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Soil erosion and runoff in different vegetation patches from semiarid Central Mexico

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ABSTRACT

Vegetation patches in arid and semiarid areas are important in the regulation of surface hydrological processes. Canopy and ground covers developed in these fertility islands are a natural cushion against the impact energy of rainfall. Also, greater levels of organic matter improve the soil physicochemical properties, promoting infiltration and reducing runoff and soil erosion in comparison with the open spaces between them. During the 2006 rainy season, four USLE-type plots were installed around representative vegetation patches with predominant individual species of Huisache (*Acacia sp*), Mesquite (*Prosopis sp*), Prickly Pear or Nopal (*Opuntia sp*) and Cardon (*Opuntia imbricata*), to evaluate soil erosion and runoff, in semiarid Central Mexico. A comparative bare surface condition (Control) was also evaluated. Vegetative canopy and ground cover were computed using digital images. Selected soil parameters were determined. Soil erosion was different for the studied vegetation conditions, decreasing as canopy and ground cover increased. There were not significant differences in runoff and soil erosion between the Control and *O. imbricata* surfaces. Runoff was reduced by 87%, 87% and 98% and soil loss by 97%, 93%, and 99% for *Acacia farnesiana*, *Prosopis laevigata* and *Opuntia sp*, respectively, as compared to the Control. Soil surface physical conditions were different between the low vegetation cover conditions (Control and *O. imbricata* surfaces) and the greater vegetation cover conditions (*A. farnesiana*, *P. laevigata* and *Opuntia sp*), indicating a positive effect of vegetation patches on the regulation of surface hydrological processes.

1. Introduction

Drylands, defined according to the World Atlas of Desertification (UNEP, 1992) as areas with a ratio of average annual precipitation (*P*) to potential evapotranspiration (PET) of less than 0.65, occupy approximately 40% (54 million km^2) of the total land area worldwide (Slaymaker and Spencer, 1998), including 24% of the American Continent (Sivakumar, 2007). In Mexico, arid and semiarid lands cover approximately 40% of the country's total area (Villa, 1981), mostly located in the north-central region.

Regardless of geographical location, arid and semiarid areas are characterized by specific vegetation and climatic conditions. Vegetation in drylands includes plants with mechanisms of resistance and/or adaptation to water stress, such as cactus, mesquites, bushes, etc. (Valles-Septién et al., 1998; Nobel, 1998). Spatial distribution patterns of vegetation in those areas are mostly identified as patches or strips of shrubs and grasses (Aguiar et al., 1992; Aguiar and Sala 1994; Facelli and Temby, 2002), often called fertility or hydrologic islands (Moro et al., 1997; Rango et al., 2006).

Climatically, arid lands are characterized by extreme temperature conditions (D'Odorico and Porporato, 2006) and torrential precipitation events with short duration and high intensity (Wei et al., 2007), which causes low infiltration and consequently water erosion and great amounts of runoff (Rango et al., 2006). All of these processes are regulated by the terrain and the overall vegetation cover (Ridolfi et al., 2008). These ecosystems are generally fragile and often susceptible to desertification (UNCCD, 2004).

Vegetation plays an important role in the regulation of hydrological processes and changes in soil properties because of the destructive forces of rainfall that cause erosion (Wei et al., 2007) and soil sealing and crusting (Regüés and Torri, 2002). In the fertility islands, erosion and surface sealing can be significantly reduced relative to bare soil as a result of canopy cover protection and improvement of soil physical, chemical and biological properties (Casermeiro et al., 2004).

In systems where perennial plants form a discontinuous cover, such as savannas and shrublands, the presence of canopy alters the microenvironment in ways that influence the activity of soil microbes (Hopmans, 2006). Scattered shrubs in arid lands are important in structuring the annual plant community. The distributions of patches may take

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the form of spots or bands between bare surfaces (Aguiar et al., 1992; Aguiar and Sala, 1994; Rango et al., 2006). This spatial heterogeneity can result in a patchwork of microenvironments that can have both facilitative and inhibitory effects on the annual plant communities associated with the dominant perennial plant species (Facelli and Temby, 2002), which influences hydrological surface processes.

Most past studies have been focused on determining the influence of semiarid patches of vegetation on localized soil physical, chemical and biological properties (Puigdefábregas, 2005; Bautista et al., 2007). Only a few studies are related to hydrological processes in the fertility islands, and even fewer on the interaction among vegetation cover, soil physical conditions and the surface hydrological processes of soil erosion and runoff (Chen et al., 2007; Bautista et al., 2007).

The aim of this study was to evaluate soil erosion and runoff under different representative dryland vegetation patches as related to soil physical conditions and canopy/ground cover, as compared to open-space areas, where soil physical and hydrological properties are believed to be different.

2. Materials and methods

2.1. Study site

The study site is located at the Santo Domingo Ranch in the municipality of Cadereyta, Queretaro, Mexico (Fig. 1) at 99° 46″ 46′ W, 20° 43″ 49′ N and 2069 m altitude. Mean annual temperature in the site is 16.7 °C and mean annual precipitation approximately 480 mm, as reported by INEGI (1996). Vegetation is dominated by Huisache (*Acacia farnesiana* (L. Willd)), Mesquite (*Prosopis laevigata* (Humb. et Bonpl. ex Willd)), Cardon (*Opuntia imbricata*) and Nopal (*Opuntia sp*) (Mastachi-Loza et al., 2010). The dominant soil is a Pellic Vertisol associated with a Haplic Phaeozem, according to the FAO Soil Classification system (INEGI, 1984).

2.2. Erosion and runoff measurements

Modified USLE-type circular plots were used for runoff and soil erosion measurements. The plots were built around the vegetation of interest using concrete blocks along the perimeter of the canopy projection, and inserted 10 cm into the ground to isolate surface and subsurface water flows. A metal-sheet plot end was placed at the bottom of the slope to convey runoff into a 10-cm PVC pipe which, in turn, delivered water and sediment into a collection system consisting of a series of two 200-L containers (Fig. 2). The second container collected the excess of the first using a connecting 4-cm tubing pipe.

In addition to the plots under the vegetation patch, a Control plot similar in shape and slope, but without vegetation and under continuous tillage to avoid crusting and weed development, was established according to the specifications of Renard et al. (1997) in order to determined the relative soil loss attributed to the vegetation island effect.

Runoff and sediment samples and measurements were taken after each rainfall event. Runoff was determined by measuring the water stage in the container and then translating it into volume using the corresponding geometric equations. A representative 1-L runoff/sediment sample was taken by mixing vigorously and homogeneously and filing the plastic bottle from the bottom up to obtain an integrated sample. The sample was then taken to the laboratory for gravimetric processing. First, the sample was flocculated with a saturated solution of aluminum sulphate, then the excess water was decanted before the solids were oven-dried at a temperature of 105 °C until constant weight was achieved. Calculations of runoff in mm and erosion rate in ton ha^{-1} were obtained for each event.

Rainfall durations, depths, and intensities were monitored using a Vaisala WXT510 sensor (Vaisala Weather Transmitter WXT510) with a CR1000 datalogger. Kinetic energy and the USLE-type rainfall erosivity index were determined using the equations proposed by Foster et al. (1982) and Wischmeier and Smith (1978). Runoff coefficients for each rainfall event were calculated as the ratio of runoff to rainfall.

2.3. Vegetation measurements

Representative individuals of *O. imbricata*, *A. farnesiana*, *P. laevigata* and *Opuntia sp*, and their ground and/or surrounding vegetation were studied. Total individual plant height and height of the trunk from the ground to the first branch bifurcation were measured using a

Fig. 1. Study site.

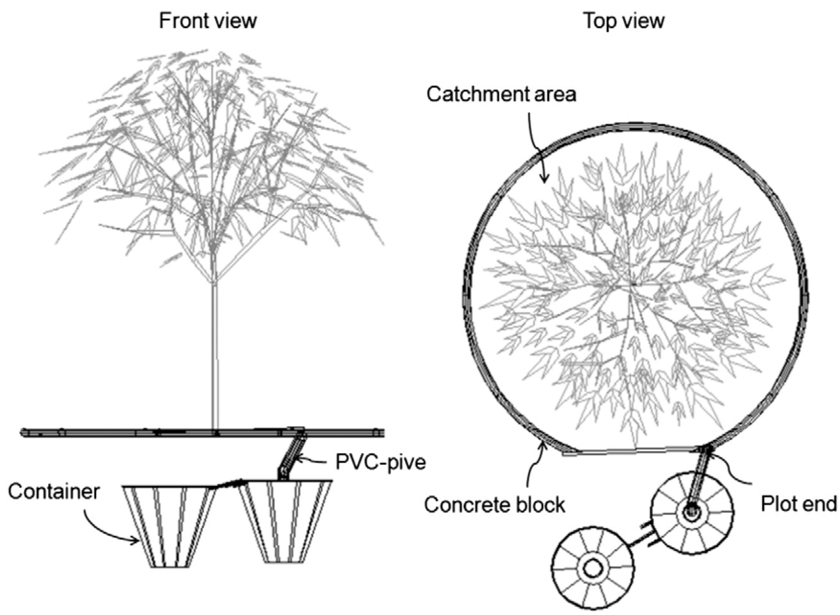

Fig. 2. Plot and collection system layout under the vegetation patch.

measuring stick. Ground and canopy cover were calculated from digital pictures taken with a FujiFilm digital camera. The pictures were taken perpendicular to the soil surface from the bottom up for canopy cover and from the top down for the ground cover, placing the camera in both cases in a plane between the canopy and the ground vegetation. Care was taken to capture the pictures at a proper time of the day to avoid shading effects. Images were pre-treated in Paint Shop Pro (v 7.04), which included cropping to an 800 × 600 pixel size and change to grey scale.

To determine percent of cover, both ground vegetation and canopy, the algorithm HISTO_GENE (LAFSINA, Parrot, 2003) was used. This procedure builds a grey scale map from the original picture assigning a gray color scale value pixel by pixel. Density distribution of the complete set of data corresponds to the *Firmagram* (Oleschko et al., 2004), which represents the picture roughness. The grey scale file generated by HISTO_GENE was analyzed with the FREQ_HIST program (LAFSINA, Parrot, 2003), which generates a histogram with the frequency of each tone in a spreadsheet file.

2.4. Soil organic matter content, bulk density, aggregate stability index and water infiltration

To avoid disturbance in the USLE-type plots, soil samples were taken from similar and adjacent vegetation sites at two different depths (0–15 and 15–30 cm) for laboratory analysis. The soil samples were air-dried before organic matter content, soil bulk density and aggregate stability analyses were performed. Organic matter content was determined using the Walkley–Black method (Nelsol and Sommers, 1982), while bulk density was determined in five replicates using the saran clod method (Blake and Hartge, 1986). Dry and wet sieving were performed to determine the aggregate stability index as the ratio between wet mean weight diameter (MWD_w) and dry mean weight diameter (MWD_d) (Kemper and Rosenau, 1986). A set of eight different sieve sizes (9520, 4760, 2000, 1180, 500, 250, 125 and 50 μm) were used. Dry sieving was accomplished using a mechanical automatic shaker during 5 min. Wet sieving was performed manually under water with similar oscillations/minute during the same period of time. MWD_w and MWD_d were determined using the following equation,

$$MWD_{(\mathrm{d,w})} = \sum_{i=1}^{n} x_i f_i$$

Where x_i is the mean diameter of each size fraction, and f_i is the corresponding fraction of oven-dried to retained soil. The same equation was used to determine the MWD_d. Infiltration rate was determined in field conditions using the double ring technique (Bouwer, 1986).

3. Results and discussion

3.1. Rainfall

One hundred and twenty six total rainfall events were registered during the year 2006, accounting for a total rainfall amount of 774 mm, which was above the historical average of 480 mm reported by INEGI (1996) for the area of study. 53% of the total events had durations of 1 h or less and 75% of them were smaller than 10 mm. Thunderstorms with high intensities and short durations were commonly observed in the area, which is in agreement with the type of precipitation often found in drylands (Rango et al., 2006). The runoff monitoring period started in May and ended in October 2006, which corresponds to the normal rainy season in the area. Seventeen runoff-producing events, accounting for approximately 50% of total rainfall were evaluated. Characteristics of rainfall events producing runoff, and consequently erosion, can be observed in Table 1.

Average duration and depth of runoff-producing events was approximately 510 min and 20 mm, respectively. The large average duration of events was influenced by very long duration events, most of which had low-intensities. Maximum single event intensities varied from approximately 6.6 mm h^{-1} up to 52.5 mm h^{-1}.

The smallest precipitation event producing runoff had a rainfall depth of 8.7 mm and only produced runoff for the Control and *O. imbricata* plots. Maximum rainfall depth registered for an event causing runoff was 60.1 mm. Both values are similar in magnitude to the reported by Wainwright et al. (2002) in semiarid Southern New Mexico. Erosivity of runoff events varied from 45 up to 1770 MJ mm ha^{-1} h^{-1}, with an average of approximately 390 MJ mm ha^{-1} h^{-1}, indicating a high potential to produce runoff and erosion (Wei et al., 2007).

3.2. Erosion and runoff for different vegetation patches

Measured runoff and soil loss data from the vegetation patches are presented in the box plots of Fig. 3. Overall, *Opuntia sp*, *P. laevigata* and *A. farnesiana* produced significantly less runoff and erosion than *O.*

Table 1
Rainfall characteristics.

Event	Date	Rainfall depth (mm)	Duration (min)	I_{30} [a] (mm h^{-1})	R factor [b] (MJ mm ha^{-1} h^{-1})
1	May/18/2006	23.90	560	8.30	96.06
2	May/27/2006	26.80	240	21.40	371.96
3	May/29/2006	17.30	1300	17.20	167.56
4	July/02/2006	12.57	320	10.91	73.45
5	July/24/2006	44.82	660	13.12	320.15
6	July/25/2006	17.50	320	18.75	165.13
7	July/26/2006	10.70	140	7.20	35.91
8	Aug/05/2006	8.70	760	8.90	39.09
9	Aug/07/2006	19.60	460	29.50	425.21
10	Aug/26/2006	60.10	1040	28.50	1178.33
11	Aug/31/2006	17.70	40	35.20	532.64
12	Sept/14/2006	10.95	140	18.47	143.07
13	Sept/22/2006	15.02	580	11.86	89.84
14	Sept/25/2006	13.33	840	9.64	61.35
15	Oct/14/2006	11.30	460	6.20	30.31
16	Oct/15/2006	18.50	400	24.70	317.59
17	Oct/16/2006	19.00	400	29.70	429.42
Min		8.70	40.00	6.20	30.31
Max		60.10	1300.00	35.20	1178.33
Mean		20.46	509.41	16.87	263.36
Total		347.79			4477.07

[a] I_{30} = 30 min maximum rainfall intensity.
[b] R factor = erosivity factor, based on Foster et al. (1982).

imbricata and the Control. The maximum values of runoff were approximately 31.5, 28.0, 6.2, 6.1 and 0.8 mm for plots with the Control, *O. imbricata*, *P. laevigata*, *A. farnesiana* and *Opuntia sp*, respectively. Total runoff measured was 113.4, 93.9, 15.1, 14.3 and 2.4 mm, for the same plots. Maximum soil loss evaluated per event corresponded to equivalent values of 1453, 1573, 81, 160 and 21 kg ha^{-1}, while cumulative soil loss values were quantified in 3792, 3949, 130, 272 and 38 kg ha^{-1} for the Control, *O. imbricata*, *P. laevigata*, *A. farnesiana* and *Opuntia sp*, respectively.

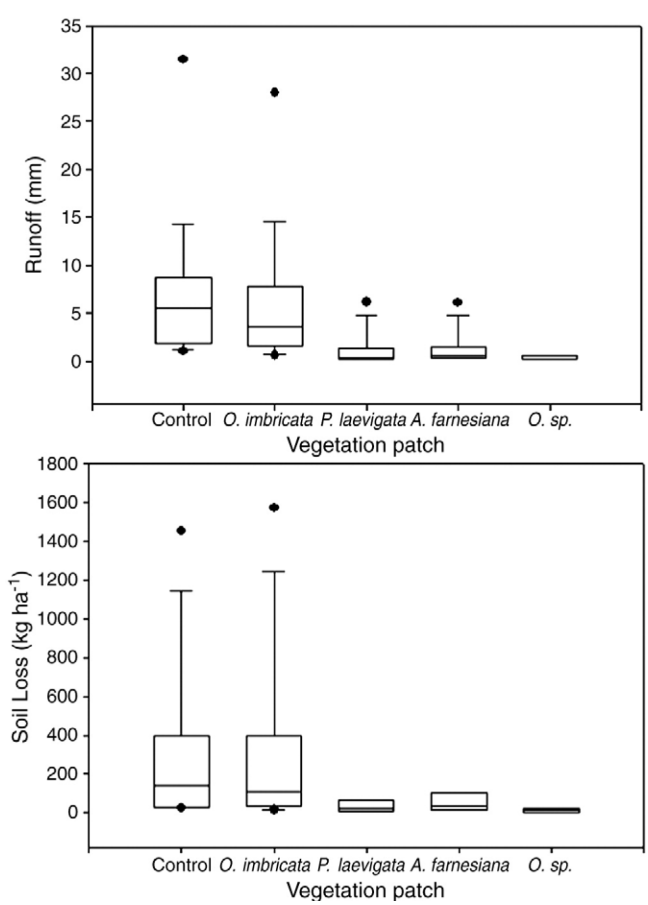

Fig. 3. Box plots for Runoff (top) and Soil Loss (bottom) under different vegetation patches.

Vegetation has a strong effect on surface runoff (Chen et al., 2007) even under conditions considered marginal. The plots of *P. laevigata*, *A. farnesiana* and *Opuntia sp* reduced runoff by 87, 87 and 98 %, respectively, as compared to the Control surface. The plot of *O. imbricata* responded similar to the Control plot.

It was observed that an increase in rainfall did not produce an increment in runoff for the patches of *Opuntia sp*. The aerial structure of this dryland species intercepts a significant amount of rainfall, which is subsequently translocated as steam flow to the soil, increasing infiltration and diminishing the potential for runoff and erosion (Puigdefábregas, 2005). In addition, it has been reported that *Opuntia*'s root system has the ability of making a quick and significant absorption of rainwater (Nobel, 1987), then reducing the amount available for runoff. Also, immediately after the first rain events, understory vegetation grows fast under Opuntia's canopy (Nobel, 1987), contributing furthermore in the protection against soil erosion.

Statistically, runoff values were similar among *P. laevigata*, *A. farnesiana* and *Opuntia sp*, and they differ from the Control and *O. imbricata*, which formed the second homogeneous group according to the Fisher's method to discriminate among means using the least significant difference (LSD) procedure ($\alpha = 0.05$).

Runoff coefficients estimated from the observed data were 0.33, 0.27, 0.04, 0.04 and 0.01 for the Control, *O. imbricata*, *P. laevigata*, *A. farnesiana* and *Opuntia sp*, respectively. The values of *P. laevigata* and *A. farnesiana* are similar to those reported by Rango et al. (2006) and Wei et al. (2007) for grassland and shrub in the Chihuahuan Desert and Loess Plateau, respectively. Nevertheless, values for bare surface and *O. imbricata* vegetation were higher than those reported by the same authors, but similar to the values for crusted soil surfaces reported by Neave and Rayburg (2007) in a semiarid area in New Mexico.

The relationship between runoff and rainfall for all studied species is shown in Fig. 4, where it can be clearly observed that there is a directly proportional effect of the amount of rain on runoff. The slope of the regression equation can be used as an indicator of the amount of runoff produced by rainfall and also as a parameter to interpret the effect of different types of vegetation or soil management on hydrological processes. The slopes of the linear regression equations were 0.46, 0.44, 0.09, 0.09 and 0.016 for the plots with the Control, *O. imbricata*, *P. laevigata* and *A. farnesiana*, and *Opuntia sp*, respectively (Table 2). Measured data supported the above estimates as the amount of runoff produced by event varied from 0.6 to 28.0 mm and from 1.0 to 31.5 mm for *O. imbricata* and the Control, respectively. The corresponding values for *P. laevigata*, *A. farnesiana*, and *Opuntia sp* varied only from 0 to 6.2 mm, 0 to 6.1, and from 0 to 0.8, respectively.

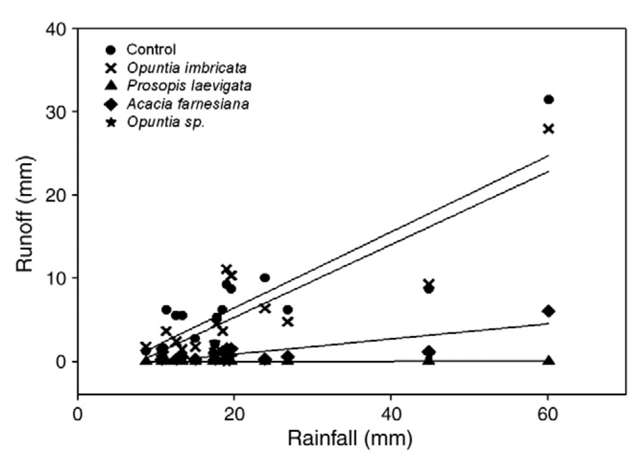

Fig. 4. Runoff–rainfall relationships for different vegetation patches during the rainy season of 2006 in semiarid Central Mexico.

Table 2
Linear regression equations relating runoff (mm) and rainfall (mm) under different patches of vegetation in semiarid Central Mexico.

Vegetation	Equation	r^2
Control	Rf = 0.456P–2.666	0.73
Opuntia imbricata	Rf = 0.437P–3.421	0.75
Prosopis laevigata	Rf = 0.093P–0.935	0.64
Acacia farnesiana	Rf = 0.091P–0.945	0.68
Opuntia sp	Rf = 0.016P–0.003	0.61

Rf = Runoff (mm), P = Rainfall (mm).

Soil erosion has long been recognized as a process closely related to the kinetic energy of rainfall in the form of the erosivity index, EI_{30} (Nyssen et al., 2005; Diodato and Bellocchi, 2007; Irvem et al., 2007; Capolongo et al., 2008). The relationship between soil loss and rainfall erosivity for the different types of vegetation can be observed in Fig. 5. Measured data indicated that low erosivity events (0 to about 300 MJ mm ha^{-1} h^{-1}) produced an average soil loss of 67 and 44 kg ha^{-1}, for the Control and *O. imbricata*, respectively; while no erosion was measured for *P. laevigata*, *A. farnesiana*, and *Opuntia sp*. On the other hand, high erosivity events (300 to about 1200 MJ mm ha^{-1} h^{-1}) yielded an average soil loss of 446 and 501 kg ha^{-1}, for the Control and *O. imbricata*, respectively; while values of only 19, 39 and 5 kg ha^{-1} of erosion were observed for *P. laevigata*, *A. farnesiana*, and *Opuntia sp*. These results indicate that fertility islands of *P. laevigata*, *A. farnesiana*, and *Opuntia sp*. were very effective in attenuating the erosive forces of the rain and runoff.

3.3. Vegetation cover

The morphological characteristics of studied vegetation are shown in Table 3. Ground cover percentage values for the plots with bare surface, *O. imbricata*, *A. farnesiana*, *P. laevigata* and *Opuntia sp* species were 0.6, 22.1, 35.3, 36.6 and 76.9%, respectively. The corresponding values for canopy cover were 0.0, 23.6, 60.0, 53.5 and 86.7%. These cover percentages are indicative of the degree of protection against soil erosion and the generation of runoff of the studied vegetation patches.

Previous results showed that there is significant difference in soil erosion and runoff among the different types of vegetation. *O. imbricata* and the Control were similar in response with greater values for both variables; while *P. laevigata*, *A. farnesiana* and *Opuntia sp* showed values significantly lower. The differences are related to the ground and canopy coverage. Runoff dependency on canopy and ground covers is shown in Fig. 6. There was an inverse relationship between the two variables (r^2 = 0.91), indicating an increase in runoff for vegetation patches with less canopy cover. This result is indicative of the importance of canopy cover in regulating runoff processes, as observed by other authors in similar conditions (Wainwright et al.,

Table 3
Characteristics of the vegetation patches studied.

		Vpa (m^2)	Th (m)	Trh (m)	CC (%)	GC (%)
	*Opuntia imbricata*	13.00	0.67	0.20	23.60	22.10
	*Prosopis laevigata*	9.00	2.05	0.69	60.00	35.30
	*Acacia farnesiana*	8.00	2.57	0.86	53.50	36.60
	*Opuntia sp*	9.00	3.08	0.45	86.70	76.90

Vpa = Vegetation patch area; Th = Total height; Trh = Trunk height; CC = Canopy cover and GC = Ground cover.

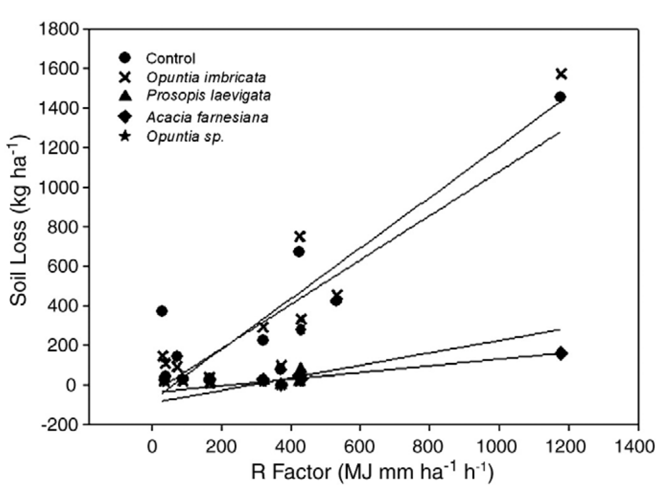

Fig. 5. Soil loss–rainfall erosivity relationships for different vegetation patches during the rainy season of 2006 in semiarid Central Mexico.

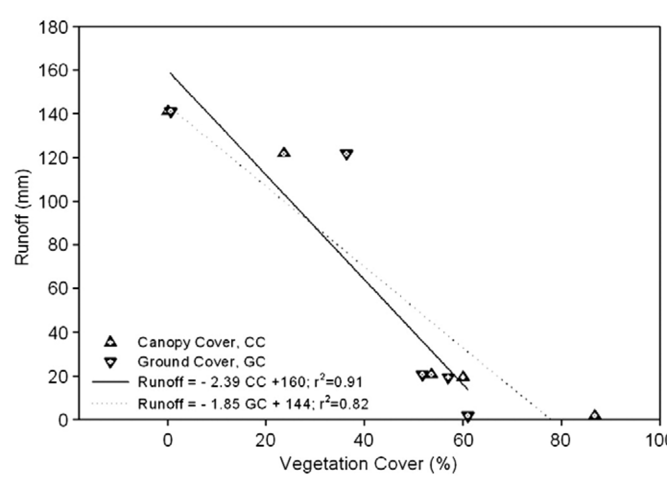

Fig. 6. Overall effect of vegetation coverage on runoff as evaluated in USLE-type plots in semiarid Central Mexico.

2002; Bautista et al., 2007). The results for the ground cover showed a similar tendency ($r^2=0.82$).

Soil loss was also lower for greater canopy and ground cover conditions, as observed in Fig. 7. According to the linear relationship found, soil loss decreased in approximately 55 kg ha^{-1} per unit percent of canopy cover. The results imply that the vegetation with greater aerial coverage better protected the soil against erosive forces of rainfall.

Ground vegetation seems to be established as a function of higher vegetation characteristics and morphology (Rango et al., 2006). *P. laevigata*, *A. farnesiana* and *Opuntia sp* had nearly 60% ground cover by understory vegetation, further contributing to reduce soil loss, as observed in Fig. 7.

Overall, a greater canopy and ground vegetation covers in vegetation patches reduced runoff and soil loss. Canopy and ground covers are responsible for rainfall interception and the decrease of raindrop impact energy, while ground cover promotes rainfall infiltration into the soil and reduces overland flow velocities and hydraulic shear stresses, thus diminishing the soil erosion potential (Erpul et al., 2002; Regüés and Torri, 2002).

The above results were supported by the USLE-C factor values, obtained using measured data and the procedures outlined by Wischmeier and Smith (1978), for all vegetation patches. The *C* values for *O. imbricata*, *A. farnesiana*, *P. laevigata* and *Opuntia sp*., were 0.643, 0.036, 0.035 and 0.009, respectively, indicating a significant reduction of the vegetation patches as compared to bare surface condition. These values are very close to those reported in other environments by Irvem et al. (2007) and Beskow et al. (2009) and are indicative of the importance of the vegetation patches in the hydrological functioning of an environment.

3.4. Soil properties

Measured values for the selected soil properties under the vegetation patches are shown in Table 4 for two depths, 0–15 cm and 15–30 cm. In general, the most significant differences among vegetation types were found on the upper 0 to 15 cm.

Organic matter content for *A. farnesiana*, *P. laevigata*, and *Opuntia s* was greater than for the Control and *O. imbricata* for both, 0–15 cm and 15–20 cm, depths. The differences however, were greater for the top layer than the bottom one. Average values of soil bulk density in the top 15 cm for the Control, *Opuntia imbricata*, *A. farnesiana*, *P. laevigata* and *Opuntia sp* were 1.24, 1.14, 1.12, 1.10 and 1.10 g cm^{-3}, respectively. In general, soil bulk density was greater for vegetation patches with no or little vegetative cover and decreased for patches with greater canopy and ground cover. Addition of organic matter to the soil improves soil structure and enhances porosity, which in turns

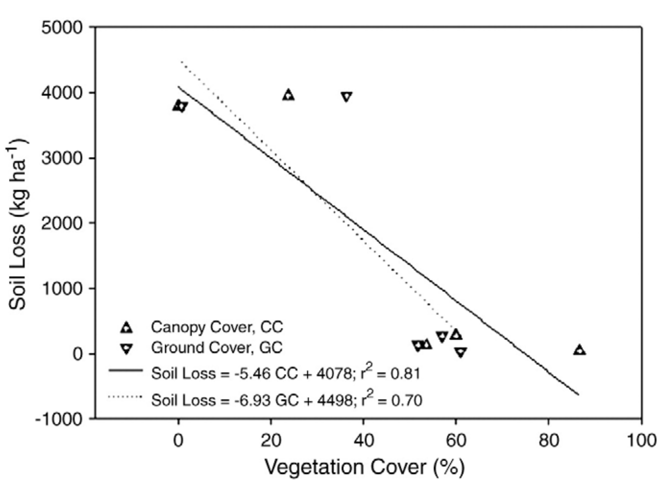

Fig. 7. Overall effect of vegetation coverage on runoff as evaluated in USLE-type plot in semiarid Central Mexico.

Table 4
Characteristics of the selected soil properties under different vegetative patches in semiarid Central Mexico.

Vegetation cover	Depth (cm)	OM (%)	BD (g cm^{-3})	MWD_d (mm)	MWD_w (mm)	IAS (mm mm^{-1})	SSI (mm h^{-1})
Control	0–15	1.07	1.24	1.23	0.28	0.22	5.23
	15–30	1.38	1.22	1.72	0.24	0.14	–
Opuntia	0–15	1.51	1.14	2.19	0.68	0.31	5.82
imbricata	15–30	1.35	1.18	1.86	0.87	0.49	–
Prosopis	0–15	2.17	1.12	3.47	1.39	0.46	8.21
laevigata	15–30	1.82	1.21	2.74	1.08	0.41	–
Acacia	0–15	2.23	1.10	3.02	1.11	0.45	11.04
farnesiana	15–30	1.97	1.18	2.62	1.08	0.41	–
Opuntia sp	0–15	1.66	1.10	7.13	2.98	0.42	21.60
	15–30	1.48	1.15	6.00	2.04	0.33	–

OM = Organic matter; BD = Bulk density; MWD_d = Dry mean weight diameter; MWD_w = Wet mean weight diameter; IAS = Index of aggregate stability and SSI = Steady state infiltration.

decreases soil density and compaction (Neary et al., 2009). Bulk density, however, was not statistically different among the vegetation patches at the depth of 15–30 cm, indicating that under semiarid conditions the effect of vegetation on soil properties may be limited to the upper layers.

Aggregate size distribution and stability were also affected by vegetation conditions, but only significantly at the 0–15 cm depth. The Index of Aggregate Stability (IAS) values, as determined by the ratio between the wet mean weight diameter and the dry mean weight, were significantly greater for *P. laevigata*, *A. farnesiana*, and *Opuntia sp* than those for the Control and *O. imbricata* conditions. A high correlation between IAS and organic matter ($r^2=0.934$) was found, indicating the importance of vegetation on the development and stability of soil structure. Mean weight diameter in natural environments has been found to be different between bare and vegetated patches (Lesschen et al., 2008), which is in agreement with the results obtained in this study.

Steady state infiltration at 2 h of initiating the double ring infiltrometer test, as estimated by the model proposed by Kostiakov–Lewis (Kostiakov, 1932), was greater for *P. laevigata*, *A. farnesiana* and *Opuntia sp* (8.21, 11.04 y 21.60 mm h^{-1}, respectively) than for the Control and *O. imbricata* (5.23 and 5.82 mm h^{-1}, respectively). Rainfall infiltration relates inversely to runoff. The results here obtained are proof of the positive effect of the vegetation patches of *P. laevigata*, *A. farnesiana* and *Opuntia sp* on increasing infiltration and thus, reducing runoff and the potential of soil erosion.

Soil loss and runoff were closely related to the measured soil properties in the vegetation patches studied, as observed in Fig. 8. For the data shown in the scatter plots, the correlation coefficient (r) between runoff and organic matter was 0.925, while the corresponding value for soil loss was 0.866. Significant correlations were also observed for the same hydrological processes and bulk density ($r=0.846$ for runoff and $r=0.764$ for soil loss), index of aggregate stability ($r=0.923$ for runoff and $r=0.910$ for soil loss) and steady state infiltration ($r=0.743$ for runoff and $r=0.681$ for soil loss).

All the results obtained, clearly demonstrate that vegetation patches of *P. laevigata*, *A. farnesiana* and *Opuntia sp* create fertility islands where soil organic matter contents are greater, bulk densities are lower, and consequently, the stability of aggregates and water intake increases, reducing the amount of runoff and soil erosion, thus enhancing the hydrological functioning of semiarid ecosystems. Isolated *O. imbricata* species do not reduce significantly soil erosion and runoff on semiarid areas, as compare to bare conditions, and neither have a positive impact on soil properties. The changes in soil surface conditions are related in this study to a greater contribution of organic matter by the leaves and roots of both annual and perennial species developed in the vegetation patches (Goebel et al., 2005; Hopmans, 2006; Neary et al., 2009).

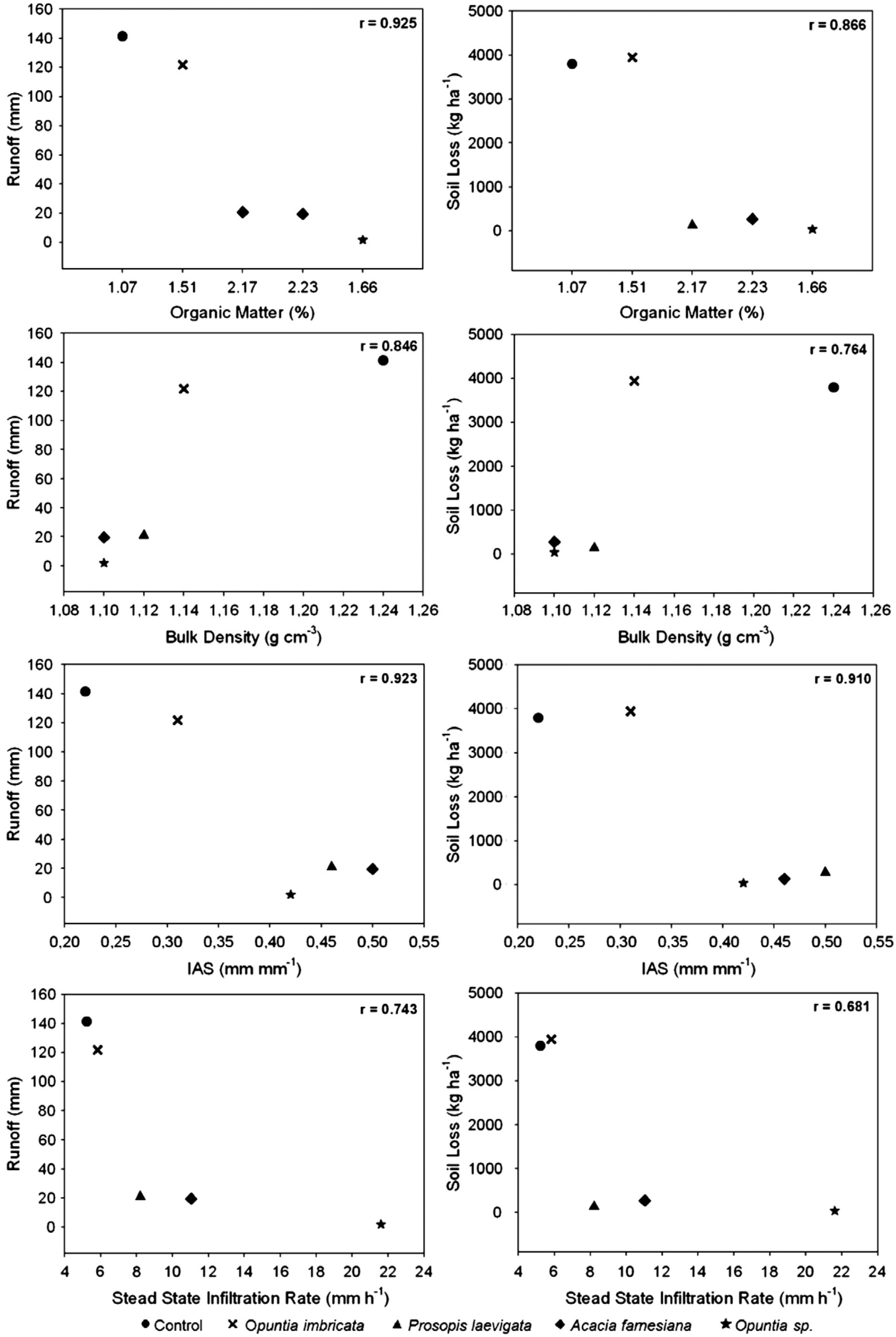

Fig. 8. Runoff and soil loss vs soil properties under different vegetation patches in semiarid Central Mexico.

4. Conclusions

Greater canopy and ground vegetation covers in vegetation patches of semiarid areas in Central Mexico reduced significantly runoff and soil loss as compared to the Control surface. Runoff was decreased by 87%, 87% and 98% by the *A. farnesiana*, *P. laevigata* and *Opuntia sp*, respectively, as compared to the Control surface condition. The corresponding decrease for soil loss was 97%, 93% and 99%, respectively. Soil surface physical properties were improved under *A. farnesiana*, *P. laevigata* and *Opuntia sp* patches as compared to the conditions in low or no vegetation cover (*O. imbricata* and Control). The species with more canopy and ground cover created fertility islands where soil organic matter contents were greater, bulk densities were lower, and consequently, the stability of aggregates and water intake increased. A close relationship was found between soil properties and the surface hydrological processes of soil erosion and runoff, enhancing the hydrological functioning of these semiarid ecosystems.

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