

Full Length Research Paper

Water and nutrient balances under selected soil and water conservation practices in semi-arid Ruzizi plain, Eastern Democratic Republic of Congo

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Received 11 July, 2021; Accepted 6 October, 2021

Soil water deficit is a major production-limiting factor in the predominantly rainfed agriculture of the Ruzizi plain, eastern Democratic Republic of Congo (DRC). Appropriate soil and water conservation (SWC) practices would be a valuable option for maximizing water uptake by plants in the context of water demand and supply unbalance. This study assessed the efficiency of selected SWC practices in improving water and nutrient (nitrogen and phosphorus) balances along the slope gradients in Ruzizi plain using a three-season field experiment. The SWC practices, tied ridges and Zai pits, improved the cumulative soil water balance by 148.7 and 21.1%, respectively, compared to conventional tillage. In the same order, the maize (*Zea mays* L.) yield performance significantly varied with SWC practices: tied ridges (2.16 t ha⁻¹) out performed the Zai pits (1.48 t ha⁻¹) and conventional tillage (1.58 t ha⁻¹). Besides, the tied ridges reduced the total nitrogen losses by 34.4–49.8%, compared to conventional tillage. However, SWC practices were only reliable when daily rainfall amounts were at reasonable threshold (>10 mm) and on low slope gradients (<8%). Therefore, tied ridges provide an opportunity as a component of an integrated soil water and nutrient management strategy to sustain the rainfed maize production in Ruzizi plain.

Key words: Tied ridges, Zai pits, rainfall variability, slope gradient, dryland, *Zea mays* L.

INTRODUCTION

Rainfed agriculture covers 80% of the world's cultivated land and contributes ~60% of the global crop production

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(Adeboye et al., 2019). In sub-Saharan Africa (SSA)'s drylands, soil water and nutrient deficits are major production-limiting factors (Cofie and Amede, 2015). Water deficit is often associated with erratic rainfall, high evapotranspirative demands (ETP) and inadequate soil water management practices (Alexandris et al., 2008; Ndehedehe et al., 2018). On the other hand, low soil fertility stems mainly in the low use of external inputs and overexploitation of lands. Consequently, these regions are consistently food insecure as a result of the food demand and production unbalance.

The Ruzizi plain is located in the great Tanganyika basin and extends over three countries: Democratic Republic of Congo (DRC), Rwanda and Burundi. Its mean annual precipitation (P) to potential evapotranspiration (PET) ratio is usually below 1 (Harrington and Tow, 2011). The annual rainfall supply (800 mm) is far below the annual atmospheric evaporative demand (1300 mm) (Bagula et al., 2016; Muhindo et al., 2016). Although the total annual rainfall is unchanged over years, there are significant shifts in intra- and inter-monthly rainfall distributions (Naithani et al., 2011). For instance, Muhindo et al. (2016) reported a decline in rainfall amounts for January, February, September and October for the last two decades and an increase of rains for April and December. This situation results in high occurrence of extreme events, such as drought and floods. Besides, extreme rainfall are associated with soil erosion and declined soil fertility (Bagula et al., 2014; 2016). Consequently, planning the rainfed agriculture has become complex as irrigation facilities and appropriate water conservation practices are lacking. This discourages farmers from investing in sustainable, productive, and economically promising practices, since farming outcomes are unpredictable (Dessart et al., 2019).

The above-described climatic condition calls for adaptive measures for efficient use of the available water resources. Several SWC practices have been promoted in dryland areas of Africa and hold potential to improve rainwater conservation practices in the Ruzizi plain (Ngetich et al., 2014). These include the tied ridges, half moon, Zaï, mulching, intercropping, etc. (Barry et al., 2008). Tied ridges technique is a practice consisting of raising the earth at a certain height; ridges being tied at constant distance (usually 2 m) to form a series of micro-catchment basins in the field. The Zaï is a farming technique consisting of digging pits in the soil ground at regular intervals during the pre-season to catch rainwater. Zaï pits and half-moons involve digging pits to accumulate water before subsequent planting. Unlike Zaï, half-moon farming technique consists of digging semi-circular basins of 2 to 6 m in diameter on gentle slopes (<3%) to retain the rainwater. These practices reduce runoff, soil, and nutrient losses (Okeyo et al., 2014; Wolka et al., 2018), and improve water storage capacity (Araya and Stroosnijder, 2010; Majaliwa et al., 2015).

However, SWC practices' efficiency is location-specific. It varies with predominant weather conditions and topography. Several authors reported variability in soil water and nutrient use efficiency by plant with slope gradients. High slope farms are often characterized by high erosion and rapid soil degradation (Wezel et al., 2002; Tijani et al., 2008; Oo et al., 2012; Mbugua et al., 2019). Besides, soil moisture is high and long-conserved under low slopes than higher ones, explaining the low cereal performances on high slopes (Tsubo et al., 2006; Mbugua et al., 2019).

Little research has been conducted on the topic in Ruzizi plain to guide farmers and decision-makers on the appropriate SWC technologies. This could allow mitigate the unpredictable farming outcomes and strengthen the farmers' food and income security in that part of the world. Bagula et al. (2013, 2016) recommended the tied ridges and Zaï pits after a series of SWC practices testing in the Ruzizi plain. However, these studies overlooked the variability in slopes as observed in the Ruzizi plain, making the extrapolation to the entire area of those studies' conclusions difficult. Thus, this study intended to assess: (1) SWC practices effects on soil water balance along the slope gradient in the Ruzizi plain, (2) rainfall amount effect on daily water balance under each SWC practices along the slope gradient, and (3) the SWC practices effect on nutrients (nitrogen and phosphorus) balance along the slope gradient. These techniques were tested on maize which is the second most important crop after cassava in the study area (Mondo et al., 2020).

MATERIALS AND METHODS

Study area description

This study was conducted in the Ruzizi plain, which is part of the Great Tanganyika basin. The Ruzizi plain spreads over three countries, DRC, Rwanda and Burundi and covers 175,000 ha (Figure 1). It is characterized by a type Aw4 tropical climate according to the Köppen Vladimir climatic classification, a bimodal rainfall regime of 600 to 900 mm and 18 to 32°C (Muhindo et al., 2016). Soils are of vertisols and arenosols types associated with solonchaks with silty to sandy related texture.

Weather data (rainfall, temperature, relative humidity, wind speed, solar radiation and ETP) during the entire experiment period (November 2017 to March 2019) are presented Table 1. These were collected using an automated Davis Vantage Pro2 weather station installed at 2 m height in the vicinity (~500 m) of the experimental field.

Composite soil samples of each plot were collected along the diagonal using a soil auger of 20 cm at depths of 0-20, 20-40, and 40-60 cm before sowing. Soil pH, soil organic carbon, total nitrogen, phosphorus and texture were analyzed. Soil pH was determined by a digital pH-meter at 1:5 (solute: solution) ratio. Soil organic carbon (SOC) was determined by the combustion method using the Walkley and Black method (Estephan et al., 2013). Total nitrogen was determined by the Kjeldahl method after the soil mineralization (Okalebo et al., 2002). The available phosphorus was determined using the modified Olsen method (Okalebo et al., 2002), and the soil texture by the hydrometer method (Estephan et al., 2013). Soil bulk density was measured by the core method in which core

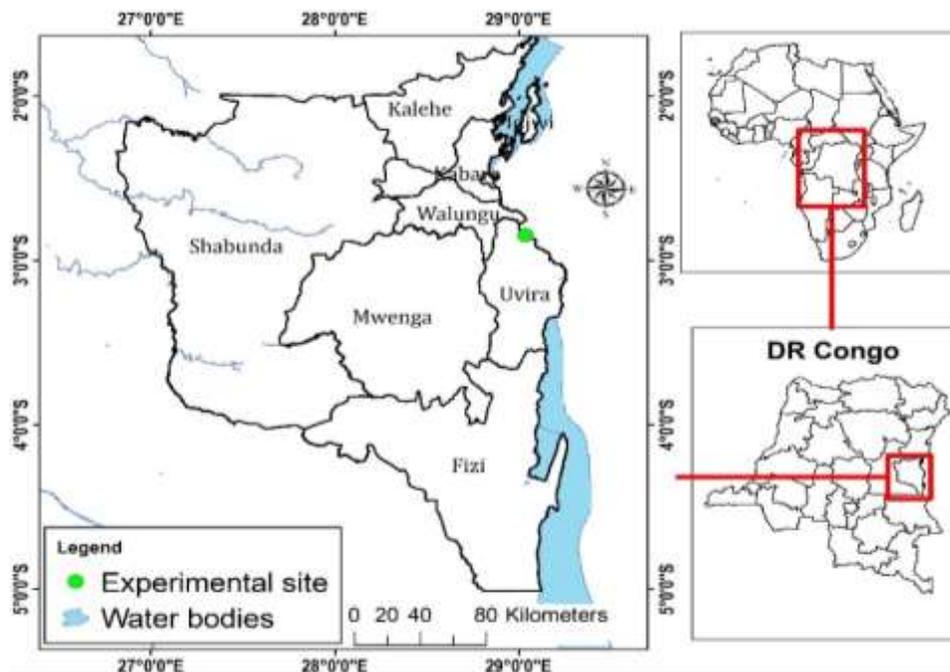


Figure 1. Location of the experimental site, Ruzizi plain, eastern DRC.

Table 1. Weather data of the experimental site during the study period.

Period	Tmin (°C)	Tmax (°C)	Rainfall (mm)	RH (%)	Wind speed (km/hr)	Solar radiation (Mj/m ² /day)	ETP (mm)
November 2017	15.2	31.9	21.7	69.2	6.8	22.1	17.0
December 2017	20.0	32.6	32.1	72.6	6.1	23.3	73.5
January 2018	19.3	30.4	44.5	73.5	5.8	32.2	91.3
February 2018	19.4	31.8	54.9	73.1	6.9	32.3	121.1
March 2018a	19.3	31.4	51.5	73.5	7.1	32.2	56.5
Total season 1	18.6	31.6	204.7	72.4	6.6	28.4	359.4
March 2018b	19.3	31.3	37.2	78.8	6.4	32.5	34.0
April 2018	19.4	30.5	147.6	78.2	5.8	32.9	85.8
May 2018	19.2	30.9	103.6	62.0	8.8	31.9	218.1
June 2018	18.6	31.5	1.1	64.3	8.3	29.4	184.2
Total season 2	19.1	31.1	289.5	70.8	7.3	31.7	522.1
November 2018	15.4	30.8	42.5	75.0	6.9	32.3	32.1
December 2018	15.3	31.4	43.8	73.9	6.0	32.3	83.6
January 2019	15.7	32.1	21.4	73.8	6.1	32.1	114.6
February 2019	16.9	32.2	12.9	75.1	6.5	31.9	66.0
March 2019	15.2	31.9	21.8	72.4	6.4	32.0	51.4
Total season 3	15.7	31.7	142.4	74.0	6.4	32.1	347.7
Mean/Sum	17.8	31.5	636.6	72.4	6.8	30.7	1229.2

Tmax (Maximum temperature), Tmin (Minimum temperature), RH (Relative Humidity), ETP (Evapotranspiration), 2018a is related to the month in season 1 (long rainy season) while 2018b is referring to season 2 (short rainy season).

samples were oven-dried at 105°C for 24 h. The pedotransfer function developed by Saxton and Rawls (2006) in sandy and sandy loam soils was used to estimate soil water characteristics and hydrodynamic properties such as permanent wilting point (1.5 MPa), field capacity (0.033 MPa), saturation point (0 MPa) and the

saturated hydraulic conductivity. The available water capacity (AWC) was estimated using the difference between the upper limit of field capacity (FC) and the lower limit of permanent wilting point (PWP).

The study area soil characteristics are presented in Table 2. A

Table 2. Soil physical properties of the experimental sites along the selected slope gradient in Ruzizi plain, eastern DRC.

Slope (%)	0-2			2-8			8-15		
	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60
Depth (cm)									
Coarse fraction (%)	2.42	4.55	0.66	4.69	45.64	34.63	31.73	23.12	33.29
Clay (g/kg)	60.7	103.3	222.7	60.0	102.0	94.0	6.7	109.3	101.3
Silt (g/kg)	261.3	313.3	95.3	386.0	338.0	216.0	423.3	287.3	281.3
Sand (g/kg)	678.0	583.3	682.0	554.0	560.0	690.0	570.0	603.3	617.3
Bulk density (g/cm ³)	1.15	1.19	1.43	1.08	1.45	1.42	1.24	1.36	1.38
pH water	7.6	7.4	7.9	7.9	7.8	7.5	8.4	8.4	8.5
SOC (g/kg)	41.2	23.4	16.5	36.7	16.8	7.7	25.4	17.2	8.2
Nitrogen (g/kg)	4.4	2.7	2.2	2.8	1.6	1.5	5.3	3.8	4.5
Phosphorus (ppm)	49.20	50.04	55.39	25.06	23.84	22.43	36.57	39.81	39.35
Saturation point (%)	56.50	56.63	46.13	59.10	45.40	46.40	53.17	48.57	55.43
Field capacity (%)	24.47	26.67	25.77	24.80	20.20	17.30	21.07	21.50	23.93
Permanent wilting point (%)	12.67	13.00	16.23	9.50	8.10	8.00	10.70	9.70	11.17
Saturated hydraulic conductivity (mm/h)	82.70	69.22	21.04	99.21	25.68	42.77	72.70	46.19	57.92
Available water capacity (cm ³ /cm ³)	0.12	0.14	0.10	0.15	0.12	0.09	0.10	0.12	0.13

significant variation in the coarse fraction for different slope gradients and soil depths was observed. For the slope gradient of 0-2%, the coarse fraction did not vary with soil depth and was 2.5% on average. The same trend was observed for slopes of 8-15% where the average for the different soil depths was 29.3%. For the slope gradient of 2-8%, the coarse fractions were 4.69, 45.6 and 34.6% for the depth of 0-20, 20-40 and 40-60 cm, respectively. The soil texture was sandy loamy for all depths and slope gradients, except for the slope of 0-2% where the soil texture was sandy clayey loam for the depth of 40-60 cm. The bulk density showed no variation with the slope gradient but varied with soil depth. An average of 1.15, 1.33 and 1.41 g cm⁻³ was recorded for the depths of 0-20, 20-40 and 40-60 cm, respectively. The water availability parameters, such as the permanent wilting point and field capacity, varied significantly along the slope gradient and soil depth. The saturation point (0 MPa) was 40.2% while the field capacity (at 0.03 MPa) was 14.03%. There was variation in soil organic carbon (SOC) for slope gradients and soil depth (Table 2). SOC was higher at slopes of 0-2% (27.03 g kg⁻¹) compared to slopes of 2-8% (20.4%) and 8-15% (16.9%). The SOC varied on different soil depths; it was 34.4, 19.1 and 10.8 g kg⁻¹ at depths of 0-20, 20-40

and 40-60 cm, respectively. The soil pH varied with slope gradients. The highest pH was recorded at the slope 8-15% (8.4).

Experimental design and field management

Field experiments were conducted in three growing seasons (November 2017 to March 2018, March 2018 to July 2018, and November 2018 to March 2019). The experiment comprised two study factors namely the slope gradients (0-2, 2-8 and 8-15%) and the SWC practices (Zaï, tied ridges, and conventional tillage as control). For all the seasons, three replications were used. The experimental subplots had a width of 4 m and a length of 6 m. Blocks and subplots within blocks were 1 m apart.

Zaï pits consisted of digging a hole of 15 cm depth and 35 cm diameter as described by Roose and Barthès (2001). The Zaï pits were spaced by 80 cm between planting rows and 50 cm within rows. The tied ridges were built by raising the earth to 50 cm height with 20 cm diameter. Long ridges (6 m) were partitioned every 2 m to avoid erosion. The ridges were 80 cm apart as described by Araya and Stroosnijder (2010) and McHugh et al.

(2007). For conventional tillage, the ploughing was done at a depth of 30 cm using a hand hoe. Maize seeds were sown at a spacing of 0.8 and 0.5 m between and within rows, respectively. NPK fertilizer (17-17-17) was applied at the planting date at the rate of 120 kg ha⁻¹ while 25 kg ha⁻¹ urea (46-0-0) was applied as a top-dressing fertilizer. Weeding was done 14, 42 and 60 days after sowing to ensure clean fields throughout the cropping season.

Maize was harvested at maturity, 110 to 130 days after sowing (DAS) for all seasons. A harvest area of 18.2 m² (5.2 m × 3.5 m) within each plot was selected for yield quantification. Harvesting was carried out manually when all leaves and husks were completely dry. Cobs were separated from husks in the field and sun-dried.

Determination of the soil water balance

The global equation of the soil water balance used in this study is presented as follows (Zhang et al., 2017):

$$\Delta\theta = P - ETPa - D - R \quad (1)$$

Where $\Delta\theta$ is the soil water balance. The inflow components

are precipitation (P) and irrigation (which was zero for this study). The outflow components included the actual evapotranspiration (ETPa), surface runoff (R) and downward drainage (D).

Based on daily rainfall, runoff, evapotranspiration and downward drainage, soil water balance (SWB) under each SWC practice was generated using the following equation:

$$SWB = \iint_0^t (\partial\theta/\partial t) dz dt = \int (P - ETP_a - D - R) dt \quad (2)$$

SWB was considered as the non-soil water balance with a non-cumulative effect where t is the time and z the variation of the different components of the water balance. This generated the non-cumulative water balance. The cumulative soil water balance (CSWB) was generated by integrating the positive SWB of the previous day as shown in the Equation 3:

$$CSWB = \int (P - ETP_a - D - R) dt + SWB \quad (3)$$

Evapotranspiration estimation

The actual ETPa used in estimating water balance was generated using the following Penman and Monteith equation:

$$ETPa = ET_o \times K_c \quad (4)$$

Where ET_o is the potential evapotranspiration calculated using Penman and Monteith equation and K_c is the maize crop coefficient which is a function of physiological stages (Piccinni et al., 2009).

Runoff and drainage data collection

Surface runoff (R) was collected using bounded runoff traps installed in each plot. The runoff trap was equipped with a V-shaped gutter to collect and transport runoff water into a 0.4 m³ storage tank connected to a 20 L plastic container in case of overflow. The runoff water in the storage tank was collected and converted into water depth (mm) by dividing the runoff volume by the plot size. The sediment samples were collected at each rain event to determine the nutrient (N and P) concentration in the laboratory.

Downward drainage (D) was collected through an installed drainage system. The drainage system consisted of a 50 cm depth and 50 cm diameter tray. The quantity of soil to be filled in the tray was estimated based on the bulk density of the different slope gradients. In this case, 122, 127 and 130 kg were filled for the slopes of 0-2, 2-8, and 8-15%, respectively. The maize was sown on the tray to maintain the suction and continuity of water and nutrient fluxes. The drainage water volume was determined in each tray and then converted into water depth (mm) by dividing the downward drainage volume by the plot size. Sediment was collected in the storage tank and was later taken to determine the nutrient (N and P) concentrations in the laboratory.

Determination of water deficit periods and drought frequency

The water deficit frequency was defined based on water availability for crops: it considered all periods with a water balance below 0. The moving average was calculated to avoid transitional fluctuations and emphasize their longer-term trend to better understand these deficit states. The moving average was estimated at five-day intervals because the water stress exceeding this interval can reduce the grain yield by as high as 30% (Ogbaga et

al., 2020). The water deficit period frequency was determined by counting days using the results from the moving average estimate.

Determination of the soil nutrient balance

Estimation of nutrient balance

Cumulative nitrogen and phosphorus quantities were determined in soil, plant and water samples (from the collected drainage and runoff). Equation 5 was used to determine the cumulative nutrient balances (CNB):

$$CNB = S + F - C_u - R_n - N_l \quad (5)$$

Where S = soil nutrient at the zero-day, F = nutrient from fertilizer application, C_u = crop nutrient uptake, R_n = nutrient loss by runoff, N_l = nutrient loss in leaching process and CNB = cumulative nutrient balance. Composite samples per crop growth stages were collected and sent to the laboratory for nitrogen and phosphorus analysis.

Estimation of nutrients in drainage and runoff sediments

At the laboratory, the runoff and downward drainage samples were placed in aluminium metal bowls. After thoroughly shaking and mixing, the suspension was poured into bowls and oven-dried at 105°C temperature. All the information on labels, the suspension volume in the runoff bottles and sediment weights were carefully recorded. Sediment yield was calculated using the total suspension volume in the main drum. Sediment weight (g) was thereafter divided by the total runoff volume from each plot to obtain sediment concentration (g/L). The total nitrogen in sediment was determined using the Kjeldahl method after mineralization of soil. The exchangeable or available phosphorus in sediments was determined by the modified Olsen method (Okalebo et al., 2002).

Estimation of plant nutrients in biomass

Crop biomasses were analyzed to determine the N and P concentrations at different plant growth stages. Three plants from each plot were cut from the soil surface to determine the aboveground dry matter (DM). These plants were then placed in a drying oven at 75°C until constant weight and the final weight was recorded. Plant samples were then milled, sieved to 1 mm and mineralized with H₂SO₄- and H₂O₂ for N and P determination, respectively. Plant N concentration was determined using the Kjeldahl method (Okalebo et al., 2002). Total phosphorus in plant was determined calorimetrically according to the method developed by Parkinson and Allen (1975).

Determination of SWB for different rainfall amounts under different SWC practices

Daily rainfall amounts were grouped into four categories as proposed by Li et al. (2013): 0, 1-10, 10-20, and 20-50 mm. The maximum daily rainfall event was below 50 mm across the three growing seasons. The cumulative and non-cumulative rain water means were calculated. The percent deviation from the control (c) or water conservation efficiency (WCE) was estimated using Equation 6 as suggested by Sahoo et al. (2016):

$$WCE = \frac{Y_{swc} - Y_c}{Y_c} \quad (6)$$

Table 3. Cumulative soil water balance (CSWB) and SWB components under selected SWC practices.

Parameter/SWC practices	Conventional tillage	Tied ridges	Zai pits	p-value
CSWB (mm)	-55.25±32.05 ^a	26.94±41.79 ^b	-43.13±36.09 ^a	p<0.001
Frequency of water deficit (%)	68.23±4.78 ^a	62.91±4.50 ^b	67.00±4.99 ^a	p<0.05
Surface runoff (%)	18.92±2.56 ^a	12.08±2.63 ^c	15.83±2.60 ^b	p<0.001
Downward drainage (%)	13.41±2.56 ^a	9.08±1.68 ^b	13.25±2.40 ^a	p<0.05

Means followed by the same letter within a row are not statistically different at 5% p-value threshold.

Table 4. Cumulative soil water balance (CSWB) and SWB components along the slope gradient.

Parameters/slope	0-2	2-8	8-15	p-value
CSWB (mm)	51.57±27.98 ^a	-34.57±29.91 ^b	-88.44±40.55 ^c	p<0.001
Frequency of water deficit (%)	61.37±4.03 ^a	67.09±4.33 ^b	69.69±5.52 ^b	p<0.001
Surface runoff (%)	7.48±1.33 ^a	15.64±0.96 ^b	23.70±2.02 ^c	p<0.001
Downward drainage (%)	17.16±2.79 ^a	10.78±1.41 ^b	7.80±1.09 ^c	p<0.001

Means followed by the same letter within a row are not statistically different at 5% p-value threshold.

Y_{swc} represents the CSWB and SWB under tied ridges or Zai while Y_c is the CSWB and SWB in the control treatments.

Statistical data analysis

Analysis of variance was conducted to determine the SWC practices effects on SWB and nutrient loss along the three slope gradients for the three growing seasons, using the Restricted Maximum Likelihood Model. The treatments effects were compared by computing the least mean squares and standard errors of difference (SED); at a p-value threshold of 0.05. In the mixed model analysis, SWC practice, slope gradient and season were considered as fixed factors. A multiple regression analysis was done to predict SWB based on physical soil properties. Variability in soil organic carbon (SOC), bulk density, soil texture, soil water characteristics, etc. was analyzed using standard descriptive statistics and analysis of variance. The Tukey HSD test was used for mean separation at the significance level of 5%. Statistical analysis was performed using R version 3.5.3.

RESULTS

Variations in soil water balance under selected SWC practices

The CSWB, surface runoff, downward drainage and water deficit frequency across the three growing seasons varied significantly with SWC practices ($p<0.05$) (Table 3). Tied ridges recorded higher CSWB (26.94 mm) and lower water deficit frequency (62.91%), surface runoff (12.08%) and downward drainage (9.08%) compared to the Zai pits and conventional tillage. The Zai pits differed from the conventional tillage only for the surface runoff (15.83 vs. 18.92%). The surface runoff's water conservation efficiencies (WCE) were 36.1 and 16.3% for

the tied ridges and Zai pits, respectively. The downward drainage's WCE were 32.2 and 1.1% for the tied ridges and Zai pits, respectively. The CSWB's WCE were 148.5 and 21.9% for tied ridges and Zai pits, respectively.

Variations in soil water balance along the slope gradient

There was a significant influence of the slope gradient on CSWB ($p<0.01$), surface runoff ($p<0.01$), downward drainage ($p<0.05$), and frequency of water deficit ($p<0.01$) (Table 4). The highest CSWB was recorded at the slope of 0-2% (51.54 mm) while the lowest was at the slope of 8-15% (-88.44 mm). The frequency of water deficit was lower for the slope of 0-2% while no significant difference was between the slopes of 2-8 (67.09%) and 8-15% (69.69%). The lowest surface runoff was observed at the slope of 0-2% (7.48%) while the highest was from the slope of 8-15% (23.7%). However, the downward drainage was highest for the slope of 0-2% and lowest at 8-15% (7.8%).

Interaction effects of SWC practices and slope gradient on soil water balance

The CSWB was highly influenced by the interaction between the SWC practices and slope gradients ($p<0.01$) (Figure 2). Tied ridges were very efficient for the slope of 0-2% (129.4 mm) compared to Zai pits (11.3 mm) and conventional tillage (-4.8 mm). However, tied ridges' CSWB for the slope of 2-8% was low and not different from 8-15% slope (-59.94 mm). Zai pits was efficient on the slope of 0-2% (30.1 mm) while it showed a highly

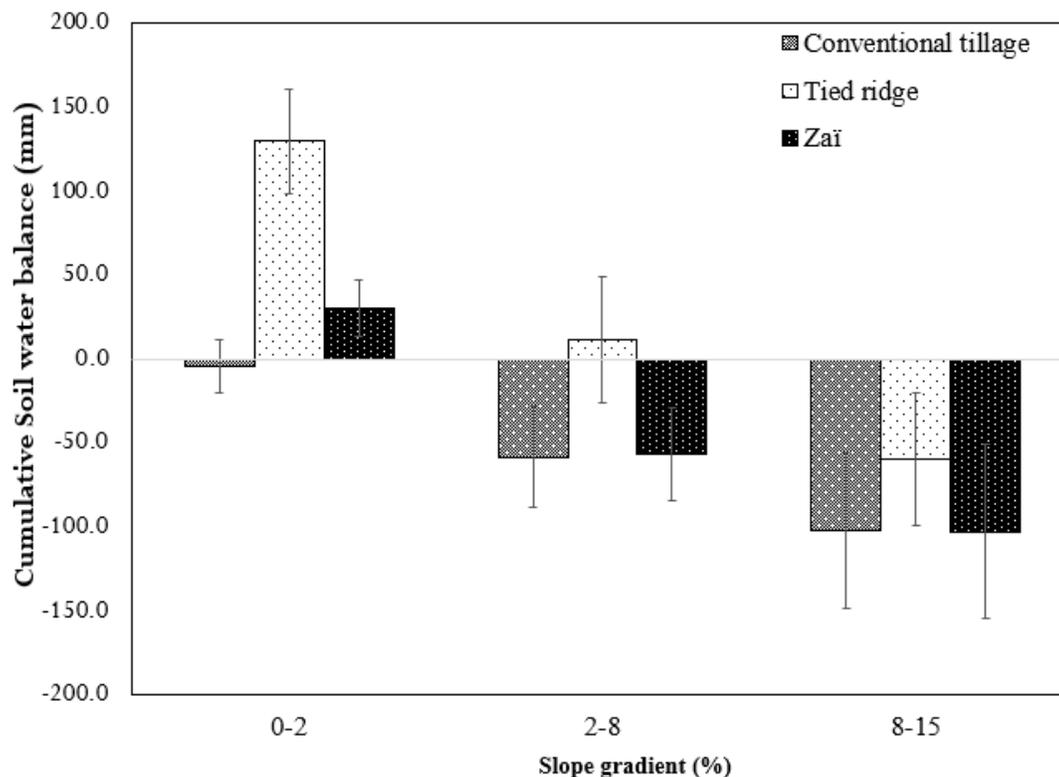


Figure 2. Interaction effects of SWC practices and slope gradients on the cumulative soil water balance.

negative balance on the slopes of 2-8 (-56.64 mm) and 8-15% (-102 mm).

A total of 204.7, 289.5, and 142.3 mm of rainfall were recorded from sowing to harvest for seasons 1, 2 and 3, respectively. On the other hand, several days of no rain were recurrent in all seasons. These represented 52.9, 66.9 and 71.5% days in seasons 1, 2 and 3, respectively (Figure 3). There were significant differences among slopes for daily SWC practices' CSWB ($p < 0.001$). Tied ridges presented more days of positive daily CSWB compared to the Zai pits and conventional tillage for all

Variations in the soil water balance under different rainfall regimes

From Figure 4a, the deviation percentages for the daily non-cumulative SWB varied with rainfall events ($p < 0.05$) and SWC practices ($p < 0.01$). Tied ridges and Zai pits had no influence on the daily SWB when rainfall was below 10 mm. Tied ridges SWB's deviation percentages were 8.8 and 10.71% for the rainfall intervals of 10-20 and 20-50 mm, respectively.

Daily cumulative SWB significantly varied with SWC practices ($p < 0.05$) and rainfall events ($p < 0.05$) (Figure 4b). The daily CSWB deviation percentages on the tied ridges and Zai pits were 9.10 and 1.8%, respectively on

slope gradients across seasons. At the plant establishment growth stage, the SWC practices recorded a high CSWB regardless of the slope (Figure 3). From the crop vegetative phase, differences were observed among the SWC practices, the trend being more pronounced at the mid- and end-plant growth phases. Once again, the tied ridges stored more water than Zai pits and conventional tillage for the three consecutive seasons (Figure 3). During the pronounced water deficit periods, no differences were observed among SWC practices and conventional tillage for CSWB.

non-rainy days. The daily CSWB deviations were 5.9 and -0.05% for tied ridges and Zai pits, respectively, when daily rains were 1-10 mm. No differences existed between the Zai pits and tied ridges for daily rains of 10-20 mm. The SWC practices' water-saving capacities were improved (by 4.8% for Zai pits and 3.4% for tied ridges) on days following 20-50 mm rains.

Cumulative N and P nutrient balances under different SWC practices along the slope gradient

Nitrogen and phosphorus losses by downward drainage, surface runoff and plant uptake are presented in Table 5. Nitrogen loss by downward drainage was influenced by the slope gradient ($p < 0.05$) but not by the SWC practices

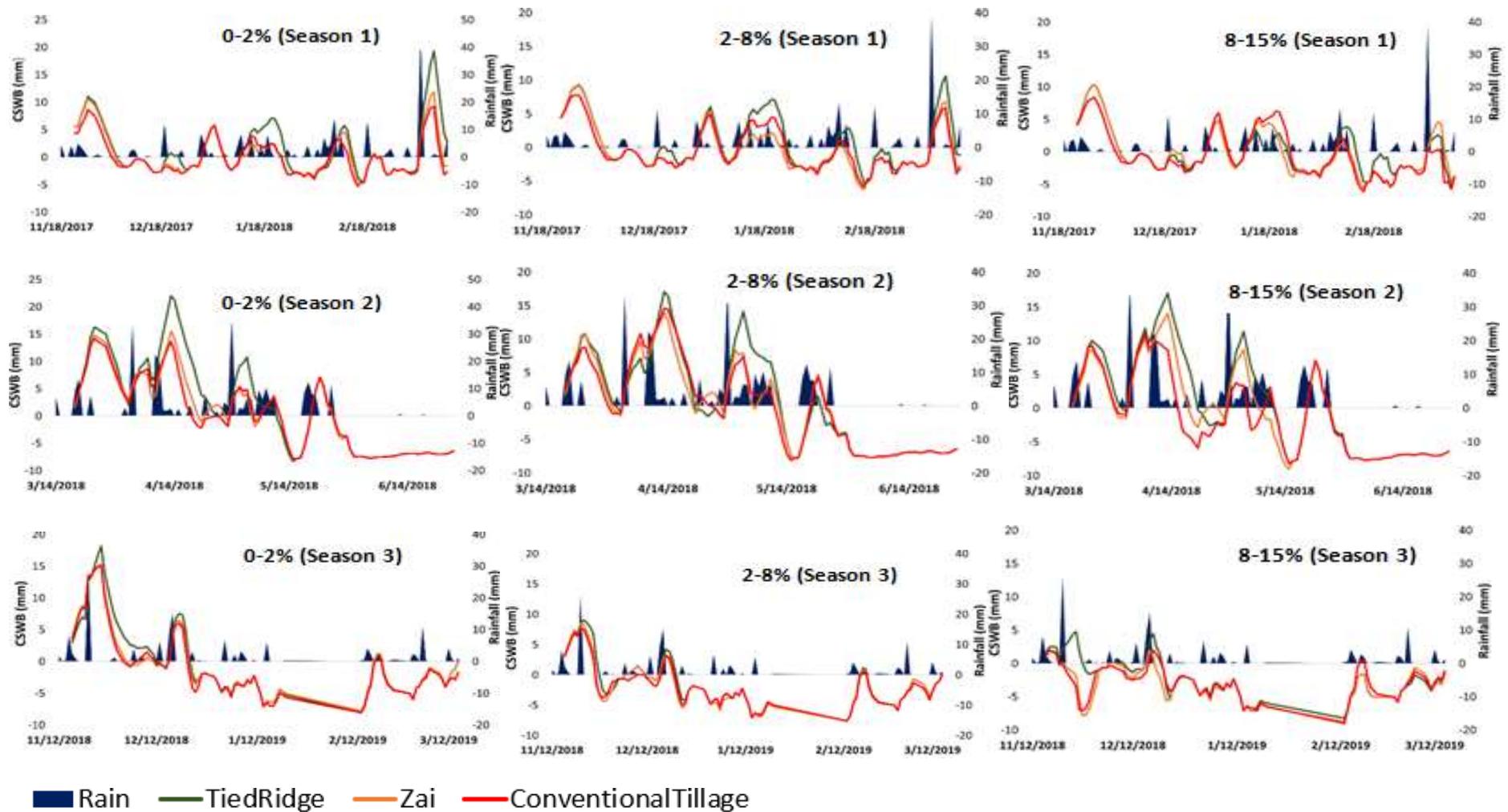


Figure 3. SWC practices' cumulative soil water balances (CSWB) for the three growing seasons along the slope gradients in Ruzizi plain. Each row represents a graph of season with different slope gradient.

($p > 0.05$). The highest downward drainage's seasonal nitrogen losses were recorded on slopes

of 0-2% (15.4 kg ha^{-1}) compared to the slopes of 2-8 (10.4 kg ha^{-1}) and 8-15% (10.5 kg ha^{-1}). The

loss of nitrogen by surface runoff was significantly influenced by SWC practices ($p < 0.05$) and slope

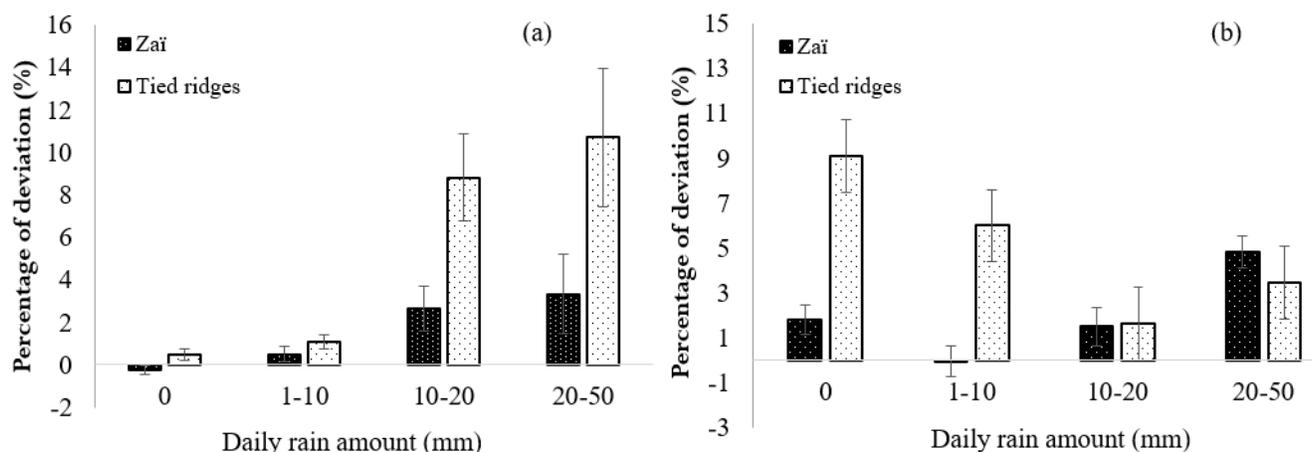


Figure 4. Daily percentage deviation of non-cumulative (a) and cumulative (b) soil water balance for different rainfall amounts

Table 5. Cumulative P and N nutrient balances under soil water conservation practices along the slope gradient.

Slopes	N drainage (kg ha ⁻¹)	N runoff (kg ha ⁻¹)	Total N loss (kg ha ⁻¹)	P drainage (kg ha ⁻¹)	P runoff (kg ha ⁻¹)	Total P loss (kg ha ⁻¹)	TN biomass (kg ha ⁻¹)	TP Biomass (kg ha ⁻¹)
Conventional tillage								
0-2	15.6±2.1 ^{ab}	30.2±3.4 ^{aa}	45.9±5.2 ^{aa}	0.78±0.12	13.9±2.0 ^{aa}	14.6±2.1 ^{aa}	184.8±21.4 ^{aa}	72.7±13.2 ^{bb}
2-8	8.4±0.6 ^{ab}	44.1±3.6 ^{ab}	52.5±4.2 ^{ab}	0.35±0.06	20.5±3.5 ^{ab}	20.9±3.5 ^{ab}	133.0±35.5 ^{ab}	55.1±15.0 ^{cc}
8-15	12.8±2.3 ^{ab}	73.5±4.2 ^{ac}	86.3±6.6 ^{ac}	0.55±0.13	27.3±4.8 ^{ab}	27.9±4.9 ^{ac}	112.0±33.5 ^{ab}	41.0±12.1 ^{cc}
Tied ridges								
0-2	13.2±2.7 ^{aa}	9.8±1.45 ^{ba}	23.1±4.0 ^{ba}	1.14±0.23	8.3±1.26 ^{aa}	9.5±1.46 ^{aa}	274.6±13.0 ^{ba}	155.9±7.2 ^{aa}
2-8	10.4±1.7 ^{ab}	34.1±2.5 ^{bb}	44.4±4.2 ^{bb}	0.71±0.18	22.0±3.9 ^{ab}	22.7±4.1 ^{ab}	144.1±37.4 ^{bb}	76.4±22.3 ^{bb}
8-15	7.1±1.29 ^{ab}	49.5±4.5 ^{bc}	56.6±5.7 ^{bc}	0.56±0.12	36.2±6.1 ^{ac}	36.8±6.2 ^{ac}	175.3±44.9 ^{bb}	77.5±22.1 ^{bb}
Zai pits								
0-2	17.4±2.5 ^{aa}	20.2±3.2 ^{aa}	37.6±5.8 ^{aa}	1.23±0.19	14.1±2.5 ^{aa}	15.3±2.7 ^{aa}	217.2±15.2 ^{aa}	100.1±11.8 ^{ba}
2-8	12.3±1.6 ^{ab}	42.1±1.3 ^{ab}	54.4±2.7 ^{ab}	0.95±0.19	31.3±4.4 ^{ac}	32.3±4.5 ^{ac}	156.9±36.0 ^{ab}	73.8±20.6 ^{bb}
8-15	11.7±2.4 ^{ab}	72.1±3.6 ^{ac}	83.8±5.7 ^{ac}	0.44±0.11	24.2±3.8 ^{ab}	24.6±3.9 ^{ab}	155.2±41.4 ^{ab}	59.7±17.2 ^{cc}

TN: Total Nitrogen, TP: Total Phosphorus. Means followed by the same letter within a column and under SWC practices are not statistically different at 5% p-value threshold.

gradients ($p < 0.01$). The highest surface runoff loss was observed on conventional tillage (49.3 kg ha^{-1}), while tied ridges recorded the lowest loss (31.1 kg ha^{-1}). The highest loss of nitrogen by surface runoff was observed on the slope of 8-15% (65.1 kg ha^{-1}) and lowest for the slope of 0-2% (20.1 kg ha^{-1}). Tied ridges reduced the total nitrogen loss by 34.4 and 49.8% on the slope of 8-15 and 0-2%, respectively, compared to the control. Zai pits reduced only 2.8 and 18.1% losses on corresponding slope gradients.

There were significant SWC practices ($p < 0.05$) and slope gradients ($p < 0.01$) effects on the plant nitrogen

uptake. Maize nitrogen uptake was higher under tied ridges ($66 \text{ kg ha}^{-1} \text{ season}^{-1}$) than the Zai pits ($58.3 \text{ kg ha}^{-1} \text{ season}^{-1}$) and conventional tillage ($47.7 \text{ kg ha}^{-1} \text{ season}^{-1}$). Higher maize nitrogen uptake was recorded on the slope of 0-2% (75.0 kg ha^{-1} per season) compared to the slopes of 2-8 and 8-15%, which recorded 49.1 and 48.2 kg ha^{-1} per season, respectively.

The phosphorus loss by downward drainage did not vary with SWC practices and slope gradients while the loss by surface runoff was influenced by slope gradients ($p < 0.05$) and the interaction between the slope and the SWC practice ($p < 0.05$). Phosphorus loss due to

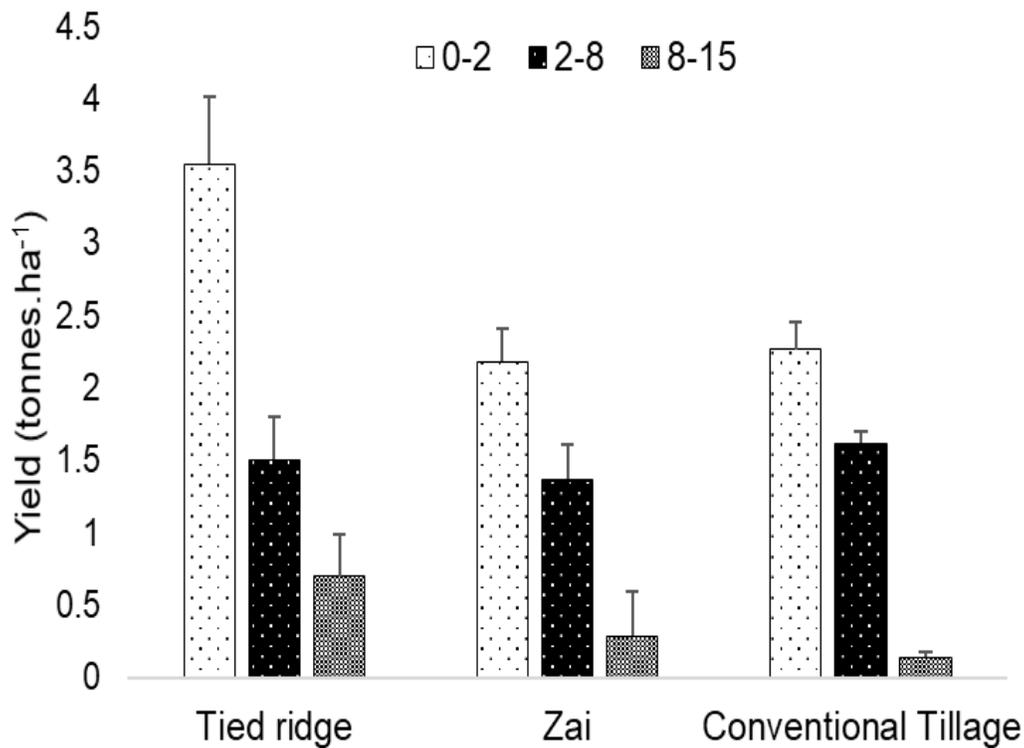


Figure 5. Maize yield variation under selected SWC practices along the slope gradient (%).

drainage was 1.04 kg ha^{-1} per season for the slope of 0-2% while no difference was observed between the slopes of 2-8% (0.64 kg ha^{-1} per season) and 8-15% (0.55 kg ha^{-1} per season). The loss of phosphorus by surface runoff was high for the slope of 8-15% (29.2 kg ha^{-1} per season) and low for the slope of 0-2% (12.1 kg ha^{-1} per season). The crop phosphorus uptake varied with SWC practices and slope gradient. Maize phosphorus uptake for all the three growing seasons was high for the slope of 0-2% (109 kg ha^{-1}) and low for the slope of 8-15% (59.4 kg ha^{-1}). Maize phosphorus uptake under tied ridges was highest (10.3 kg ha^{-1}) compared to the Zaï pits (77.9 kg ha^{-1}) and conventional tillage (56.3 kg ha^{-1}) for the three growing seasons.

Effect of SWC practices on maize yield along the slope gradient

Figure 5 shows a significant difference in yield due to slope gradients ($p < 0.01$) and SWC practices significantly ($p < 0.01$). The maize grain yield was higher at 0-2% slope (2.67 t ha^{-1}) than 8-15% (0.38 t ha^{-1}), making a decline of 85.7%. Based on grain yield, tied ridges had the best yield (2.16 t ha^{-1}) than Zaï pits (1.48 t ha^{-1}) and conventional tillage (1.58 t ha^{-1}). The increment of yield due to tied ridges was 38.7% compared to the control

(conventional tillage). The interactions between SWC practices and slope gradient influenced maize yield significantly ($p < 0.01$). The yield difference among SWC practices was observed at the slope of 0-2 and 8-15%, while no difference between SWC practices was observed at 2-8%. The highest yield was observed for tied ridges (3.55 t ha^{-1}) at the slope of 0-2% and the lowest at 8-15% (0.14 t ha^{-1}) for conventional tillage. No difference was observed between SWC practices at the slope of 2-8%.

DISCUSSION

Variations in soil water balance under selected soil water conservation practices

Tied ridges presented the highest cumulative soil water balance (CSWB) compared to Zaï pits and conventional tillage, by significantly reducing the surface runoff and downward drainage. The highest CSWB improvement was observed on the slope of 0-2% and the lowest was on 8-15%. The water conservation efficiency (WCE) was high on tied ridges than Zaï pits. Several studies had previously reported the ability of tied ridges to improve soil water balance in sub-Saharan Africa (McHugh et al., 2007; Ngetich et al., 2014; Wolka et al., 2018). Most of

the studies focused on a single water balance component and showed that SWB varies mainly with weather characteristics, slope gradient, soil properties and the SWC techniques (Mudatenguha et al., 2014; Grum et al., 2017). It is essential to focus on how each of these components contributes to the CSWB and thereby thoroughly understand the slopes and SWC practices effects.

The CSWB (y) was linearly reduced by the surface runoff (x_1), downward drainage (x_2) and the frequency of days with water deficit (x_3) across the three growing seasons ($y = 489.3 - 6.89x_1 - 1.8x_2 - 5.7x_3$, $R^2=0.93$; $p<0.001$).

The highest CSWB obtained from lower slopes (0-2%) could be mainly explained by the variations in runoff along the slope gradient. These results agreed with scholars who observed significant variations in surface runoff along the slope gradient (McHugh et al., 2007; Ngetich et al., 2014; Grum et al. 2017). McHugh et al. (2007) reported a surface runoff of 20 to 27% on the lands with steep slopes (9-11%), compared to gently sloping (0-3%) and sloping plots (4-8%). For some extreme rainfall events, Ngetich et al. (2014) showed that the runoff could reach 60% for the same slope gradient, as also confirmed by our study. Conversely, the downward drainage was high on the slope of 0-2% compared to the slopes of 2-8 and 8-15%. This could be attributed to the Ruzizi plain soil textural composition and the high concentration-time of rainwater on surfaces because of reduced water flow on 0 to 2% slope compared to steep slopes. Several studies on sandy soils showed a high water loss by drainage on lower slopes (McHugh et al., 2007; Liu et al., 2014). In addition, the coarse fraction in the study area was low on the slope of 0-2%. Generally, sandy dominated soils with a high proportion of coarse fractions tend to be more permeable, hence favouring high drainage.

The tied ridges controlled surface runoff more effectively than Zaï pits and conventional tillage. This corroborates with the findings of other scholars on the ability of tied ridges to reduce surface runoff (Okeyo et al., 2014; Wolka et al., 2018) and to induce a favourable distribution of rainwater for a better water and nutrient use efficiency (McHugh et al., 2007; Wolka et al., 2018). The tied ridges structure partly explains its performance: the earth elevation is set perpendicularly to the slope direction, and therefore, it reduces the overland flow speed, retains the water in the soil profile and forms an on-field storage pit. The above-described structure induces a counterforce that causes water to deposit its charge and gradually infiltrate laterally into the ridge coppices (Mupangwa et al., 2012). There is no structure for the conventional tillage to reduce surface runoff while for Zaï pits the soil is excavated on the downhill side (Wolka et al., 2018).

The tied ridges efficacy in capturing rainwater declined

with steeper slope gradient and high rainfall intensity. In one hand, high slope plots are often characterized by high erosion and rapid soil degradation (Wezel et al. 2002; Tijani et al., 2008; Oo et al., 2012; Mbugua et al. 2019). Besides, soil moisture is high and long-conserved under lower slopes than higher ones, explaining the low cereal performances on high slopes (Tsubo et al., 2006; Mbugua et al., 2019). On the other hand, heavy rains worsened soil erosion and nutrient losses and damaged established SWC practices. McHugh et al. (2007) reported the destruction of most ridges by heavy rains on the 9-11% slope gradient in Northern Ethiopia and which led to high surface runoff.

Tied ridges significantly reduced the downward drainage on the slopes of 0-2% compared to conventional tillage and Zaï pits. No differences existed between Zaï pits and conventional tillage. Tied ridges form an obstruction to the runoff as water first flows laterally before starting a vertical movement or capillary rise. In contrast, the water diffusion for Zaï pits and conventional tillage is only vertical. These results can also be explained by the low compaction rate when raising the soil to establish ridges. This improves water retention and proper restructuring of micropore diameters as observed by Moran et al. (2006). This process allows the soil micropores to retain water and limit the infiltration into the water table and the water loss through evaporation.

The frequency of days with water deficit was lower for tied ridges while it was statistically the same for Zaï pits and conventional tillage. A high frequency of days with water deficit was recorded on the higher slopes and could be attributed to weather characteristics, the surface runoff and downward drainage under the different SWC practices and slope gradients. Across growing seasons, the CSWB was characterized by a high ETP demand (1229.2 mm) compared the rainfall interception (636.6 mm). The high ETP demand was associated with high diurnal temperatures (31.5°C max) and an average solar radiation of 30.7 MJ m⁻² day⁻¹. The ETP and rainfall distributions varied significantly with the plant growth stages; the water deficits being pronounced at the mid to end stages of the growing cycle.

Variation of the soil nutrient balance under different SWC practices along the soil gradient

Tied ridges significantly reduced nitrogen and phosphorus losses compared to the Zaï pits. This performance is associated with this SWC practice ability to reduce the surface runoff and downward drainage (Ngetich et al., 2014; Deng et al., 2019). We also observed a strong relationship between the runoff, drainage amount and the total nitrogen losses ($p<0.01$) as opposed to the phosphorus losses that were only

associated with the surface runoff. Li et al. (2015) reported that the P loss is mainly caused by loaded sediments in the runoff, while it is relatively low in the subsurface flow. Other studies observed that the amount of runoff and sediment increases with the slope gradient and rainfall intensity (Fu et al., 2016; Deng et al., 2019). It is noteworthy that nutrient losses by runoff tended to decrease toward the end of the cropping season. It was mainly due to the vegetation cover, which may have reduced the splash effects of raindrops and the speed of the resulting runoff water (Araya and Stroosnijder, 2010; Li et al., 2015). It is noteworthy that the crop's nutrient export was higher under tied ridges as it produced more biomass than the Zaï pits and conventional tillage. It negatively affected the soil nutrient balance for both phosphorus and nitrogen. The increase in crop nutrient exports by the tied ridges would require the restitution after each harvest.

Effect of SWC practices on maize yield along the slope gradient

The tied ridges farming practice was efficient in improving maize yield under water deficient conditions. In fact, tied ridges recorded the highest yield on slopes of 0-2% compared to Zaï pits and conventional tillage. On slopes of 2-8%, no difference was observed among the three SWC practices. This can be attributed to the high-water saving capacity of tied ridges. During the experiment, the cumulative water balance was high on plots where maize was grown under tied ridges due to the reduction of runoff. It was also high at the slope of 0-2% compared to maize grown on slopes of 2-8 and 8-15%. Our findings agree with Wolka et al. (2018) showing that 83% of reviewed trials in Sub-Saharan Africa recorded a positive effect of tied ridges in improving yield in low rainfall areas (<1000 mm year⁻¹).

Conclusion

This study assessed the effects of SWC practices on soil water and nutrient balances along the slope gradient in the Ruzizi plain. Tied ridges provided a high cumulative soil water balance, reduced frequency of days with water deficit, and the surface runoff. This translated in high maize yield on this SWC practice compared to Zaï pits and conventional tillage. Regardless of the SWC technique and growing season, low slopes gave consistently better cumulative soil water balances. Tied ridges significantly reduced nitrogen and phosphorus losses compared to Zaï pits and conventional tillage and, therefore, provide an opportunity in coping with water scarcity in the Ruzizi plain. Its efficiency can be improved with micro irrigation during prolonged drought. The

application of organic matter could also be recommended for improving the soil water retention capacity of the Ruzizi plain sandy soils. Whenever tied ridges are applied, the nutrient restitution would be necessary to compensate the high nutrient exports for a sustainable soil nutrient management.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

This research was supported by the capacity-building competitive grant "Training the Next Generation of Scientists for Africa" funded by Carnegie Cooperation of New York through the Regional Universities Forum for Capacity Building in Agriculture (RUFORUM) and the Université Evangélique en Afrique under the project "University Research and Teaching Quality Improvement" funded by Pain pour le Monde (Project A-COD-2018-0383).

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