Catena 121 (2014) 288–296

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effects of selected soil and water conservation techniques on runoff, sediment yield and maize productivity under sub-humid and semi-arid conditions in Kenya

K.F. Ngetich [a,*], J. Diels [b], C.A. Shisanya [a], J.N. Mugwe [a], M. Mucheru-muna [a], D.N. Mugendi [c]

[a] *Kenyatta University, P.O. Box 43844-00100, Nairobi, Kenya*
[b] *K.U. Leuven, Department of Earth and Environmental Sciences, Celestijnenlaan 200E, Box 2411, B-3001 Leuven, Belgium*
[c] *Embu University College, P.O. Box Embu 6-60100, Embu, Kenya*

ARTICLE INFO

Article history:
Received 14 June 2013
Received in revised form 7 May 2014
Accepted 26 May 2014
Available online xxxx

Keywords:
Tillage
Mbili intercropping
Mulching
Erosion

ABSTRACT

The aim of this work is to investigate the consequences of selected soil and water conservation techniques and tillage practices on runoff amounts, sediment yield and maize yields under semi-arid and sub-humid environments. Field trials were set in Kigogo primary school in Meru South Sub-County, Tharaka Nithi County, representing the sub-humid conditions, and Machang'a secondary in Mbeere South Sub-County, Embu County (semi-arid) in the central highlands of Kenya. The experiment layout was a randomized complete block design and the treatments were implemented in runoff plots. Tied ridging (TR) was the most efficient technique in reducing runoff and sediment yield and at the same time boosting crop yields in the semi-arid region. It significantly ($p < 0.05$) reduced sediment yields by 94% compared to the conventional tillage (CT) during the study period. The effects were particularly strong in periods of below average rainfall (dry seasons). During the drier season of short rains 2010 (SR10), grain yield under TR was 7 times higher compared to CT ($p < 0.01$). In the sub-humid region, minimum tillage (MT) generated high runoff but relatively low sediment yield compared to CT. During periods of enough rainfall (over 450 mm per season) in the drier site, intercropping suppressed maize yields significantly ($p < 0.01$) by 42% compared to conventional tillage in the drier site. The results on the magnitude of runoff and sediment under the different soil and farm management practices are crucial in selection and promotion of valid farm management practices and tillage alternatives that not only abate soil erosion but also boost agricultural productivity in both sub-humid and semi-arid agro-ecological zones.

1. Introduction

Erosion by water is a primary agent of soil degradation at the global scale, affecting 1094 million ha, or roughly 56% of the land experiencing human induced degradation (Oldeman et al., 1991). Most regions of the humid tropics of Africa suffer from severe land degradation because of water erosion with its detrimental impact on food and agricultural productivity and production (Defersha and Melesse, 2012a).

In Kenya, soil erosion is mainly due to surface-water runoff. According to El Swaify et al. (1982), erosion rates of up to 200 ton/ha/yr have been noted in Kenya. Based on the Revised Universal Soil Loss Equation, Angima et al. (2003) predicted that total annual soil loss variation from one overland flow segment to the next ranged from 134 Mg ha^{-1} per year for slopes with average slope length and steepness (LS) factors of 0–10 to 549 Mg ha^{-1} per year for slopes with average LS-factors of 20–30 in the central Kenyan highland conditions. Soil degradation by accelerated erosion implies long-term decline in the soil's productivity and in the moderating capacity of its environment and is therefore a serious problem (Lal, 2001). The problem is more pronounced in the marginal lands, such as most semi-arid parts of Kenya, due to erratic and highly variable rainfall both spatially and temporally. The rainfall often occurs as high intensity, short duration giving rise to severe soil erosion especially early in the cropping season when the ground is still bare (Chikozho, 2010; Trabucco et al., 2008). Besides the undesirable effect of soil erosion, soil moisture is generally limited and crop growth is almost always stressed by drought during the growing season, resulting in decreased and unsustainable crop yields especially in the marginal lands.

The quantification of the forms/type, rate, and extent of erosion has been the primary goal of soil erosion-related research worldwide. As a result, much more is known about the erosion process than the consequences of erosion (Pierce and Lal, 1994). There is a lack of information on the effect of erosion on crop yields and efficiency of management practices.

The main limitation in stabilizing and increasing grain yields in rainfed farming systems of dry-spell prone areas is crop water stress

---

* Corresponding author at: Department of Agricultural Resource Management, Kenyatta University, P.O. Box 43844-00100, Nairobi, Kenya. Tel.: +254 721 289 269.
E-mail address: felixngetich@gmail.com (K.F. Ngetich).

http://dx.doi.org/10.1016/j.catena.2014.05.026

caused by inefficient use of total available seasonal rainwater (McHugh et al., 2007). Even during periods of high seasonal rainfall, if the interval between consecutive rain events is too long it can cause total pasture and crop failure (Tilahun, 2006). The risk of drought in sub-Saharan Africa is also linked to lack of available water as a result of deteriorated soil physical characteristics (Stroosnijder and Slegers, 2008) accelerated by physical processes such as soil erosion due to runoff. Runoff is a major force that initiates soil movement, transports sediments and accounts for the redistribution of rainfall water (Malam Issa et al., 2011). Runoff can be caused by low infiltration rates as a result of soil physical properties such as crusting, compaction, expanding clay minerals or due to saturation, slope surface management as well as rainfall properties. Infiltration capacity is the most important factor controlling runoff. Soil infiltration capacity is related to spatial variability of soil properties such as structure, organic matter content, soil texture and antecedent soil moisture (Vaezi et al., 2010). Soil structure is strongly influenced by processes such as tillage, cropping system and climate.

Management of soil through conventional tillage changes soil water storage, evaporation losses and soil susceptibility to runoff generation. Most small scale farmers practice it. The advantages are clear: weeds are well controlled and the sowing and planting operation can be done effectively (Jin et al., 2007). However, the conventional tillage practices are very far from being sustainable and environmentally compatible from a soil and water conservation perspective because of the uncovered soil surface (Jin et al., 2007). In addition to the obvious effects on erosion rates and water losses through runoff, soil disturbance during regular tillage enhances direct evaporation of water from the soil surface. Increased evaporation of water with tillage has also been attributed to enhanced vapor flow near the surface and greater absorption of radiation by a tilled surface (Schwartz et al., 2010). Knowledge on the merits and demerits of conventional tillage notwithstanding, there is a gap in the quantification of runoff generation, sediment yields and impact on crop yields under rainfed farming systems and different soil types in the tropics.

Minimum tillage has the potential to reduce structural degradation of soil, or may reverse it, compared to conventional tillage systems (Karunatilake and van Es, 2002). Soil physical properties that are influenced by minimum tillage include bulk density, infiltration and water retention (Osunbitan et al., 2004). Improved infiltration of rainwater into the soil potentially increases water availability to plants, reduces surface runoff and improves groundwater recharge (Lipic et al., 2005). Depending on the exact technique, minimum tillage can substantially reduce soil erosion. For instance, in a study by Towery (1998) minimum tillage reduced soil erosion by 68%. Albeit the beneficial effect of minimum tillage especially on soil erosion reduction being known, there is paucity of quantitative data on its effect on runoff reduction and crop yield performance.

Mulch cover reduces surface runoff and holds rainwater on the soil surface thereby giving it more time to infiltrate into the soil (Mupangwa et al., 2007). It also shades the soil, serves as a water vapor barrier against evaporation losses and increases infiltration (Mulumba and Lal, 2008). Deng et al. (2006) reports an improved water-use efficiency by 10–20% as a result of reduced soil evaporation and increased plant transpiration attributed to mulching while Bezborodov et al. (2010) reports that, straw mulching has been shown to increase water-use efficiency from 1.55 to 1.84 kg m^{-3} maize. Mulching is a promising soil management practice that can increase soil water storage especially in semi-arid regions (Deng et al., 2006; Wang et al., 2009; Zhang et al., 2009). Despite the high potential of mulch, its effect for increasing yield would depend on the amount of precipitation during the crop growth season (Wang et al., 2009). Besides the runoff reduction, mulching affects hydro-thermal regime of soils by moderating soil temperature and reducing soil water evaporation component of evapotranspiration and controls weeds by their smothering action (Arora et al., 2011). Soil biota increase in a mulched soil environment thereby improving nutrient cycling and organic matter build up over a period of several years (Holland, 2004). Although the highlighted potential benefits can lead to improvements in crop yields, there is a lack of quantitative data on the effect of mulch on runoff reduction, sediment yield reduction and ultimately their effect on crop yields under sub-humid, arid and semi-arid environments of tropical regions.

Legume-cereal intercropping is common throughout East and Southern Africa (Giller, 2001). Farmers commonly intercrop to secure food production by averting risk and to maximize utilization of land and labor. When crops are complimentary in terms of growth pattern, aboveground canopy, rooting system, and their water and nutrient demand, intercropping effectively enables a more efficient utilization of available resources (sunlight, moisture and soil nutrients) and can result in relatively higher yields than when crops are grown separately, as pure stands (Mucheru-muna et al., 2010). Besides fertility related benefits, intercropping ensures good ground cover which can reduce runoff and increase infiltration (Olasantan, 1988). Increased infiltration rate in an intercrop may also be caused by increased soil biota activity as a result of lower soil temperature (Hulugalle and Ezumah, 1991). A special feature of intercrops is that, for some time during growth the component crops compete with each other for available resources (Fukai and Trenbath, 1993) leading to overall lower benefits when one of the resources is highly limiting. In order to overcome this limitation, studies have been done on the best arrangement of the intercropped crops and the best intercropping system recommended for Kenya is an innovative, improved intercropping system, named Mbili (kiswahili for “two”, and an acronym for “Managing Beneficial Interactions in Legume Intercrops”); two maize rows are alternated by two legume rows, also known as a two-by-two staggered arrangement (Mucheru-muna et al., 2010; Tungani et al., 2002; Woomer, 2007). Mbili system superiority has been tested in the Central Highlands of Kenya by Mucheru-muna et al. (2010) and recommended based on its effect on the fertility status of the soil, but limited information is available on its impact on runoff generation and sediment yields under rainfed conditions.

Tied ridging can decrease runoff, increase water infiltration and consequently greater water storage than with either flat planting or open ridging. Planting on tied ridges has been found to result in striking yield increases on the Alfisols of the West African semi-arid tropics (Hulugalle, 1987). Apart from tied ridging reducing runoff, it increases profile water content and hence root growth and development. If poorly implemented, ridging can act as waterways and may cause erosion and this is the main reason of tied ridging; connecting the ridges every 2–3 m so that small basins are formed (Nuti et al., 2009; Temesgen et al., 2009). The exact impact of tied ridging effect on runoff and sediment yield reduction in the tropics under rainfed conditions is lacking.

Adoption of appropriate on-farm crop management strategies and tillage practices can be the key in reducing runoff generation and soil erosion. These appropriate management practices can increase available water content, enhance soil fertility and reduce sediment loss compared to the conventional practices. Therefore, understanding runoff, soil erosion, sediment yield and how they affect maize yield and agricultural productivity is essential for developing practices and policies for decision making, planning and reduction of soil erosion.

Based on this assumption, runoff plots were installed at two sites with varying agro-ecological conditions. The objective of the study was to evaluate the effects of minimum tillage, mulching, conventional tillage, tied ridging and Mbili intercropping on runoff amounts, sediment yield and maize yields under semi-arid and sub-humid environments in the Central Highlands of Kenya.

2. Materials and methods

2.1. Study area

The field research was carried at two contrasting sites in Central Kenya (Fig. 1): Kigogo (0°23′S and 37°37′E) in Meru South Sub-

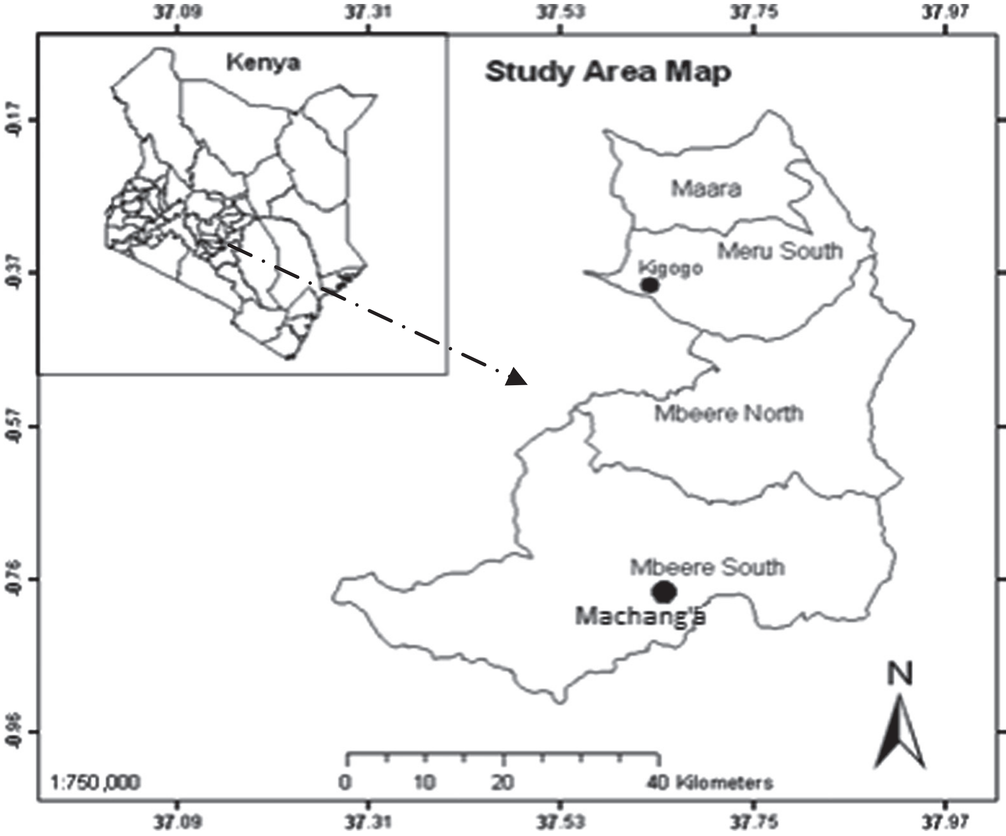

Fig. 1. Map showing the study sites.

County, Tharaka Nithi County and Machang'a (0°46′S and 37°39′E) Mbeere South Sub-County, in Embu County. The farmers in the region primarily rely on small-scale rainfed farming, which is mostly non-mechanized and involves little use of external inputs.

Machang'a site lies at an altitude of 1106 m above the sea level on the South-Eastern slopes of Mount Kenya, with a mean annual temperature ranging from 20.7 to 22.5 °C with an average annual rainfall between 700 and 900 mm. The rainfall is bimodal with long rains (LR) from mid March to June and short rains (SR) from mid October to February, hence two cropping seasons per year. The soil type of the experimental site is Plinthic Cambisol (FAO and UNESCO, 1988). The prevalent soil texture in the site is sandy clay loam with about 30% clay, 10% silt and 60% sand. The site is characteristic of marginal region with low agricultural potential and is situated in the Lower Midland Agro-ecological Zones 4 (LM4). Lower Midland 4 is a Livestock-Millet Zone characterized by short to very short cropping season. These zones are suitable for common beans (*Phaseolus vulgaris*), Dry land composite and hybrid maize (*Zea mays*), sorghum (*Sorghum bicolor*) green grams (*Vigna radiata*), cowpeas (*Vigna unguiculata*), and chick peas (*Cicer arietinum*) among other pulses (Jaetzold et al., 2006). It is representative of semi-arid agro-climatic conditions with relatively low agricultural production potential. Although the region is more suitable for drought tolerant crops and livestock rearing (Jaetzold et al., 2006), major crops grown by most households are maize (*Z. mays*), cowpeas (*V. unguiculata*), pigeon peas (*Cajanus cajan*) and common beans (*P. vulgaris*).

Kigogo lies in the Upper Midland Agro-ecological Zone 3 (UM3) on the Eastern slopes of Mount Kenya, at an altitude of 1398 m above the sea level and an annual mean temperature of 20 °C and total annual rainfall ranging from 1200 to 1400 mm. The rainfall is bimodal with long rains (LR) from March to June and short rains (SR) from October to December. The soil type at the experimental field is a Humic Nitisol (FAO and UNESCO, 1988). The prevalent soil texture in the site is clay with about 78% clay, 14% silt and 8% sand. Upper midland 3 (UM 3) is a marginal coffee zone having intermediate to short rains (Jaetzold et al., 2006). Major crops grown are beans (*P. vulgaris*), Irish potatoes (*Solanum tuberosum*), sweet potatoes (*Ipomoea batatas*), cabbages (*Brassica oleracea*), kales (*B. oleracea* L.), tomatoes (*Solanum lycopersicum*), onions (*Allium cepa*), and maize (*Z. mays*). The farmers in the region primarily rely on small-scale rainfed farming, which is mostly non-mechanized and involves minimal use of external inputs.

2.2. Field experiments

The experimental layout for the runoff experiment was a randomized complete block design with four treatments replicated thrice leading to 4 experimental units per replicate and a total of 12 units per site. The treatments for Kigogo were minimum tillage (MT), conventional tillage (CT), Mbili intercrop (MI) and mulching (MC) at a rate of 5 Mg ha^{-1}. In Machang'a, the treatments were the same as Kigogo except MT was replaced with tied ridges (TR), the justification of the variation being that, given the agro-ecological conditions prevailing in Machang'a, it was logical to focus on technologies that are likely to increase the soil's available water content.

The experiment was implemented in the runoff plots (described in Section 2.4) for three seasons: long rains season of 2010 (LR10), short rains season of 2010 (SR10) and long rains seasons of 2011 (LR11). The slope where experimental units were installed in Machang'a was between 4 and 5% and in Kigogo it was 9.5 to 12%. The test crop was maize (*Z. mays*), DH04 variety for Machang'a and H513 for Kigogo. Three maize seeds per hill were planted with a spacing of 0.9 m between and 0.6 m within the rows in Machang'a and 0.75 m between by 0.25 m within the rows for Kigogo, and were thinned out to 2 per hill two weeks after emergence. Inorganic fertilizers (NPK, 23:23:0 and triple super phosphate, TSP) were spot applied during planting at a rate of 60 kg N ha^{-1}, the recommended rates. Phosphorous was applied as

Triple Super Phosphate to give a total of 90 kg P ha^{-1}. Tillage was done by hand hoeing to a depth of about 0.15 m. Weeding was done using hand hoe when required to ensure that clean fields as much as possible throughout the seasons and pests were controlled when necessary following conventional best practices. Above ground biomass yields were determined on dry weight basis after harvesting and sun drying until constant weight. Grain yield quantities were measured at 13.5% moisture content.

2.3. Rainfall

Daily rainfall measurements were taken using tipping-bucket, data logging rain gauge, Hobo, model; RG3-M (manufactured by Onset Computer Corporation Company) with a 0.2 mm resolution installed within the research sites. The data loggers were launched and read out, and data were exported to excel worksheets for further processing using HOBOware Pro Version 3.2.2. Daily rainfall (Fig. 2) was calculated by multiplying the number of tips per day (09:00 h) by 0.2 mm tipping bucket resolution of the rain gauge.

2.4. Runoff data collection

Runoff plots measuring 3 m width by 12 m long (along the slope) were bounded on three (top width and length across the slope) sides by installing galvanized corrugated metal sheets buried at least 25 cm in the ground and 25 cm left above the ground surface. At the bottom end of the plot, a gutter, designed to slope towards one end, was installed to collect and convey runoff into a 200 liter storage tank via a 7.6 cm diameter drain pipe. Given the limited storage capacity, the tank was modified so that in cases of high runoff, excess runoff that would lead to storage tank overflow was accounted for. Seventy eight holes per storage tank were perforated using 8.4328 mm (3/8″) drill bits at a constant height from the bottom so that all the holes were on the same plane (level). One of the holes was fitted with hose pipe that drained to a smaller (20 l) container. The tanks were calibrated at the site following the dynamic calibration procedure as described by Okoba and Sterk (2006). Total runoff in storage tank was measured after thoroughly mixing and sampling for sediment concentration determinations in the laboratory. In cases of excess runoff, overflow volumes were determined and also sampled separately for sediment concentration determinations. After every storm event and having sampled and measured the necessary parameters, gutters and storage tanks were cleaned and set for the next rainfall. All samples were oven-dried at 105 °C until constant weight. The sediment yield data from the storage tank overflow were rescaled by multiplying with the number of the holes per tank and summed up with the main storage tank sediment to give the total sediment yield per rainfall.

2.5. Curve number determination

Daily runoff and daily rainfall were analyzed together to obtain runoff curve number (CN) for each runoff plot per rainfall event then averaged to give the indicative CN for the treatments. The following Eqs. (1) and (2) (SCS, 2004) were used for CN derivation.

$$Q = \frac{(P-0.2S)^2}{P-I_a+S} \tag{1}$$

With $P \geq I_a$; $S \geq I_a + F$; $F = P - I_a - Q$ and $I_a = 0.2S$.

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \tag{2}$$

Where P is precipitation (mm), I_a is initial abstraction (mm), Q is runoff (mm), S is storage parameter, F is the actual retention after runoff begins and CN is the curve number. The initial abstraction ratio was assumed to have a value 0.2. To account for the effects of antecedent moisture condition (AMC) on runoff production, an overall CN per site was derived by averaging the various CNs per treatment per site after which S was obtained using Eq. (3).

$$S = 254\left(\frac{100}{CN} - 1\right) \tag{3}$$

The obtained S was taken to be for average conditions (AMC II). It was then used to derive AMCs I and III using Eqs. (4) and (5) (Raes et al., 2009).

$$CN_{AMC\ I} = -16.91 + 1.348\ CN_{AMC\ II} - 0.01379\ CN^2_{AMC\ II} + 0.0001172\ CN^3_{AMC\ II}$$

With

$$0 \leq CN_{AMC\ I} \leq 100. \tag{4}$$

$$CN_{AMC\ III} = 2.5838 + 1.9449\ CN_{AMC\ II} - 0.014216\ CN^2_{AMC\ II} + 0.000045829\ CN^3_{AMC\ II}$$

With

$$0 \leq CN_{AMC\ III} \leq 100. \tag{5}$$

The AMC I and AMC III were plotted to represent the ‘error-bands’ to describe departure of surface runoff from the average as a result of rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature among others.

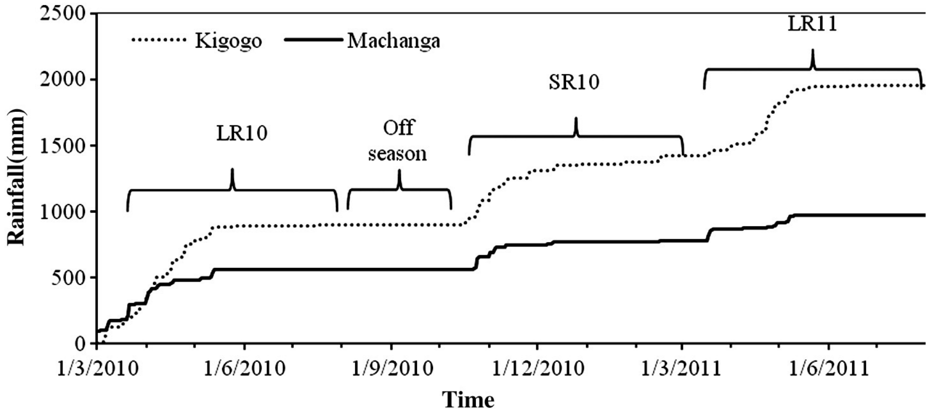

Fig. 2. Cumulative rainfall (mm) for the two research sites over the entire study period. The season durations are indicated.

2.6. Data analysis

Grain, biomass and sediment yield data were analyzed with a mixed model analysis of variance (ANOVA) treating the four management options as fixed effects, and the three seasons per site and replication (season) as random effects. Diagnostic checks on potentially influential and outlying random and residual effects were performed on the data as a first step in the analysis using studentized residual approach. This allowed for quick graphical checks of fitted residuals in assessing distributional assumptions such as variance homogeneity and lack/presence of serial correlation, and to examine the need to add or transform fixed model effects. Diagnostic plots suggested heterogeneity of variances, that is, the variability of the data changed according to one or more factors. Heterogeneity of variances was accounted for by modeling the covariance structure with a power-of-the-mean model (POM) (Littell et al., 2006). Kenward and Roger (1997) correction for standard errors and *F*-statistics and a generalized procedure to obtain degrees of freedom were included in the model. In order to fit the POM model, initial values for the intercept and slope as well as starting values for the covariance parameters were provided from external data set derived using ordinary least squares i.e., by using a linear regression model that assumed the errors to be identically independently distributed. To improve on the model convergence by avoiding residual variance to become too small when estimating variance in the POM model, rescaling of sediment yield data was done so that all parameters were of the same order of magnitude. Rescaling does not affect the results, except that Least Squared means (LSMeans) had to be scaled back before utilizing the results. The ANOVA was conducted using the Mixed procedure in SAS 9.2 (SAS Institute, 2004). When the treatment effects were found to be statistically significant, standard error of difference (SED) post hoc range test was used to determine how the treatments differed from each other at an alpha level of 0.05.

Runoff coefficient (RC) was determined and expressed in percentage using Eq. (6)

$$\mathrm{RC} = (\text{Runoff depth } / \text{Rainfall depth}) \times 100 \tag{6}$$

Sediment yield per plot was determined using Eq. (7) and expressed in Mg ha^{-1}.

$$\text{Sediment loss} = \frac{\text{Sediment concentration } \left(\frac{\text{g}}{\text{l}}\right) \times \text{Runoff volume (l)}}{\text{Plot area } (36 \text{ m}^2)} \tag{7}$$

3. Results and discussion

3.1. Runoff coefficient

The cumulative rainfall amounts received during the study in both sites are shown in Fig. 2. Generally, Kigogo site received more rainfall compared to Machang'a in all the seasons.

The average runoff coefficient per treatment during the study period was lower in Kigogo than in Machang'a which had the highest RC. In Kigogo, NT had significantly ($p < 0.01$) the highest RC compared to MC while CT and MI were not significantly different from each other or any other treatment. Although the rainfall amounts were generally very low in Machang'a (less than 400 mm per season), there was a high prevalence of runoff CT having significantly ($p < 0.01$) the highest RC followed by MI and MC which were both significantly different from CT but not between each other and lastly TR (Fig. 3). In other words, CT generated high runoff while TR was more efficient in reducing runoff.

The high runoff coefficient observed in Machang'a's CT despite the relatively low rainfall amounts (about 400 mm per season on average) can be explained by the prevailing soil type coupled with climatic effects in the site. In marginal environments with predominantly silty soils, high rainfall intensities and frequent dry spells lead to the formation of surface seals and crusts which alters the hydrological properties of a soil (Twomlow and Bruneau, 2000). Soil crusting combined with CT method might result to high runoff generation. Frequency and intensity of tillage practices alter the soil bulk density and soil organic carbon in the plow layer (Jin et al., 2007) in a manner that is not favorable for aggregate stability leading to an increase in soil's susceptibility to erosion. Mamedov et al. (2002) found that the effect of antecedent moisture on runoff and soil loss was very pronounced in clay soil, while in silt loam soil, the effect was negligible. The observation can be explained based on the soil physical property dynamics as a result of conventionally tilling the soil. Soil retains more water when the tilled layer is more porous or when soil fragments are large, with large macro-pores between them. The altered pore size distribution as a result of conventional tillage is very unstable and tends to change as the season progress which is often the case for structurally unstable soils that settle due to post-tillage rainfall (Karunatilake and Van Es, 2002). Up to a 300% increase in macroporosity after plowing and subsequent decrease upon soil settling have been measured by van Es (1993). Furthermore, high rainfall intensities coupled with crust sensitive soil types can result in a significant production of surface over-land flow in crop fields (Rockström, 1998). Surface sealing, a dynamic process during rainfall, is mostly ignored in many soil erosion studies, although surface sealing due to raindrop impact and its effect on infiltration rate has been recognized for a long time (Fohrer and Rudolph, 1999).

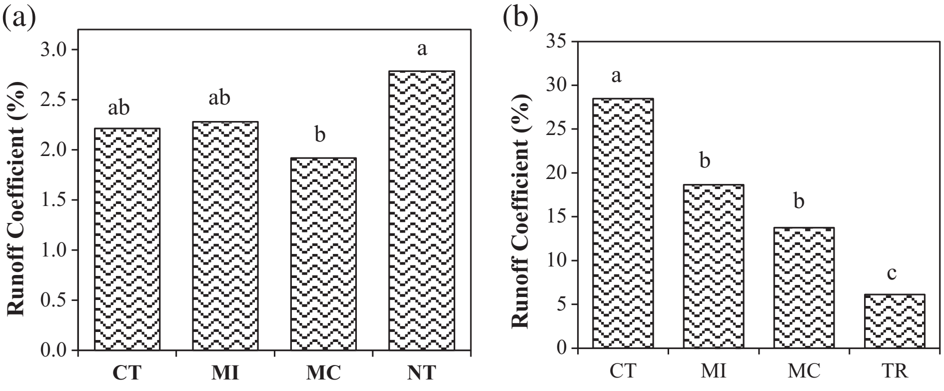

Fig. 3. Average runoff coefficient per treatment during the SR10 and LR11 seasons in Kigogo (a) and Machang'a (b). Bars having the same superscript letter are not significantly different at $p = 0.05$.

Table 1
Runoff curve number values for Antecedent Moisture Classes (AMC) II and their corresponding values for AMCs I (dry) and III (wet) for the treatments and average potential maximum retention (S).

Site	AMC	CT	MI	MC	NT	Mean CN	S (mm)
Kigogo	I	48	49	48	49	48	271
	II	68	69	68	69	69	117
	III	84	84	84	84	84	49
Machang'a	I	76	71	69	62	70	110
	II	89	86	84	80	85	46
	III	95	94	93	91	93	19

The CN values for the different treatments per site are shown in Table 1. The average CN of AMC II for Kigogo was 69 while that of Machang'a was 85. Also, the derived average S was almost three times higher in Kigogo compared to Machang'a (Table 1).

The rainfall–runoff relationship plots showed that runoff generation increased with increase in rainfall amounts in Kigogo while in Machang'a, the relationship was more erratic (Fig. 4). In Machang'a, the rainfall amounts were generally low while the runoff was comparatively high. There was an instance where low rainfall events of less than 20 mm were generating runoff amounts beyond the AMC III and at the same time very high rainfall events generating comparatively very low runoff (below AMC I). Generally, the rainfall versus runoff plot distribution was randomly distributed between AMC I and AMC III CN curves. CT generated the most runoff in almost all rainfall events during the entire study period followed by MI while TR effectively reduced runoff generation during rainfall events of both high and low amounts.

In Kigogo, rainfall amounts per event were generally high compared to Machang'a but runoff generation was very low. The relationship between runoff versus rainfall followed the expected trend; runoff increases with an increase in rainfall. Most of the rainfall with high amounts fell between CN AMC II and AMC III. Contrary to the observation in Machang'a, MC and CT reduced runoff as shown by comparatively lower values while MI was intermediate, Fig. 4.

The runoff–rainfall relationship as influenced by the treatments in Machang'a might be attributed to antecedent runoff conditions. They include rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature, which can influence variability in CN. Defersha and Melesse (2012b) concluded that, factors such as rainfall intensity, topography, and soil properties are the important parameters that determine runoff, erosion and sediment concentration. The high runoff generation observed during relatively low rainfall was probably due to erosivity, that is, rainfall's capacity to cause erosion as a result of its properties: raindrop size, frequency, duration and their velocities of impact when multiplied together coupled with soil erodibility and densification of the soil.

The overall temporal change in runoff discharge rate in Kigogo could be explained by the temporal variation of soil infiltration (Jin et al., 2007), just like in an infiltration experiment conducted by Schiettecatte et al. (2005), where they observed a pattern that can be attributed to high infiltration rates at the beginning of rainfall event, followed by a relatively rapid decline and an asymptotic approach to a near constant value. Specifically, NT consistently generated high runoff, an indication of low infiltration leading to lower soil water content recharge in the soil. The observation can be attributed to micro and macro pores' dynamics as influenced by minimum tillage practices. Under minimum tillage, total porosity is usually smaller than conventional tillage, but pore systems are more continuous because of worm and root channels and vertical cracks between peds that are not disturbed (Karunatilake and Van Es, 2002). Also, given the soil type in the site, most of the runoff generated was likely a consequence of the saturation of the upper part of the soil. In a 3-year experiment with five different mulching rates, Jordán et al. (2010) demonstrated that application of straw mulching to cultivated soils contributed to a general improvement of soil physical and chemical characteristics and reduced runoff and erosional response to rainfall. Hatfield et al. (2001) reports a 34–50% reduction in soil water evaporation as a result of crop residue mulching.

3.2. Sediment yield

Conventional tillage led to high sediment yields over the entire study period in both sites (Fig. 5).

The sediment yield difference was significant between CT and mulching by 40% ($p < 0.05$), between MI and mulching by 28% ($p < 0.05$) and between CT and NT by 32% ($p < 0.05$) in Kigogo (Fig. 5a). Conventional tillage roughens the soil surface and breaks apart any soil crust. This leads to increased water storage as a result of increased infiltration into soil. Increasing mulch application rates contributed to an increase in soil porosity, stability of aggregates, and organic matter content and a decrease in bulk density and hence lower sediment yield in the MI treatments as observed by Jordán et al. (2010). Defersha and Melesse (2012b) showed that, the highest total sediment yield over the study period was observed on cultivated land (162.38 g m^{-2}) hence the observed high sediment yields in CT are not unique. The main source of the high sediment yields is due to regular disturbance of the soil surface in CT.

In Machang'a CT generated the highest amount of sediment yield followed by MI and mulching while tied ridges was the least (Fig. 5b).

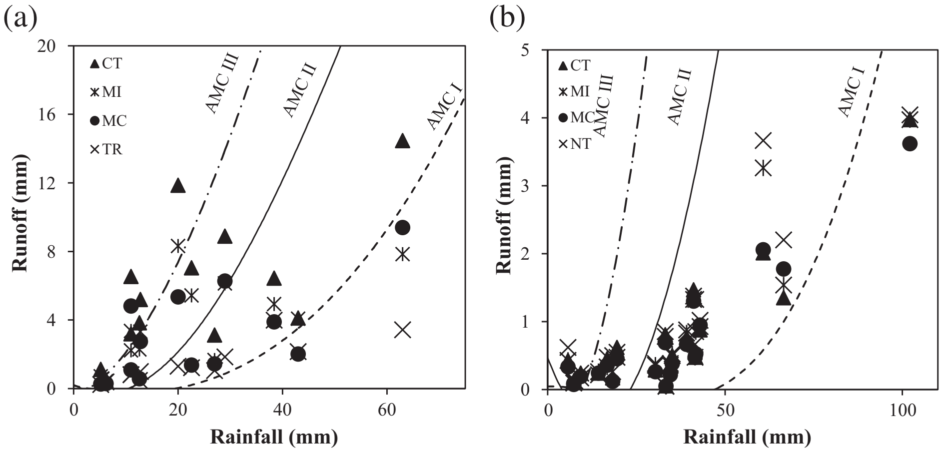

Fig. 4. Daily rainfall–runoff relationships fitted with Antecedent Moisture Classes I, II, and III for the four in the two sites: Machang'a (a) and Kigogo (b).

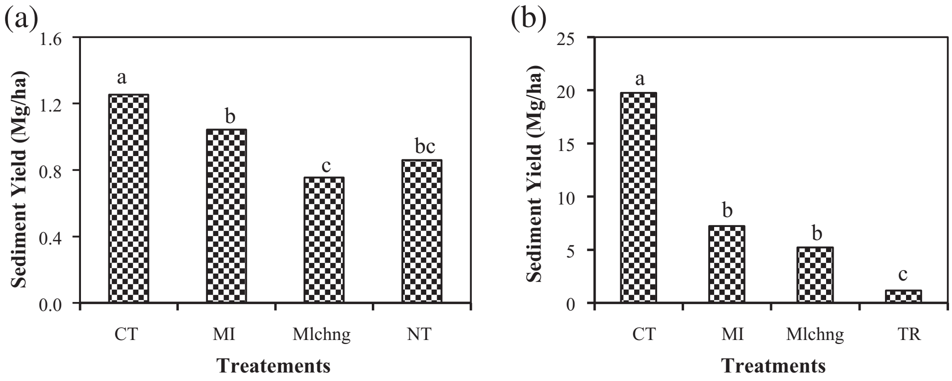

Fig. 5. Graphs showing total (two seasons) sediment yields per treatment for Kigogo (a) and Machang'a (b) sites. Bars having the same superscript letter are not significantly different at $p < 0.05$.

Compared to CT, the sediment yield difference of TR was significantly ($p < 0.01$) the highest (94% less) followed by mulching (73.5%) and the least was MI (63.3%), though not statistically different. There was no statistical difference between MI and Mulching treatments in Machang'a. During all the field trial period, there was high prevalence of termite infestation specifically on the MC plots especially in Machang'a. The termite activities were always high after rainfall events which, coupled with prevailing atmospheric conditions (Mando and Stroosnijder, 1996) in the region, such as high temperatures, resulted in higher and faster degradation rates of mulch in Machang'a compared to Kigogo. The soil surface cover effect of mulch was not strongly affected by the degradation since by the time the termite effect was pronounced, mostly the crop would have established enough canopy to cover the soil surface and maintain low soil water loss through evaporation, presumably as low as that of mulch or even better. The comparatively high degradation rate of mulch in Machang'a ensured minimal amount of mulch remaining by the end of each season. Besides the soil and water conservation benefits of mulching, studies in the semi-arid and arid tropics of Africa have demonstrated that mulch can be used as a sustainable restoration practice for crusted soils, through the stimulation of termite activity (Mando and Miedema, 1997) which can have beneficial effects especially on soil physical properties. Termite-mediated processes have been shown to increase water infiltration and storage, decomposition, soil carbon, water use efficiency and productivity (Ouédraogo et al., 2007; Rouland et al., 2003). As a result of these, by default, the process would likely reduce crust formation on crust susceptible soils of Machang'a and hence less runoff generation leading to low sediment yields.

3.3. Maize yield

Comparative biomass and grain yield performance between the three seasons in the two sites indicate that there was better performance of biomass and grain yields during the SR10 for Kigogo and LR10 in Machang'a sites while LR10 and LR11 for Kigogo and SR10 and L11 for Machang'a were the worst seasons (Table 2).

The differences in maize performance of the different seasons can be attributed to rainfall amounts and patterns that were experienced during the seasons (Fig. 2). In Kigogo, rainfall amount was high in LR10 and SR10 compared to L11 while in Machang'a, the amount was above the seasonal average and the onset was timely in LR10, neither too late nor too early even though the cessation was no different from any other season. The yield differences observed between the sites were due to the prevailing climatic conditions in the regions and also the crop varietal differences. Due to the relatively low rainfall amounts (on average about 400 mm per season) and poor distribution in Machang'a, short duration maize varieties (e.g. DH04) were used in order to cope with and produce within the short duration when the available soil moisture was sufficient for crop growth and development. Also the soil types are different with Machang'a having sandy clay loams within the plow layer and a restrictive (to root development) plinthite layer within the top 1 m depth while Kigogo has clayey soils and a deep soil profile.

In Kigogo, grain yields under CT were significantly ($p < 0.05$) the highest followed by MC while MT and MI were low without significant difference between them in the LR10 season (Table 2). The high grain yield in Kigogo was probably because of the prevailing agro-ecological conditions coupled with prevailing soil type/properties as expounded in the site description section. Conventional tillage facilitated soil profile water recharge at the beginning of each season as a courtesy to soil disturbance, an attribute that is lacking in MT. Compared to MI, there was a limited competition for the limited resources such as water, sunlight and plant nutrients under CT. It has been observed that, sometimes MT decreases grain yields during the first season of implementation, but after several years of cropping with better-adapted management techniques, yield increases have been observed (Astatke et al., 2003).

Mbili intercrop suppressed both the grain and biomass yields significantly ($p < 0.05$) in Machang'a during the LR10 season which was the best season in the site. The other treatments had comparatively high yields with no significant differences between them. Ensuring good ground cover by intercropping can reduce runoff and increase infiltration (Olasantan, 1988) during seasons of above average rainfall.

Table 2
Grain and total above ground biomass yields as influenced by the selected treatments.

Treatment	Grain ($Mg\ ha^{-1}$)	Biomass ($Mg\ ha^{-1}$)	Grain ($Mg\ ha^{-1}$)	Biomass ($Mg\ ha^{-1}$)
	Kigogo		Machang'a	
LR10				
CT	6.09^{a}	15.09^{a}	2.91^{a}	7.43^{a}
MI	4.43^{c}	13.15^{b}	1.70^{b}	5.10^{b}
MT/TR	4.67^{c}	13.59^{b}	2.70^{a}	7.16^{a}
MC	5.24^{b}	13.68^{b}	2.64^{a}	7.10^{a}
SED	0.45	0.85	0.34	0.92
SR10				
CT	7.03^{a}	17.16^{a}	0.15^{b}	1.08^{c}
MI	7.13^{a}	17.36^{a}	0.07^{b}	0.80^{d}
MT/TR	5.62^{b}	15.20^{b}	1.23^{a}	3.36^{a}
MC	5.84^{b}	15.53^{b}	0.38^{b}	2.23^{b}
SED	0.74	1.18	0.35	0.75
LR11				
CT	5.30^{b}	12.85^{b}	0	0.18^{b}
MI	7.01^{a}	15.62^{a}	0	0.21^{b}
MT/TR	5.69^{b}	10.61^{c}	0	0.55^{a}
MC	6.06^{b}	11.79^{bc}	0	0.59^{a}
SED	0.87	1.68	0	0.07

Different letters among treatments represent significant differences at a $p < 0.05$ significance level.

Increased infiltration rate in an intercrop may also be caused by increased earthworm activity as a result of lower soil temperature (Hulugalle and Ezumah, 1991) and enhanced soil biota activity. However, under semi-arid conditions coupled with additive nature of intercropping practice, water availability at depth may be reduced rapidly because of the more rapid development of leaf area and hence higher water use and hence might explain the low yields under MI treatments. Hulugalle (1987) highlighted that, during years with above-average rainfall, TR can result in a greater proportion of roots being concentrated in the surface regions besides water logging-induced plant water stress being more likely to occur in crop.

In the SR10 season in Kigogo, CT and MI led to significantly ($p < 0.05$) higher maize grain yields (7.62 and 17.36 Mg ha^{-1}, respectively) with no significant differences between the two. Mulching and MT significantly ($p < 0.05$) suppressed the yields (15.20 and 15.53 Mg ha^{-1}) although there was no significant difference between them. Compared to SR10 yields of the same site, MI showed tremendously positive impact on yields, from being the lowest (4.43 Mg ha^{-1}) in the previous season to the best performer (7.13 Mg ha^{-1}). There was comparatively less increase due to MC and CT treatments while MT had the lowest increase in grain yields by about 0.95 Mg ha^{-1} compared to previous season. The biomass yields in the same season and site had a similar trend as the grain yields.

Due to low rainfall amounts in Machang'a in the SR10 season, crop performance was low compared to the previous season but the treatment effects were most conspicuous. Tied ridging had the highest positive effect on yields (1.23 Mg ha^{-1}) followed by MC, CT and MI in that order. Compared to CT, TR grain yields were over 7 times higher. Without the TR treatment, SR10 would have been considered a totally failed season as far as grain yields were concerned but given the kind of agroclimatic conditions, even stover yields are considered precious especially as animals feed and for soil water conservation purposes. The same trend as in grain yields was observed in the biomass production with the only difference being that there was a significant difference between all the treatments. The difference between TR (the highest) biomass yields and CT was over two fold. Planting on ridges which are subsequently ‘tied’ by construction of earthen bunds at right angles to the ridges, at intervals of 1–2 m, has been found to result in striking yield increases on the Alfisols of the West African semi-arid tropics (Hulugalle, 1987). Besides TR reducing runoff, it increases profile water content and hence root growth and development. The increase in available soil content can play a great role in drought effect mitigation availing moisture to crops especially when prolonged dry spells coincide with crop's sensitive phonological stages. FAO (2002) reports that impact of drought stress on crop productivity is particularly severe when the drought coincides with the moisture-sensitive stage of the crop and if farmers have no management alternatives to overcome the problem. Planting crops on tied ridges has been shown to increase grain yields in years of below-average rainfall, whereas in years of above-average rainfall, grain yields are unaffected (Hulugalle, 1987).

Unlike the previous two seasons, in LR11, CT was the worst performer while MI was significantly ($p < 0.05$) the highest (7.01 Mg ha^{-1}) (Table 2). Improved ground cover achieved by an additive intercrop contributes to reduced soil erosion and hence better retention of soil fertility, particularly when spreading-type cultivars are used as the shorter component (Stoop, 1986). The moisture environment immediately below the soil surface is commonly improved by intercropping (Fukai and Trenbath, 1993). The soil surface under an intercrop is not as exposed as in the sole crops hence evaporative loss from it is reduced. In a drying cycle, the moisture content of the surface soil layer is often higher under intercrop than under sole crop (Fukai and Trenbath, 1993).

The LR11 season was the worst season in terms of rainfall amounts in both sites, but unlike Kigogo, there was a total crop failure in Machang'a and hence the reason of nil values in grain and only stover yields are shown (Table 2). Although the biomass production was too low in Machang'a, TR and MC had high biomass yield compared to CT and MI. The low performance can be attributed to prolonged dry spells between when the first crop was established and the period of sufficient rainfall that lasted for more than 18 days (based on rainfall observations/records during the season). This led to drying up of the initially planted crops necessitating re-planting, which is not only an expensive process, but very risky given that the later it establishes a crop, the higher the likelihood of early crop senescence as a result of rainfall cessation. It is not always the case that when rainfall onset dates are late, then automatically cessation will be late. This underlines the impact of rainfall variability especially to small scale farmers who are constrained by resources and labor. The challenge is not unique to the region alone but it has been documented by others. For instance, Rockström (2003) corroborates it through the observation that, intra-seasonal dry spells during the cropping season have become a common feature and their impact on crop production is often severe, especially if they coincide with critical stages of crop development. In the semi-arid areas severe crop yield reductions due to dry spells occur once or twice in every five years (Rockström et al., 2002).

Biomass yields in Kigogo were relatively high in LR10 and SR10 seasons. The treatment effects followed the same trend as those of the grain yields in both seasons with CT having the highest yields. There was no significant difference between MI and MT in the two seasons. The observed trend was probably due to the fact that the biomass yield is inclusive of the grain yields. In LR11, biomass yields were generally low and the treatment effects were better manifested through the grain performance which was generally higher compared to the previous season except for CT. In Machang'a, the biomass yield also followed the grain yield performance except during the LR11 when there was a total crop failure, hence low amounts of biomass. Based on the observed biomass trends that followed grain yields, it can be inferred that, treatment effects on the biomass were probably the same as the effects it had on the grain yields. The biomass response to treatment differences was most likely for the same reasons explained for the grain responses.

4. Conclusion

The study clearly showed that under water limiting conditions, the TR technique is very efficient in reducing both runoff amounts and sediment yields. It also influences maize productivity positively even when the total rainfall amounts were below average. It was observed that CT accelerates soil loss as signified by high sediment yields in both sides irrespective of the rainfall pattern. Under sub-humid conditions, MT generated high runoff amounts but low sediment yields while its effect on maize productivity seems to improve with time, though slowly. Mbili intercropping has a crop positive effect on yields in the sub-humid region and very negative in the semi-arid regions especially during the periods of above average rainfall. It might be useful to explore further the interaction effects of various on-farm technologies such as minimum tillage combined with Mbili intercrop in the sub-humid region and tied ridging combined with Mbili intercrop in the semi-arid region in order to enhance and sustain crop production in the these agroclimatic regions. The results on the magnitude of runoff and sediment under the different soil and farm management practices are crucial in the selection and promotion of valid farm management practices and tillage alternatives that not only abate soil erosion but also boost agricultural productivity in the sub-humid and semi-arid agroclimatic zones of the tropics.

Acknowledgments

The authors wish to thank the Belgian Directorate General for Development Cooperation (DGDC), through the Flemish Interuniversity Council–University Development Cooperation (VLIR-UDC) for providing financial support (Project number. ZEIN2008PR349) and VLIR-UOS for providing a Short Research Stay (SRS) fellowship to one of the authors during data analysis and first draft paper writing at KU Leuven, Belgium.

References

Angima, S.D., Stott, D.E., Neill, M.K., Ong, C.K., Weesies, G.A., 2003. Soil erosion prediction using RUSLE for central Kenyan highland conditions. Agric. Ecosyst. Environ. 97, 295–308.

Arora, V.K., Singh, C.B., Sidhu, S., Thind, S.S., 2011. Irrigation, tillage and mulching effects on soybean yield and water productivity in relation to soil texture. Agric. Water Manag. 98, 563–568.

Astatke, A., Jabbar, M., Tanner, D., 2003. Participatory conservation tillage research: an experience with minimum tillage on an Ethiopian highland Vertisol. Agric. Ecosyst. Environ. 95, 401–415.

Bezborodov, G. a, Shadmanov, D.K., Mirhashimov, R.T., Yuldashev, T., Qureshi, A.S., Noble, A.D., Qadir, M., 2010. Mulching and water quality effects on soil salinity and sodicity dynamics and cotton productivity in Central Asia. Agric. Ecosyst. Environ. 138, 95–102.

Chikozho, C., 2010. Applied social research and action priorities for adaptation to climate change and rainfall variability in the rainfed agricultural sector of Zimbabwe. Phys. Chem. Earth 35, 780–790.

Defersha, M.B., Melesse, A.M., 2012a. Field-scale investigation of the effect of land use on sediment yield and runoff using runoff plot data and models in the Mara River basin, Kenya. Catena 89, 54–64.

Defersha, M.B., Melesse, A.M., 2012b. Effect of rainfall intensity, slope and antecedent moisture content on sediment concentration and sediment enrichment ratio. Catena 90, 47–52.

Deng, Xi-P., Shan, L., Zhang, H., Turner, N.C., 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. Agric. Water Manag. 80, 23–40.

El Swaify, S.A., Dangler, E.W., Armstrong, C.L., 1982. Soil Erosion by Water in the Tropics. College of Tropical Agriculture and Human Resources University of Hawaii Honolulu, Hawaii, p. 173.

FAO, 2002. Crops and Drops. Making the Best Use of Water for Agriculture. FAO, Rome, Italy.

FAO, UNESCO, 1988. Soil map of the world. Revised legend. FAO World Soil Resources Reports 60, FAO, Rome. Reprinted as Technical Paper, 20. ISRIC, Wageningen (1989, 138 pp.).

Fohrer, N., Rudolph, A., 1999. Changing soil and surface conditions during rainfall Single rainstorm subsequent rainstorms. Soil Water 3–4, 355–375.

Fukai, S., Trenbath, B.R., 1993. Processes determining intercrop productivity and yields of component crops. Science 34, 247–271.

Giller, K.E., 2001. Nitrogen Fixation in Tropical Cropping Systems, 2nd edition. CAB International, Wallingford, p. 423.

Hatfield, J.L., Sauer, T.J., Prueger, J.H., 2001. Managing soils to achieve greater water use efficiency; a review. Agron. J. 93, 271–280.

Holland, J., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ. 103, 1–25.

Hulugalle, N.R., 1987. Effect of tied ridges on soil water content, evapotranspiration, root growth and yield of cowpeas in the Sudan Savanna of Burkina Faso. Field Crop Res. 17, 219–228.

Hulugalle, N.R., Ezumah, H.C., 1991. Effects of cassava-based cropping systems on physico-chemical properties of soil and earthworm casts in a tropical Alfisol. Agric. Ecosyst. Environ. 35, 55–63.

Jaetzold, R., Schmidt, H., Hornet, Z.B., Shisanya, C.A., 2006. Farm Management Handbook of Kenya, 2nd edition. Natural Conditions and Farm Information, vol. 11/C. Eastern Province. Ministry of Agriculture/GTZ, Nairobi, Kenya.

Jin, K., Cornelis, W.M., Schiettecatte, W., Lu, J.J., Yao, Y.Y., Wu, H.J., Gabriels, D., De Neve, S., Cai, D.X., Jin, J.Y., Hartmann, R., 2007. Effects of different management practices on the soil-water balance and crop yield for improved dryland farming in the Chinese Loess Plateau. Soil Tillage Res. 96, 131–144.

Jordán, A., Zavala, L.M., Gil, J., 2010. Effects of mulching on soil physical properties and runoff under semi-arid conditions in southern Spain. Catena 81, 77–85.

Karunatilake, U.P., Van Es, H.M.V., 2002. Rainfall and tillage effects on soil structure after alfalfa conversion to maize on a clay loam soil in New York. Science 67, 135–146.

Kenward, M.G., Roger, J.H., 1997. Small sample inference for fixed effects from restricted maximum likelihood. Biometrics 53, 983–997.

Lal, R., 2001. Soil degradation by erosion. Land Degrad. Dev. 12, 519–539.

Lipic, J., Kus, J., Slowinska-Jurkiewicz, A., Nosalewicz, A., 2005. Soil porosity and water infiltration as influenced by tillage methods. Soil Tillage Res. 89, 210–220.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., Schabenberger, O., 2006. SAS for Mixed Models, 2nd ed. SAS Institute Inc., Cary, NC, p. 814.

Malam Issa, O., Valentin, C., Rajot, J.L., Cerdan, O., Desprats, J.-F., Bouchet, T., 2011. Runoff generation fostered by physical and biological crusts in semi-arid sandy soils. Geoderma 167–168, 22–29.

Mamedov, A.L., Shainberg, I., Levy, G.J., 2002. Wetting rate and sodicity effects on interrill erosion from semi-arid Israeli soils. Soil Tillage Res. 68, 121–132.

Mando, A., Miedema, R., 1997. Termite-induced change in soil structure after mulching degraded crusted soil in the Sahel. Appl. Soil Ecol. 6, 241–249.

Mando, A., Stroosnijder, L., 1996. Effects of termites on infiltration into crusted soil. Geoderma 74, 107–113.

McHugh, O.V., Steenhuis, T.S., Fernandes, E.C.M., 2007. Performance of in situ rainwater conservation tillage techniques on dry spell mitigation and erosion control in the drought-prone North Wello zone of the Ethiopian highlands. Soil Tillage Res. 97, 19–36.

Mucheru-muna, M., Pypers, P., Mugendi, D., Kung, J., Mugwe, J., Merckx, R., Vanlauwe, B., 2010. Field Crops Research A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. Field Crop Res. 115, 132–139.

Mulumba, L.N., Lal, R., 2008. Mulching effects on selected soil physical properties. Soil Tillage Res. 98, 106–111.

Mupangwa, W., Twomlow, S., Walker, S., Hove, L., 2007. Effect of minimum tillage and mulching on maize (*Zea mays* L.) yield and water content of clayey and sandy soils. Phys. Chem. Earth 32, 1127–1134.

Nuti, R.C., Lamb, M.C., Sorensen, R.B., Turman, C.C., 2009. Agronomic and economic response to furrow diking tillage in irrigated and non-irrigated cotton (*Gossypium hirsutum* L.). Agric. Water Manag. 96, 1078–1084.

Okoba, B.O., Sterk, G., 2006. Farmers' identification of erosion indicators and related erosion damage in the Central Highlands of Kenya. Catena 65, 292–301.

Olasantan, F.O., 1988. Intercropping of cassava (*Manihot esculenta*) with maize or cowpea under different row arrangements. Field Crop Res. 19, 41–50.

Oldeman, L.R., Hakkeling, R.T.A., Sombroek, W.G., 1991. World Map of the Status of Human-induced Soil Degradation. International Soil Reference and Information Centre, Wageningen and United Nations Environmental Programme, Nairobi, p. 34.

Osunbitan, J.A., Oyedele, D.J., Adekalu, K.O., 2004. Tillage effects on bulky density, hydraulic conductivity and strength of a loamy sand soil in south western Nigeria. Soil Tillage Res. 82, 57–64.

Ouédraogo, E., Brussaard, L., Stroosnijder, L., 2007. Soil fauna and organic amendment interactions affect soil carbon and crop performance in semi-arid West Africa. Biol. Fertil. Soils 44, 343–351.

Pierce, F.J., Lal, R., 1994. Monitoring soil erosion's impact on crop productivity. In: Lal, R. (Ed.), Soil Erosion Research Methods. Soil and Water Conservation Society, Ankeny, Iowa.

Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009. AquaCrop — the FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agron. J. 101, 438–447.

Rockström, J., 1998. Seasonal rainfall partitioning under run-on and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modelling. J. Hydrol. 210, 68–92.

Rockström, J., 2003. Resilience building and water demand management for drought mitigation. Phys. Chem. Earth 28, 869–877.

Rockström, J., Barron, J., Fox, P., 2002. Rainwater management for increased productivity among small-holder farmers in drought prone environments. Phys. Chem. Earth 27, 949–959.

Rouland, C., Lepage, M., Chotte, J.L., Diouf, M., Ndiaye, D., Ndiaye, S., Seugé, C., Brauman, A., 2003. Experimental manipulation of termites (Isoptera, Macro-termitinae) foraging patterns in a Sahelo-Sudanese savanna: effect of litter quality. Insect. Soc. 50, 309–316.

SAS Institute Inc., 2004. SAS/STAT® 9.1 User's Guide. p. 5121 (Cary, NC, USA).

Schiettecatte, W., Jin, K., Yao, Y., Cornelis, W.M., Lu, J., Wu, H., Cai, D., Verbist, K., Gabriels, D., Hartmann, R., 2005. Influence of simulated rainfall on physical properties of a conventionally tilled loess soil. Catena 64, 209–221.

Schwartz, R.C., Baumhardt, R.L., Evett, S.R., 2010. Tillage effects on soil water redistribution and bare soil evaporation throughout a season. Soil Tillage Res. 110, 210–221.

Soil Conservation Service (SCS), 2004. Hydrology. Chapter 10 National Engineering Handbook. Soil Conservation Service: USDA, Washington, DC, USA, p. 22.

Stoop, W.A., 1986. Agronomic management of cereal/cowpea cropping systems for major toposequence land types in the West African savanna. Field Crop Res. 14, 310–319.

Stroosnijder, L., Slegers, M., 2008. Soil degradation and droughts in sub-Saharan Africa. In: Dazzi, C., Costantini, E. (Eds.), The Soils of Tomorrow: Soils Changing in a Changing World. Catena, 39, pp. 413–425.

Temesgen, M., Hoogmoed, W.B., Rockström, J., Savenije, H.H.G., 2009. Conservation tillage implements and systems for smallholder farmers in semi-arid Ethiopia. Soil Tillage Res. 104, 185–191.

Tilahun, K., 2006. Analysis of rainfall climate and evapotranspiration in arid and semi-arid regions of Ethiopia using data over the last half a century. J. Arid Environ. 64, 474–487.

Towery, D., 1998. No-till's impact on water quality. Proceedings of the Sixth Argentine National Congress of Direct Drilling Mar de Plata, Argentina, AAPRESID, pp. 17–26.

Trabucco, A., Zomer, R.J., Bossio, D.A., Straaten, O.V., Verchot, L.V., 2008. Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies. Environment 126, 81–97.

Tungani, J.O., Mukhwana, E., Woomer, P.L., 2002. Mbili is Number 1: A Handbook for Innovative Maize–Legume Intercropping. SACRED Africa, Bungoma, Kenya.

Twomlow, S.J., Bruneau, P.M.C., 2000. The influence of tillage on semi-arid soil–water regimes in Zimbabwe. Geoderma 95, 33–51.

Vaezi, A.R., Bahrami, H.A., Sadeghi, S.H., Mahdian, M.H., 2010. Modeling relationship between runoff and soil properties in dry-farming lands, NW Iran. Hydrol. Earth Syst. Sci. Discuss. 7, 2577–2607.

van Es, H.M., 1993. Evaluation of temporal, spatial and tillage-induced variability for parameterization of soil infiltration. Geoderma 60, 187–199.

Wang, Y., Xie, Z., Malhi, S.S., Vera, C.L., Zhang, Y., Wang, J., 2009. Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yield in the semi-arid Loess Plateau, China. Agric. Water Manag. 96, 374–382.

Woomer, P.L., 2007. Costs and returns of soil fertility management options in Western Kenya. In: Bationo, A., Waswa, B., Kihara, J., Kimetu, J. (Eds.), Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities. Springer, the Netherlands, pp. 881–890.

Zhang, S., Grip, H., Tong, Y., Yang, X., Wang, Q., Lo, L., 2009. Effects of mulching and catch cropping on soil temperature, soil moisture and wheat yield on the Loess Plateau of China. Soil Tillage Res. 102, 78–86.