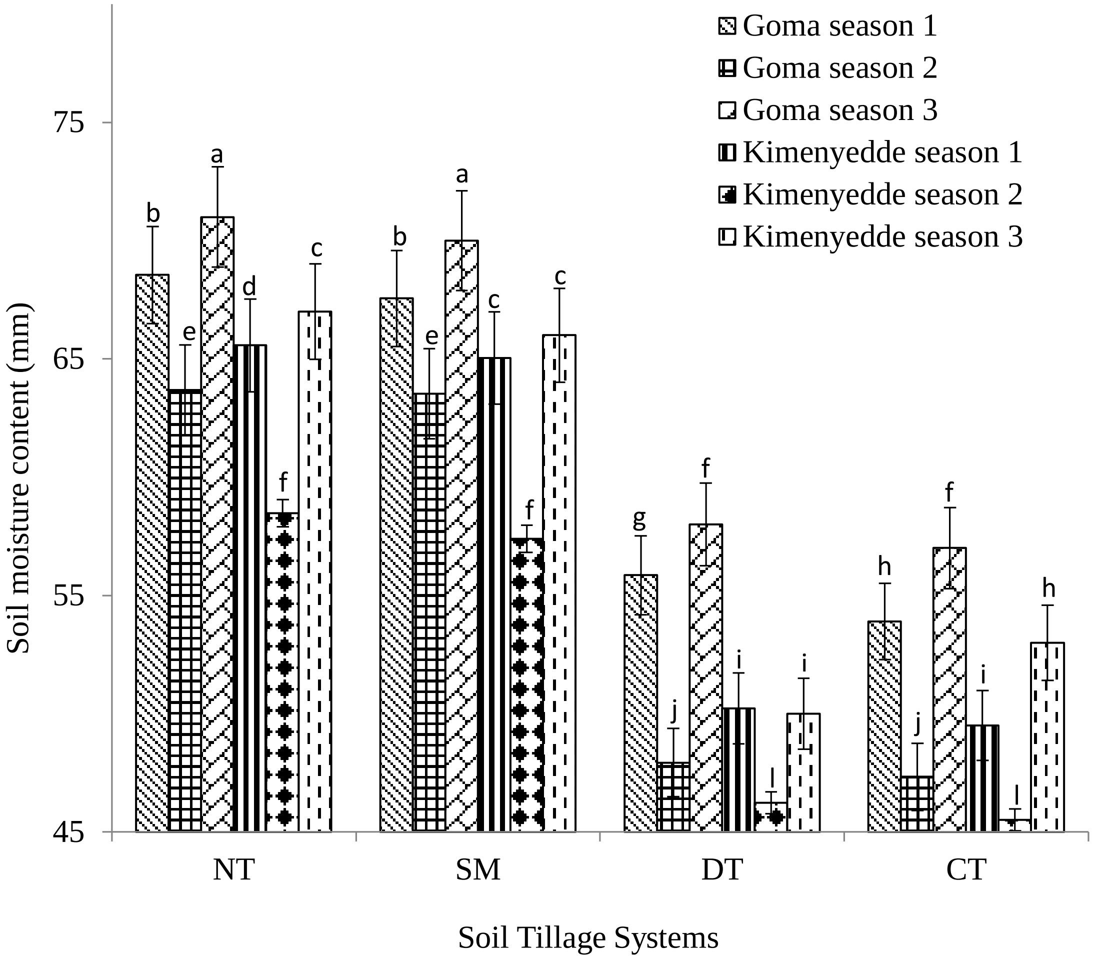


**Figure 9:** Soil Moisture Content under Different Soil Tillage Systems at Goma and Kimenyedde Experimental Sites in Mukono District, Uganda. The letters: a, b, c, d, e, f, g, h, and i represent significance at a 5% significant level. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage

## 4.4 Soil Water Storage Dynamics

The SWS varied seasonally among soil tillage systems (Fig. 10 & 11). Mean SWS (averaged across soil tillage systems and sites) in 100 cm soil profile at planting was highest during the 2020 growing season (56 mm), followed by the first season of 2019 (55 mm), and lowest during the second season of 2019 (51 mm). A similar trend was recorded at harvesting, with the 2020 growing season (24 mm) having the greatest SWS, followed by the first season of 2019 (23 mm) and then the second season of 2019 (22 mm). The effect of soil tillage systems on SWS was significant at planting with the highest SWS under NT (57 mm) and SM (56 mm) than DT (51 mm) and CT (51 mm). A similar trend was observed at harvesting with the greatest SWS under NT (27 mm) and SM (27 mm) than DT (19 mm) and CT (18 mm).

The effect of soil depth on SWS was not significant at planting, but SWS declined with soil depth with 55 mm at 0-20 cm; 54 mm at 20-30 cm; 53 mm at 30-60 cm; and 52 mm at 60-100 cm. At harvesting, 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 site on SWS was not significant, but Goma experimental site (23 mm) preserved more soil water than Kimenyedde experimental site (22 mm).

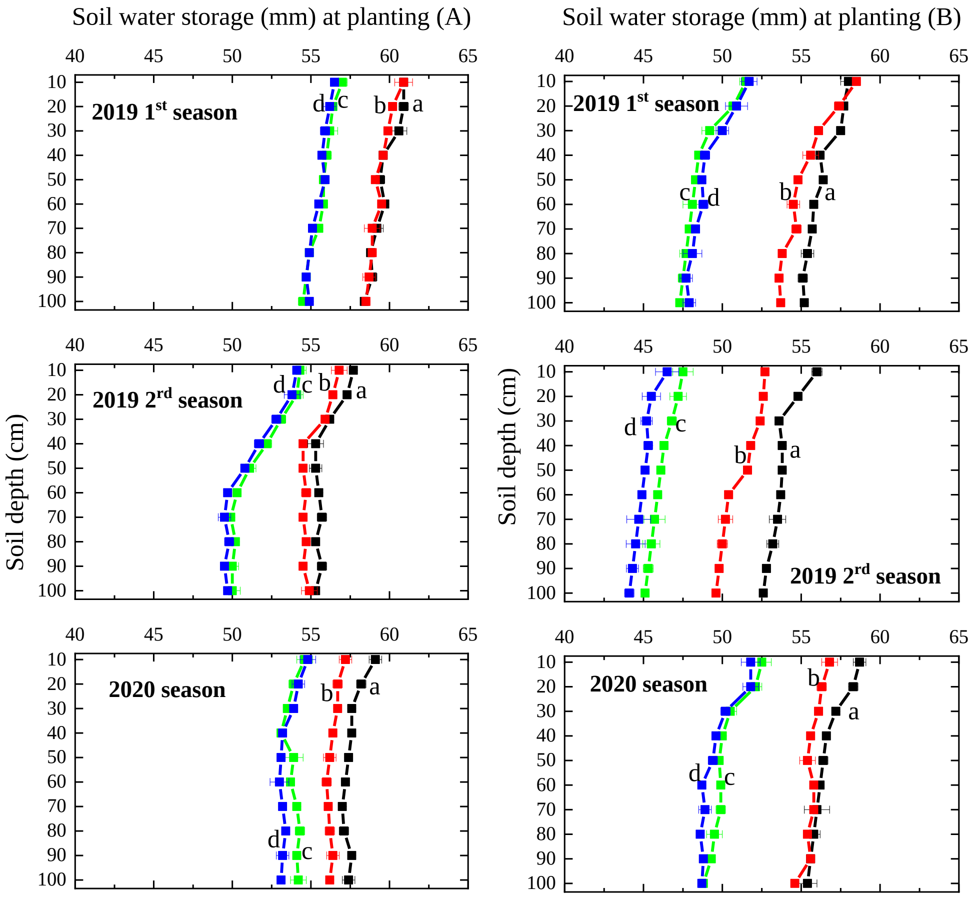


**Figure 10:** Soil Water Storage at 0-100 cm Soil Depth under NT (a), SM (b), DT (c), and CT (d) at a Time of Common Bean Planting at Goma (A) and Kimenyedde (B) Experimental Sites

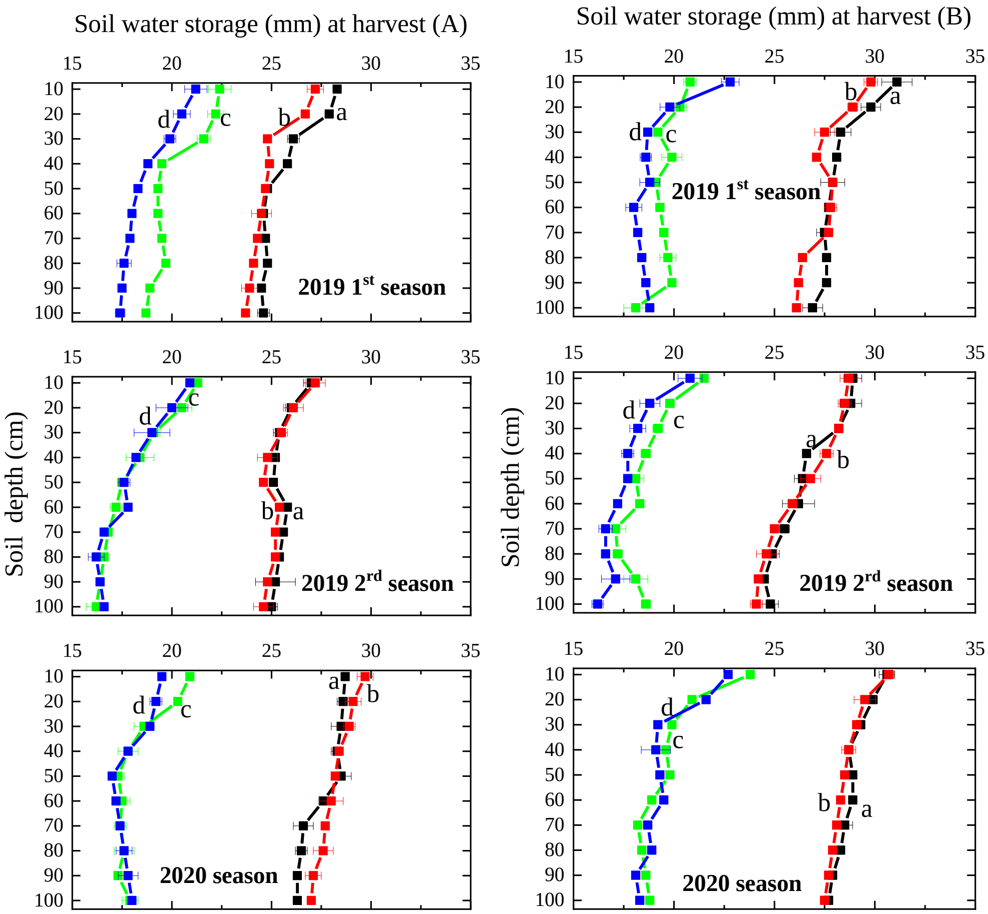


**Figure 11:** Soil Water Storage at 0-100 cm Soil Depth under NT (a), SM (b), DT (c), and CT (d) at a Time of Common Bean Harvesting at Goma (A) and Kimenyedde (B) Experimental Sites

## 4.5 Effect of Soil Tillage Systems and Season on Surface Runoff Volume

The results related to the total seasonal SRV in two experimental sites are presented in Table 11. The SRV varied significantly among soil tillage systems (*p* = 0.000, F = 242.40), experimental sites (*p* = 0.041, F = 132.33), and seasons (*p* = 0.031, F = 102.12). The interactions between experimental site × season × soil tillage systems also significantly (*p* = 0.030, F = 153.16) affected SRV. Unsurprisingly, CT depicts the highest SRV, while NT registered the lowest, as illustrated in Table 11. At Goma experimental site, 21% (281 mm) of the total rainfall (1332 mm) received in the first season was converted to surface runoff under NT, 29% (392 mm) under SM with soil tillage down the slope (SM-TDS), 29% (381 mm) under SM with soil tillage perpendicular to the slope (SM-TPS). At the same site and season, over 60% (801 mm) and 56%

(744 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, CT produced the highest SRV of 80% (1071 mm) and 75% (1000 mm) in TDS and TPS plots, respectively of the total rainfall (1332 mm). At the same site during the second season, 19% (215 mm) of the total received rainfall (1121 mm) was converted to surface runoff under NT. About 22% (250 mm) and 22% (246 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, SRV was 55% (612 mm) and 50% (565 mm) under DT-TDS and DT-TPS, respectively, at Goma experimental site. Correspondingly, 70% (781 mm) and 67% (749 mm) of the total rainfall was converted to SRV under CT with tillage down the slope (CT-TDS) and CT with tillage perpendicular to the slope (CT-TPS), respectively during the second season at Goma experimental site. During the third season, 21% (292 mm) of the total rainfall (1364 mm) was converted to surface runoff under NT. Around 29% (400 mm) and 28% (382 mm) of the total rainfall was converted to surface runoff under SM-TDS and SM-TPS, respectively. Out of the total rainfall received (1364 mm) in the third season, SRV was 60% (812 mm) and 55% (752 mm) under DT-TDS and DT-TPS, respectively. Similarly, 79% (1083 mm) and 75% (1020 mm) of the total rainfall was converted to SRV under CT-TDS and CT-TPS, respectively during the third season at Goma experimental site (Table 11).

At Kimenyedde experimental site, 20% (245 mm) of the total received rainfall (1203 mm) in the first season was converted to surface runoff under NT, 21% (252 mm) under SM-TDS, and 21% (246 mm) under SM-TPS. At the same site and season, 57% (689 mm) and 50% (608 mm) of the total rainfall was converted to surface runoff under DT-TDS and DT-TPS, respectively. Around 76% (913 mm) and 67% (802 mm) of the total received rainfall in the first season was converted to surface runoff under CT-TDS and CT-TPS plots, respectively. At the same site during the second season, 17% (165 mm) of the total received rainfall (952 mm) was converted to surface runoff under NT, 19% (178 mm) and 18% (172 mm) under SM-TDS and SM-TPS, respectively. The SRV was 50% (471 mm) and 44% (416 mm) under DT-TDS and DT-TPS, respectively at Kimenyedde experimental site in the second season. Similarly, TDS plots produced higher SRV than TPS plots under CT, with 60% (574 mm) and 55% (525 mm) SRV, respectively. During the third season, 20% (250 mm) of the total rainfall (1231 mm) was converted to surface runoff under NT. Around 21% (261 mm) and 21% (252 mm) of the total rainfall was converted to surface runoff under SM-TDS and SM-TPS, respectively. Out of the total rainfall received (1231 mm) in the third season, SRV was 56% (691 mm) and 51% (621 mm) under DT-TDS and DT-TPS, respectively. Similarly, 75% (922 mm) and 67% (818 mm) of the total rainfall was converted to SRV under CT-TDS and CT-TPS, respectively during the third season at Kimenyedde experimental site (Table 11).

**Table 11:** Rainfall Characteristics, Surface Runoff Volume, and Effect of Sites, Seasons, Soil Tillage Systems, and their Interactions on Surface Runoff Volume from the Common Bean Farms at Goma and Kimenyedde Experimental Sites in Mukono District, Uganda

| *Site* | *Season* | *Rainfall characteristics* | | | | *Surface runoff volume (mm)* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **TR (mm)** | **R (mm)** | **RD** | **NT** | **SM** | | **DT** | | **CT** | |
| | | | | | | **TDS** | **TPS** | **TDS** | **TPS** | **TDS** | **TPS** |
| Goma | One | 1332 | 5 | 55 | 281 | 392 | 381 | 801 | 744 | 1071 | 1000 |
| | Two | 1121 | 4 | 48 | 215 | 250 | 246 | 612 | 565 | 781 | 749 |
| | Three | 1364 | 6 | 57 | 292 | 400 | 382 | 812 | 752 | 1083 | 1020 |
| | All seasons | 3817 | 16 | 160 | 788 | 1041 | 1009 | 2225 | 2060 | 2935 | 2769 |
| Kimenyedde | One | 1203 | 5 | 50 | 245 | 252 | 246 | 689 | 608 | 912 | 802 |
| | Two | 952 | 4 | 46 | 165 | 178 | 172 | 471 | 416 | 574 | 525 |
| | Three | 1231 | 5 | 51 | 250 | 261 | 252 | 691 | 621 | 922 | 818 |
| | All seasons | 3386 | 14 | 147 | 660 | 692 | 670 | 1851 | 1646 | 2409 | 2145 |

| | **ANOVA for SRV** | |
|---|---|---|
| **Factor** | **F-value** | ***p*-value** |
| Site | 132.33 | **0.041** |
| Season | 102.12 | **0.031** |
| Tillage system | 242.40 | **0.000** |
| Site × Season | 91.00 | **0.046** |
| Site × Tillage system | 82.01 | Ns |
| Tillage system × Season | 105.10 | Ns |
| Site × Season × 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

## 4.6 Effect of Soil Tillage Systems on Suspended Sediment Concentration and Sediment Yield

Results of SSC and SY in two experimental sites are summarized in Table 12. The SSC varied significantly among soil tillage systems ($p$ = 0.000, F = 81.12), experimental sites ($p$ = 0.020, F =

99.51), and seasons ($p$ = 0.000, F = 201.01). The SY was also significantly different among soil tillage systems ($p$ = 0.001, F = 92.66), experimental sites ($p$ = 0.031, F = 100.23), and seasons ($p$ = 0.000, F = 158.61) (Table 12). At Goma experimental site, the highest SSC was observed under CT (2.41 ± 0.3 g $L^{-1}$), followed by DT (1.90 ± 0.4 g $L^{-1}$), SM (0.68 ± 0.1 g $L^{-1}$), and NT (0.65 ± 0.1 g $L^{-1}$), with SY of 171.41, 101.50, 17.75, and 12.19 kg $ha^{-1}$, respectively, during the first season. At the same site during the second season, slightly lower SSC than that of the first season was recorded under all soil tillage systems with mean SSC of 1.40 ± 0.5, 1.21 ± 0.4, 0.60 ± 0.1, and 0.58 ± 0.1 g $L^{-1}$, under CT, DT, SM, and NT, respectively. The SY of 122.92, 85.40, 14.98, and 10.31 kg $ha^{-1}$ were recorded in the CT, DT, SM, and NT, respectively. The third season produced the highest SSC and SY. The mean SSC was 2.65 ± 0.5, 2.00 ± 0.4, 0.72 ± 0.1, and 0.68 ± 0.1 g $L^{-1}$ under CT, DT, SM, and NT, respectively. The SY during the third season was 183.01, 110.62, 17.81, and 12.31 kg $ha^{-1}$ under CT, DT, SM, and NT, respectively.

At Kimenyedde experimental site, SSC and SY were lower than that at Goma experimental site under all soil tillage systems (Table 12). During the first season at Kimenyedde experimental site, mean SSC of 2.12, 1.53, 0.62, and 0.59 g $L^{-1}$, with the respective SY of 128.98, 70.32, 10.42, and 9.65 kg $ha^{-1}$ were recorded under CT, DT, SM, and NT systems. Similarly, the lowest SSC was observed under NT during the second season (0.43 ± 0.1 g $L^{-1}$), for which no significant ($p > 0.05$) difference was observed with that under SM (0.44 ± 0.1 g $L^{-1}$). More than nine and ten times higher SSC were recorded under DT (1.56 ± 0.3 g $L^{-1}$) and CT (1.59 ± 0.4 g $L^{-1}$), respectively, than under NT. The SY of 100.88, 58.97, 10.23, and 8.73 kg $ha^{-1}$ were recorded under CT, DT, SM, and NT, respectively, during the second season at Kimenyedde experimental site. At the same site during the third season, the highest SSC and SY were recorded (Table 12). The mean SSC were 2.73 ± 0.4, 1.56 ± 0.3, 0.69 ± 0.1, and 0.62 ± 0.1 g $L^{-1}$ under CT, DT, SM, and NT, respectively. The SY was 133.12, 75.01, 10.61, 9.68 kg $ha^{-1}$ were recorded under CT, DT, SM, and NT, respectively.

**Table 12:** Suspended Sediment Concentration, Sediment Yield, and Effects of Sites, Seasons, Soil Tillage Systems, and their Interactions on Suspended Sediment Concentration and Sediment Yield under Common Bean Farms at Goma and Kimenyedde Sites in Mukono District, Uganda

| **Site** | **Season** | **NT** | | **SM** | | **DT** | | **CT** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **SY (kg ha$^{-1}$)** | **SSC (g L$^{-1}$)** | **SY (kg ha$^{-1}$)** | **SSC (g L$^{-1}$)** | **SY (kg ha$^{-1}$)** | **SSC (g L$^{-1}$)** | **SY (kg ha$^{-1}$)** | **SSC (g L$^{-1}$)** |
| Goma | One | 12.19 | 0.65±0.1*$^{c}$ | 17.75 | 0.68±0.1$^{c}$ | 101.50 | 1.90±0.4$^{b}$ | 171.41 | 2.41±0.3$^{a}$ |
| | Two | 10.31 | 0.58±0.1$^{b}$ | 14.98 | 0.60±0.1$^{b}$ | 85.40 | 1.21±0.4$^{a}$ | 122.92 | 1.40±0.5$^{a}$ |
| | Three | 12.31 | 0.68±0.1$^{d}$ | 17.81 | 0.72±0.1$^{c}$ | 110.62 | 2.00±0.4$^{b}$ | 183.01 | 2.65±0.5$^{a}$ |
| | All seasons | 11.60 | 0.64±0.1 | 16.85 | 0.67±0.2 | 99.17 | 1.70±0.3 | 159.11 | 2.15±0.5 |
| Kimenyedde | One | 9.65 | 0.59±0.1$^{c}$ | 10.42 | 0.65±0.1$^{c}$ | 70.32 | 1.53±0.4$^{b}$ | 128.98 | 2.12±0.3$^{a}$ |
| | Two | 8.73 | 0.43±0.1$^{b}$ | 10.23 | 0.44±0.1$^{b}$ | 58.97 | 1.56±0.3$^{a}$ | 100.88 | 1.59±0.4$^{a}$ |
| | Three | 9.68 | 0.62±0.1$^{c}$ | 10.61 | 0.69±0.1$^{c}$ | 75.01 | 1.56±0.3$^{b}$ | 133.12 | 2.73±0.4$^{a}$ |
| | All seasons | 9.35 | 0.55±0.1 | 10.52 | 0.59±0.1 | 68.10 | 1.55±0.4 | 120.99 | 2.15±0.5 |

| | **SSC** | | **SY** | |
|---|---|---|---|---|
| **Factor** | **F-value** | ***p*-value** | **F-value** | ***p*-value** |
| Site | 99.51 | **0.020** | 100.23 | **0.031** |
| Season | 201.01 | **0.000** | 158.61 | **0.000** |
| Tillage system | 81.12 | **0.000** | 92.66 | **0.001** |
| Site × Season | 111.09 | **0.022** | 124.00 | **0.028** |
| Site × Tillage system | 87.08 | ns | 52.41 | Ns |
| Tillage system × Season | 74.34 | ns | 83.75 | Ns |
| Site × Season × Tillage system | 72.53 | **0.042** | 99.13 | **0.038** |

*Values are arithmetic means of SSC and SY for soil tillage systems at Goma and Kimenyedde experimental sites in Mukono District, Uganda. The superscript lower-case letters (a, b, c, d) in the rows represent significance at 5% for SSC and SY. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage; SY is for sediment yield; 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

## 4.7 Relationships between Rainfall Characteristics, Surface Runoff Volume, and Sediment Yield

Table 13 presents the results of Pearson correlation analysis between rainfall amount (RF) and rainfall intensity at 10 minutes ($RI_{10}$) with SRV and SY for four soil tillage systems for both experimental sites. At Goma experimental site, the correlation matrix (Table 13) showed that SRV positively associated with RF and $RI_{10}$ with *r*-values ranging from 0.63-0.87 and 0.65-0.92, respectively, across seasons. Correspondingly, SY positively associated with RF and $RI_{10}$ at Goma site. Although *r*-values for SY and RF were higher (> 60) for most of the soil tillage systems for all seasons, very weak correlations were observed between SY and RF under NT (*r* =

0.077) and DT (*r* = 0.068) during the second season. The $RI_{10}$ also showed some weak correlations with SY under DT (*r* = 0.014) and CT (*r* = 0.062) in the second season (Table 13).

At Kimenyedde experimental site, SRV positively correlated with RF and $RI_{10}$ with *r*-values ranging from 0.51-0.89 and 0.66-0.89, respectively, across all seasons. Correspondingly, SY positively associated with RF with *r*-values ranging from 0.32-0.75. Like at Goma experimental site, weak correlations were observed between SY and RF under NT (*r* = 0.32) and SM (*r* = 0.017) during the second season. The $RI_{10}$ showed weak correlations with SY under NT (*r* = 0.043) and CT (*r* = 0.051) in the second season (Table 13).

**Table 13:** Pearson Correlation Matrix between Surface Runoff Volume, Sediment Yield with Rainfall Amount and Rainfall Intensity 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* |
| | | SY | 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** |
| | | SY | 0.077 | 0.45* | 0.60* | 0.66* | 0.068 | 0.014 | 0.42* | 0.062 |
| | Three | SRV | 0.78* | 0.90* | 0.65* | 0.80* | 0.80* | 0.77* | 0.65* | 0.81* |
| | | SY | 0.66* | 0.79* | 0.62* | 0.60* | 0.59* | 0.75* | 0.77* | 0.65* |
| | All seasons | SRV | 0.85* | 0.82* | 0.73* | 0.74* | 0.76** | 0.84** | 0.70** | 0.59** |
| | | SY | 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** |
| | | SY | 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** |
| | | SY | 0.32 | 0.043 | 0.017 | 0.73* | 0.68* | 0.72** | 0.65* | 0.051 |
| | Three | SRV | 0.75* | 0.72* | 0.81* | 0.75* | 0.91* | 0.70* | 0.81* | 0.82** |
| | | SY | 0.49* | 0.38 | 0.42* | 0.75* | 0.81* | 0.65* | 0.66* | 0.70* |
| | All seasons | SRV | 0.82* | 0.70* | 0.71* | 0.89** | 0.83** | 0.68** | 0.82** | 0.77** |
| | | SY | 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; SRV is for surface runoff volume; SY is for sediment yield

## 4.8 Common Bean Grain Yield

Grain yields under soil tillage systems during the three seasons in the two experimental sites are presented in Fig. 12. Grain yields were considerably affected by seasons, soil tillage systems, and experimental sites. Seasonally, grain yields were 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, grain yields 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 yields by 3, 41, and 45% compared with SM, DT, and CT systems, respectively. When grain yields were compared between sites, Goma site (1506 kg ha$^{-1}$) produced 11% more yields than Kimenyedde site (1359 kg ha$^{-1}$).

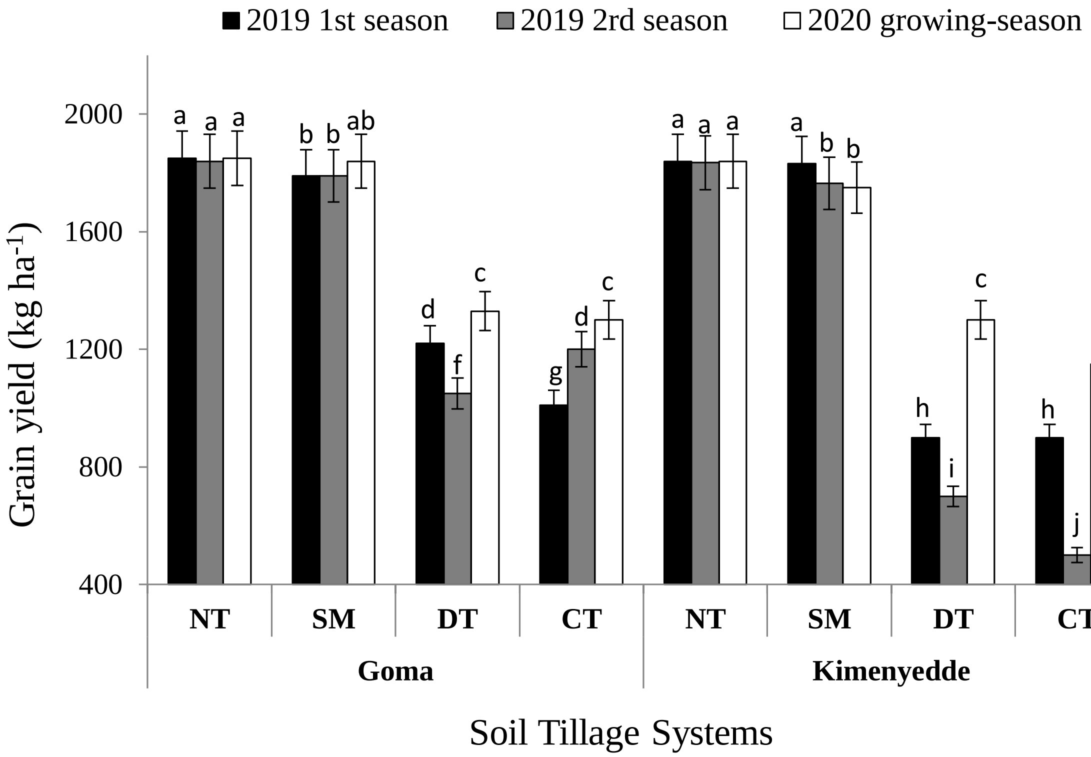


**Figure 12:** Effect of Soil Tillage Systems and Seasons on Common Bean Grain Yield at Goma and Kimenyedde Experimental Sites. Bars over the mean indicate a standard error, and the lower case letters indicate significance at 0.05. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage

## 4.9 Evapotranspiration and Water Use Efficiency

Table 14 presents ET and WUE-grain under the different soil tillage systems in three growing seasons at Goma and Kimenyedde experimental sites. The AET and the PET were not statistically different in the current study (Table 14). The AET significantly ($p < 0.05$) varied among soil tillage systems, but no statistical differences in AET were observed in seasons and experimental sites. The interactions between soil tillage system × experimental site and soil tillage system × season were also significant. Averaged across soil tillage systems and sites, AET was highest in the second season of 2019 (142 mm), followed by the first season of 2019 (131 mm), and lowest in the 2020 growing season (129 mm). The highest AET was recorded under CT (171 mm) and DT (168 mm), while NT (98 mm) and SM (99 mm) had the lowest AET. Averaged across all seasons, Goma site (133 mm) had a slightly lower evaporative demand than Kimenyedde site (145 mm).

The WUE-grain significantly ($p < 0.05$) varied among seasons and soil tillage systems. The interactions between experimental sites × seasons, experimental sites × soil tillage systems, and soil tillage system × season were also significant. Averaged across soil tillage systems and sites, 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 systems 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 WUE-grain between experimental sites, Goma site (1.28 kg $m^{-3}$) had slightly higher WUE-grain than Kimenyedde site (1.12 kg $m^{-3}$).

**Table 14:** Actual and Potential Evapotranspiration and Water Use Efficiency-yield for Common Beans under Different Soil Tillage Systems and Effect of Site, Season, Soil Tillage Systems on Evapotranspiration and Water Use Efficiency-yield at Goma and Kimenyedde Sites in Mukono District, Uganda

| *Experimental site* | *Growing season* | *Soil tillage system* | *PET* | *AET* | *WUE-yield* |
|---|---|---|---|---|---|
| | | | **mm** | | **kg m$^{-3}$** |
| Goma | 2019 1st season | NT | $97^{e}$ | $95^{e}$ | $1.94^{a}$ |
| | | SM | $96^{e}$ | $96^{e}$ | $1.79^{b}$ |
| | | DT | $160^{d}$ | $158^{d}$ | $0.77^{g}$ |
| | | CT | $163^{c}$ | $162^{c}$ | $0.62^{h}$ |
| | 2019 2nd season | NT | $100^{e}$ | $99^{e}$ | $1.80^{b}$ |
| | | SM | $100^{e}$ | $100^{e}$ | $1.69^{c}$ |
| | | DT | $166^{c}$ | $163^{c}$ | $0.65^{h}$ |
| | | CT | $170^{b}$ | $169^{b}$ | $0.71^{g}$ |
| | 2020 growing season | NT | $96^{e}$ | $96^{e}$ | $1.92^{a}$ |
| | | SM | $97^{e}$ | $97^{e}$ | $1.86^{b}$ |
| | | DT | $159^{d}$ | $158^{d}$ | $0.84^{f}$ |
| | | CT | $160^{d}$ | $160^{d}$ | $0.81^{f}$ |
| Kimenyedde | 2019 1st season | NT | $96^{e}$ | $95^{e}$ | $1.76^{c}$ |
| | | SM | $98^{e}$ | $97^{e}$ | $1.65^{d}$ |
| | | DT | $162^{d}$ | $161^{d}$ | $0.56^{h}$ |
| | | CT | $164^{c}$ | $164^{c}$ | $0.55^{h}$ |
| | 2019 2nd season | NT | $107^{f}$ | $106^{f}$ | $1.58^{d}$ |
| | | SM | $107^{f}$ | $107^{f}$ | $1.43^{e}$ |
| | | DT | $179^{a}$ | $177^{a}$ | $0.39^{i}$ |
| | | CT | $178^{a}$ | $178^{a}$ | $0.28^{i}$ |
| | 2020 growing season | NT | $97^{e}$ | $96^{e}$ | $1.78^{bc}$ |
| | | SM | $97^{e}$ | $97^{e}$ | $1.70^{c}$ |
| | | DT | $160^{d}$ | $159^{d}$ | $0.82^{f}$ |
| | | CT | $164^{c}$ | $163^{c}$ | $0.71^{g}$ |

| **Factor** | **ANOVA-table** | | | |
|---|---|---|---|---|
| | **AET (mm)** | | **WUE-yield (kg m$^{-3}$)** | |
| | **F-value** | ***p*-value** | **F-value** | ***p*-value** |
| Experimental site | 131.201 | **0.040** | 150.311 | **0.042** |
| Season | 125.221 | **0.021** | 221.006 | **0.048** |
| Soil tillage system | 064.521 | **0.001** | 085.510 | **0.002** |
| Experimental site × Season | 151.000 | **0.036** | 321.012 | **0.049** |
| Experimental site × Soil tillage system | 092.021 | ns | 100.030 | Ns |
| Soil tillage system × Season | 105.104 | **0.031** | 204.214 | **0.021** |
| Experimental site × Season × Soil tillage system | 153.160 | ns | 075.126 | Ns |

NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage; AET is for actual evapotranspiration; PET is for potential evapotranspiration; WUE-yield is for grain yield water use efficiency. Values with the same superscript letters within a column are not significantly different at $p = 0.05$. The *p*-values marked in bold are considered significant ($p < 0.05$); non- significant *p*-values are reported as "ns" in the ANOVA.

## 4.10 Gross Cost, Net Profit, and Benefit-cost Ratio

The cost of production/gross cost and economic benefits/net profit of the common beans under the different soil tillage systems in Goma and Kimenyedde experimental sites are shown in Table 15. The gross cost varied significantly ($p < 0.05$) among soil tillage systems, with DT having two and one and half times higher gross cost than NT and CT, respectively. Gross cost for DT and SM were indistinguishable. The net profit was five and three times higher under NT system compared with DT and CT systems, respectively. The BCR was greater than one under NT and SM and less than one under DT and CT (Table 15).

**Table 15:** Estimated 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 16 Months

| *Tillage system* | *Gross cost (USD ha$^{-1}$)* | *Gross revenue (USD ha$^{-1}$)* | *Net profit (USD ha$^{-1}$)* | *Benefit-cost ratio* |
|---|---|---|---|---|
| NT | 642$^{c}$ | 2471$^{a}$ | 1829$^{a}$ | 2.85$^{a}$ |
| SM | 1173$^{a}$ | 2352$^{a}$ | 1179$^{b}$ | 1.01$^{b}$ |
| DT | 1181$^{a}$ | 1523$^{b}$ | 342$^{d}$ | 0.29$^{d}$ |
| CT | 787$^{b}$ | 1419$^{c}$ | 631$^{c}$ | 0.80$^{c}$ |
| ***F-statistics*** | *102.34* | *98.64* | *99.95* | *59.41* |

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

## 4.11 Model Sensitivity Analysis

All the important parameters for SRV and SY components were included in a sensitivity analysis. The SRV was more sensitive to $CN_2$, CNIC, and RCFC, while SY was mainly sensitive to PEC, $CN_2$, APM, and CNIC (Table 16). Calibration values for $CN_2$ were 23, 24, 35, and 55 for NT, SM, DT and CT, respectively, at Goma experimental site. At Kimenyedde experimental site, $CN_2$ values were 22, 22, 30, and 50 for NT, SM, DT and CT, respectively. The PEC values were 0.21, 0.21, 0.24, and 0.26 for NT, SM, DT and CT, respectively, at Goma experimental site. At Kimenyedde experimental site, PEC values were 0.20, 0.20, 0.30, and 0.65 for NT, SM, DT and CT, respectively. The CNIC, SRV adjustment factor (Parm92), and APM were calibrated to 1.5, 1.2, and 1.0, respectively. The rest of the parameter values were kept at APEX defaults.

**Table 16:** APEX Model Sensitive Parameters Considered in this Study

| *Parameter* | *Description* | *Range* | *Ranking* | | *Final value* |
|---|---|---|---|---|---|
| | | | **Runoff** | **Sediment** | |
| $CN_2$ | Initial input of condition 2 curve number | 20-90 | 1 | 2 | 23[a] (NT), 24[a] (SM), 35[a] (DT), 55[a] (CT): Goma<br>22[a] (NT), 22[a] (SM), 30[a] (DT), 50[a] (CT): Kimenyedde |
| PEC | Erosion control practice factor | 0.1-1.0 | 10 | 1 | 0.21[a] (NT), 0.21[a] (SM), 0.24[a] (DT), 0.26[a] (CT): Goma<br>0.20[a] (NT), 0.20[a] (SM), 0.30[a] (DT), 0.65[a] (CT): Kimenyedde |
| DIFFW | Difference of soil water contents at field capacity and wilting point | 0.03-0.16 | 9 | 7 | 0.15 |
| SATC | Saturated conductivity | 8-50 | 7 | 12 | 9.4 |
| SEC (parm12) | Soil evaporation coefficient | 1.5-2.5 | 12 | 13 | 1.5 |
| PCF (parm17) | Soil evaporation-plant cover factor | 0.0-0.5 | 14 | 11 | 0.1 |
| RCNIA(parm20) | Runoff curve number initial abstraction | 0.05-0.4 | 4 | 6 | 0.2 |
| HPETE (parm34) | Hargreaves PET equation exponent | 0.5 - 0.6 | 13 | 9 | 0.6 |
| CNIC (parm42) | Curve number index coefficient | 0.5-5.0 | 2 | 4 | 1.5[a] |
| RCFC (parm46) | RUSLE C factor exponential residue coefficient | 0.5-5.0 | 3 | 5 | 1.5 |
| RCF (parm47) | RUSLE C factor exponential crop height coefficient | 0.01-3.0 | 8 | 8 | 0.01 |
| RIC (parm50) | Rainfall interception coefficient | 0.05-0.3 | 5 | 10 | 0.1 |
| Parm90 | Subsurface flow factor | 1-100 | 15 | 15 | 1 |
| Parm92 | Runoff volume adjustment factor | 0.1–2.0 | 6 | 14 | 1.2[a] |
| APM | Peak runoff rate-rainfall energy adjustment factor | 0.1-1.0 | 11 | 3 | 1.0[a] |

[a] Values were calibrated. The rest of the parameter values are APEX defaults

## 4.12 Calibrated and Validated for Surface Runoff under Different Soil Tillage Systems

The calibration and validation results of SRV under four soil tillage systems for two experimental sites are presented in Table 17 & appendices 3-6. The simulated SRV was in good agreement with the observed data at both sites irrespective of the soil tillage system. When the APEX model was calibrated, model parameters were adjusted to maximize model performance for SRV within all the soil tillage systems, which resulted in very good $R^2$ and NSE-values, but slightly over predicted SRV under NT (PBIAS = -10.47) and SM (PBIAS = -9.32) at Goma site. Similarly, APEX model calibration also slightly over estimated SRV under NT (PBIAS = -6.51) and SM (PBIAS = -4.36) at Kimenyedde experimental site. The APEX model slightly under estimated SRV under DT (PBIAS = 12.91) and CT (PBIAS = 10.61) at Goma site. Similar results were observed at Kimenyedde site: DT (PBIAS = 7.19) and CT (PBIAS = 14.15). The $R^2$-values on calibration for SRV under NT, SM, DT, and CT were 0.88, 0.94, 0.93, and 0.92, respectively, at Goma experimental site (Fig. 13 A). At Kimenyedde experimental site, $R^2$-values were 0.95, 0.96, 0.97, and 0.95 for NT, SM, DT, and CT, respectively (Appendix 11). The NSE-values on calibration for SRV under NT, SM, DT, and CT were 0.76, 0.93, 0.91, and 0.92, respectively, at Goma site. Similarly, high NSE-values of 0.90, 0.95, 0.96, and 0.94 under NT, SM, DT, and CT, respectively, on calibration for SRV were observed at Kimenyedde experimental site (Table 17).

**Table 17:** APEX Model Calibrated and Validated Surface Runoff Volume at Goma and Kimenyedde Experimental Sites

| *Soil tillage system* | ***Calibration*** | | | ***Validation*** | | |
|---|---|---|---|---|---|---|
| | **$R^2$** | **NSE** | **PBIAS** | **$R^2$** | **NSE** | **PBIAS** |
| **Goma experimental site** | | | | | | |
| NT | 0.88 | 0.76 | -10.47 | 0.93 | 0.79 | -2.10 |
| SM | 0.94 | 0.93 | -9.32 | 0.96 | 0.96 | -4.52 |
| DT | 0.93 | 0.91 | 12.91 | 0.95 | 0.94 | 11.74 |
| CT | 0.92 | 0.92 | 10.61 | 0.97 | 0.94 | 15.68 |
| **Kimenyedde experimental site** | | | | | | |
| NT | 0.95 | 0.90 | -6.51 | 0.95 | 0.93 | -2.65 |
| SM | 0.96 | 0.95 | -4.36 | 0.97 | 0.98 | -5.58 |
| DT | 0.97 | 0.96 | 7.19 | 0.76 | 0.99 | 12.36 |
| CT | 0.95 | 0.94 | 14.15 | 0.95 | 0.97 | 3.22 |

$R^2$ is for the coefficient of determination; NSE is for Nash-Sutcliffe efficiency; PBIAS is for percent bias; NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage

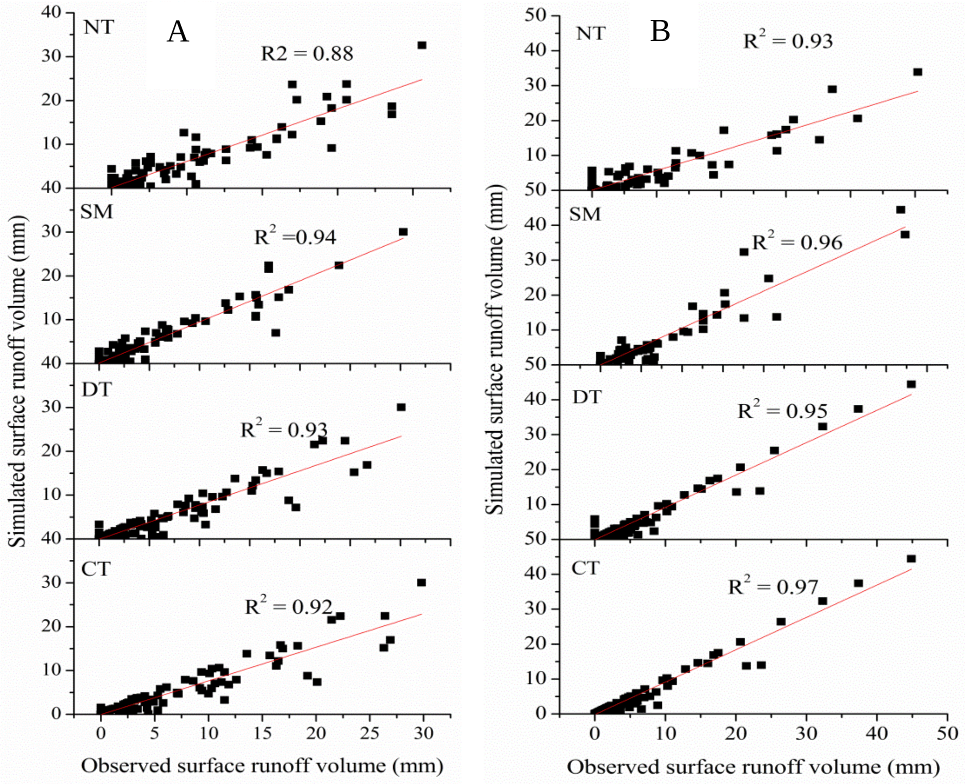


**Figure 13:** Relationships Between Surface Runoff Volume Observed from Field Experiments and Simulated with APEX for the model calibration (A) and Validation (B) at Goma Site

Simulated SRV results with the calibrated model for validation were very close to the results of the field experiments (Fig. 14 & 15). The cumulative observed SRV (317 mm) during the validation period (January-July 2021) was 21 mm less than the simulated SRV (338 mm) under the NT system at Goma experimental site. Similarly, the model over estimated SRV under SM with the observed cumulative values (356 mm) less than the simulated values (371 mm) by 15 mm. Under DT and CT, SRV was under estimated by the model. The cumulative observed and simulated SRV were 458 and 449 mm, respectively under DT. Under CT, cumulative SRV were 508 and 493 mm for observed and simulated SRV, respectively at Goma experimental site. At Kimenyedde experimental site, a similar trend was observed, where the model over estimated SRV under NT and SM, and under estimated SRV under DT and CT. The cumulative SRV during the validation period for the observed and simulation were 290 and 302 mm, respectively, under NT at Kimenyedde experimental site. The observed and estimated cumulative SRV under SM were 334 and 342 mm, respectively. The cumulative observed and simulated SRV were 421 and 403 mm, respectively under DT. Under CT, cumulative SRV was 464 and 452 mm for observed and simulated SRV values, respectively at Kimenyedde experimental site (Fig. 15 B). The PBIAS-values for SRV under all soil tillage systems and experimental sites were within ±20% range (Table 17). The $R^2$-values on validation for SRV under NT, SM, DT, and CT were 0.93, 0.96, 0.95, and 0.9, respectively, at Goma experimental site (Fig. 13 B). At Kimenyedde experimental site, $R^2$-values on validation for SRV under NT, SM, DT, and CT were 0.95, 0.96, 0.97, and 0.95, respectively (Appendix 11). The NSE-values on validation for SRV under NT, SM, DT, and CT were 0.79, 0.96, 0.94, and 0.94, respectively, at Goma experimental site. At Kimenyedde experimental site, NSE-values on model validation were 0.93, 0.98, 0.99, and 0.97 under NT, SM, DT, and CT, respectively (Table 17).

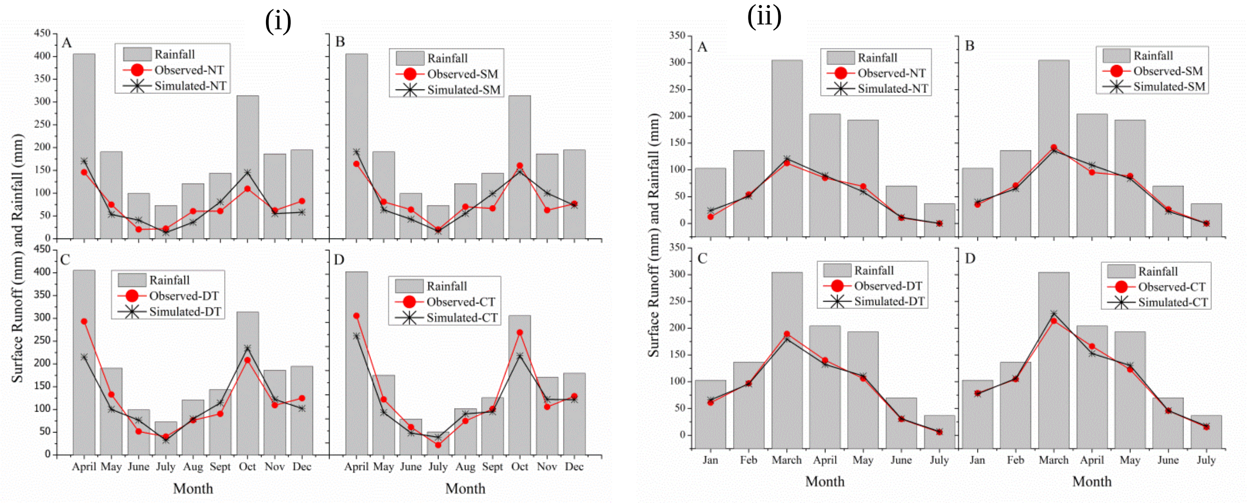


**Figure 14:** Calibrated (i) and Validated (ii) Surface Runoff Volume at Goma Experimental Site under Different Soil Tillage Systems

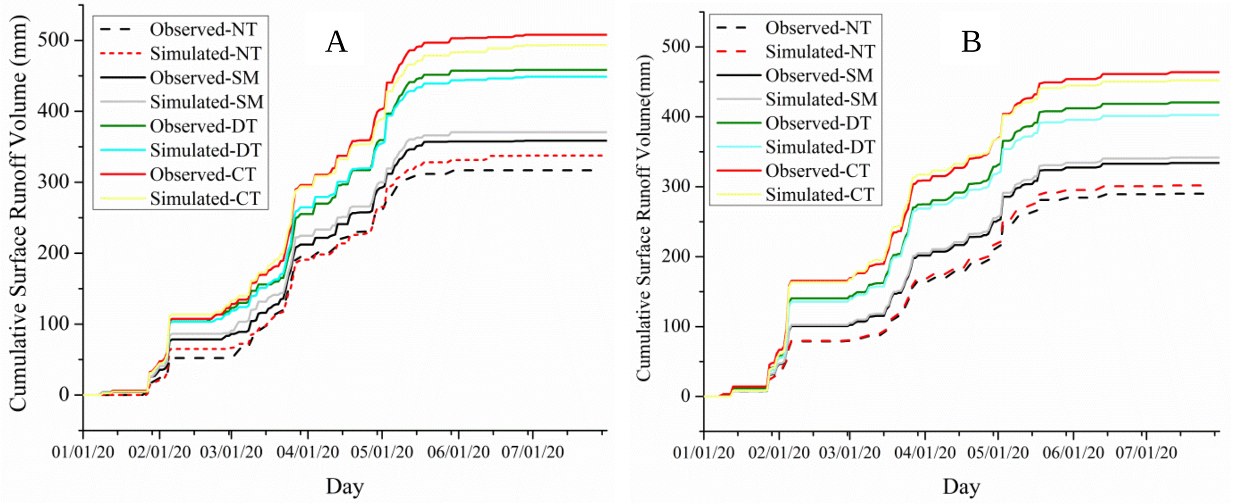


**Figure 15:** Cumulative Validated Surface Runoff Volume under Different Soil Tillage Systems at Goma (A) and Kimenyedde (B) Experimental Sites

## 4.13 Calibrated and Validated for Sediment Yield under Different Soil Tillage Systems

Table 18 and appendices 7-10 present the results from calibration and validation of the APEX model for SY under different soil tillage systems for two experimental sites. From PBIAS results, the APEX model slightly over estimated SY under NT and SM at both sites. The SY under DT and CT were slightly under estimated by the model. However, regardless of soil tillage systems and sites, PBIAS-values were within ±13% range. The $R^2$-values of on calibration for SY under NT, SM, DT, and CT were 0.71, 0.82, 0.80, and 0.79, respectively, at Goma experimental site. At Kimenyedde experimental site, $R^2$-values were 0.69, 0.70, 0.78, and 0.79 for NT, SM, DT, and CT, respectively. The NSE-values on calibration for SY under NT, SM, DT, and CT were 0.77, 0.81, 0.80, and 0.77, respectively, at Goma experimental site. The NSE-values of 0.66, 0.67, 0.75, and 0.79 under NT, SM, DT, and CT, respectively for SY, were observed at Kimenyedde experimental site (Table 18).

**Table 18:** APEX Model Calibration and Validation for Sediment Yield at Goma and Kimenyedde Experimental Sites

| *Soil tillage system* | *Calibration* | | | *Validation* | | |
|---|---|---|---|---|---|---|
| | **$R^2$** | **NSE** | **PBIAS** | **$R^2$** | **NSE** | **PBIAS** |
| **Goma experimental site** | | | | | | |
| NT | 0.71 | 0.77 | -13.62 | 0.89 | 0.70 | -8.69 |
| SM | 0.82 | 0.81 | -3.33 | 0.92 | 0.87 | -3.78 |
| DT | 0.80 | 0.80 | 4.85 | 0.81 | 0.81 | 11.28 |
| CT | 0.79 | 0.77 | 10.16 | 0.83 | 0.80 | 13.15 |
| **Kimenyedde experimental site** | | | | | | |
| NT | 0.69 | 0.66 | -13.12 | 0.76 | 0.79 | -3.14 |
| SM | 0.70 | 0.67 | -12.41 | 0.88 | 0.76 | -9.68 |
| DT | 0.78 | 0.75 | 8.52 | 0.80 | 0.81 | 4.55 |
| CT | 0.79 | 0.79 | 2.35 | 0.82 | 0.82 | 10.61 |

$R^2$ is for the coefficient of determination; NSE is for Nash-Sutcliffe efficiency; PBIAS is for percent bias; NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; CT is for conventional tillage

On validation of the APEX model, cumulative simulated SY results were very close to the results of the field experiments (Fig. 16 & 17). At Goma site, the cumulative SY during the validation period for the observed and simulation were 147.11 and 155.65 kg ha$^{-1}$, respectively. The observed and estimated cumulative SY under SM were 168.74 and 176.21 kg ha$^{-1}$, respectively. The cumulative observed and simulated SY were 211.47 and 204.47 kg ha$^{-1}$, respectively under DT. Under CT, cumulative SY was 283.91 and 277.71 kg ha$^{-1}$ for observed and simulated SY values, respectively at Goma site (Fig. 17 A). The cumulative observed and simulated SY were 119.94 and 126.72 kg ha$^{-1}$, respectively under NT during the validation period at Kimenyedde site. Under SM, the cumulative observed and simulated SY values were 138.89 and 144.21 kg ha$^{-1}$, respectively. The cumulative observed and simulated SY were 181.47 and 174.47 kg ha$^{-1}$, respectively under DT. Under CT, cumulative SY were 253.91 and 243.21 for observed and simulated SY, respectively at Kimenyedde site (Fig. 17 B). The $R^2$-values on validation for SY under NT, SM, DT, and CT were 0.89, 0.92, 0.81, and 0.83, respectively, at Goma experimental site. At Kimenyedde site, $R^2$-values for SY under NT, SM, DT, and CT were 0.76, 0.88, 0.80, and 0.82, respectively. The NSE-values on validation for sediment yield under NT, SM, DT, and CT were 0.70, 0.87, 0.81, and 0.80, respectively, at Goma experimental site. At Kimenyedde experimental site, the NSE-values of the model were 0.79, 0.76, 0.81, and 0.82 under NT, SM, DT, and CT, respectively (Table 18).

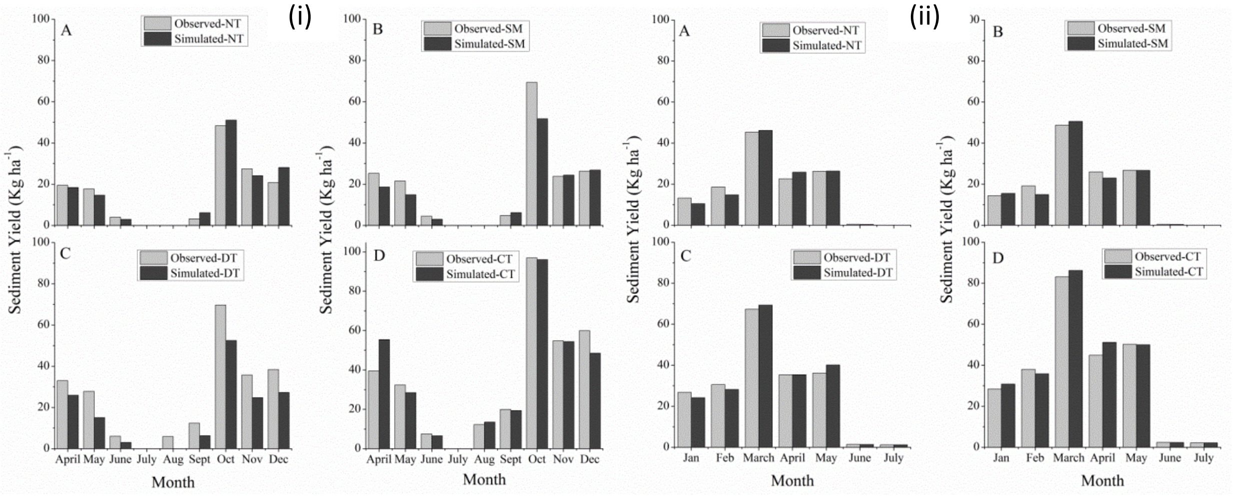


**Figure 16:** Calibrated (i) and Validated (ii) Sediment Yield at Kimenyedde Experimental Site under Different Soil Tillage Systems

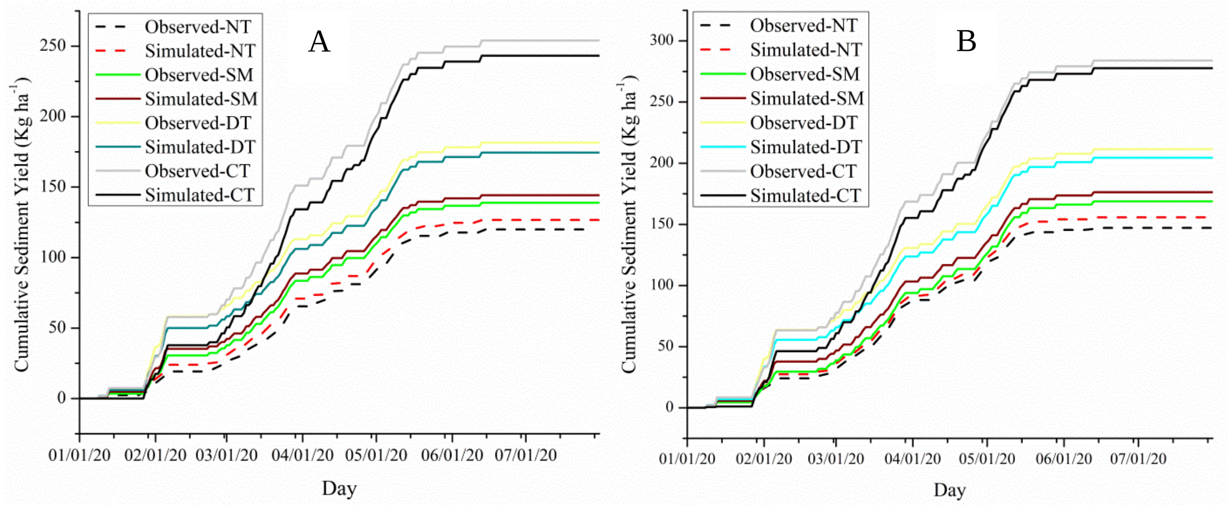


**Figure 17:** Cumulative Validated Sediment Yield under Different Soil Tillage Systems at Goma (A) and Kimenyedde (B) Experimental Sites

# CHAPTER FIVE

# DISCUSSION

## 5.1 Variations in Soil Characteristics under Different Soil Tillage Systems

The soil tillage systems influenced soil OC, N content, and soil BD (Table 10). 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 10; Rahman *et al.* (2008)]. The higher soil pH-values under NT and SM could be attributed to the decomposition of the organic matter [Table 10; Rhoton (2000)], which increased electrolytes concentration (McCauley *et al.*, 2017; Rahman *et al.*, 2008) under NT and SM systems. 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 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 10; 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 & Schlegel, 2010).

The N content was higher under NT and SM than under DT and CT systems (Table 10), 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/cm$^3$ 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.

## 5.2 Effect of Soil Tillage Systems on Steady-state Infiltration Rate

The steady-state IR significantly ($p$ = 0.000, F = 96.34) varied among soil tillage systems with the lowest steady-state IR under CT and DT, while the highest under NT and SM (Fig. 8). The current results are in line with observations reported in 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 IR under NT (17 mm/min) compared with under CT (4 mm/min). Similarly, Fan *et al.* (2013) reported a 59 and 16% higher IR 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 IR 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 soil aggregate, which exposed the soil to the impact of direct raindrops (Abu-Hamdeh *et al.*, 2006; Glanville & 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 IR. Conversely, conservation systems are advantageous in increasing IR primarily due to residue retention that provides enough time to the water before running off (Celik & Ersahin, 2011; Fan *et al.*, 2013; Wang *et al.*, 2011).

The IR significantly (*p* = 0.029, F = 2.56) varied between the experimental sites with higher IR observed at Kimenyedde experimental site than Goma site (Fig. 8). These variations in 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) at Goma experimental site could have led to seal formation on the soil surface, resulting in reduced water infiltration (Lado *et al.*, 2004; Mamedov *et al.*, 2001; Stern *et al.*, 1991).

### 5.3 Effect of Soil Tillage Systems on Soil Moisture Content

The SMC significantly (*p* = 0.000, F= 120.01) varied among the soil tillage systems, with the highest SMC under NT and the lowest under CT system. The current observations are in line with the findings of Kladivko (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 CT systems. Filho *et al.* (2013) reported a 10 and 6, 7 and 6% increase in SMC at 0-5 and 5-10 cm depth under NT and RT, respectively, compared with CT. In the Pampas region of Argentina, Alvarez and Steinbach (2009) observed 13-14% more SMC under NT than tilled plots. Soil water retention under NT and SM could be explained by the presence of crop residues and mulches; which increased water infiltration into the soil and reduced evaporation rate (Šarauskis *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 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 soil tillage systems, significantly ($p < 0.05$) higher SMC was observed at Goma than Kimenyedde experimental site (Fig. 9). The variations in soil types and rainfall amounts could have been the primary cause of the differences in SMC at 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 at Goma and Kimenyedde experimental sites could considerably explain the variations in 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 11), which could have resulted in higher SMC.

## 5.4 Seasonal Variations in the Soil Water Storage among Soil Tillage Systems

The highest values of SWS were recorded during the 2020 growing season and the first season of 2019. Probably, during the 2020 growing season and the first season of 2019, higher precipitation amount (Fig. 7) improved the hydraulic properties and increased SWS. Precipitation amount and distribution can significantly influence SWS both in space and time (Semalulu *et al.*, 2015).

The influence of soil tillage systems on SWS was highly significant at harvesting than at planting. The SWS decreased as soil tillage intensity increased (Fig. 10 & 11). The effect of soil tillage systems on 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 conservation tillage compared to CT. The indistinguishable SWS under NT and SM signifies that 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 among seasons on SWS were appreciable at Kimenyedde and negligible at Goma experimental site. The lower SWS at Kimenyedde experimental site were probably due to the higher evaporative demand (Table 14) and lower precipitation amount (Fig. 7; Table 11). Therefore, soil tillage technologies (such as mulch tillage) that reduce soil disturbances would be vital for areas with higher evaporative demands, e.g. Kimenyedde experimental site, which would help in increasing water retention and water availability to the crops.

### 5.5 Effect of Soil Tillage Systems and Seasons on Surface Runoff Volume

The SRV significantly varied among the soil tillage systems ($p$ = 0.000, F = 242.40), with the highest SRV under CT, followed by DT, SM, and was lowest under NT (Table 11). The lower SRV observed under NT and SM indicated that majority of rainfall received infiltrated into the soil (Fig. 8). 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 RT) relative to the CT. As reported by Akinbile (2010), the magnitude of surface runoff greatly depends on the IR, which in turn is controlled by the inherent properties of the soil (Akinbile *et al.*, 2016; Bhatt & Khera, 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 & Catt, 2004).

Goma experimental site showed relatively higher SRV as opposed to Kimenyedde experimental site (Table 11), 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 IR and evaporation. In line with the current observations, Inocencio *et al.* (2003) reported significantly lower SRV in soils with low clay content than soils with high clay content. Additionally, the slightly higher rainfall at Goma than

Kimenyedde experimental site (Table 11) 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 & Catt, 2004).

## 5.6 Effect of Soil Tillage Systems on Suspended Sediment Concentration and Sediment Yield

Soil tillage systems significantly influenced SSC (F = 81.12, $p = 0.000$) and SY ($p = 0.001$, F = 92.66) with the lowest SSC and SY recorded under NT and the highest under CT (Table 12). The current results are consistent with the findings of Tiessen *et al.* (2010) and Truman *et al.* (2005), who observed four times higher SY under CT than under NT system. Soil tillage systems with crop residues (NT and SM) significantly reduced SSC and SY than soil tillage systems 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), Dagnew *et al.* (2017), and Bagagiolo *et al.* (2018), SSC is influenced by soil and management practices; and disturbed ecosystems tend to produce more SSC than natural and undisturbed ecosystems. Bagagiolo *et al.* (2018) reported 2 to 4 times higher SSC under NT than under CT system. Fawcett *et al.* (1994), Wauchope (1978), and Tiessen *et al.* (2010) reported a 44 to 90% reduction in SY under conservation tillage practices relative to CT system. Owens *et al.* (2002) and Pulley and Collins (2020) respectively recorded 2.2 and 5.4 times more SY under disturbed soils than under 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 decreased erosion (Tiessen *et al.*, 2010). The

SSC varied seasonally, probably because of the variations in seasonal runoff, which influence sediment transport capacity.

## 5.7 Effect of Rainfall Amount and Intensity on Surface Runoff Volume and Sediment Yield

Strong and significant ($p < 0.05$) correlations were observed between SRV with rainfall amount (RF) and rainfall intensity at 10 minutes ($RI_{10}$) (Table 13). 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 influence IR, SMC, and SWS (Bronstert & Bárdossy, 2003); which affect the magnitude of surface runoff.

The SY was strongly and positively influenced by both rainfall amount and rainfall intensity (Table 13). In the relatively dry soils with low rainfall amount and rainfall intensity, suspended sediment response is often low and *vice versa* (Lana-Renault *et al.*, 2007). The increase in SY with precipitation amount (Table 13) was primarily due to the increase in SRV with the associated detachment of the soil from the surface.

## 5.8 Effect of Soil Tillage Systems on 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 soil tillage systems. Although the current precipitation (392-538 mm) was within the range (300-500 mm) of precipitation suitable for common bean production (Beebe *et al.*, 2011), precipitation distribution and dry spells were common during the seasons. These dry spells (which occurred for about ten days at the flowering stage) could have affected grain yields in the current study. Mubiru *et al.* (2018) noted that the low crop productivity in SSA under the rainfed agricultural systems is primarily due to uneven distribution of precipitation across the seasons than low annual precipitation.

When averaged across soil tillage systems and sites, grain yields produced in the 2020 growing season (1545 kg $ha^{-1}$) and the first season of 2019 (1418 kg $ha^{-1}$) was significantly higher than grain yields 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 grain yields.

Conservation tillage practices of reducing/eliminating tillage and retaining crop residues and mulches significantly impacted grain yields 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 grain yields 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 crop residues and mulches. The DT and CT significantly lost water inform of evapotranspiration through frequent weeding (Table 14). Additionally, crop residues and mulches under NT and SM could have improved nutrient supply to crops under these systems (Table 10), which improved grain yields. Both Mrabet (2000) and Cantero-Martínez *et al.* (2007) concluded that the higher yields 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, grain yield varied among seasons and sites. The low and variable grain yields under DT and CT at Goma and Kimenyedde sites were primarily due to the spatial differences in precipitation distribution [Fig. 7; Uganda National Meteorological Authority (UNMA) (2019)]. Averaged across seasons and soil tillage systems, Goma site had higher grain yields than Kimenyedde experimental site. The higher grain yields at Goma site was not only because of the higher precipitation but also because the precipitation was evenly distributed (less than five consecutive dry days) than that of Kimenyedde, which had a dry spell of twelve days.

## 5.9 Effect of Soil Tillage Systems on Water Use Efficiency

Averaged across soil tillage systems and experimental sites, 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 14). The WUE-grain was most remarkable in the 2020 growing season and the first season of 2019 because of better precipitation distribution and crop yields in both seasons. Lower WUE-grain was observed in the second season of 2019 due to the higher evaporative demand in this season (Table 14) and lower grain yields 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 common bean fields during the season with short and erratic precipitation.

The WUE-grain was highest under NT and SM and lowest under DT and CT systems (Table 14). The smaller quantities grain yields and higher AET under DT and CT were responsible for the low WUE-grain in these soil tillage systems relative to NT and SM systems. 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 yields on WUE-grain for various crops and reported a correlation (r) of 0.834 between grain yields and WUE-grain. Additionally, variations in SWS among soil tillage systems could be responsible for the considerably high variations of WUE-grain in these tillage systems. Studies by Angadi *et al.* (2008) and Mbava *et al.* (2020) 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 yields 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.

## 5.10 Variations in Gross Cost and Economic Returns under different Soil Tillage Systems

The gross cost varied significantly ($p < 0.05$) among soil tillage systems (Table 15) 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 common bean fields, who reported higher gross costs under CT than conservation tillage practices. The reduced gross cost under NT could primarily be attributed to the less labor required for management practices such as cultivation, machinery, and weeding, since weeds were controlled using herbicides. Additionally, crop residues and mulches under NT helped suppress weeds, which reduced costs of herbicide and labor, hence further lowering gross cost (Lal *et al.*, 2003). The DT, CT, and SM systems 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 land during seedbed preparation and constant weeding episodes increased gross cost under CT and DT (Mloza-Banda & Nanthambwe, 2011).

Economic benefits (in terms of net profit) varied significantly ($p < 0.05$) among soil tillage systems, with the highest net profit under NT and the lowest under DT (Table 15). 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 grain yield under these soil tillage systems than under NT and SM systems. Franke *et al.* (2014) noted that low quantities of grain yield have regularly reduced profitability in the eastern Africa region. The argument seems to be necessary, as Kihara *et al.* (2011) also reported that net profit from a given soil tillage practice is often based on the quantities of yield from that particular soil tillage practice.

Additionally, BCR was > 1 under NT and SM and < 1 under DT and CT systems. Similar observations were reported by Jabran and Aulahk (2015) in wheat fields, 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.

Despite the benefits (i.e. improving yield, soil-water conservation, and economic returns) of conservation tillage practices, its adoption rate is very slow in Uganda. Several factors have been attributed to the slow adoption rate of conservation tillage practices in Uganda, but the principal among them are; competition for crop residues for use as animal fodder (Corbeels *et al.*, 2014; Giller *et al.*, 2009) and lack of knowledge and information by the small holder farmers about conservation tillage practices (Kaweesa *et al.*, 2018).

## 5.11 APEX Sensitivity, Calibration, and Validation for Surface Runoff Volume and Sediment Yield

The selection of the APEX parameters used in the sensitivity analysis was based on Mudgal *et al.* (2010). The SRV was strongly affected by $CN_2$ and CNIC parameters. In addition to $CN_2$ and CNIC, the SY component was strongly influenced by PEC and APM (Table 16). Other studies, e.g. Assefa *et al.* (2018), Kumar *et al.* (2011), Wang *et al.* (2006), and Green *et al.* (2006), showed a need to calibrate for $CN_2$ and CNIC in soil hydrological evaluation with simulation models. In line with the current study, Bracmort *et al.* (2006) reported high sensitivity of PEC and APM in SY simulation.

The APEX model estimates of SRV and SY were excellent when the calibrated APEX was used to simulate SRV and SY for the validation period (Table 17 & 18). Other studies showed satisfactory results for surface runoff calibration and validation with the APEX model (Luo & Wang, 2019; Wang *et al.*, 2008). Francesconi *et al.* (2014) in northeast Indiana, Assefa *et al.* (2018) in SSA, and Wang *et al.* (2009) in China, all reported good results in the calibration and validation of APEX model for SRV and SY. For both SRV and SY, NSE-values were > 0.5, which met the criteria of this study. Krause *et al.* (2005) and Moriasi *et al.* (2007) suggested a lower bound of NSE-values (0.5) to be sufficient for monthly comparisons of the simulated and observed SRV and SY data. The PBIAS-values for both SRV and SY under all soil tillage systems and sites were within a range of ±20% upon validation. Moriasi *et al.* (2007) and Wang *et al.* (2012) reported PBIAS-values within ±20 and ±45% for SRV and SY, respectively, as standards for a satisfactory APEX model.

# CHAPTER SIX

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

In this study, the effect of soil tillage systems on SRV, IR, SMC, SWS, SSC, and SY at a farm level was evaluated. The study also investigated the effect of soil tillage systems, seasons, and locality on WUE-grain, grain yield, and economic returns in the common bean fields. The APEX model was also applied to estimate the effect of soil tillage systems on SRV and SY in Mukono District, Uganda. The results showed that SRV, SSC/SY, IR, and SMC were significantly ($p < 0.05$) influenced by the soil tillage systems, tillage direction, seasons, and experimental sites. The CT system with TDS increased SRV by 2-6 fold compared with other tillage systems. Results of NT and SM for two seasons (6 months) indicated the advantage of NT and SM in reducing SRV and SY and improving IR and SMC in common bean fields. Adoption of NT and SM systems could help reduce environmental degradation issues currently affecting the African continent.

The NT and SM improved soil water conservation and WUE-grain, saving about 44 and 42% of soil water than the CT system. However, this study suggested that conservation tillage practices' ability to conserve water depends mainly on 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 yields. The higher grain yield and lower AET under NT and SM were the main reason behind the higher WUE-grain in these soil tillage systems.

Water scarcity and moisture deficiency are increasingly affecting Uganda's crop production. 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 tillage practice in a given locality must, therefore, be economically justified. In this study, the net profit was 3 and 5 times higher under NT than under CT and DT systems, respectively, indicating that NT and SM are economically feasible for central Uganda due to their higher economic returns.

The APEX model calibration and validation for SRV provided excellent results ($R^2 > 0.80$; NSE > 0.60, and PBIAS = ±15) under all soil tillage systems. Good results ($R^2 = 0.69$-0.92; NSE = 0.66-82, and PBIAS = ±13) were obtained when APEX model was calibrated and validated for SY. Overall, this study showed that the APEX model could be successfully applied to evaluate the impacts of the different soil tillage systems on SRV and SY in central Uganda.

## 6.2 Recommendations

In the current study, NT and SM systems are recommended for adoption in central Uganda due to their extraordinary ability to increase the IR, SWS and reduce SRV and SSC/SY. Therefore, minimising soil disturbances and maintaining soil surface cover is highly recommended as a feasible and affordable mechanism in reducing soil and environmental degradation. The CT system was the greatest source of SRV and SY, and it should be prioritized for conservation actions.

The current study identified the soil tillage systems that could boost grain yield while increasing soil-water conservation. Based on the results, a model soil-water conservation practice for any farm is yet possible. For environmental degradation abatement options, tradeoffs should be principally considered by taking into account crop productivity, ecosystem services, and soil-water conservation. But to arrive at the best combination of tradeoffs between environmental conservation and crop productivity options, an all-inclusive learning process where farmers and scientists continuously cooperate/collaborate to experiment and produce data sets is recommended.

The government and local institutions should accommodate the current research outputs on soil-water conservation in the decision-making and planning policies. Creating awareness and capacity building through training of the local government officials and local farmers will reduce the knowledge gap of cropping technologies and environmental conservation.

The impact of agriculture on the environment has emerged strongly since the onset of farming by man. Crop production has been and remains the basis of our development, yet is more detrimental to the environment than many other activities of man in our planet. Improving the use of computer-based simulation models for agricultural developments and planning could reduce the uncertainties created by anthropogenic activities, thus increasing effective allocation of resources. Due to the complexity of soil tillage practice and cropping systems in agro-ecological and sociopolitical aspects, conclusive decisions on the application of the APEX model or any simulation model across geographies is challenging. Therefore, several studies are required to evaluate the applicability of the APEX model in all regions of Uganda.

While the current study is case-specific and was conducted within one and half - years' time scale, it has valuable information that can inform the future on potential options to explore tradeoffs between environmental issues and economic returns. However, due to the variability in climate conditions and soil types, related studies should be carried out in other areas to generalize the findings over a long-term.

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# APPENDICES

(a) No-tillage

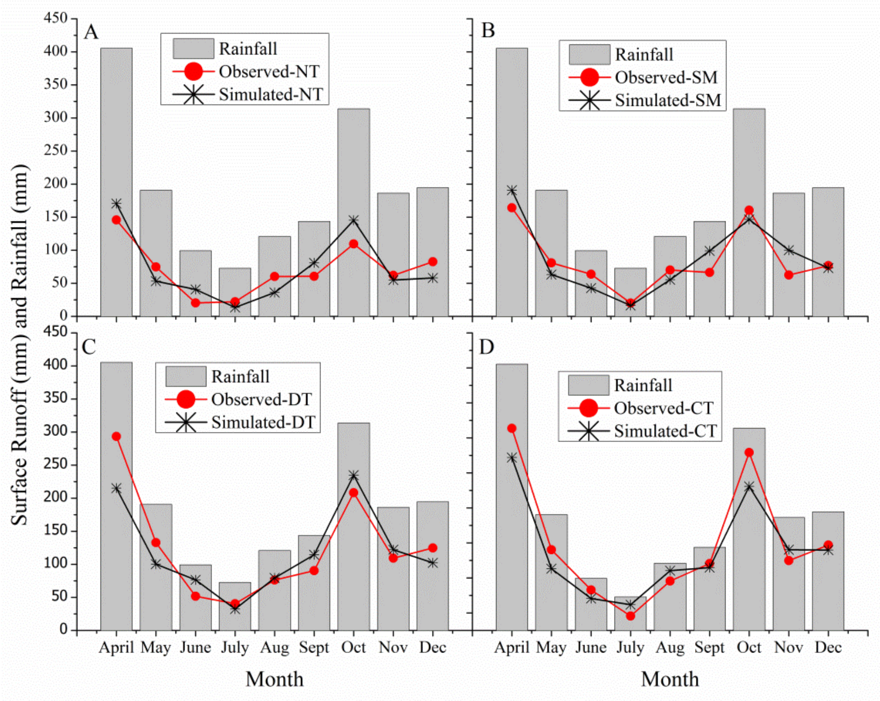
(b) Stubble-mulching

(c) Deep tillage

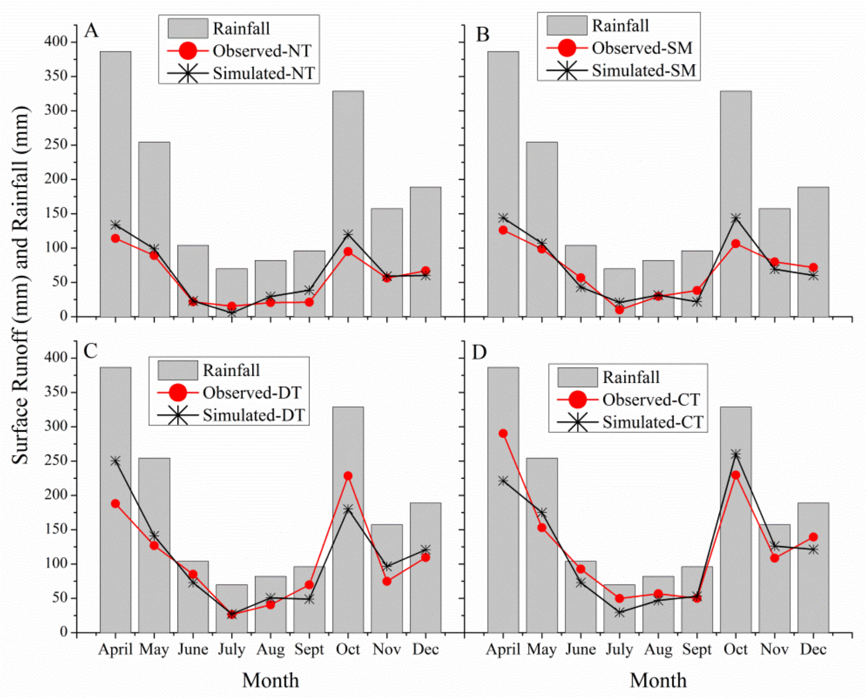
(d) Conventional tillage

**Appendix 1:** Common Bean Fields under Different Soil Tillage Systems in Mukono District, Central Uganda

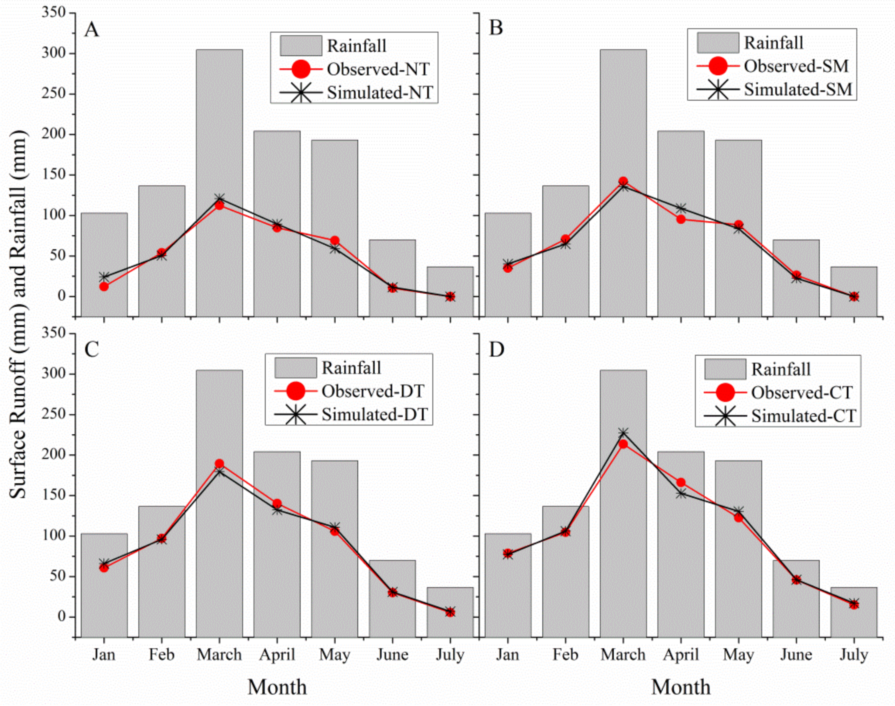
**Appendix 2:** Measurement of Infiltration Rate before the Seedbed Preparation



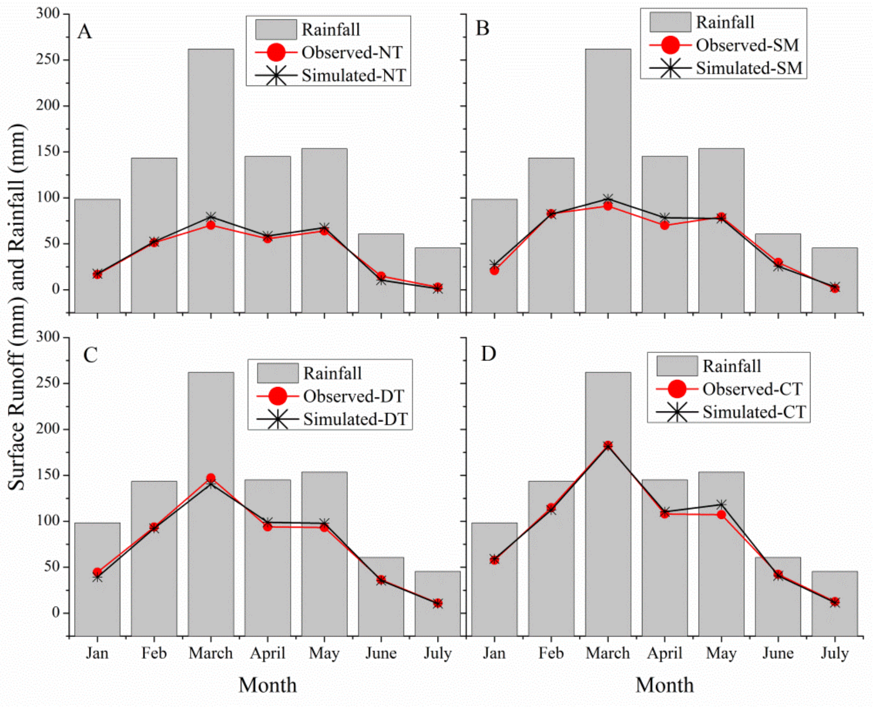
**Appendix 3:** Simulated versus Observed Monthly Surface Runoff Volume at Goma Experimental Site for the Calibration Period



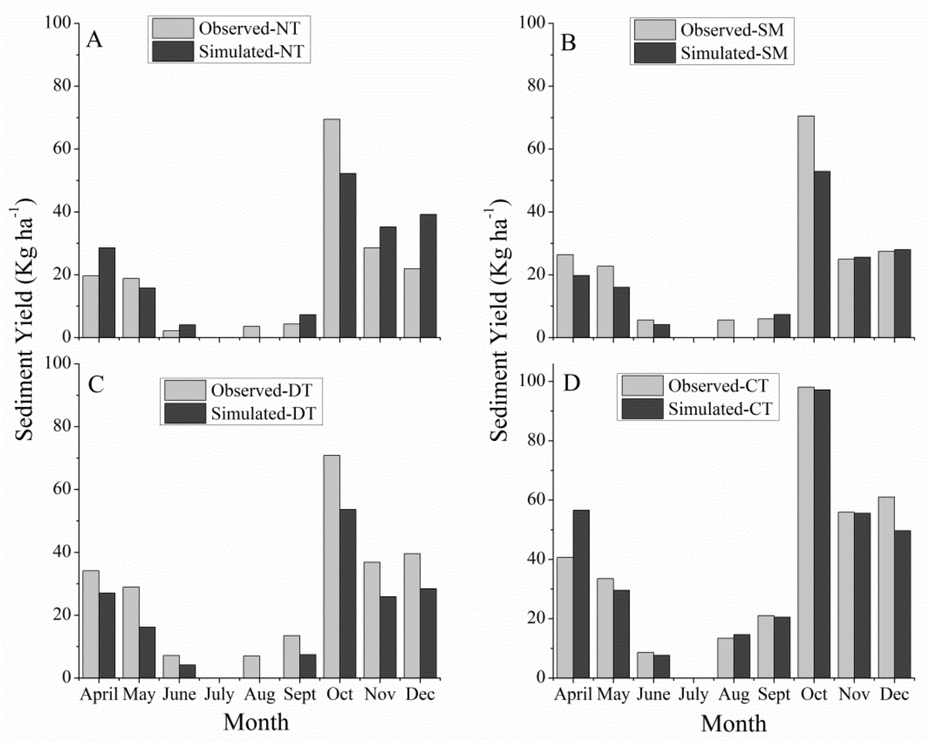
**Appendix 4:** Simulated versus Observed Monthly Surface Runoff Volume at Kimenyedde Experimental Site for the Calibration Period



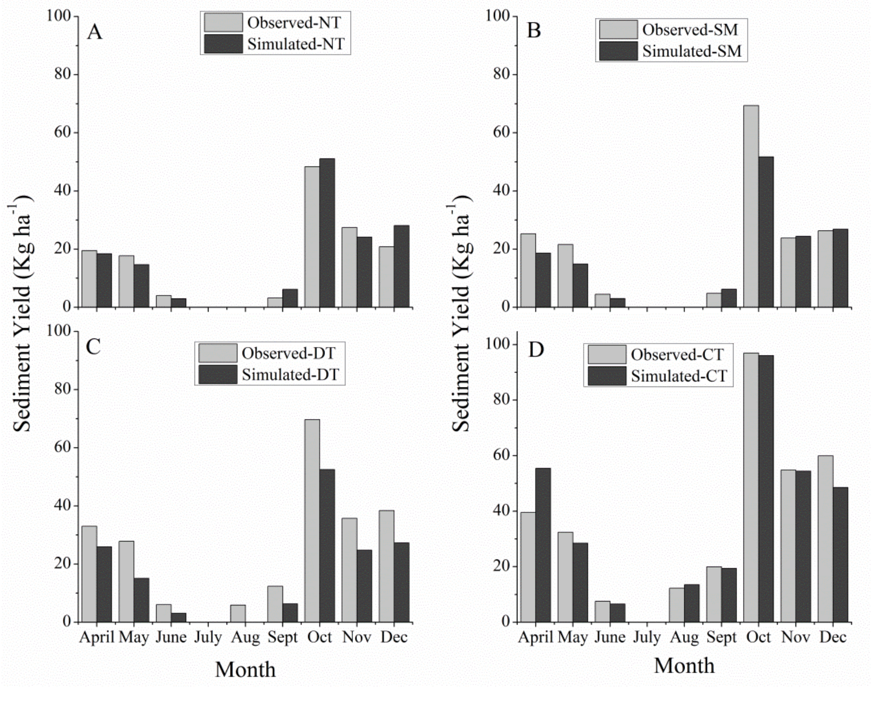
**Appendix 5:** Simulated versus Observed Monthly Surface Runoff Volume at Goma Experimental Site for the Validation Period



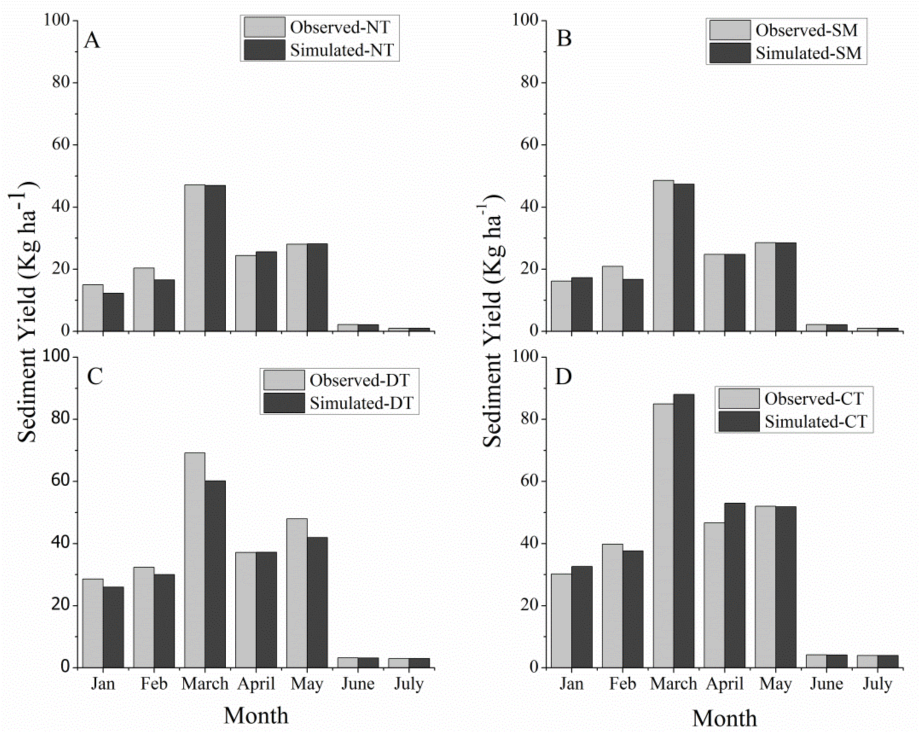
**Appendix 6:** Simulated versus Observed Monthly Surface Runoff Volume at Kimenyedde Experimental Site for the Validation Period



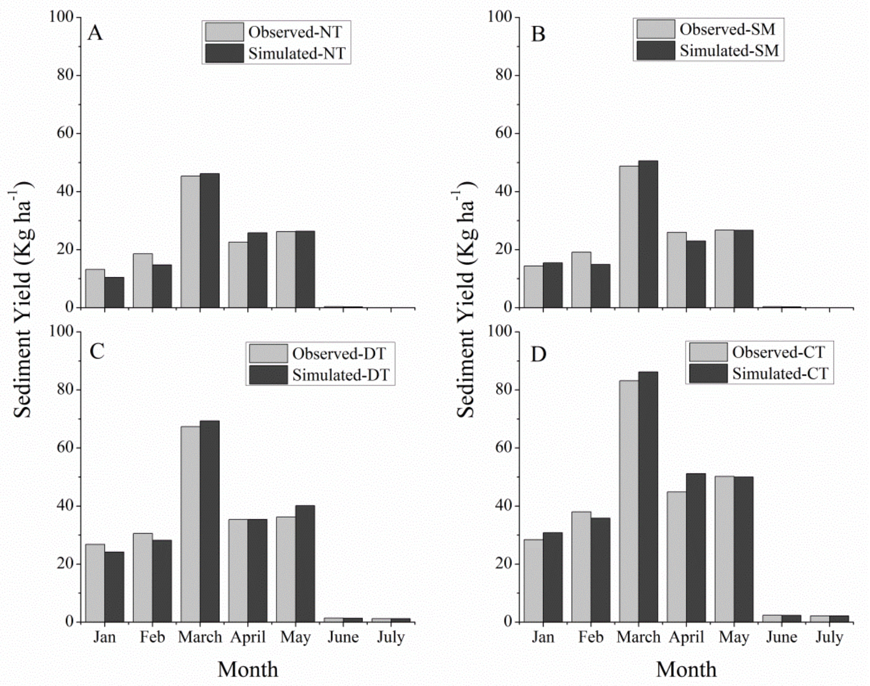
**Appendix 7:** Simulated versus Observed Monthly Sediment Yield at Goma Experimental Site for the Calibration Period



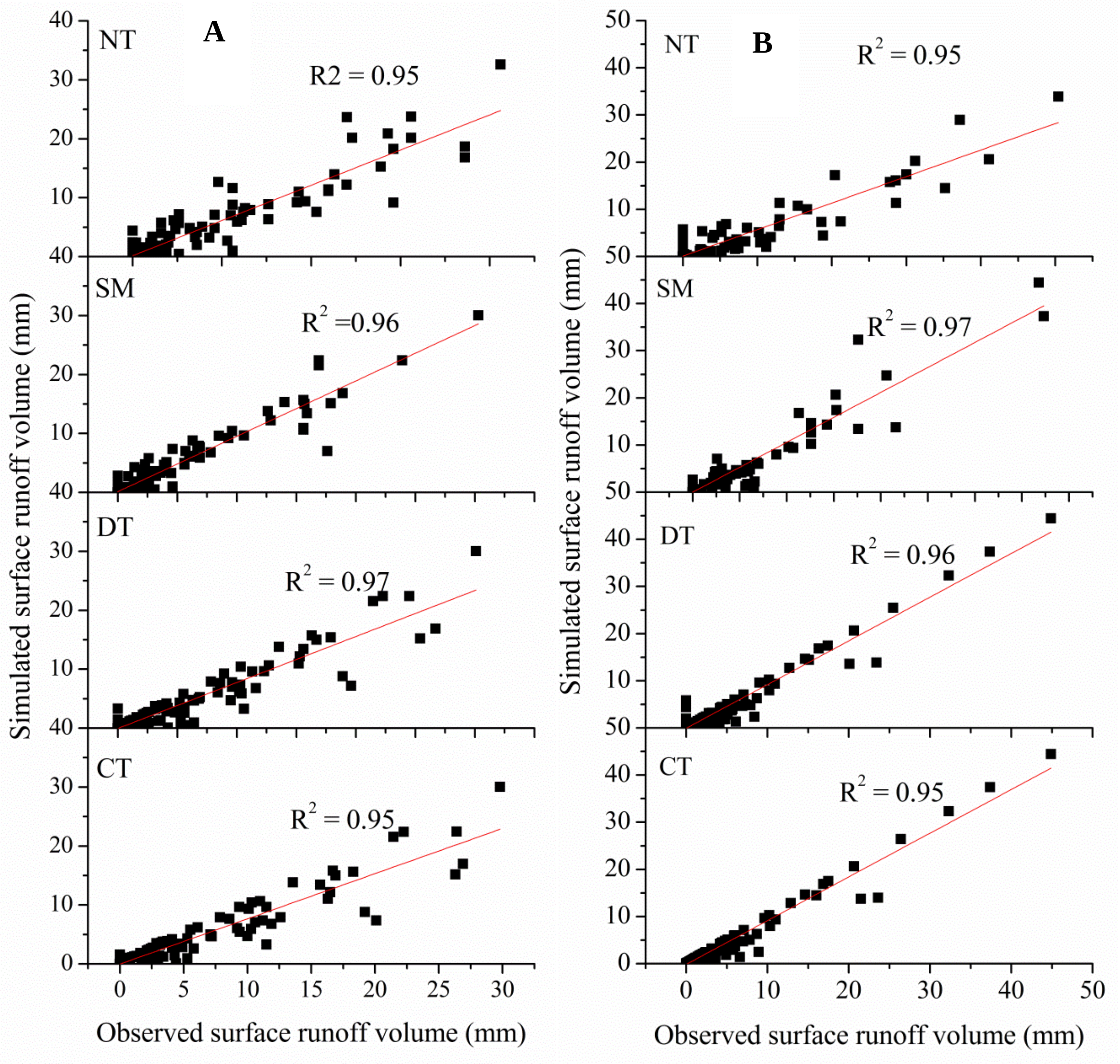
**Appendix 8:** Simulated versus Observed Monthly Sediment Yield at Kimenyedde Experimental Site for the Calibration Period



**Appendix 9:** Simulated versus Observed Monthly Sediment Yield at Goma Experimental Site for the Validation Period



**Appendix 10:** Simulated versus Observed Monthly Sediment Yield at Kimenyedde Experimental Site for the Validation Period



**Appendix 11:** Relationships Between Surface Runoff Volume Observed from Field Experiments and Simulated with APEX for the model calibration (A) and Validation (B) at Kimenyedde Site

## RESEARCH OUTPUTS

### JOURNAL PUBLICATIONS (In SCI- Indexad Journals)

1- **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. https://doi.org/https://doi.org/10.1016/j.heliyon.2020.e05616

2- **Fatumah, N.,** Tilahun, S. A., & Mohammed, S. (2021). Water use efficiency, grain yield, and economic benefits of common beans (*Phaseolus vulgaris* L.) under four soil tillage systems in Mukono District, Uganda. *Heliyon*, *7*(2), e06308. https://doi.org/https://doi.org/10.1016/j.heliyon.2021.e06308

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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 ($2.41 \pm 0.3$ g $L^{-1}$) in Goma experimental site during the first season and NT ($0.43 \pm 0.1$ g $L^{-1}$) in Kimenyedde experimental site during the second season, respectively. The SSL was highest under CT in both Goma (147.17 kg $ha^{-1}season^{-1}$) and Kimenyedde (114.93 kg $ha^{-1}season^{-1}$), and lowest under NT with the means of 11.25 and 9.19 kg $ha^{-1}season^{-1}$ 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; Jouanjean 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 Agriculture 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

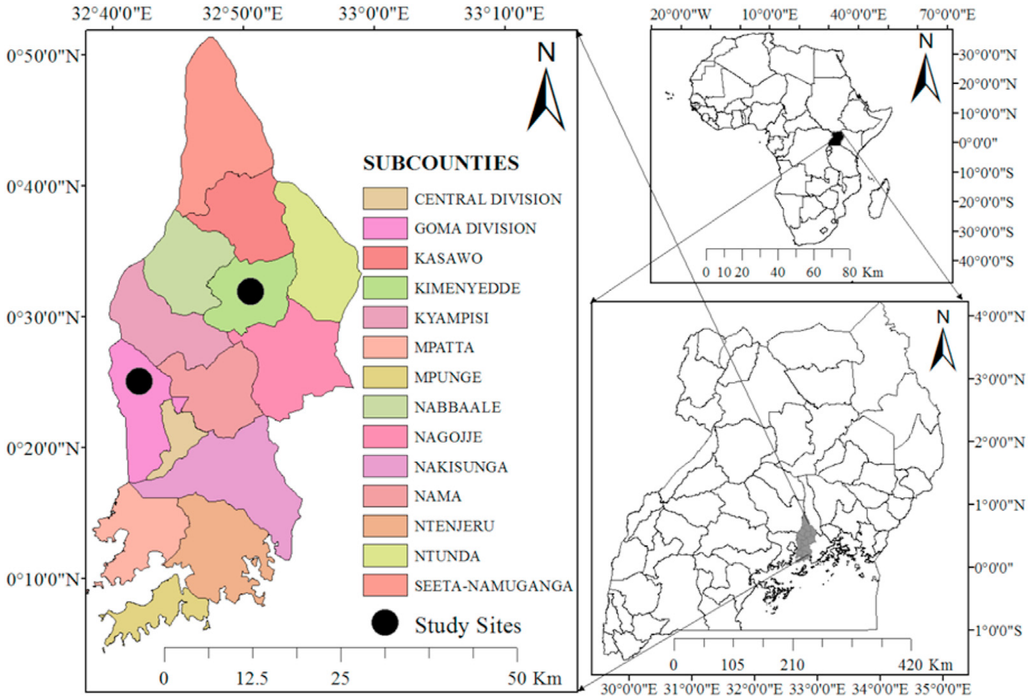

**Figure 1.** Map showing the study sites in Goma and Kimenyedde Sub-counties, Mukono District, Uganda: the map was developed using Arc-GIS software.

(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):

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

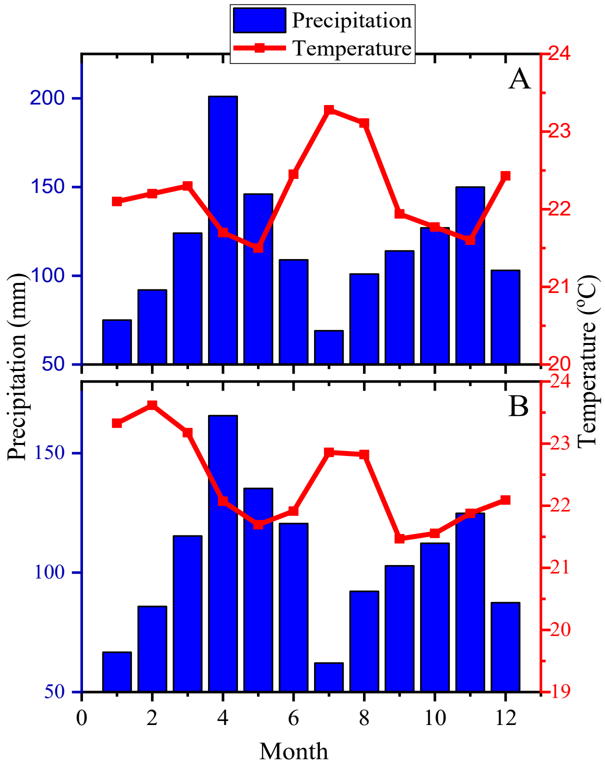

**Figure 2.** Average monthly precipitation and ambient temperature for Goma (A) and Kimenyedde (B) experimental sites from 2005-2018 (Data obtained from Climate Change Knowledge Portal; https://climateknowledgeportal.worldbank.org/download-data) (World Bank, 2018).

**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<br>TPS | No | Yes | Roundup: Glyphosate 360 g/L |
| DT | 40 | Huard plough | TDS<br>TPS | No | No | - |
| CT | 15 | Huard plough | TDS<br>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.

The SSL (g/ha) was then converted to kg ha$^{-1}$ using Eq. (2):

$$SSL\left(\frac{kg}{ha}\right) = \frac{SSL\left(\frac{g}{ha}\right)}{1000}$$

Equation 2

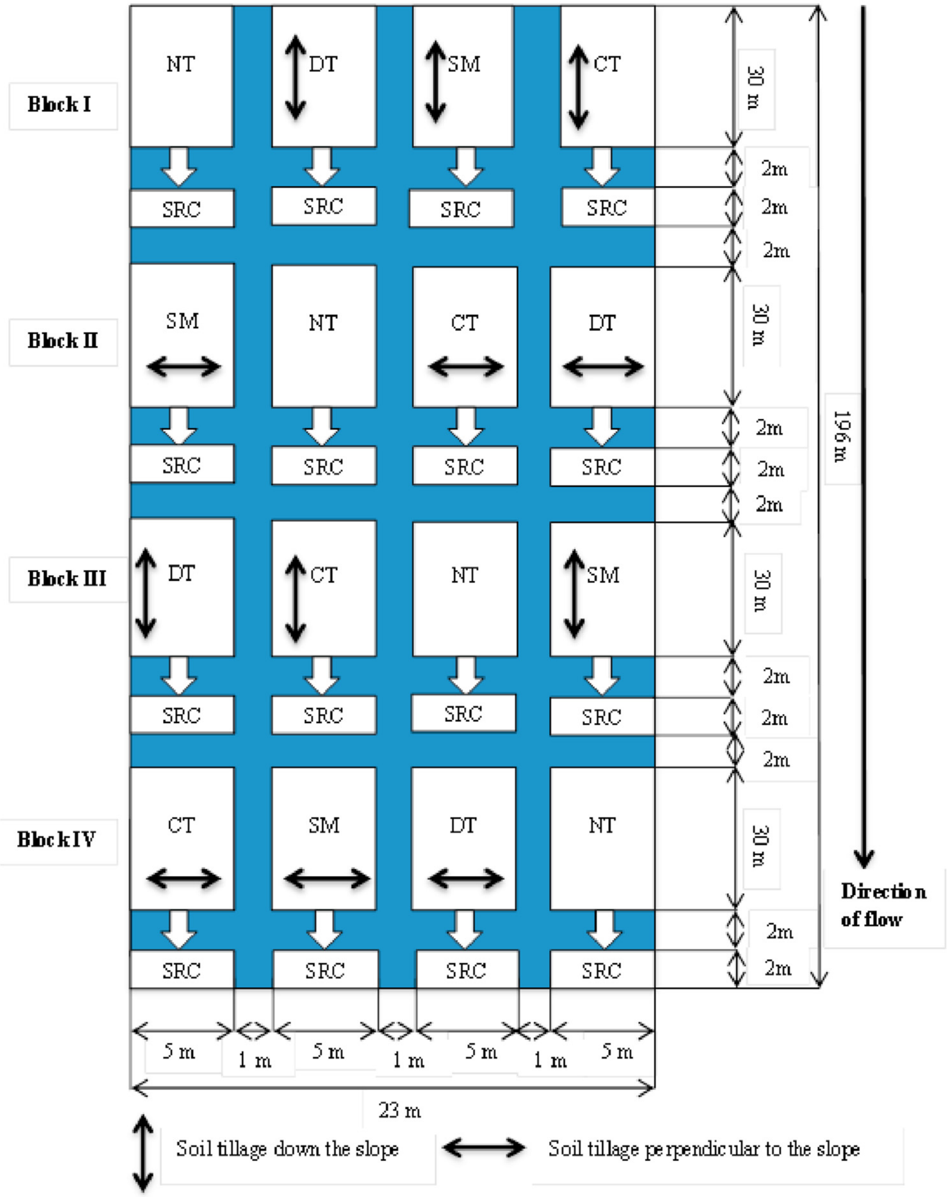

**Figure 3.** Schematic diagram showing the field layout. NT: no-tillage; DT: deep tillage; SM: stubble mulch; CT: conventional tillage; SRC: surface runoff collection tanks.

**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 Bogena 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 $\log_{10}$-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 × season × 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 × Season | 91.00 | **0.046** |
| Site × Tillage system | 82.01 | ns |
| Tillage system × Season | 105.10 | ns |
| Site × Season × 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 ± 0.3 g $L^{-1}$), followed by DT (1.90 ± 0.4 g $L^{-1}$), SM (0.68 ± 0.1 g $L^{-1}$), and NT (0.65 ± 0.1 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 ± 0.5, 1.21 ± 0.4, 0.60 ± 0.1, and 0.58 ± 0.1 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 ± 0.1 g $L^{-1}$), for which no significant ($p > 0.05$) difference was observed with that under the SM (0.44 ± 0.1 g $L^{-1}$). More than nine and ten times higher SSC were recorded under the DT (1.56 ± 0.3 g $L^{-1}$) and CT (1.59 ± 0.4 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 (kg $ha^{-1}season^{-1}$), 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 | SSC | SSL | SSC | SSL | SSC | SSL | SSC |
| | | (kg $ha^{-1}$) | (g $L^{-1}$) | (kg $ha^{-1}$) | (g $L^{-1}$) | (kg $ha^{-1}$) | (g $L^{-1}$) | (kg $ha^{-1}$) | (g $L^{-1}$) |
| Goma | One | 12.19 | $0.65 \pm 0.1^{*,c}$ | 17.75 | $0.68 \pm 0.1^{c}$ | 101.50 | $1.90 \pm 0.4^{b}$ | 171.41 | $2.41 \pm 0.3^{a}$ |
| | Two | 10.31 | $0.58 \pm 0.1^{b}$ | 14.98 | $0.60 \pm 0.1^{b}$ | 85.40 | $1.21 \pm 0.4^{a}$ | 122.92 | $1.40 \pm 0.5^{a}$ |
| | 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 | $0.59 \pm 0.1^{c}$ | 10.42 | $0.62 \pm 0.1^{c}$ | 70.32 | $1.53 \pm 0.4^{b}$ | 128.98 | $2.12 \pm 0.3^{a}$ |
| | Two | 8.73 | $0.43 \pm 0.1^{b}$ | 10.23 | $0.44 \pm 0.1^{b}$ | 58.97 | $1.56 \pm 0.3^{a}$ | 100.88 | $1.59 \pm 0.4^{a}$ |
| | 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** | | | ***p*-value** | | |
| Site | | | | 99.51 | | | **0.020** | | |
| Season | | | | 201.01 | | | **0.000** | | |
| Tillage system | | | | 81.12 | | | **0.000** | | |
| Site × Season | | | | 111.09 | | | **0.022** | | |
| Site × Tillage system | | | | 87.08 | | | ns | | |
| Tillage system × Season | | | | 74.34 | | | ns | | |
| Site × Season × Tillage system | | | | 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 ($RI_{10}$) 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 $RI_{10}$ 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 $RI_{10}$ in Goma site. Although the *r*-values between SSC and RF were higher (>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 $RI_{10}$ 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 $RI_{10}$ 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 $RI_{10}$ 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,

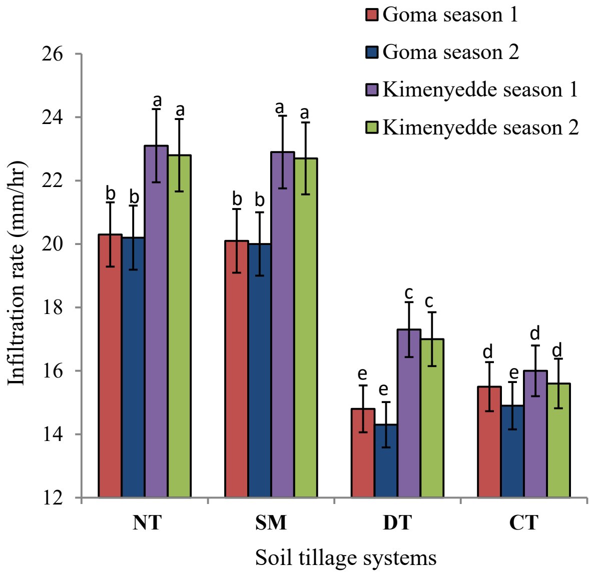

**Figure 5.** Steady-state infiltration rate for the soil tillage systems in Goma and Kimenyedde experimental sites in Mukono District, Uganda. The letters: a, b, c, d, and e represent significance at 5% significant level. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; and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

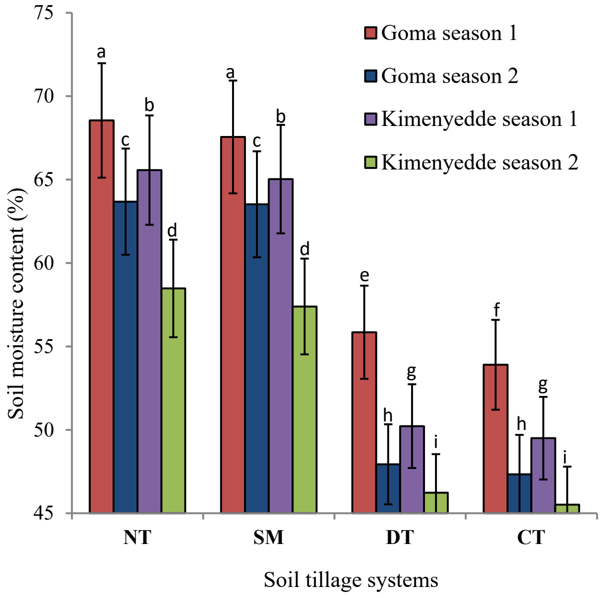

**Figure 6.** Soil moisture content for the soil tillage systems in Goma and Kimenyedde experimental sites in Mukono District, Uganda. The letters: a, b, c, d, e, f, g, h, and i represent significance at 5% significant level. NT is for no-tillage; SM is for stubble-mulching; DT is for deep tillage; and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

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 Dagnew 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 ($RI_{10}$) (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.

### 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 Kladivko (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 (Šarauskis 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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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

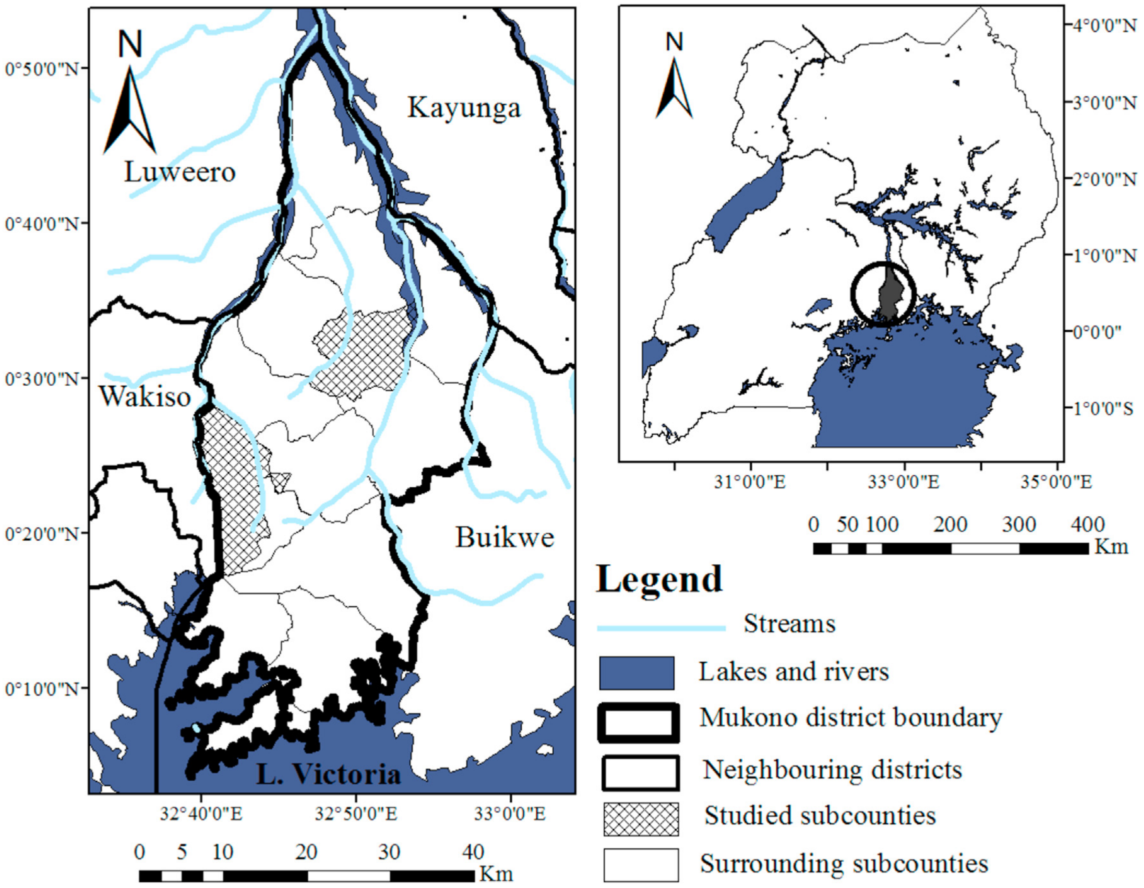


**Figure 1.** Map of the study area showing sites where the experiments were conducted: the map was developed using Arc-GIS software.

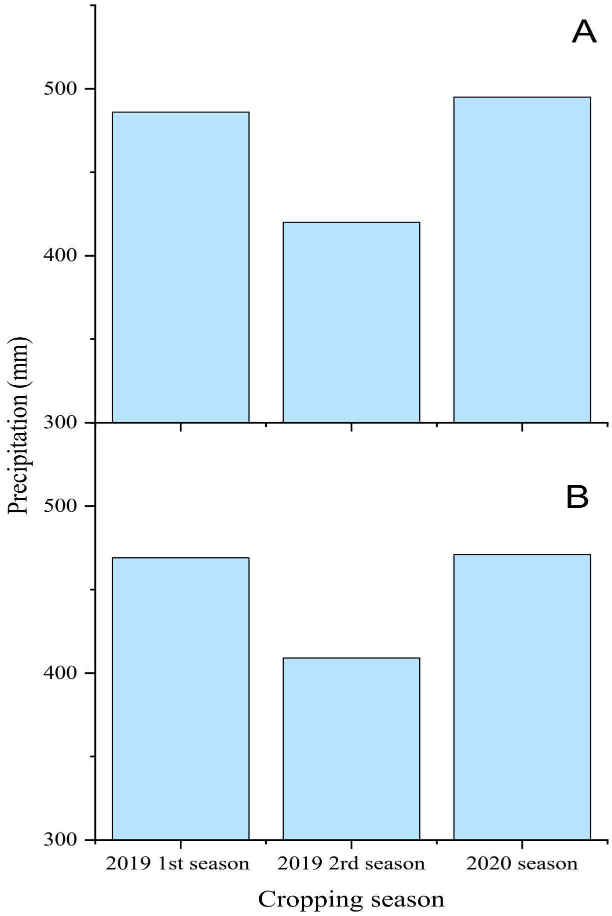


**Figure 2.** Average long-term (2005–2018) seasonal precipitation for Goma (A) and Kimenyedde (B) experimental sites for the three seasons (Data obtained from Climate Change Knowledge Portal; https://climateknowledgeportal.worldbank.org/download-data) (World Bank, 2018).

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 ($C_2H_7NO_2$) 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):

$$SWS = \frac{BD}{\rho w} \times SWC \times D \tag{1}$$

where SWS is the soil water storage (mm); BD is the bulk density (g dry soil cm$^{-3}$); ρw 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).

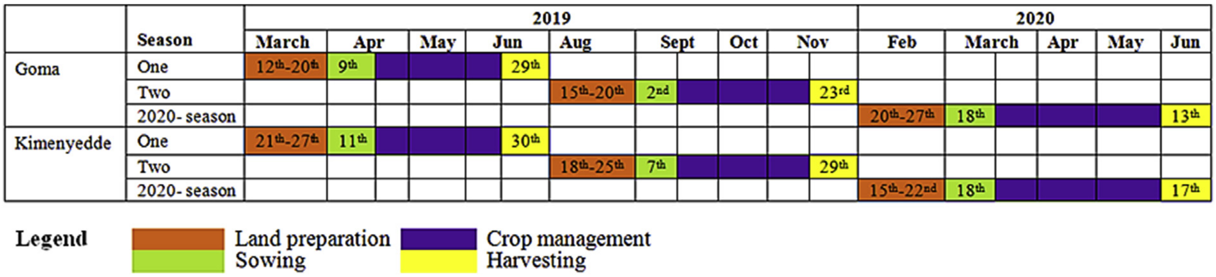
The soil water balance method was used to determine the ET using Eq. (2) (Bodner et al., 2007):

$$ET = P + W - D_R - R_O \pm \Delta SWS \tag{2}$$

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 | 🟧 12th-20th | 🟩 9th<br>🟪 | 🟪 | 🟪<br>🟨 29th | | | | | | | | | |
| | Two | | | | | 🟧 15th-20th | 🟩 2nd<br>🟪 | 🟪 | 🟪<br>🟨 23rd | | | | | |
| | 2020- season | | | | | | | | | 🟧 20th-27th | 🟩 18th<br>🟪 | 🟪 | 🟪 | 🟨 13th |
| Kimenyedde | One | 🟧 21th-27th | 🟩 11th<br>🟪 | 🟪 | 🟪<br>🟨 30th | | | | | | | | | |
| | Two | | | | | 🟧 18th-25th | 🟩 7th<br>🟪 | 🟪 | 🟪<br>🟨 29th | | | | | |
| | 2020- season | | | | | | | | | 🟧 15th-22nd | 🟩 18th<br>🟪 | 🟪 | 🟪 | 🟨 17th |

**Legend**

🟧 Land preparation
🟩 Sowing
🟪 Crop management
🟨 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).

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

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).

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

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)

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

### 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 $Log_{10}$ 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.

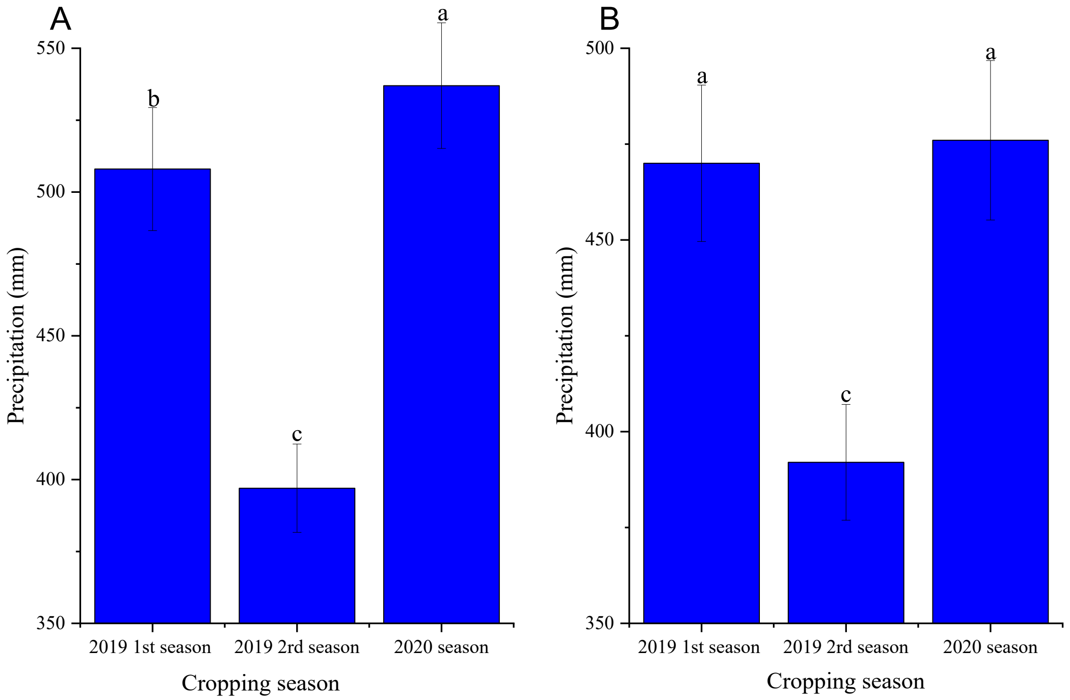


**Figure 4.** Mean seasonal precipitation distribution at Goma (A) and Kimenyedde (B) experimental sites for the three growing seasons. Bars above the mean indicate the standard error.

## 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 ± 01 | 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.

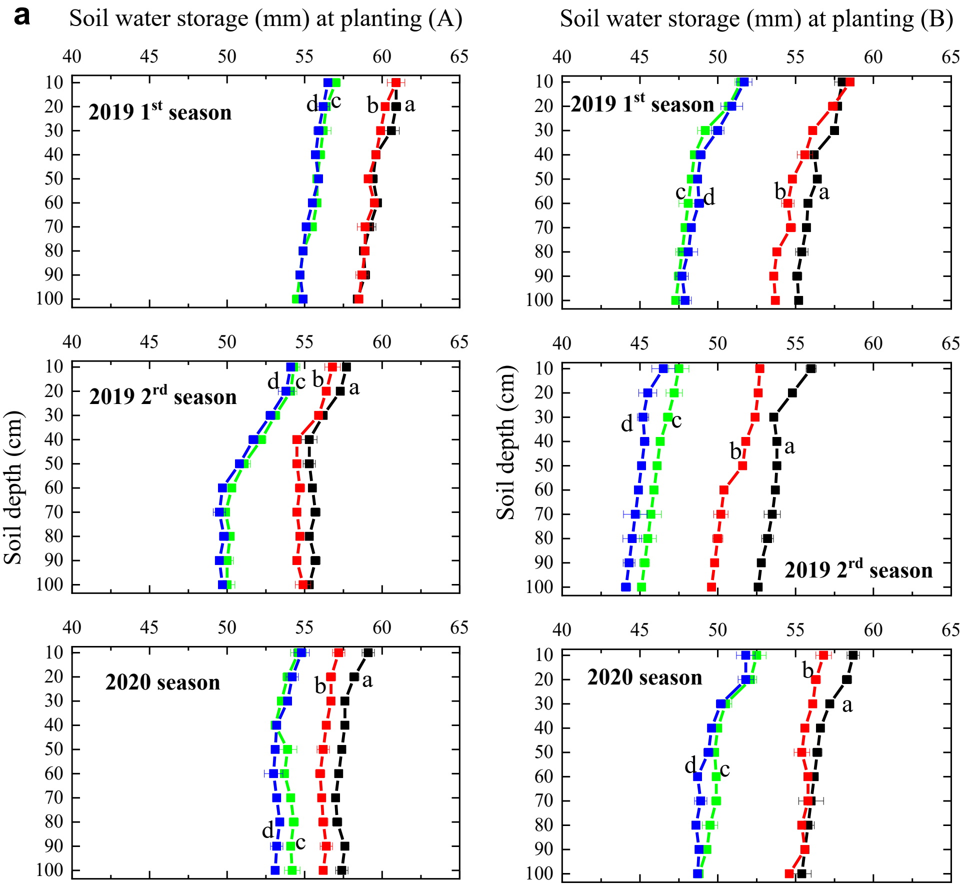


**Figure 5a.** Soil water storage at 0–100 cm soil depth under NT (a), SM (b), DT (c), and CT (d) at a time of common bean planting at Goma (A) and Kimenyedde (B) experimental sites.

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-

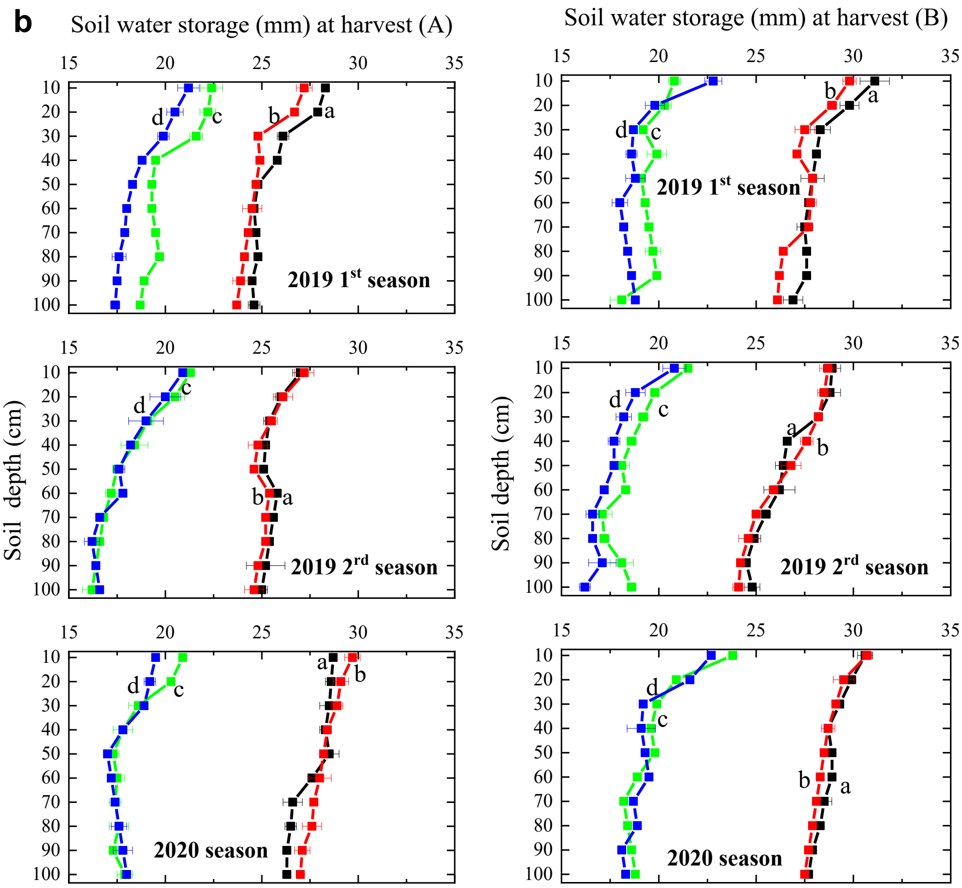


**Figure 5b.** Soil water storage at 0–100 cm soil depth under NT (a), SM (b), DT (c), and CT (d) at a time of common bean harvesting at Goma (A) and Kimenyedde (B) experimental sites.

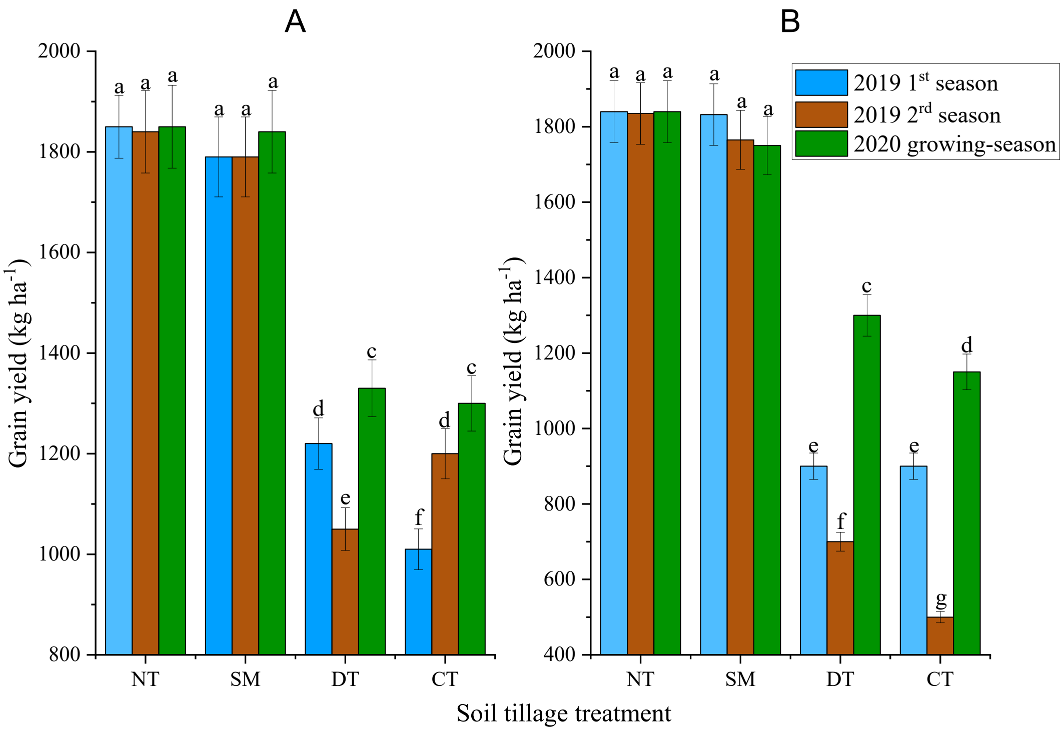


**Figure 6.** Effect of soil tillage treatments and seasons on common bean grain yield at Goma (A) and Kimenyedde (B) experimental sites. Bars over the mean indicate the standard errors, and the lower case letters indicate significance at 0.05. NT is for no-tillage; SM is for stubble-mulching; DT is 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 1st 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 2nd 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 1st 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 2nd 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/$cm^3$ 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 thanwater-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 Aulahk (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.

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