Geoderma 237–238 (2015) 283–297

Contents lists available at ScienceDirect

Geoderma

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

Improving rainwater-use in Cabo Verde drylands by reducing runoff and erosion

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ARTICLE INFO

Article history:
Received 3 July 2014
Received in revised form 22 August 2014
Accepted 16 September 2014
Available online xxxx

Keywords:
Runoff
Erosion
Land management techniques
Rainwater-use
Dryland
Cabo Verde

ABSTRACT

Dryland agriculture in Cabo Verde copes with steep slopes, inadequate practices, irregular intense rain, recurrent droughts, high runoff rates, severe soil erosion and declining fertility, leading to the inefficient use of rainwater. Maize and beans occupy >80% of the arable land in low-input, low-yielding subsistence farming. Three collaborative field trials were conducted in different agroecological zones to evaluate the effects of water-conservation techniques (mulching of crop residue, a soil surfactant and pigeon-pea hedges) combined with organic amendments (compost and animal or green manure) on runoff and soil loss. During the 2011 and 2012 rainy seasons, three treatments and one control (traditional practice) were applied to 44- and 24-m^2 field plots. A local maize variety and two types of beans were planted. Runoff and suspended sediments were collected and quantified after each daily erosive rainfall. Runoff occurred for rainfalls ≥50 mm (slope <10%, loamy Kastanozem), ≥60 mm (slope ≤23%, silt–clay–loam Regosol) and ≥40 mm (slope ≤37%, sandy loam Cambisol). Runoff was significantly reduced only with the mulch treatment on the slope >10% and in the treatment of surfactant with organic amendment on the slope <10%. Soil loss reached 16.6, 5.1, 6.6 and 0.4 Mg ha^{-1} on the Regosol (≤23% slope) for the control, surfactant, pigeon-pea and mulch/pigeon-pea (with organic amendment) treatments, respectively; 3.2, 0.9, 1.3 and 0.1 Mg ha^{-1} on the Cambisol (≤37% slope) and <0. 2 Mg ha^{-1} for all treatments and control on the Kastanozem (<10% slope). Erosion was highly positively correlated with runoff. Mulch with pigeon-pea combined with an organic amendment significantly reduced runoff and erosion from agricultural fields on steep slopes, contributing to improved use of rainwater at the plot level. Sustainable land management techniques, such as mulching with pigeon-pea hedges and an organic amendment, should be advocated and promoted for the semiarid hillsides of Cabo Verde prone to erosion to increase rainwater-use and to prevent further soil degradation.

1. Introduction

A combination of harsh climatic conditions, human pressure on limited natural resources, nutrient depletion and geomorphologic and pedological factors has led to environmental degradation in semiarid sub-Saharan Africa (Smolikowski et al., 2001; Ryan and Spencer, 2001). Land degradation reduces water productivity at the field scale and affects water availability, quality and storage (Gao et al., 2014). The strong links between water use and land degradation and management allow the improvement of rainwater-use efficiency (RWUE) by properly managing the land through use of sustainable land management techniques and approaches (Bossio et al., 2010). RWUE is a measure of the biomass or grain yield produced per increment in precipitation (Hatfield et al., 2001). A wide range of land-management techniques is available to improve RWUE in dryland farming systems (Erenstein, 2003; Rockstrom et al., 2002, 2009; Stroosnijder, 2003, 2009; Stroosnijder et al., 2012; Turner, 2004; WOCAT, 2007).

The World Overview of Conservation Approaches and Technologies (WOCAT, 2007) defines land-management technologies or soil- and water-conservation (SWC) techniques as “agronomic, vegetative, structural and/or management measures that prevent and control land degradation and enhance productivity in the field”. These solutions may include: mechanical structures (e.g. terraces, check dams, contour stone walls and contour ridges), biological structures (e.g. afforestation and strips of vegetation), manipulation of the surface soil (e.g. tillage, mulching and soil amendments such as surfactants, compost and animal and green manure), rainwater harvesting (e.g. reservoirs and retaining dams) and agronomic measures (e.g. drought-resistant species and varieties, short-cycle varieties, crop rotation, animal and green manures, appropriate fertilizer use, compost and weed control). These SWC practices improve soil quality (Araya and Stroosnijder, 2010; Tesfaye et al., 2014), decrease erosion (less runoff and nutrient

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http://dx.doi.org/10.1016/j.geoderma.2014.09.015
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losses) and increase infiltration (less surface evaporation) (Xu et al., 2012; Zhao et al., 2013) and the efficient use of green water, i.e. the fraction of rainwater used for biomass production (Stroosnijder, 2003). Some of these measures succeed under certain combinations of conditions but may fail in other settings, so they require testing under specific conditions, taking into account the perception and knowledge of the farmers.

Land degradation is a major environmental issue in Cabo Verde, an island country off the western coast of Africa. The degradation has been associated with prolonged droughts and inadequate dryland agricultural practices such as the cultivation of steep slopes and bare soils (Langworthy and Finan, 1997; Mannaerts, 1993; Tavares et al., 2013). Both a lack of rain, through drought, and excess rain, through erosion and runoff, are drivers of land degradation. Paradoxically, rain in this semiarid Sahelian country is both responsible for land degradation and the limiting factor determining dryland yields.

Though dryland farming is a subsistence activity, it is very important for the livelihoods of smallholder farmers that rely on it for food production. Farmers must have a selection of integrated management options (Stroosnijder, 2003) that would provide sufficient benefits against reasonable costs and simultaneously reduce dryland degradation and maintain sustainable yields, as the application of conservation strategies depends on the farmers (Huenchuleo et al., 2012; Thapa and Yila, 2012).

Dryland farming in Cabo Verde is dominated by a continuous cultivation of maize intercropped with beans and occupies over 80% of the arable land. This farming system must cope with steep slopes, short and irregular rains, recurrent droughts, severe storms, water losses through rapid runoff and high rates of evaporation and increasing land degradation due to erosion and declining fertility, leading to an inefficient use of rainwater. To stop land degradation and desertification, successive governments since Cabo Verde's independence in 1975 have supported a long-term program of soil and resource conservation as a centerpiece of their agricultural policy (NAPA, 2007). The predominant strategies of SWC have focused on the construction of rural structures that retard sedimentation flow and increase infiltration and the widespread reforestation of marginal soils (steep slopes and semiarid rangeland). These strategies have included the implementation of a series of measures, both mechanical and biological with the most common ones in hillslopes being: a. terraces which are structures comprising leveled strips running across the slope at vertical intervals that potentially reduce erosion and sediment transport up to 50%; b. contour stone walls which are slope stabilizing structures built along a contour line, using on-site stones that slow down runoff, promote infiltration and trap sediment; c. vegetation barriers which consist in planting lines of species, such as *Aloe vera*, *Leucaena leucocephala* and *Fucraea gigantean*, particularly in places without stones, impeding the erosion processes and allowing accumulation of sediments behind the vegetation barriers; d. vegetation surface cover which consists in the use of plants such as thorn shrubs to protect sensitive areas from overland flow; and reforestation which consists in the plantation of drought-resistant species, both as SCW measure and strategy against desertification (INIDA/DESIRE, 2008; Ferreira et al., 2012; Tavares et al., 2013). The implemented strategies do not include agronomic measures or soil surface manipulation such as mulching and soil amendments that prevent and control land degradation and enhance productivity at field scale. Thus, despite the governmental efforts to reverse the processes at the watershed scale, soil erosion, low rainwater use efficiency and land degradation are still very problematic (Tavares et al., 2013), and dryland yields remain low (FAO, 2003, 2014), even in years of sufficient annual rainfall.

This study evaluates the effects of selected soil- and water-conservation techniques in Cabo Verde dryland for improving the efficiency of rainwater through the reduction of runoff and soil loss from rain-fed agricultural fields. More specifically, we test the effectiveness of residue mulching, soil surfactant and pigeon pea barriers combined with organic amendments (i.e. compost, animal manure and green manure) on surface runoff and soil loss. The selection of the techniques combined traditional and scientific knowledge in a field-based participatory approach, with the perceptions and contributions of the farmers playing a major role.

2. Materials and methods

2.1. Study site characterization and soil properties

This study was conducted in three sites (S. Jorge — site I; Serrado — site II; and Órgãos Pequenos — site III) of the Ribeira Seca watershed, which is the largest watershed in Santiago, the main agricultural island of Cabo Verde (Fig. 1). The watershed has a drainage surface of approximately 72 km^2 and extends across four agro-ecological zones of the Cabo Verde classification: semiarid (49%), arid (20%), subhumid (20%) and humid (11%) (Diniz and Matos, 1986).

The climate is characterized by a dry season of 8–9 months (November–June) and a short, humid season of 3–4 months (July–October). Rainfall is extremely heterogeneous and has an irregular spatiotemporal distribution, with annual precipitation varying from $<$200 mm downstream to 650 mm upstream of the watershed. The 30-year mean annual rainfall (1980–2010) was 437, 300 and 310 mm at experimental sites I, II and III, respectively, with most of the rain falling in August and September (INMG, 2010). The predominant land use is rain-fed (i.e. dryland) agriculture covering $>$83% of the area, comprising maize, several varieties of beans and groundnuts.

The sites were selected based on their specific characteristics of soil, agro-ecological zone (AEZ), slope and agricultural practices present. Site I is characterized by a low slope ($<$10%) and loamy Kastanozem on a terraced field at a research station in the subhumid to humid zone (351 m a.s.l. and mean annual rainfall of AEZ of 437 mm). Site II is characterized by a steep slope (37%), a sandy loam Cambisol and marked symptom rill erosion on a farm, in the semiarid zone (183 m a.s.l. and mean annual rainfall of AEZ of 300 mm). Site III is characterized by moderate to steep slopes (23%) and a silt–clay–loam Regosol subject to erosion by mass flow in which the soil is protected with stone and plant barriers at field edges and is located on a farm at the junction of the semiarid and subhumid zones (204 m a.s.l and mean annual rainfall of AEZ of 310 mm).

The initial physical and chemical properties of the soil varied among the three sites but were homogeneous within the sites (Table 1) in texture, bulk density, slope and total N and extractable-P contents. The soils at sites I, II and III had loam, sandy loam and silt–clay–loam textures, respectively. Organic-matter content was low at sites II and III and average at site I (INIDA, 1997). All sites were low in total N, particularly sites II and III with $<$10 mg N g^{-1} and the extractable-P content was average to high. Bulk density varied from 1.16 g cm^{-3} at site III to 1.42 g cm^{-3} at site I. The soil pH was neutral to slightly alkaline. The slope was gentle at site I (8%), moderate at site III (23%) and steep at site II (37%). The infiltration rate was highest at site II, followed by site I and site III, which had the lowest water infiltration.

2.2. Selection of technologies and treatments

We based our selection of treatments on a comprehensive review of the literature of land-management technologies in drylands and on one workshop for stakeholders. We prepared a list of ten techniques with the potential to increase the efficiency of rainwater within the Ribeira Seca watershed, taking into account the biophysical characteristics of the study area, the socioeconomic conditions of the farmers, the cost of the techniques and their applicability in the watershed. Most of these techniques were selected from the WOCAT database (WOCAT, 2007).

Twenty-two farmers of the Ribeira Seca watershed participated in a local workshop for stakeholders in March 2011, before the start of the field experiments. The farmers were asked to: (1) identify and group the primary constraints of dryland production, (2) discuss the list of potential technologies for addressing the primary constraints, (3) select and rank these technologies and (4) group these technologies into

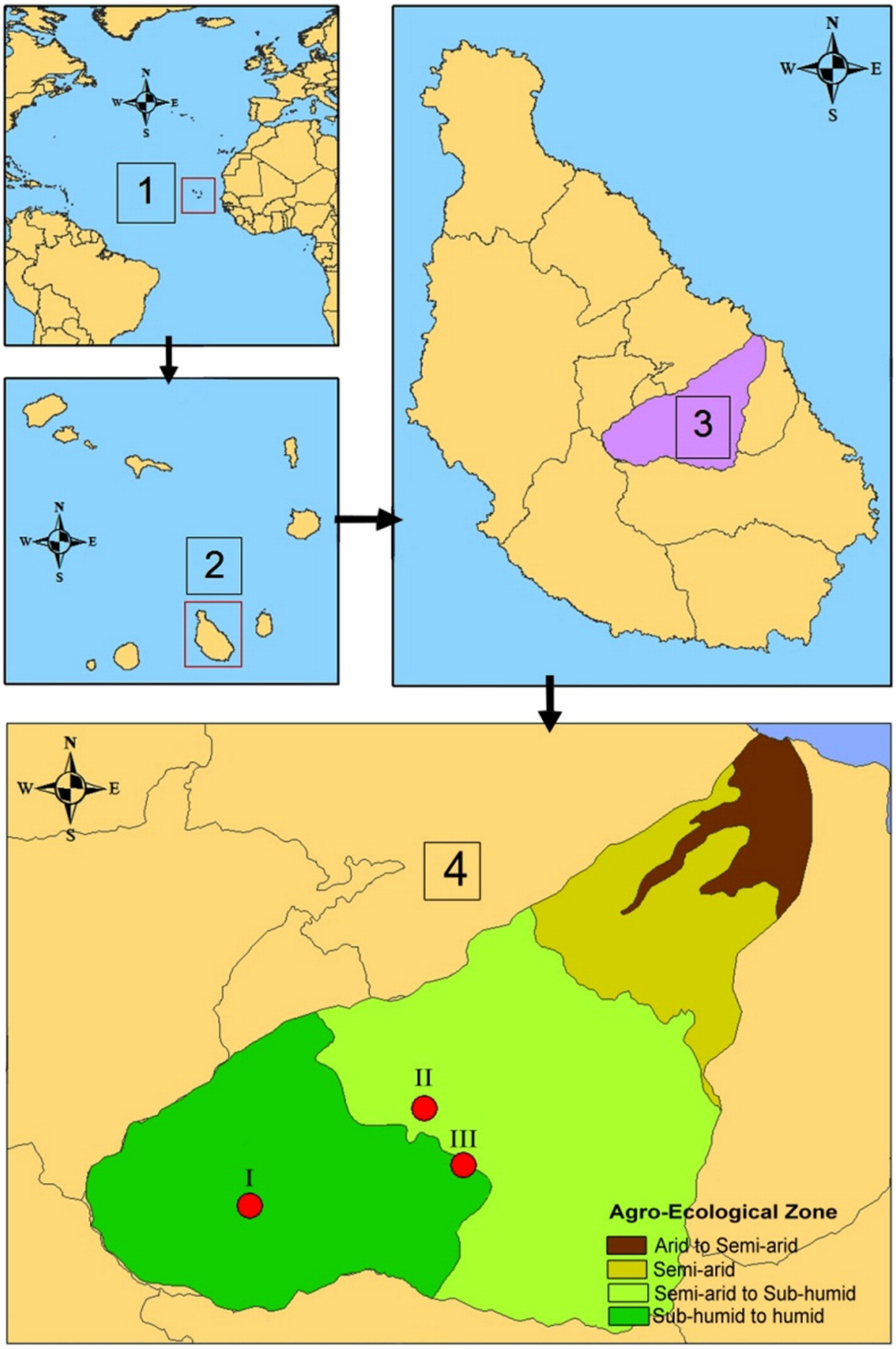

Fig. 1. Location of (1) Cabo Verde, (2) Santiago, (3) the Ribeira Seca watershed and (4) the experimental sites and agroecological zones. I, site I (São Jorge); II, site II (Serrado) and III, site III (Orgãos Pequenos).

three categories representing low, medium and high levels of investment. The promising technologies were assessed and selected using a simplified version of the participatory approach developed by Schwilch et al. (2009) and applied by Tavares et al. (2013), which combines collective learning and decision-making with the application of evaluated global best practices.

The farmers identified and grouped the constraints into eight main priorities and proposed solutions for each. Soil loss, low fertility and

Table 1
Initial soil properties (0–20 cm) at the experimental sites, site slope and total seasonal rainfall in 2011 and 2012.

Site	Soil texture	Slope %	pH (H_2O)	Initial soil moisture 2011/2012 %	Bd* g cm^{-3}	OM** g 100 g^{-1}	Total N mg g^{-1}	P$_{ext}$*** µg g^{-1}	K**** mm h^{-1}	Total rainfall 2011/2012 mm
I	Loam	8	7.3	7.1/7.2	1.42	2.50	1.27	12.39	17.86	565/572
II	Sandy loam	37	7.1	6.8/6.6	1.25	1.10	0.56	5.81	40.84	481/519
III	Silt–clay–loam	23	6.9	7.5/8.1	1.16	1.57	0.86	8.15	10.67	549/540

*Bd, bulk density; **OM, organic matter; ***extractable P; ****K, initial infiltration rate.

Table 2
Main dryland problems and solutions as perceived and prioritized by stakeholders.

Priority constrains/problems	Solutions
1. Soil loss, weeding with hoes	— Contour stone walls with vegetation — Hedges with drought-resistant species (*L. leucocephala*, *Aloe vera* or pigeon-pea) — Direct seeding/conservation agriculture — Partial hand-weeding
2. Weak soils (low fertility)	— Application of animal manure — Contour-stone walls combined with plant barriers
3. Water loss by runoff	Contour-stone walls combined with hedges
4. No maintenance of SWC structures	Maintenance cost of SWC structures shared among farmers and governmental institutions
5. Absence of crop rotation Pest infestation Intensive use of soils Resistance of farmers to follow technical guidelines	Strengthen the capacity of farmers through information, training, sensitization and exchange with other farmers
6. Low involvement of young people in dryland farming	— Involvement of schools and parents/educators in sensitizing youth to the importance of agriculture — Increase dryland productivity — Choice of adapted species and crop varieties based on soil characteristics
7. Shortage and irregularity of rain Strong, hot winds (Harmatan)	— Harvest rainwater for irrigation, converting dryland into irrigated land — Adequate species and varieties — Combination with livestock production — Soil protection
8. Shortage and high cost of field labor	— Increase dryland productivity

runoff from agricultural fields emerged as the three main constraints. For the three highest-priority problems, the farmers recommended the use of contour stone walls, vegetation hedges using drought-resistant species along contour lines, conservation farming (mulch) with partial weeding and animal manure (Table 2)

Based on the farmers' preferences for each study site, the selected technologies were combined into three treatments (T1–T3) which were compared to an untreated control (T0). The treatments varied among the sites, depending on the local availability of residue mulch, the source of organic amendments and the preferences of the local farmers. Each treatment contained an organic amendment (compost, animal manure or green manure) and a water-management technique (residue mulch, soil surfactant and/or pigeon-pea (*Cajanus cajan*) hedges) (Table 3).

2.3. Experimental set-up

The experiments were conducted during the 2011 and 2012 rainy seasons, from August to October. The experimental plots were 11 × 4 m in the two on-farm trials (Fig. 2A–C) and 6 × 4 m in the trial at the research station. The smaller plot size at the research station was due to limited availability of land. Each experimental plot was isolated by a 25-cm metal sheet hammered a few centimeters into the soil. The sheets were funneled into a large polyethylene tube at the bottom of the plots to channel the runoff water and soil loss to a covered 100- or 200-L barrel (Fig. 2A).

The experiments had a randomized design with the three treatments and one control replicated three times (Fig. 2B).

For T1–T3, planting pits (20 cm wide and 15 cm deep) were dug with a hoe and distanced 75 cm in the rows and 80 cm between the rows. Organic amendments (compost, animal or green manure) were applied manually to the bottoms of the pits and covered with a small amount of soil. The agricultural soil surfactant IrrigAid Gold ACA 1848 (Aquatrols, from USA) was diluted in water and sprayed on the soil surface after seeding with a hand-pressure pulverizer. Three types of crop residue were applied to the surface as mulch (4 t ha^{-1}) to cover 60–80% of the soil surface (Table 3).

The crops used in the experiments were maize (*Zea mays*) and two local types of beans (*Vigna unguiculata*, or cowpea, and *Lablab purpureus*, or feijão pedra). After the first significant rain (>20 mm), the crops were planted by placing three maize and four bean seeds (two of each type of bean) in each planting pit, thus forming a seed cluster. For the plots with pigeon-pea hedges (T2–T3), two pigeon-pea seeds were alternated along two lines 50 cm apart to form double-row hedges 3 m apart (Fig. 2A). Maize and beans were planted between the hedges. The planting density was approximately 16 ,300 seed clusters per hectare in all plots, including the control.

Weeds were removed from all plots twice during the rainy season, approximately three and six weeks after planting, either with a hoe or by hand, with minimum disturbance of the soil, except for the control plot, where weeding was always with a hoe.

2.4. Data collection and calculations

We collected three composite soil samples to a depth of 20 cm from each site at the end of the dry season before the experiments began to characterize the soil of the experimental sites. Laboratory analyses were conducted at the Instituto Nacional de Investigação e Desenvolvimento Agrário's (INIDA) laboratory applying methods currently in use in the laboratory. These included texture by pipette method; bulk density by core method (Blake and Hartge, 1986), pH (H_2O) by potentiometer, EC, nitrogen (N) content by Kjeldahl digestion (Jackson, 1982), phosphorus (P) content by Olsen (Olsen and Sommers, 1982) and organic-matter content by Walkley Black (Nelson and Sommers, 1982).

Infiltration rate and soil penetrability were measured at the beginning and end of the experiments with a minidisk infiltrometer (Fig. 2C-4) and a hand-held penetrometer, respectively, for each treatment.

Simple rain gauges and automatic data loggers were installed at each experimental site to measure the amount and intensity of rainfall (Figs. 2C-3 and 5). However, due to malfunction of the data logger, it was not possible to retrieve rainfall intensity data.

The amount of runoff water in the barrels was measured after each daily erosive rainfall event (hereafter, event[1]) and 1 L of the suspended sediment was collected after stirring the total runoff for laboratory analysis (Sadeghi et al., 2008). The sediment was weighed after filtration and oven drying. Soil loss (g m^{-2}) per event was determined by multiplying the sediment concentration (g L^{-1}) by the volume of runoff (L). Individual rates of runoff (L m^{-2}) and soil loss per event was calculated for each treatment and added-up to obtain total seasonal rates of runoff and soil loss. The specific erosion rate per treatment, in g m^{-2} mm^{-1} rain, was also calculated.

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[1] Event refers to one or more rainfalls in a rainy day, with runoff and/or sediment occurrence.

Table 3
Description of the treatments applied at each experimental site.

Treatment	Site I (São Jorge)	Site II (Serrado)	Site III (O. Pequenos)
T0 (control)	Traditional maize/bean intercropping (no input)	Traditional maize/bean intercropping (no input)	Traditional maize/bean intercropping (no input)
T1	Animal manure (4 t ha^{-1}) + soil surfactant (1 t ha^{-1})	Compost (4 t ha^{-1}) + soil surfactant (1 mL m^{-2})	Animal manure (4 t ha^{-1}) + soil surfactant (1 mL m^{-2})
T2	Compost (4 t ha^{-1}) + soil surfactant (1 mL m^{-2})	Pigeon-pea hedges + animal manure (4 t ha^{-1}) + soil surfactant (1 mL m^{-2})	Pigeon-pea hedges + green manure (1 t ha−1 *L. leucocephala* De Wit prunings) + soil surfactant (1 mL m^{-2})
T3	Mulch (4 t ha^{-1} banana leaves) + compost (4 t ha^{-1})	Mulch (4 t ha^{-1} *P. maximum* grass) + pigeon-pea hedges + animal manure (4 t ha^{-1})	Mulch (4 t ha^{-1} *P. maximum* grass) + pigeon-pea hedges + green manure (1 t ha^{-1} *L. leucocephala* De Wit prunings)

Daily rainfall erosivity, expressed as EI_{30} parameter, was estimated using a power-law equation developed by Mannaerts and Gabriels (2000) and modified by Sanchez-Moreno et al. (2014):

$$EI_{30} = 0.26\,(P_{24})^{1.31},$$

in which, EI_{30} is the rainfall energy intensity or erosivity in KJ m^{-2} mm h^{-1} and P_{24} the daily rainfall amount in mm. Only rainfall amounts ≥9.0 mm were included in the calculations. Seasonal erosivity was estimated by adding daily EI_{30} values.

The reductions in total runoff and soil loss due to the treatments were calculated using the formula:

$$R = (C - T)/C * 100$$

where R is the reduction in runoff or soil loss (in %) and C and T are the amounts of runoff or sediment (in L m^{-2} or g m^{-2}, respectively) in the

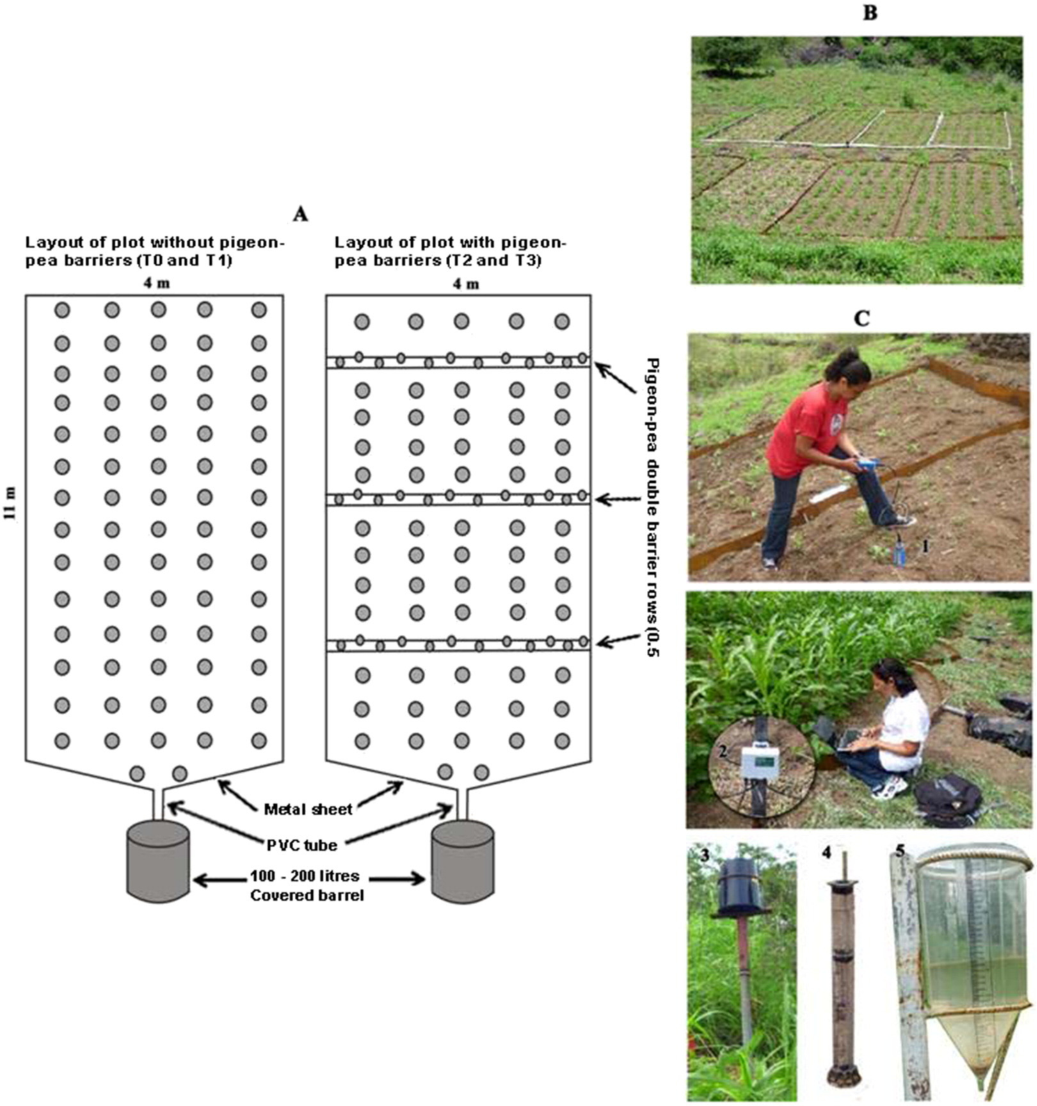

Fig. 2. Layout and aspects of the 11 × 4 m erosion plots (sites II and III). (A) Schematic layout of a plot, (B) field layout of the plots and (C) measuring instruments: 1, Trime TDR moisture meter; 2, Em5b ECH2O moisture-meter logger; 3, automatic rain gauge; 4, minidisk infiltrometer and 5, simple rain gauge.

control and treatments, respectively. The mean total runoff and sedimentation rates of the control plot were taken as the reference values (C). The total yearly runoff coefficient (Cr) was calculated for total growing-season erosive periods of rain using the equation:

$$Cr = (Q/R) * 100$$

where Q is the runoff volume (in mm) and R is the total rainfall producing runoff (in mm).

The volumetric soil-moisture content was measured after each event at a depth of 15 cm, both within and between the planting pits, using a TRIME® time-domain reflectrometric (TDR) moisture meter (Eijkelkamp, Giesbeek-The Netherlands) (Fig. 2C-1).

Soil cover was estimated at each event during each season, using a modified grid method (Chambers and Brown, 1983) by placing a 1 m × 1 m frame on the ground surface in each plot and visually estimating the amount of soil covered by plants and crop residue within the frame, including the applied mulch. This method was also reinforced with observations and analysis of plot photographs.

2.5. Data analysis

All statistical analyses were performed using SPSS 19.0. We used the ANOVA to test for the significance of the treatments on total seasonal runoff and soil loss that were normally distributed, and used the post-hoc Dunnett's T3 test for non-homogenous variances to identify significant differences among the treatments. The runoff and soil loss data for rainfall event were not normally distributed following the KS test, so we tested for significant differences among specific treatments for each site using the non-parametric Kruskal–Wallis and Mann–Whitney U-tests. We performed all tests applying a probability value of 0.05. A principal component analysis (PCA) of treatment, soil cover, total runoff, total sediment, site slope, rainfall amount, soil moisture in the planting pits and soil penetrability was conducted, and components with eigenvalues over Keiser's criterion of 1 were extracted.

Correlation and regression analysis of the different variables were also performed.

The data were split by site and event for analyzing the treatment effect on runoff and soil loss throughout the rainy seasons.

3. Results

3.1. Rainfall characteristics

Total seasonal rainfall was 565, 481 and 549 mm in 2011 and 572, 519 and 540 mm in 2012 at sites I, II and III, respectively (Table 1). These values were substantially higher than the average precipitation for all three sites for August to October from 1980–2010. The total rainfall did not significantly differ among the sites for each year, but the distribution varied considerably (Fig. 3). The 2011 rainy season began

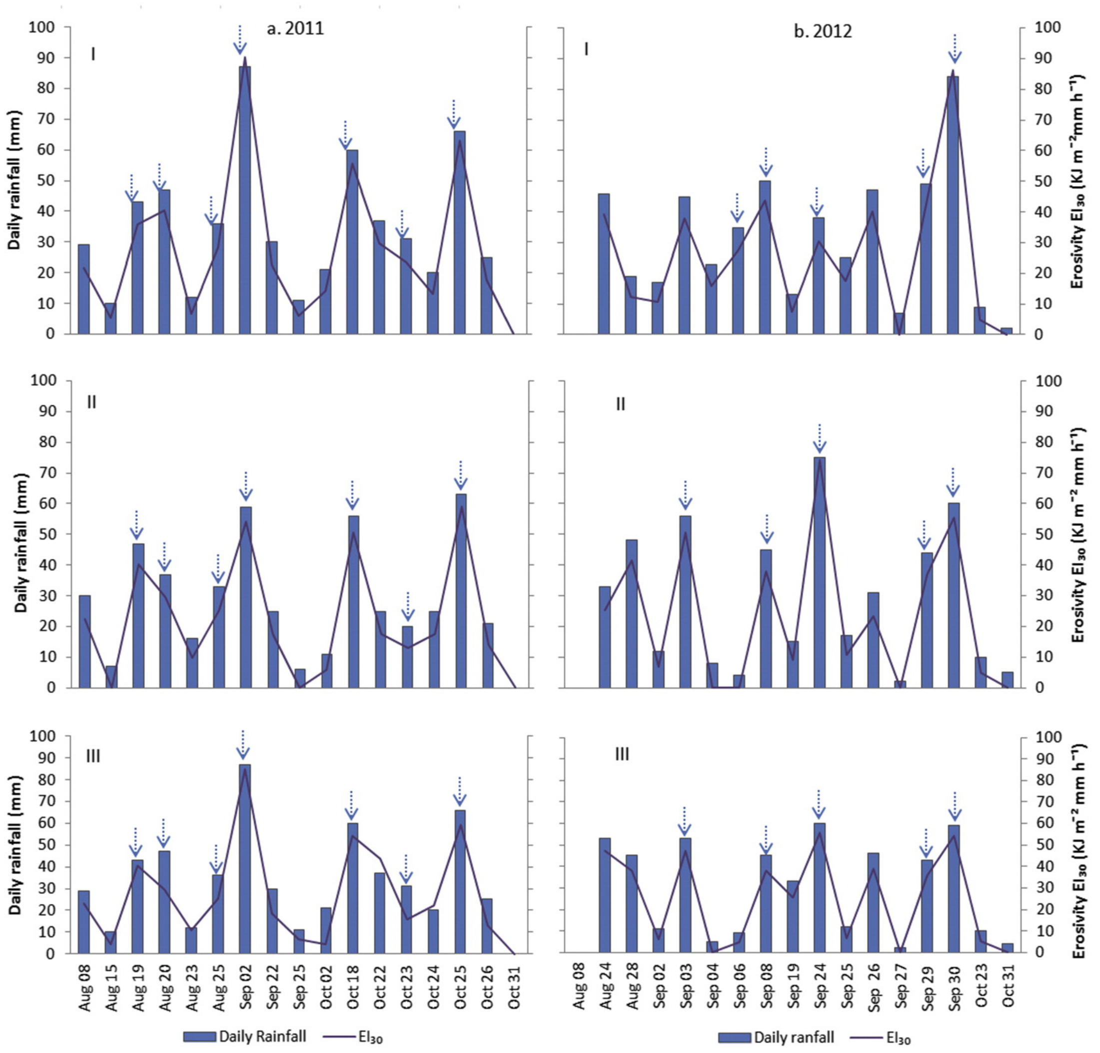

Fig. 3. Daily rainfall distribution and daily rainfall erosivity (EI_{30}) over the (a) 2011 and (b) 2012 rainy seasons at the three experimental sites. EI_{30} was calculated with the ~~KE~~-I relationship developed for Cabo Verde (Sanchez-Moreno et al., 2014). Arrows indicate erosive rainfall events (rainfall causing runoff).

earlier (August 8) and continued until the end of October but with a dry period of 20 days in September that affected crop development. The first rain in 2012, however, fell in late August and continued well distributed throughout September with 12 days of rain, but no rain fell in October. Of the 16 rainy days in 2011, five were light rains (<20 mm), three were heavy rains (>50 mm) and eight were moderate rains (20–50 mm). Of the 18 rainy days in 2012, five were <20 mm, only one was >50 mm and the others were 20–50 mm for all three sites (Fig. 3).

In 2011, seasonal rainfall erosivity EI_{30} (in KJ m^{-2} mm h^{-1}) was 473, 378 and 457 for sites I, II and III, respectively, with the highest monthly value occurring in October and the lowest in September. The highest daily EI_{30} values (in KJ m^{-2} mm h^{-1}) were 90 and 85, corresponding to 87 and 83 mm rainfall, respectively, and occurred at sites I and III, both on September 02 (Fig. 3). At site II, daily values were lower and the highest (59) occurred on October 25. In 2012, seasonal erosivity values were slightly lower for sites I (417) and III (403) and similar for site II (377), while the highest monthly value occurred in September. The highest daily EI_{30} values were 86, 74 and 56 for sites I, II and III, respectively, corresponding to 84, 75 and 60 mm rainfalls, occurring on September 24 at sites II and III and on September 30 at site I (Fig. 3).

3.2. Effect of treatments on runoff and soil loss

3.2.1. Total seasonal runoff and soil loss

3.2.1.1. Runoff. All treatments generally produced significantly less seasonal runoff than the control, with T3 much better ($P < 0.01$) than all other treatments at all three sites on both years (Table 4A). T3 had the lowest seasonal runoff rate (0.1 L m^{-2}) at site I in 2012, and T0 had the highest rate (20 L m^{-2}) at site II in 2012. Total runoff was significantly higher for all treatments and the control in 2012 than in 2011. Compared to T0, T3 reduced total runoff by 84% (site II) to 90% (site I) in 2011 and by 95% (site III) to 99% (sites I and II) in 2012. Runoff generation for both years was in the order T3 < T1 = T2 < T0 at site I and in the order T3 < T1 = T2 = T0 at sites II and III. For slopes > 10% (sites II and III), only the mulch treatment (T3) significantly reduced runoff, and the soil surfactant combined with either manure or compost (T1/T2) significantly reduced runoff on the slope < 10% (site I). Runoff reduction followed the order T3 > T1 ≥ T2 for 2011 and T3 > T2 > T1 for 2012 at sites II and III and T3 > T2 > T1 for 2011 and T3 > T2 > T1 for 2012 at site I. These results confirm the high effectiveness of T3 at all sites.

The runoff coefficients for the two years were low, varying from nearly negligible at site I in 2011 to 6.7% at site II in 2012 (Table 5A). T3 had the lowest proportion of seasonal rainfall lost as runoff, and T0 had the highest. T1 and T2 did not generally differ in either year at any of the sites. Even though 2012 had fewer events, T0, T1 and T2 had higher runoff coefficients in 2012 than 2011, except for T2 at site III.

3.2.1.2. Soil loss. All treatments generally lost significantly ($P < 0.05$) less soil than the control. T3 had the lowest rate of soil loss at all three sites in both years (Table 4B). Site III had the highest rates of soil loss in 2011, reaching 16.6, 5.1, 6.6 and 0.4 Mg ha^{-1} for T0, T1, T2 and T3, respectively. The rates at site II were 3.2, 0.9, 1.3 and 0.1 Mg ha^{-1} for the same treatments. The rates were very low at site I; T0 had the highest rate (0.2 Mg ha^{-1}), and T1, T2 and T3 had negligible rates. These trends were similar in 2012, but the highest rate of soil loss was only 1.6 Mg ha^{-1} (T0). T1 did not generally differ significantly ($P > 0.05$) from T2, but both lost significantly ($P < 0.05$) less soil than T0. The

Table 4
(A) Total runoff (mean ± standard deviation) and runoff reduction and (B) total soil loss (mean ± standard deviation) and reduction in soil loss at each experimental site for the 2011 and 2012 rainy seasons as a function of treatment. Lowercase letters indicate significant differences (Dunnet T3 test) between the treatments at the same site ($P < 0.05$): a < b < c < d. For detailed treatment descriptions, see Table 3. Site I did not include pigeon-pea hedges.

A

Treatment	I		II		III	
	Runoff (L m^{-2})	% reduction in runoff	Runoff (L m^{-2})	% reduction in runoff	Runoff (L m^{-2})	% reduction in runoff
2011						
T0	6.17 ± 2.16c	0	11.3 ± 1.95b	0	15.0 ± 0.41b	0
T1	2.98 ± 2.50b	52	9.00 ± 0.25b	20	12.6 ± 1.05b	16
T2	2.65 ± 1.39b	57	9.20 ± 2.28b	19	13.2 ± 2.15b	12
T3	0.70 ± 0.33a	90	1.83 ± 0.67a	84	6.65 ± 3.48a	86
ANOVA (0.05)	0.000		0.000		0.000	
2012						
T0	12.1 ± 1.76c	0	20.1 ± 0.23c	0	16.4 ± 1.64b	0
T1	6.81 ± 1.08b	44	17.6 ± 0.53bc	12	14.8 ± 1.59b	10
T2	8.33 ± 2.65b	31	15. 4 ± 2.29b	23	11.3 ± 4.25b	31
T3	0.11 ± 0.19a	99	0.17 ± 0.10a	99	0.75 ± 1.30a	95
ANOVA (0.05)	0.000		0.000		0.000	

B

Treatment	I		II		III	
	Soil loss (g m^{-2})[*]	% reduction in soil loss	Soil loss (g m^{-2})	% reduction in soil loss	Soil loss (g m^{-2})	% reduction in soil loss
2011						
T0	16.9 ± 5.21c	0	321 ± 132d	0	1660 ± 288c	0
T1	4.18 ± 1.43a	75	91.7 ± 12.3b	71	506 ± 382b	70
T2	8.44 ± 2.36b	50	128 ± 28.6c	60	661 ± 366b	60
T3	1.74 ± 1.10a	90	6.77 ± 4.81a	98	44.3 ± 26.0a	97
ANOVA (0.05)	0.005		0.000		0.000	
2012						
T0	38.9 ± 17.6c	0	104 ± 18.4c	0	156 ± 15.6c	0
T1	8.99 ± 3.66b	77	35.2 ± 16.4b	66	41.0 ± 15.1b	74
T2	9.90 ± 6.42b	75	48.1 ± 18.4b	54	25.0 ± 14.4b	84
T3	0.02 ± 0.01a	100	0.05 ± 0.04a	100	0.68 ± 0.12a	100
ANOVA (0.05)	0.005		0.000		0.000	

[*] g m^{-2} = 10^{-2} Mg ha^{-1}.

Table 5

(A) Runoff coefficients (%) and (B) specific erosion rate (g m^{-2} mm^{-1}rain) for the treatments at sites I, II and III in 2011 and 2012. Seasonal erosive rainfall amounts (mm) were: Site I — 452; Site II — 386; Site III — 318 in 2011; and Site I — 296; Site II — 300; Site III — 292 in 2012. For treatment descriptions, see Table 3. Site I did not include pigeon-pea hedges.

Treatment	Site I		Site II		Site III	
	2011	2012	2011	2012	2011	2012
A						
T0	1.4 ± 0.5	4.1 ± 0.5	2.9 ± 0.5	6.7 ± 0.1	4.7 ± 0.1	5.6 ± 0.6
T1	0.7 ± 0.6	2.3 ± 0.3	2.3 ± 0.1	5.7 ± 0.2	4.0 ± 0.3	5.1 ± 0.5
T2	0.6 ± 0.3	3.0 ± 0.8	2.4 ± 0.6	5.1 ± 0.7	4.3 ± 0.7	3.9 ± 1.4
T3	0.2 ± 0.1	0 ± 0.1	0.5 ± 0.2	0.1 ± 0.0	2.1 ± 1.1	0.3 ± 0.1
B						
T0	0.04 ± 0.01	0.13 ± 0.06	0.83 ± 0.34	0.35 ± 0.06	5.22 ± 0.91	0.53 ± 0.05
T1	0.01 ± 0.00	0.03 ± 0.01	0.24 ± 0.03	0.12 ± 0.05	1.59 ± 1.20	0.14 ± 0.05
T2	0.02 ± 0.01	0.03 ± 0.02	0.33 ± 0.07	0.16 ± 0.06	2.08 ± 1.15	0.09 ± 0.05
T3	0.00 ± 0.00	0.00 ± 0.00	0.02 ± 0.01	0.00 ± 0.00	0.14 ± 0.08	0.00 ± 0.00

mean rates of soil loss were 0.8, 1.34 and 7.2 Mg ha^{-1} in 2011 and 0.1, 0.5 and 0.6 Mg ha^{-1} in 2012 at sites I, II and III, respectively. The highest mean rates of soil loss for the two years were 0.3, 2.1 and 9.1 Mg ha^{-1} at sites I, II and III, respectively.

All treatments had significantly less soil loss in 2011 compared to the control, but the effect varied among the sites in the orders T3 = T1 < T2 < T0 at site I, T3 < T1 < T2 < T0 at site II and T3 < T1 = T2 < T0 at site III. The order in 2012 was T3 < T1 = T2 < T0 for all sites. These results indicate that T3 was best at reducing soil loss. The effectiveness of the T2 at sites II and III increased from 2011 to 2012.

The reduction of soil loss due to the treatments was variable (Table 4B), with T2 producing the lowest reduction (54%) at site II in 2012 and T3 the highest (100%) at all sites, also in 2012. Soil loss was low in 2012, except at site II, but the magnitude of reduction was higher than in 2011 for all treatments. The order of reductions was T3 > T1 > T2, except T2 produced a larger reduction than T1 at site III in 2012. These results also confirm the high effectiveness of T3, which reduced soil loss between 90% (site I) and 98% (site II) in 2011 and completely eliminated soil loss in 2012. Total soil loss was higher in 2011 than in 2012 at the sites with steeper slopes (II and III), but total runoff was higher. Both runoff and sediment yield were lowest in 2011 and highest in 2012 at the low-slope site (I), despite more rainfall events in 2011. All treatments resulted in more reduction in soil loss rates than in runoff rates at all sites, but T3 also resulted in high runoff reduction. The standard deviations from the means of seasonal runoff and sediment yield in the treatments were very high in both years (Table 4A and B), indicating the variable effects of the treatments.

The specific soil loss rates (g m^{-2} mm^{-1}rain) show negligible values for site I in both seasons, for all treatments and control, with T3 eliminating erosion completely (Table 5B). The highest values were obtained at site III in 2011 for T0 (5.22) T1 (1.59), T2 (2.08) and T3 (0.14). Except for site I, values for 2011 were higher than for 2012, for all treatments and sites, following the order T0 > T2 > T1 > T3.

3.2.2. Runoff and sediment yield per rainfall events

Of the 16 rainy days during the 2011 growing season, seven produced runoff at sites I and II and six at site III from August 19 to October 25. Of the 18 rainy days in 2012, five produced runoff during September but not simultaneously at all sites; the rainfall on September 3 caused runoff at sites II and III but not at site I and the rainfall on September 6 caused runoff only at site I (Fig. 3). The first three events for 2012 generated very little runoff and sediment at all sites, even though soil cover was low and the soil surface was still affected by disturbance from field work after the first rain.

The amount of runoff per event varied among the treatments and sites (Fig. 4 I–III). Rainfalls <40 mm generally only produced runoff when the rain fell shortly (1–5 days) after an earlier rainfall and when the soil was still wet, reaching saturation with a small amount of rain. Runoff was generally low for all events in both years at site I with a low slope gradient (Fig. 4-I), with the highest runoff generation (3–4 L m^{-2}) in the control plot for the heaviest events on September 2 (87 mm) in 2011 and on September 29 and 30 (133 mm) in 2012. Runoff was generally low, but T3 had significantly less runoff than T0 for all events. Runoff from T1 and T2 was not consistently significantly different from T0. For events <47 mm in the first year, all treatments contributed to less runoff generation than the control, while for events, the effects of T1 and T2 were similar to that of T0. Only five events caused significant runoff in 2012, in which T2 was similar to T0, while T1 and T3 had significantly ($P < 0.05$) less runoff than T0, suggesting positive effects for both manure combined with soil surfactant and mulch combined with compost.

Erosion rates were low at site I for events ≤43 mm in 2011 and ≤35 mm in 2012 (Fig. 4-I), and no significant effects of the treatments ($P > 0.05$) were observed. For heavier events, however, all treatments generated significantly ($P < 0.05$) less sediment compared to the control in both years. T1 and T2 did not differ significantly for most events in both years.

For the steepest slope (site II), the highest runoff rate in 2011 occurred over the last two heavy events (>70 mm) even though soil cover was high for all treatments, while the most significant runoff in 2012 occurred over the last four events from September 8 to 29 (Fig. 4-II). All treatments generally had a positive effect on runoff, with T3 generating significantly ($P < 0.05$) less runoff than all other treatments and control over the two years. T1 and T2, however, did not differ significantly from T0 in 2011, except for the first and last events. In 2012, T2 and T3 generated less runoff than T0 for all events, and T1 was similar to T0 for events >75 mm. Soil loss at this site followed a trend identical to that of runoff, with T3 producing the best results in both years. The magnitude of soil loss, however, was relatively low for all events and treatments.

On the moderate slope (site III), all treatments produced significantly less runoff than the control for all events, with T3 again having the least runoff (Fig. 4-III), while the effect of the other treatments depended on the event. High runoff rates, generating large amounts of sediment, occurred in 2011 for heavy events from September 2 to October 25. The 59 mm event on October 18, though, did not generate large amounts of runoff. T3 produced the least amount of runoff and sediment. In 2012, T3 still produced the lowest runoff and soil loss. For 45 mm (September 8) and 60 mm (September 24) events, runoff from T1 and T2 did not differ from T0. Despite the large variability among the events, and even though T1 and T2 may have contributed to reduce runoff and/or soil loss, T3 produced the best results, nearly eliminating runoff and soil loss at all sites in both years.

3.3. Soil cover

Soil cover was highest for T3 and lowest for T0 in both years and for all sites and events, with the general effect of the treatments in the order T3 > T2 > T1 > T0 (Fig. 5). T1 and T2 were identical at site I in either year,

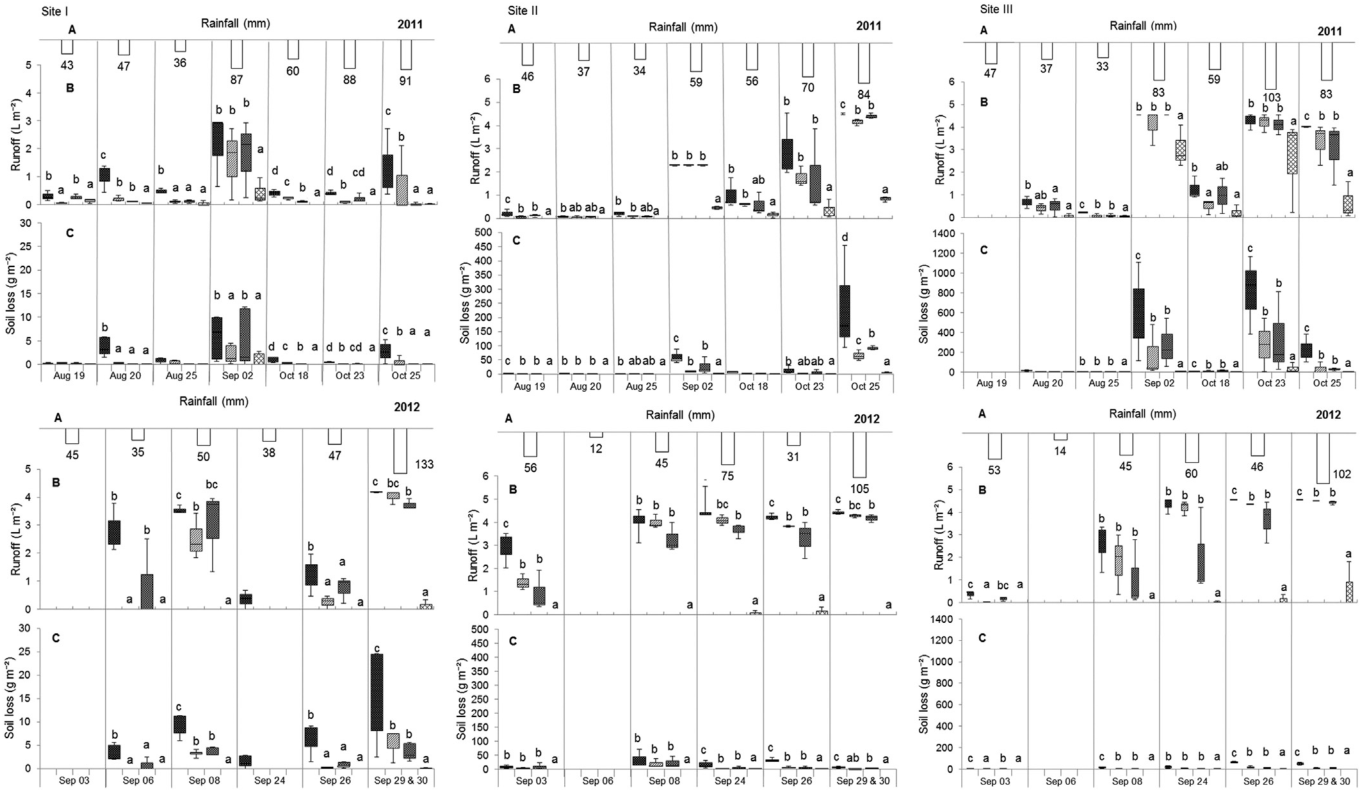

Fig. 4. I–III — Treatment effects on runoff (B) and sediment (C) per erosive rainfall event (A) during the 2011 and 2012 rainy seasons at sites I, II and III. For each date on the x-axis, treatments from left to right are T0, T1, T2 and T3. Lowercase letters indicate significant differences (Mann–Whitney *U*-test): a < b < c < d. For treatment descriptions, see Table 3.

but T2 had a larger effect than T1 at sites II and III, particularly in 2012. Soil cover varied for all treatments from as low as 8% (T0) at the beginning of the 2011 season to 100% at the end, and from 10% (T0, all sites) to 93% (T3, site III) in 2012, with none of the treatments reaching 100%. Except for T3 that showed a constant trend in the two years, the other treatments and the control varied more throughout the seasons, but more so in 2011.

3.4. Effect of treatments on soil-moisture content

The effect of the treatments on soil moisture, inside and between the planting pits, differed among the sites in 2012 for the various rains (Fig. 6). At site I, T3 had a significantly ($P < 0.05$) higher moisture content relative to T0 both inside and between the planting pits for the last rain (133 mm) and also inside the pits for the rain on September 26 (47 mm). T3, however, did not differ significantly ($P > 0.05$) from the other treatments. Moisture content at site II was higher in the treated plots than in the control for most of the rains, both inside and between pits, but the effects of the treatments were not statistically significant ($P > 0.05$) for any of the events. Moisture content at site III, however, was significantly higher for T2 and T3, particularly for the last three events (60, 46 and 102 mm), both inside and between pits, while the contents were identical in T0 and T1.

Soil moisture was generally higher between than in the pits for all treatments, events and sites. Only T3 had consistently higher moisture contents between the pits, while the other treatments had significantly higher moisture contents mainly inside the pits. The mean seasonal soil-moisture contents at the sites followed the orders II ≤ I (20–21%) < II (30%) inside the pits and II ≤ I (22–23%) < III (32%) between the pits.

3.5. Relationships between the various parameters

3.5.1. Runoff–erosion relationship

In general, runoff and soil loss were reasonably well positively correlated ($\alpha = 0.001$) in both years at all sites, but the correlation was strongest in 2012. The order of correlation (Pearson) among the sites was II (0.756) > III (0.708) > I (0.595) in 2011 and I (0.800) > II (0.790) > III (0.693) in 2012. However, soil loss did not linearly increase with increase in runoff for all treatments, at all sites. In 2011, for T0, the runoff–erosion relationship coefficient (r^2) was significant ($p < 0.05$) only at site II (0.804); for T1, at sites I (0.981) and II (0.998); for T2, only at site II (0.969); and for T3, at all sites (≥ 0.924). In 2012, except for T3 that had significant r^2 values at all sites (1.000), T0–T2 only had significant values at site III (0.996, 0.996 and 0.934, for T0, T1 and T2, respectively).

3.5.2. Factors influencing runoff and soil loss

The three principal components (PCs) extracted explained 91 and 87% of the variance in the data in 2011 and 2012, respectively. The main components in 2011 were: soil cover (42%), treatment (19%) and rainfall (30%). PC1 (soil cover) explained 49% of the variance in 2012, with treatment and rainfall mainly related to PC2 and PC3, respectively (Fig. 7).

Runoff and soil loss were positively correlated with slope and rainfall but negatively correlated with soil cover and initial soil-infiltration rate in both years. Rainfall, however, was more strongly correlated with soil loss, and slope was more strongly correlated with runoff (Table 6). Runoff was high on the steepest landscape (site II), but sediment yield was lower than at site III, which had a lower slope.

In 2011, parameters such as runoff, sediment, treatment and soil cover were more strongly associated with PC1; rainfall, slope and

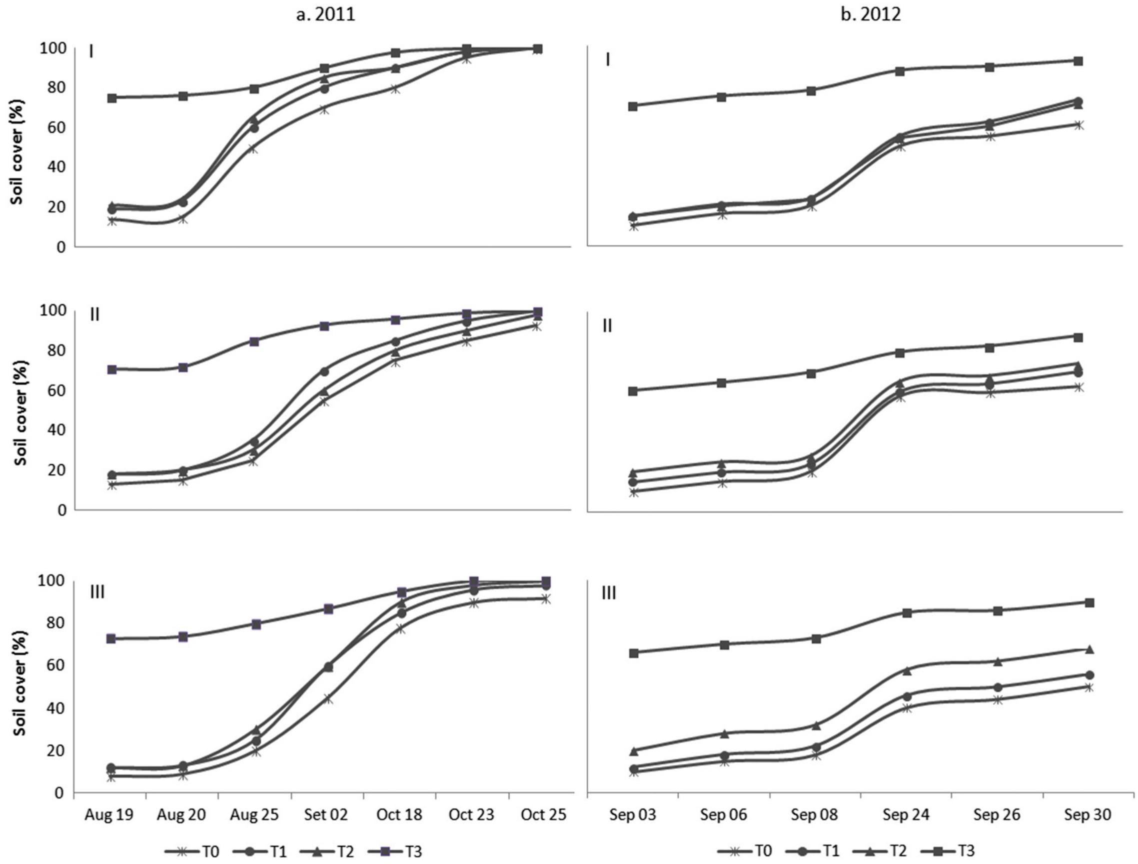

Fig. 5. Estimated soil cover for daily erosive rainfall events at sites I (São Jorge), II (Serrado) and III (O. Pequenos) in the 2011 (a) and 2012 (b) seasons, as influenced by the treatments. Planting dates were: August 7–8, 2011 and August 28–29, 2012. For treatment descriptions, see Table 3.

infiltration were more strongly associated with PC2 and soil moisture was mostly correlated with PC3 (Table 6). In 2012, however, rainfall and infiltration rate were strongly associated with PC3, slope was associated with PC2 and all other parameters were more strongly associated with PC1.

4. Discussion

4.1. Effect of treatments on runoff and soil loss

4.1.1. Runoff

Our results indicate that runoff and soil loss are not generated for rainfall <50 mm and soil moisture ≤20% for low-slope areas with medium-textured soils. Runoff can be expected for rainfall >40 mm, regardless of soil-moisture content, for coarse-textured soil on steep slopes. This confirms the results of Smolikowski et al. (2001) who reported runoff in Cabo Verde Regosols (>50% slope) only for rainfall >40 mm and intensity (I_{30}) > 40 mm h^{-1}. For finer-textured soil (silt–clay–loam) on moderate slopes (≥23%), runoff will likely occur for rainfall >60 mm and soil moisture ≥30%.

All rainfall events in 2012 occurred in September, so the soil remained moist during this period; increasing the amount of rainfall did not change soil-moisture contents to any great extent. The increase in soil moisture accompanying the application of mulch, pigeon-pea hedges and organic amendments at sites I and III corroborated the numerous studies (Montenegro et al., 2013; Ramakrishna et al., 2006; Bu et al., 2013) that have reported the positive effect of mulch and compost on soil-moisture content. The lower soil-moisture contents inside than between the planting pits may have been due to the use of water by the plants.

Runoff occurs when rain intensity exceeds the infiltration capacity of the soil, which measures the ability of the soil to absorb and transmit water (Lal, 1975; Le Bissonais et al., 2005). Runoff occurs more commonly in arid and semiarid regions, where rain intensities (or erosivity) are high and soil infiltration is impeded by surface crusting, dryness or rock fragments (Cerdà, 1996, 2001). The generation of runoff is an important factor in soil loss (Le Bissonais et al., 2005) and has a strong relationship with the incidence of erosion. Regosols are susceptible to runoff when saturated (Smolikowski et al., 2001). The fact that, on Regosols with slopes up to 23%, and on Cambisols up to 37%, only the treatment combining mulch with pigeon-pea hedges and an organic amendment had a significant effect in runoff reduction highlights the high efficacy of the mulch in preventing runoff. This is due to the fact that runoff is reduced by pigeon-pea, splash effect reduced by mulch and the infiltration capacity of the soils increased by mulch.

Residue mulch, as a system that maintains a protective cover of vegetation on the soil surface, has been widely used to reduce runoff and erosion from agricultural fields. The beneficial effects of mulching include protection of the soil against rain impact, decrease in runoff velocity and improved infiltration capacity of the soil (Zougmoré et al., 2003). Protecting the soil surface with a dead or living cover is an effective way to control erosion (Lal, 1975; Mando, 1997; Novara et al., 2013).

The positive effect of organic amendments (e.g. compost and animal or green manure) on the reduction of runoff and soil loss in semiarid areas has been reported by several authors (Cogle et al., 2002; Srinivasarao et al., 2014; Zougmoré et al., 2003). Zougmoré et al. (2003) reported an 87% reduction in runoff and 75% reduction in soil loss with compost application in Bukina Faso. These organic amendments contribute to the integrity of soil particles, increasing aggregate stability and decreasing erosion rates.

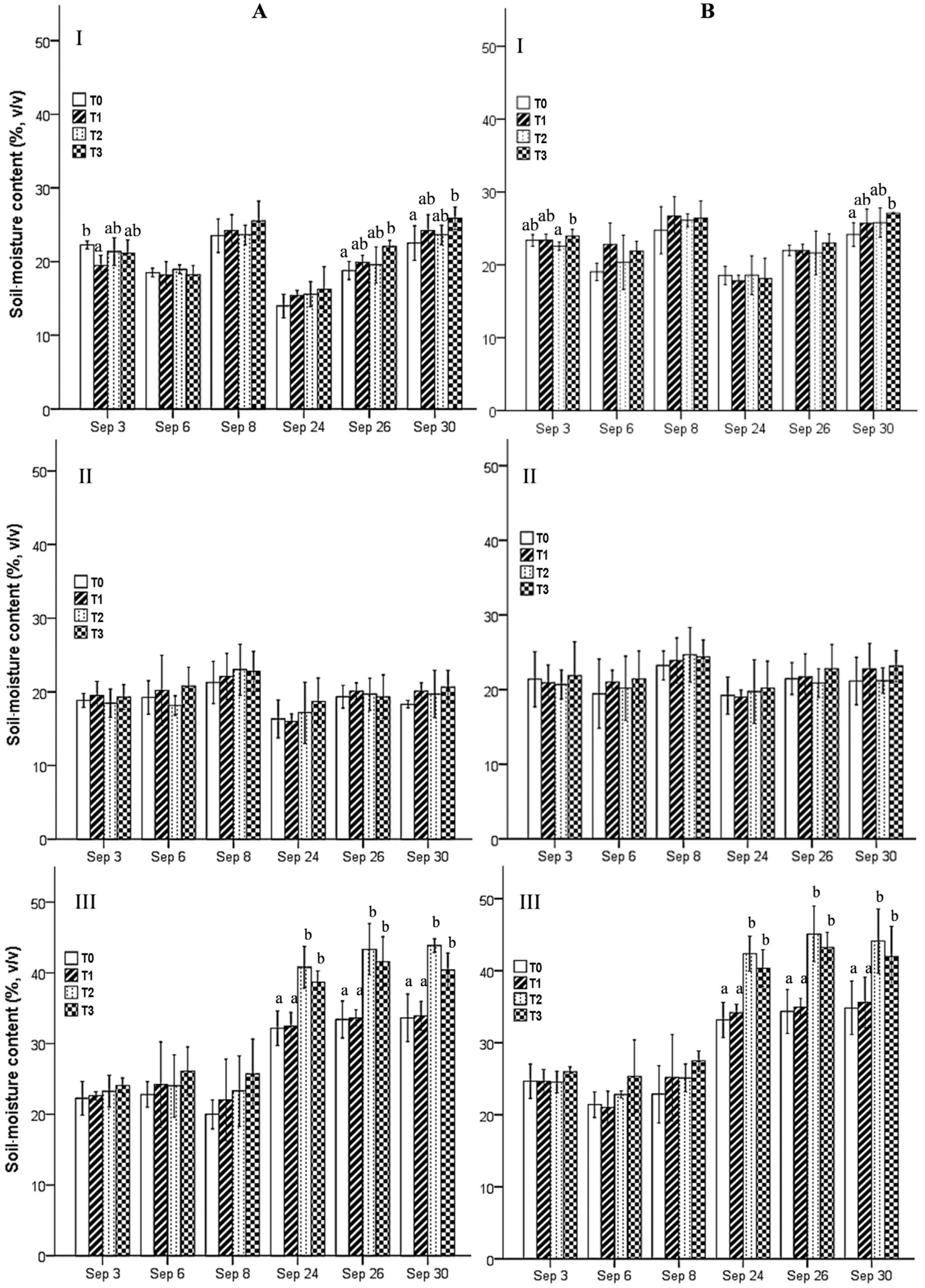

Fig. 6. Soil-moisture contents at 15-cm depths (A) inside and (B) between the planting pits for the various treatments at sites I, II and III during the 2012 rains. Lowercase letters indicate significant differences: a < b. For treatment descriptions, see Table 3.

Soil surfactants are designed to improve infiltration, distribution and retention of water (Mobs et al., 2012), runoff and water-use efficiency (Cooley et al, 2009; Lentz, 2003); thus the already high infiltration rate of the soils could explain the lack of response from the soil surfactant on runoff, obtained in the study on the sandy- and silt-clay loam soils. Also, as those soils are on steep slopes, thus subject to runoff, under these conditions, a single application may not be enough.

In our study, the pigeon-pea hedges without mulch at sites II and III were not effective in reducing runoff in the first year, and the effectiveness of the combination of mulch and hedges was mostly due to the

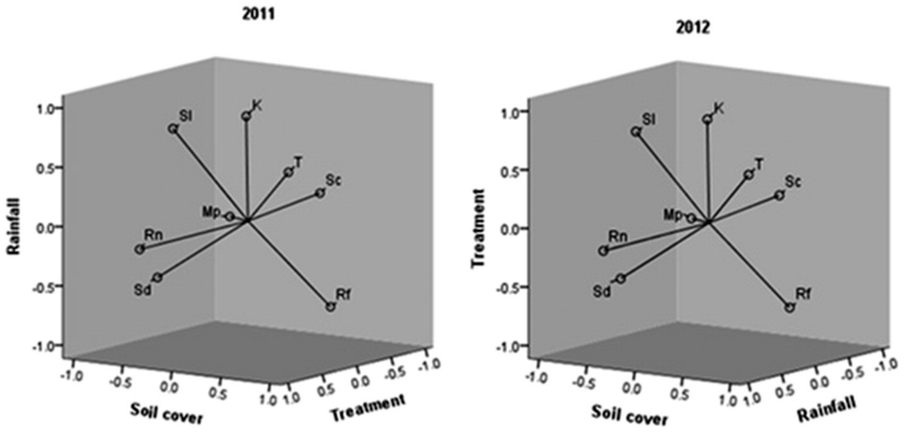

Fig. 7. PCA plots for the 2011 and 2012 rainy seasons showing the three PCs extracted in both years. T, treatment; Rf, rainfall; Rn, runoff; Sd, sediment; Sl, slope; Mp, soil moisture in pits; Sc, soil cover; K, initial infiltration rate.

mulch. Pigeon pea, as a perennial crop, does not develop a full canopy that can reduce the effect of rain drops on runoff during the first year. In 2012, however, the pigeon-pea plants developed a full canopy and deeper roots, and the hedges were better able to keep the soil in place, decreasing runoff to 11 and 21% at sites II and III, respectively, compared to the plots without hedges. Smolikowski et al. (2001) reported a 35% reduction in surface runoff with hedges of *L. Leucocephala* alone, comparatively to traditional maize and beans without hedges, on similar conditions.

The low runoff coefficients for all treatments (0.1–5.7%) and the control (1.4–6.7%) demonstrated the high permeability and infiltration potential of the soils regardless of treatment. They can also be due to the relatively low erosivity values registered for daily rainfalls during the two seasons when compared to extreme values (EI$_{30}$ of 200–300 KJ m^2 mm h–1) reported by Sanchez-Moreno et al., 2014. These results are comparable to the 5% reported by Smolikowski et al. (2001) on steeper slopes (50%) even though the runoff coefficient for individual storms reached 49%. But they are lower than those reported by other authors (Botha et al., 2003; Hensley et al., 2000) stating that runoff can represent between 8 and 49% of the annual rainfall in semiarid areas with fine-textured soils, depending on the prevailing conditions.

The higher runoff coefficients in 2012 may be attributed to the concentration of rainfall in a shorter period, more aggressive (high erosivity) rainfall events and constantly wet soils. After a long dry period from September 2 to October 18 in 2011, a heavy rainfall of 59 mm did not generate large amounts of runoff, because the dry soil absorbed the water and rainfall erosivity was low.

4.1.2. Soil loss

Soil loss reached 16.6, 5.1, 6.6 and 0.4 Mg ha^{-1} on the Regosol (site III) for the control, surfactant, pigeon-pea and mulch/pigeon-pea (with organic amendment) treatments, respectively; 3.2, 0.9, 1.3 and 0.1 Mg ha^{-1} on the Cambisol (site II) and <0. 2 Mg ha^{-1} for all treatments and control on the Kastanozem (site I). These results indicate that, at all sites, the traditional farming system lost more soil than the soil and water conservation treatments tested, but the magnitude of soil loss only exceeded the tolerable threshold values at sites II and III, in the 2011 rainy season.

Table 6
PC matrix for the 2011 and 2012 experimental seasons showing the relationships between various parameters and the main components.

Parameter	PCs 2011			PCs 2012		
	1	2	3	1	2	3
Treatment	0.67	0.53	0.36	0.87	0.37	−0.08
Runoff	−0.83	−0.27	0.39	−0.93	0.37	0.04
Soil loss	−0.57	−0.46	0.50	−0.84	0.01	−0.28
Rainfall	0.67	−0.69	−0.24	0.33	−0.57	0.72
Soil moisture in pits	0.39	0.20	0.83	0.73	0.10	−0.24
Soil cover	0.85	0.35	0.17	0.89	0.37	−0.05
Slope	−0.66	0.74	0.16	−0.38	0.92	0.016
Infiltration rate	−0.35	0.78	−0.47	−0.20	0.69	0.69

The mean erosion rate from 1994 to 1996 found by Smolikowski et al. (2001) for traditional farming plots was 16 Mg ha^{-1} y^{-1} under similar agropedological conditions but on a steeper (50%) slope. The results obtained in our study in 2011 and those obtained by Querido (1999) and Smolikowski et al. (2001) confirmed that soil erosion on Cabo Verde semiarid, steep hillsides under current traditional rain-fed farming can be excessive.

Despite the steeper slopes and possibly more aggressive rains as suggested by the EI$_{30}$ values, the mean erosion rates in this study, particularly for sites I and II, are lower than those in other semiarid Sahelian countries. Roose (1977) reported the mean annual soil losses of 0.2–20 Mg ha^{-1} under different crops growing on glacis with less than a 3% slope in Burkina Faso, and Martin (1995) measured a mean annual soil loss of 9 Mg ha^{-1} on cultivated land in Niger, with maximum losses reaching 18.5 Mg ha^{-1} y^{-1}. In Nigeria, Ande et al. (2009) reported rates of 12.8 and 9.4 Mg ha^{-1}, respectively, for rocky hill with >15% slope and for low land. Most of these studies consider the tolerable threshold value of 12 Mg ha^{-1} (Lal, 1998). However, given the shallow soils and the aggressive character of the rains in Cabo Verde (Sanchez-Moreno et al., 2013), the acceptable threshold rate should be substantially lower to ensure long-term production sustainability.

On the Kastanozem (<10% slope), soil loss was not significant as the rates were below the acceptable threshold value of 3.6 Mg ha^{-1} for moderately deep soils (FAO, 1993), even for the traditional farming system (control). On the Cambisol, the highest soil loss rate for the control was slightly higher than the acceptable erosion threshold of <3.0 Mg ha^{-1} y^{-1} for shallow soils, following the FAO criteria based on soil depth (FAO, 1993), with all treatments lowering soil loss below the threshold value. On the Regosol, even though all treatments strongly reduced soil loss, only the treatment combining mulch with pigeon-pea and an organic amendment was able to effectively prevent soil loss, lowering the rates below the acceptable threshold of 3.0 Mg ha^{-1}, as it nearly eliminated soil loss.

Tavares and Amiotte-Suchet (2007) reported that areas of rain-fed farming on Santiago were at severe risk of erosion by water, with 90–95% of the dryland area at high to very high risk. Sanchez-Moreno et al. (2013) also reported soil losses of 43 Mg ha^{-1} for extreme rain event in the watershed. For a more sustainable rain-fed farming system, the susceptibility to runoff and erosion should thus be reduced by applying conservation techniques of land management such as mulch combined with an organic amendment, with or without pigeon-pea hedges. The additional advantage of pigeon-pea (for increasing soil conservation, soil fertility and the production of biomass and food) can be an incentive to farmers. Pigeon-pea, as a perennial crop with roots deeper than those of maize and beans, can continue to produce biomass and to provide soil cover after the maize and beans have been harvested.

4.1.3. Relationships between the parameters

Soil loss increased with increasing runoff, but at different magnitudes at each site for the different treatments, indicating that, despite runoff being the major cause of soil loss, other factors were also involved. The higher rates of soil loss recorded at site III in 2011 than in 2012, despite identical runoff rates, confirm that runoff rate was not solely responsible for soil loss as also showed by the high specific soil loss rate (g m^{-2} mm^{-1} rain) and the variable runoff–erosion relationship coefficient (see Section 3.5). Mud flow and rill erosion were observed for the highly erosive daily rainfalls of September 2 (83 mm) and October 23 (103 mm) that transported large amounts of sediment and deposited them at the bottom of the slope, particularly for the control. Rills and mass transport may thus contribute substantially to the high erosion rate in this type of soil with a high content of silt and clay that swells as the water enters the soil, increasing its weight on the slope.

The pigeon-pea hedges (T2) were more effective in reducing soil loss rates than runoff rates.

The high effectiveness of the treatment combining mulch with pigeon-pea hedges in reducing both erosion and runoff rates in the traditional system to negligible levels is likely due to the protection of the mulch and vegetation, controlling splash, runoff, rills and mass flow, as also reported by Ali et al. (2007) and Zheng et al. (2007). Thus the combination does not only reduce runoff volume, but also change the runoff–erosion relationship.

Several interrelated factors, namely amount, erosivity and frequency of rainfall (which affect moisture levels and time to saturation), degree of soil cover, slope and soil properties such as texture and infiltration rate influenced the runoff and soil loss during the study period, but soil cover was the main factor followed by rainfall and the treatments (see Section 3.5). The positive influence of soil cover on both runoff and soil loss indicates the importance of maintaining some residue on the soil surface during erosive rainfall events, as also reported by Cerdà (2001), Hartanto et al. (2003) and Kairis et al. (2013). The mulch provided a high degree of soil cover, which limits runoff by providing a physical barrier and protecting the soil surface from the erosive energy of rainfall. As the surface cover was high towards the end of the experimental seasons, the differences in runoff between the treatments and the control were less accentuated.

The rates of runoff were more influenced by the site slope and the rates of soil loss were more strongly influenced by the amount and erosivity of rainfall, partially explaining the highest runoff rates observed at the steepest landscape, but highest soil loss rate for a less steep landscape. Even though the slope is assumed to have a positive relationship with soil loss (Wischmeier and Smith, 1965), this study found a decline in soil loss for the steepest slope, a finding also reported by Defersha et al. (2011) in Ethiopia highlands. The effect of the slope on runoff and soil loss also depended on soil type and antecedent moisture.

4.2. A promising technique for the control of erosion and runoff for Cabo Verde dryland hillsides and its adoption by farmers

Our results show that a combination of an organic amendment with residue mulch and pigeon-pea hedges is very effective in controlling runoff and soil loss on the hillsides cultivated with dryland crops. Despite the benefits of this new technique for soil and environmental conservation, its adoption may not be easy or rapid due to economic reasons and the limited availability of organic amendments and plant material for mulching, particularly during drier years. Smaller amounts of residue mulch should thus be tested. Efforts to develop sustainable agricultural systems acceptable to the local population must be continued. Evaluations of the cost-effectiveness of these techniques, the yield benefits and the nutrient losses through runoff and erosion would be important for establishing the most sustainable options for the farmers under these semiarid conditions.

The techniques tested in these experiments were selected with the participation of local stakeholders, and farmers were involved in the field trials. This level of participation could facilitate the adoption of the technique. Farmers could be motivated to adopt the new SWC technique by hosting demonstration plots, interacting with each other and being educated about the need to protect the soil. A participatory approach such as the farmer-led technology-transfer model for transferring technologies for the management of natural resources, that gives farmers a central role in the process, could promote adoption.

5. Conclusions and recommendations

The erosive character of rainfall in Cabo Verde associated with the traditional practice of rain-fed farming can cause considerable losses of soil and water from agricultural fields, leading to soil degradation. The soils of the experimental sites had relatively high capacities for water retention and low runoff rates, but their continuous cultivation without protection will eventually accelerate the degradation of the land. Erosion was highly positively correlated with runoff.

With this study, we conclude that a combination of mulch, pigeon-pea hedges and an organic amendment on steep slopes can significantly reduce runoff and erosion from dryland agricultural fields in Cabo Verde, thus contributing to a more efficient use of rainwater at the field level. Mulch or a soil surfactant combined with an organic amendment can also improve the use of rainwater on gentle slopes with low erodibility.

A shortcoming of the implementation of this combined technique, which includes some components of conservation farming, could be the lack of crop residue for use as mulch. This constraint, however, could be overcome by including a cover crop in the system to use as mulch. In addition, the pigeon-pea used as hedges could be pruned and also used as mulch. If the steep hillsides must be used for cultivating traditional crops such as maize and beans, and because land degradation must be stopped, then the agronomic practice of mulching combined with an organic amendment should be advocated to conserve soil and water. Pigeon-pea, either as hedges or intercropped with the maize and bean crops, should also be endorsed as a more permanent soil cover.

Given the variability of rainfall distribution between the two years of study and the limited erosion and runoff data at the plot level, there is a need to conduct experiments for longer periods to consolidate data, establish trends and standardize tolerable threshold erosion rates for the semiarid steep hillsides.

Effective farmer involvement through demonstration plots, farmer interactions and education about the need to protect the soil will be crucial for the successful implementation of such techniques. For the Cabo Verde semiarid hillsides, we recommend that sustainable land management techniques that increase rainwater-use and prevent further degradation of the natural resources be advocated and implemented.

Acknowledgments

We are grateful to the Netherlands Universities Foundation for International Cooperation (Nuffic) for funding this research (through the NFP-PhD-10/132), the Instituto Nacional de Investigação e Desenvolvimento Agrário of Cabo Verde (INIDA) for providing logistic support and laboratory facilities during the field experiments and the DESIRE project Desertification Mitigation and Remediation of Land — A Global Approach for Local Solutions (under EF6 — contract # 037046 GOCE) for providing the framework for the study and partial funds for the field work. We also thank the farmers of Ribeira Seca for their collaboration in the workshops and field experiments and the personnel of INIDA's soil laboratory for their assistance in the analyses.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geoderma.2014.09.015. These data include Google maps of the most important areas described in this article.

References

Ali, I., Khan, F., Bhatti, A.U., 2007. Soil and nutrient losses by water erosion under monocropping and legume inter-cropping on sloping land. Pak. J. Agric. Res. 20, 3–4.

Ande, O.T., Alaga, Y., Oluwatosin, G.A., 2009. Soil erosion prediction using MMF model on highly dissected hilly terrain of Ekti environs in southwestern Nigeria. Int. J. Phys. Sci. 4 (2), 53–57.

Araya, A., Stroosnijder, L., 2010. Effects of tied ridges and mulch on barley (*Hordeum vulgare*) rainwater use efficiency and production in Northern Ethiopia. Agric. Water Manag. 97, 841–847.

Blake, G.R., Hartge, K., 1986. Bulk density, In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, 2nd edition Agronomy Monograph vol. 9. America Society of Agronomy, Madison, Wis, USA, pp. 363–375.

Bossio, D., Geheb, K., Critchley, W., 2010. Managing water by managing land: addressing land degradation to improve water productivity and rural livelihoods. Agric. Water Manag. 97, 536–542.

Botha, J.J., van Rensburg, L.D., Anderson, J.J., Henseley, M., Machelli, M.S., van Saden, P.P., Kundhland, G., Groenewald, D.G., Baiphethi, M.N., 2003. Water Conservation Techniques on Small Plots in Semi-arid Areas to Enhance Rainfall use Efficiency, Food Security and Sustainable Crop Production. Report No 1176/1/03. Water Research Commission. WRC, Pretoria, South Africa.

Bu, L.-d., Liu, J.-l., Zhu, L., Luo, S.-s., Chen, X.-p., Li, S.-q., Hill, R.L., Zhao, Y., 2013. The effects of mulching on maize growth, yield and water use in a semi-arid region. Agric. Water Manag. 123, 71–78.

Cerdà, A., 1996. Seasonal variability of infiltration rates under contrasting slope conditions in Southeast Spain. Geoderma 69, 217–232.

Cerdà, A., 2001. Effects of rock fragment on soil infiltration, inter-rill runoff and erosion. Eur. J. Soil Sci. 52 (1), 59–68.

Chambers, J.C., Brown, R.W., 1983. Methods for vegetation sampling and analysis on revegetated mined lands. Gen. Tech. Rep. INT-151. USDA Forest Service, Intermountain Forest and range experiment station, Ogden, UT.

Cogle, A.L., Rao, K.P.C., Yule, D.F., Smith, G.D., George, P.J., Srinivasan, S.T., Jangawad, L., 2002. Soil management for Alfisols in the semiarid tropics: erosion, enrichment and runoff. Soil Use Manag. 18, 10–17.

Cooley, E.T., Lowery, B., Kelling, K.A., Speth, P.E., Madison, F.W., Bland, W.I., Tapsieva, A., 2009. Surfactant use to improve soil water distribution and reduce nitrate leaching in potatoes. Soil Sci. 174, 321–329.

Defersha, M.B., Quraishi, S., Melesse, A., 2011. The effect of slope steepness and antecedent moisture content on interril erosion, runoff and sediment size distribution in the highlands of Ethiopia. Hydrol. Earth Syst. Sci. 15, 2367–2375.

Diniz, A.C., Matos, G.S., 1986. Carta de Zonagem Agro-ecológica e de Vegetação de Cabo Verde: I-Ilha de Santiago. Garcia da Orta; Serie de botanica 8 (1-2), pp. 39–82.

Erenstein, O., 2003. Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crop. Agric. Ecosyst. Environ. 100, 17–37.

FAO, 1993. Agro-ecological land resources assessment for agricultural development planning. World Soils Resources Report 71 (ISSN 0532-04).

FAO, 2003. Agriculture and Food in Cape VerdeAvailable at: http://earthtrends.wri.org/pdf_library/country_profiles/agr_cou_132.pdf (assessed in, 2014).

FAO, 2014. Evolution of Crop Production. FAOSTAT, Country Profile CVPAvailable at: http://faostat.fao.org/site/567/default (Assessed in 2014).

Ferreira, A.J.D., Tavares, J., Baptista, I., Coelho, C.O.A., Reis, A., Varela, L., Bentub, J., 2012. Efficiency of overland and erosion mitigation techniques at Ribeira Seca, Santiago Island, Cape Verde. In: Wong, T.S.W. (Ed.), Overland Flow and Surface RunoffHydrological Science and Engineering Book Series. Nova Science Publishers, Inc., TOWN, pp. 113–135.

Gao, X., Wu, P., Zhao, X., Wang, J., Shi, Y., 2014. Effects of land use on soil moisture variation in a semi-arid catchment: implications for land and agricultural water management. Land Degrad. Dev. 25, 163–172. http://dx.doi.org/10.1002/ldr.1156.

Hartanto, H., Prabhu, R., Widayat, A., Asdack, C., 2003. Factors affecting runoff and soil erosion: plot-level soil loss monitoring for assessing sustainability of forest management. For. Ecol. Manag. 180, 361–374.

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

Hensley, M., Bennie, A.T.P., van Rensburg, L.D., Botha, J.J., 2000. Review of 'plant available water' aspects of water use efficiency under irrigated and dryland conditions. Water SA 37 (No. 5).

Huenchuleo, C., Barkmann, J., Villalobos, P., 2012. Social psychology predictors for the adoption of soil conservation measures in Central Chile. Land Degrad. Dev. 23, 483–495. http://dx.doi.org/10.1002/ldr.1093.

INIDA, 1997. Manual de fertilidade do solo e fertilização das culturas. República de Cabo Verde, São Jorge dos Órgãos.

INIDA/DESIRE, 2008. Characterization of the Ribeira Seca — Santiago Island — Cape Verde hotspot. Field Guide to the DESIRE 2nd Plenary Meeting.

INMG, 2010. Dados anuais de pluviometria referentes as estações de São Jorge, Vale de mesa e Ribeirinh. Instituto Nacional de Metereologia e Geofisica.

Jackson, M.L., 1982. Soil Chemical Analysis. Prentice-Hall Inc., England, New Jersey. USA.

Kairis, O., Karavatis, C., Kounalaki, A., Salvati, L., Kosmas, C., 2013. The effect of land management practices on soil erosion and land degradation in an olive grove. Soil Use Manag. 29, 597–606.

Lal, R., 1975. Role of mulching techniques in tropical soil and water management. Technical Bulletin IITA, Ibadan, Nigeria.

Lal, R., 1998. Mulching effects on runoff, soil erosion and crop response on Alfisols in Western Nigeria. J. Sustain. Agric. 11 (2/3).

Langworthy, M., Finan, T., 1997. Waiting for rain: agriculture and ecological imbalance in Cape Verde. Technology and Engineer Book. Lynne Rienner Publishers, (212 pp.).

Le Bissonais, Y., Daroussin, J., Jamagne, M., Lambert, J.J., le Bas, C., King, D., Cerdan, O., Léonard, J., Bresson, L.M., Jones, R., 2005. Pan-European soil crusting and erodibility assessment from the European Soil Geographical Database using pedotransfer rules. Adv. Environ. Monit. Model. 2, 1–15.

Lentz, R.D., 2003. Inhibiting water infiltration with polyacrylamide and surfactants: application for irrigated agriculture. J. Soil Water Conserv. 58 (5), 290–300.

Mando, A., 1997. The effect of mulch on the water balance of Sahelian-crusted soil. Soil Technol. 11, 121–138.

Mannaerts, C.M., 1993. Assessment of the Transferability of Laboratory Rainfall — Runoff and Rainfall — Soil Loss Relationship to Field and Catchment Scales: A Study in the Cape Verde Islands(PhD. thesis) ITC, The Netherlands.

Mannaerts, C.M., Gabriels, D., 2000. Rainfall erosivity in Cape Verde. Soil Tillage Res. 55, 207–212.

Martin, P., 1995. Ader Doutchi Macgia (Niger). Notes sur l'historique des stratégies de Lutte antiérosif. Bull. Réseau Erosion 15, 266–282.

Mobs, T.L., Peters, R.T., Davenport, J.R., Evans, M.A., Wu, J.Q., 2012. J. Soil Water Conserv. 67 (4), 275–285.

Montenegro, A.A.A., Abrantes, J.R.C.B., Lima, J.L.M.P., Singh, V.P., Santos, T.E.M., 2013. Impact of mulching in soil and water dynamics under intermittent simulated rainfall. Catena 109, 139–149.

NAPA, 2007. National Adaptation Programme of Action on Climate Change, 2008–2012. GEF/UNDP, Cape Verde.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Kenney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Am. Soc. Agron, Madison, Wisconsin, USA, pp. 539–577.

Novara, A., Cristina, L., Guaitoli, F., Santoro, A., Cerda, A., 2013. Managing soil nitrate with cover crops and buffer strips in Sicilian vineyards. Solid Earth 4, 255–262.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page, A.L., Miller, R.H., Kenney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Am. Soc. Agron, Madison, Wisconsin, USA, pp. 403–430.

Querido, A.L., 1999. Watershed system analysis for evaluating the efficiency of soil and water conservation works: a case study of Ribeira Seca, Island of Santiago, Cape Verde. Master's thesis. International Institute for Aerospace Survey and Earth Science. Enschede. The Netherlands. Unpublished.

Ramakrishna, A., Tam, H.M., Wani, S.P., Long, T.D., 2006. Effect of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. Field Crop Res. 95, 115–125.

Rockstrom, 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.

Rockstrom, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, L., Barron, J., Mutua, J., Damgaard-Larsen, S., 2009. Conservation farming strategies in East and Southern Africa: yields and rainwater productivity from on-farm action research. Soil Tillage Res. 103, 23–32.

Roose, R., 1977. Erosion et ruissellement en Afrique de l'Ouest. Vingt annees de measures en petites parcelles experimentalesColl. Travaux et Documents No. 78., ORSTOM, Paris.

Ryan, J.G., Spencer, D.C., 2001. Future challenges and opportunities for agricultural R&D in the semi-arid tropics. International Crops Research Institute for the Semi-Arid tropics, Patanchero India.

Sadeghi, S.H.R., Azari, M., Ghaderi Vangah, B., 2008. Field evaluation of hill slope erosion model (HEM) in Iran. Biosyst. Eng. 99, 304–311.

Sanchez-Moreno, J.F., Jetten, V., Mannaerts, C.M., Tavares, J.P., 2013. Selecting best mapping strategies for storm runoff modeling in a mountainous semi-arid area. Earth Surf. Process. Landf. http://dx.doi.org/10.1002/esp.3501.

Sanchez-Moreno, J.F., Mannaerts, C.M., Jetten, V., 2014. Rainfall erosivity mapping for Santiago Island, Cape Verde. Geoderma 217–218, 74–82.

Schwilch, G., Bachmann, F., Liniger, H.P., 2009. Appraising and selecting conservation measures to mitigate desertification and land degradation based on stakeholder participation and global best practices. Land Degrad. Dev. 20, 308–326.

Smolikowski, B., Puig, H., Roose, E., 2001. Influence of soil protection techniques on runoff, erosion and plant production on semi-arid hillsides of Cabo Verde. Agric. Ecosyst. Environ. 87, 67–80.

Srinivasarao, C.H., Venkateswarlu, B., Lal, R., Singh, A.K., Kundu, S., Vittal, K.P.R., Patel, J., Patel, M.M., 2014. Long-term manuring and fertilizer effects on depletion of soil organic stocks under Pearl millet-cluster vean-castor rotation in Western India. Land Degrad. Dev. 25, 173–183. http://dx.doi.org/10.1002/ldr.1158.

Stroosnijder, L., 2003. Technologies for improving Green Water use efficiency in West Africa. Water Conservation Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa. Symposium and Workshop, Bloemfontein, South Africa.

Stroosnijder, L., 2009. Modifying land management in order to improve efficiency of rainwater use in the African highlands. Soil Tillage Res. 103, 247–256.

Stroosnijder, L., Moore, D., Alharbi, A., Argaman, E., Biazin, B., van den Elsen, E., 2012. Improving water use efficiency in drylands. Curr. Opin. Environ. Sustain. 4, 1–10.

Tavares, J., Amiotte-Suchet, P., 2007. Rainfall erosion risk mapping in volcanic soils of Santiago Island, Cape Verde Arquipelago. Afr. Geosci. Rev. 14, 399–414.

Tavares, J., Ferreira, A.J.D., Reis, E.A., Baptista, I., Amoros, R., Costa, L., Furtado, A.M., Coelho, C., 2013. Appraising and selecting strategies to combat and mitigate desertification based on stakeholder knowledge and global best practices in Cape Verde Archipelago. Land Degrad. Dev. 25, 45–57.

Tesfaye, A., Negatu, W., Brouwer, R., van der Zaag, P., 2014. Understanding soil conservation decision of farmers in the Gedeb watershed, Ethiopia. Land Degrad. Dev. 25, 71–79. http://dx.doi.org/10.1002/ldr.2187.

Thapa, G.B., Yila, O.M., 2012. Farmers' land management practices and status of agricultural land in the Jos Plateau, Nigeria. Land Degrad. Dev. 23, 263–277. http://dx.doi.org/10.1002/ldr.1079.

Turner, N.C., 2004. Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems. J. Exp. Bot. Vol. 55, 407 (Water saving Agriculture Special Issue, pp. 2413–2425).

Wischmeier, W.H., Smith, D.D., 1965. Predicting Rainfall-Erosion Losses From Cropland East of the Rocky Mountains, Agriculture Handbook No.282, USDA, Washington, DC.

WOCAT, 2007. Where the Land is Greener — Case Studies and Analysis of Soil and Water Conservation Initiatives Worldwide. In: Liniger, Hanspeter, Critchley, William (Eds.), .

Xu, Q.X., Wang, T.W., CAI, C.F., Li, Z.X., SHI, Z.H., 2012. Effects of soil conservation on soil properties of citrus orchards in the Three-Gorges Area, China. Land Degrad. Dev. 23, 34–42. http://dx.doi.org/10.1002/ldr.1045.

Zhao, G., Mu, X., Wen, Z., Wang, F., Gao, P., 2013. Soil erosion, conservation, and Eco-environment changes in the Loess Plateau of China. Land Degrad. Dev. 24, 499–510. http://dx.doi.org/10.1002/ldr.2246.

Zheng, Mingguo, Qiangguo, Cai, Hao, Chen, 2007. Effect of vegetation on runoff-sediment yield relationship at spatial scales in hilly areas of the Loess Plateau, North China. Acta Ecol. Sin. 27 (9), 3572–3581.

Zougmoré, R., Mando, A., Ringersma, J., Stroosnijder, L., 2003. Effect of combined water and nutrient management on runoff and sorghum yield in Semiarid Burkina Faso. Soil Use Manag. 19, 257–264.