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Soil Erosion Processes in Semiarid Areas: The Importance of Native Vegetation

Rebeca Vásquez-Méndez¹, Eusebio Ventura-Ramos¹,
Klavdia Oleschko², Luis Hernández-Sandoval¹
and Miguel Angel Domínguez-Cortázar¹

¹University of Queretaro (UAQ)

²Universidad Nacional Autónoma de México (UNAM)
México

1. Introduction

Arid and semiarid zones cover approximately 40% of the land surface, with a continuous increase in the area by desertification processes, induced mainly by anthropogenic activities and/or climatic change (IPCC, 2008). The process of desertification affects the world at ecological, economic and social levels (Salih, 1998).

Maestre et al. (2006) considers that desertification produces biophysics and socioeconomics consequences, with the later including household debt increasing, loss of traditional knowledge and local traditions, people migration, reduction of food production, costs of living increases, poor supplies in quality and quantity, increase in poverty, and political instability (Sivakumar, 2007). The UNCCD (2004), considers that over 250 000 million of people are directly affected by desertification, mostly in regions with significant poverty and marginalization in the world. In the case of Mexico, experts estimate that each year, between 700 000 and 900 000 people are forced to leave Mexico's rural dry land areas in search of better livelihood in urban areas, including foreign countries.

On the other hand, biophysics consequences involve the loss of soil and vegetation cover, reduction in soil fertility and biodiversity, reduction in rainfall infiltration rates, and modification of local climate (Maestre et al., 2006). Soils of arid and semiarid zones are very susceptible of water erosion (Cornelis, 2006) mostly due to the scarce vegetation cover, low organic matter content and the small resistance to the erosion forces. The magnitude of water erosion also depends on their texture, water content, evaporation, percolation and lixiviation. These soil characteristics are not favorable to the resistance of the soil to water erosion (D'Odorico & Porporato, 2006). In terms of soil orders, typical arid and semiarid zone soils around the world include Aridosol, Alfisols, Entisols, Molisols, and Vertisols (Dregne, 1976).

In arid and semiarid areas, soils with little or no vegetation cover are exposed to torrential precipitation events, which are characterized by short durations and high intensities, and are prompt to the occurrence of physical and chemical processes that change the surface layer conditions, such as surface sealing and crusting. When the surface is dry, a hard layer is formed (crust). Crusting soils are typical of these dry areas, where soil degradation is

induced soils by diminishing infiltration rates and increasing runoff and erosion rates (Ries & Hirt, 2008).

Arid and semiarid areas are considered fragile environments where vegetation cover is scarce and where soil erosion processes occur rapidly and severely after rainfall events fall in these areas. However, even under those conditions, the importance of native vegetation is very significant in the regulation of surface hydrological processes.

The objective of this chapter is to discuss through a study case from a semiarid area in Querétaro, Mexico, the importance of native vegetation on the regulation of soil erosion processes. An extensive work on the quantification of vegetation changes in space and time (Chen et al., 2006; Moro et al., 2007) has been done for arid and semiarid areas. However, only few efforts have been directed towards a better understanding of the hydrological functioning and the native vegetation-soil relationships (Huxman et al., 2004, Bautista et al., 2007; Vásquez-Méndez et al., 2010) compared with other environmental variables.

2. Precipitation

Precipitation is, without doubt, the most important component of the land-atmospheric system accountable for shaping the climatic state and variability of water in the soil and atmosphere (Wang et al., 2006). Precipitation is a major factor controlling the hydrological cycle of a region and, thereby, also the ecological and geomorphologic processes. This meteorological phenomenon has many characteristics, and the relative amount of rain and snow, their seasonal timing, and the volumes and intensities of rainfall events affect ecological developments and water management activities (Jong & Jetten, 2007).

Prediction of mean annual values is useful in areas where annual rainfall tends to follow a normal probability distribution (Figure 1). In arid and semiarid zones, annual rainfall distributions typically show a pronounced skew and correspond better to lognormal, extreme value or Pearson Type III probability density functions. In contrast to temperate regions, semiarid ecosystems are also more impacted by extreme events, such as severe storms, floods and droughts (Mannaerts & Gabriels, 2000).

In semiarid zones, the distribution of precipitation through the year is not uniform, and usually they are intermittent. In particular, in arid and hiperarid areas, it is possible that in some years precipitation does not occur at all (Salas, 2000). In general, the precipitation in these areas is characterized by torrential events, occurring in short time spans and at high rainfall intensities (Rango et al., 2006; Wei et al., 2007). It has been observed that the precipitation pulses promote biological activities in plants, soil and the ecosystems as a whole. Furthermore, these events are important drivers for soil physical processes (Huxman et al., 2004; Dekker et al., 2007). However, the influence of rainfall characteristics on the vegetation-soil relationship has been poor studied compared with other environmental variables (Huxman et al., 2004).

Rainfall precipitation is high variable in semiarid areas. Events in the semiarid area of Cadereyta, Querétaro, Mexico, for a 3 years period of registration showed that rainfall depth varied from 1 to 74 mm. The time span of occurrence varied from 5 minutes to 2 days. Also, 60% to rainfall events have a rainfall depth smaller than 5 mm (Figure 1). This percentage increased to 75% when considering events smaller than 10 mm. On average, only 10 rainfall events greater than 20 mm occurred per year, with a low probability of occurrence but with high potential consequences due to their erosivity (Figure 2).

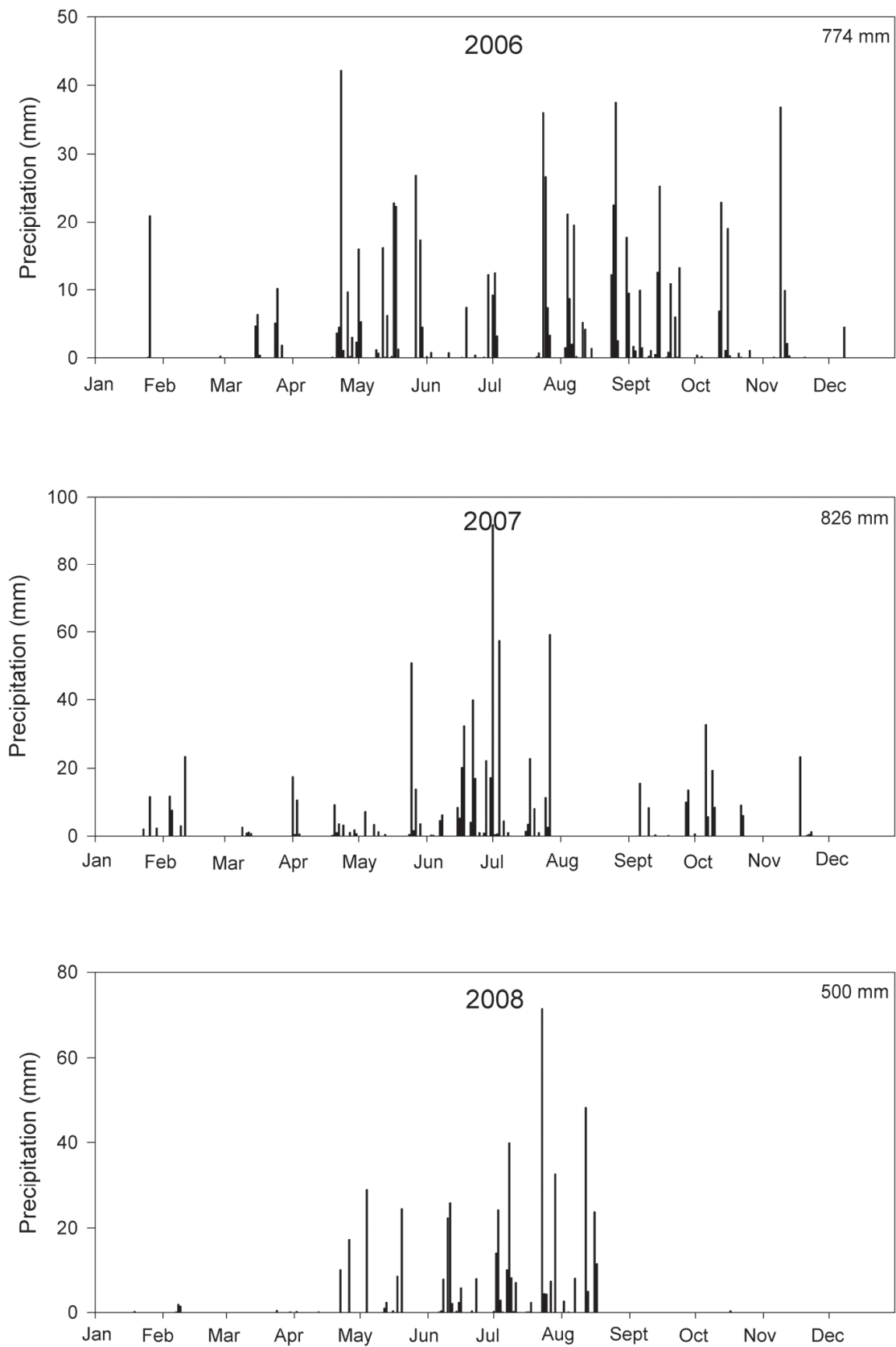


Fig. 1. Histogram distribution by year, with different characteristics in amount of year in Cadereyta de Montes, Queretaro, Mexico.

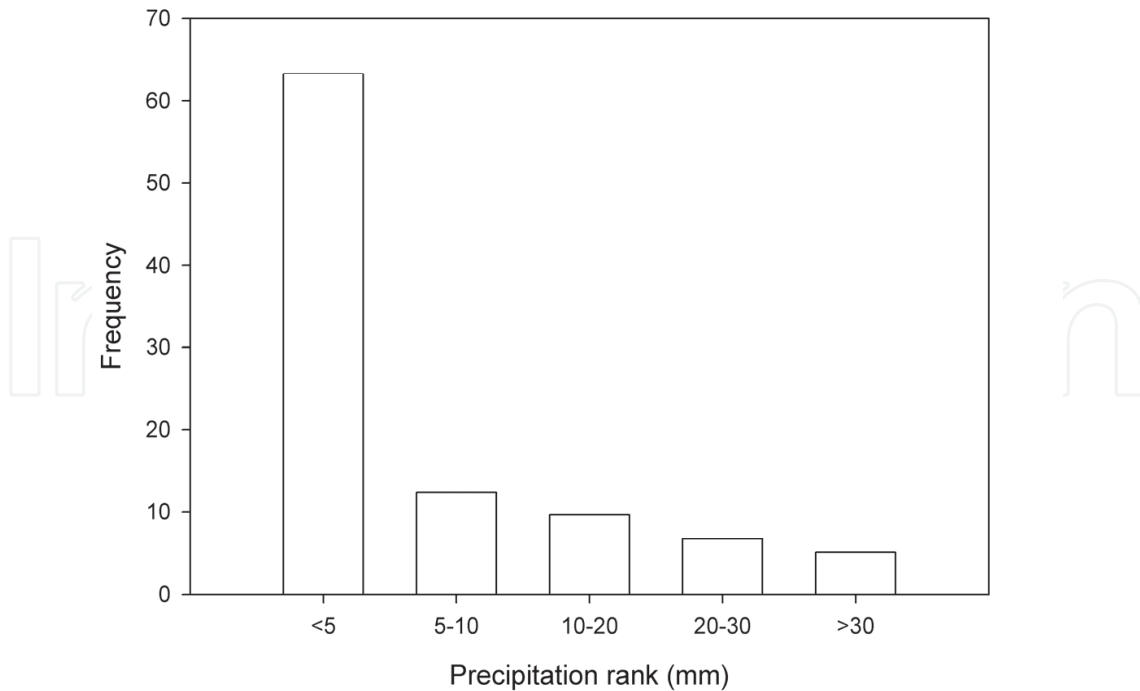


Fig. 2. Precipitation histogram for the years 2006, 2007 and 2008 at Cadereyta, Queretaro, Mexico.

One of the main factors related to the erosion potential of rain is the rainfall frequency and different magnitudes of events in combination with the soil geomorphic thresholds (Bisigato et al., 2009). High intensities of rainfall are the main factor driving the runoff processes (Renard et al., 1974).

Mean, maximum and maximum intensity in 30 minutes are shown in Figure 3 for the Cadereyta area. Overall, the values of intensities varied from 0.71 to 88.2 mm h⁻¹. Maximum

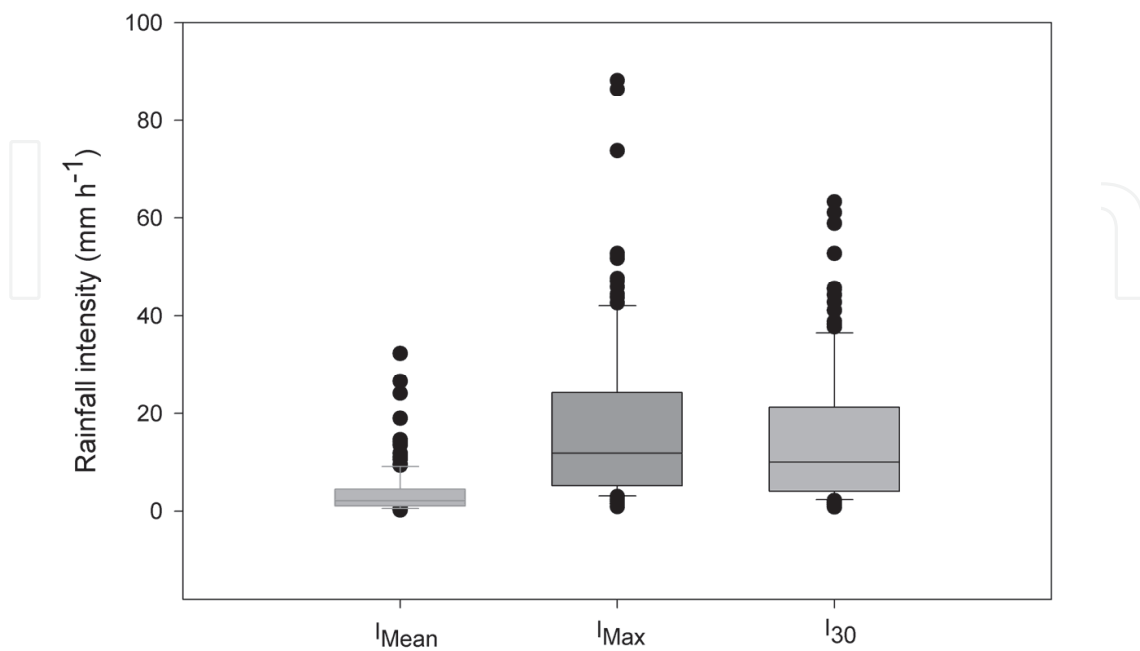


Fig. 3. Box plot of rainfall intensity by events measured in the semiarid of Mexico.

rainfall intensity in semiarid areas is comparable with the intensities from tropical climates (Hoyos et al., 2005). EI30 is an important parameter for compute erosivity of a rainfall event. The mean value of I30 was 15 mm h⁻¹, while maxim values were from 40 to 60 mm h⁻¹, typical values registered in this arid and semiarid areas (Hussein et al., 1994; Wei et al., 2007; Stone et al., 2008).

3. Vegetation

Vegetation patterns in arid and semiarid ecosystems are characterized by the size and spatial distribution of the higher plant-cover patches. These patches have its main distribution in spots or bands distributed as a mosaic (Aguiar & Sala, 1999). The spots are generally isodiametric or with irregular circular shapes, and the bands range from 1 to less than 100 m (Aguiar & Sala, 1999). Investigators have documented the presence of “islands of fertility” or “resource islands” in arid and semiarid ecosystems at individual plant scale (Moro et al., 1997; Aguiar & Salas 1999; Facelli & Temby, 2002; Rango et al., 2006).

These areas can also be considered as hydrologic islands, and they are observed at the individual plant scale as well as in large area patterns of banded vegetation, where playettes and beaded drainage networks run-on and water infiltration stimulates vegetation growth (Rango et al., 2006).

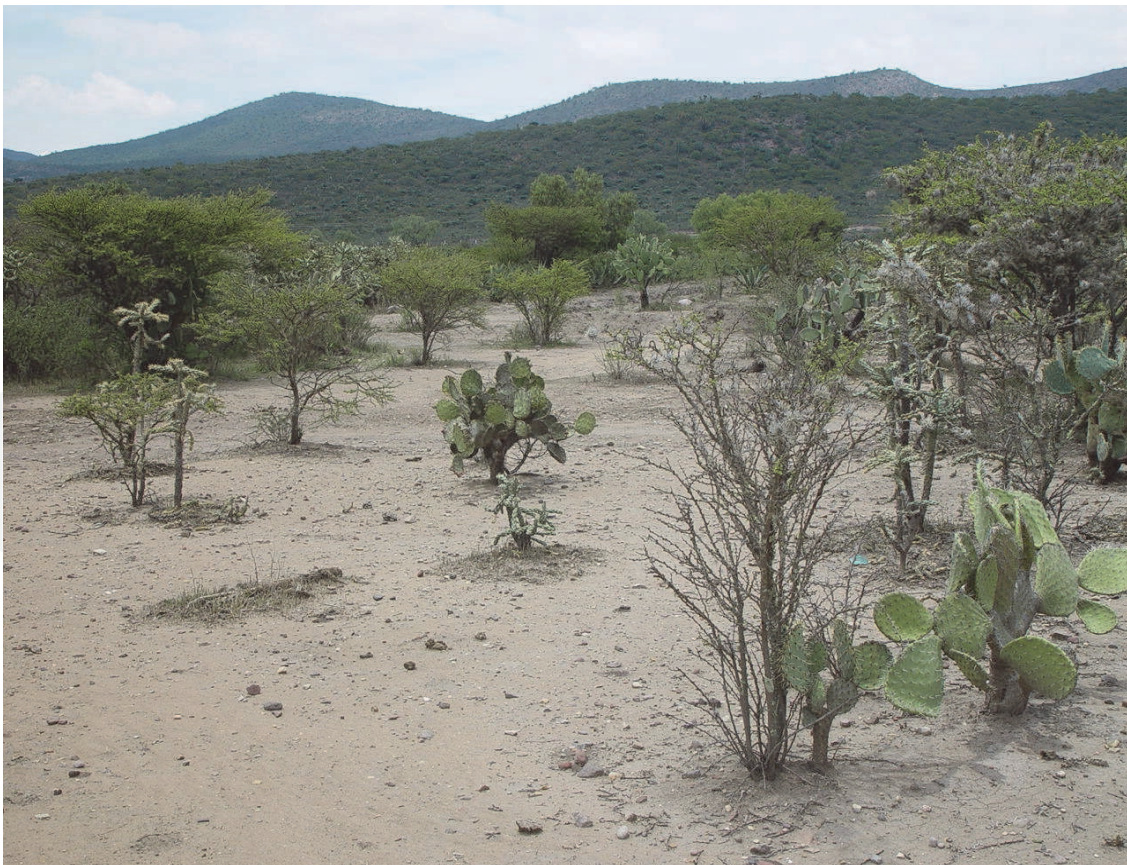


Fig. 4. Typical distribution of native vegetation in a semiarid environment of Central Mexico.

Water availability it is a limiting factor in the productivity of arid and semiarid ecosystems. Plants use the necessary water for their metabolic processes. Studies such as those of Fowler (1986) and Nobel (1990) have demonstrated that the species of arid and semiarid regions are characterized by several different patterns of roots distribution. Perennials root zones are wider and deeper than those of annuals. As a matter of fact, phreatophytes are often very deeprooted.

Simpson & Solbring (1977) recognize three major methods of native plant strategies:

- Specialized photosynthesis (Crassulacean Acid Metabolism or CAM), which leads the plant to open their stomas during the night when temperatures are low and the loss of water by transpiration can be reduced.
- Xerophytic life forms, which allow plants to resist extremely, negative potentials. This group of plants is characterized by small leaves with thick epidermis, sunken stomata, and extensive root networks.
- Phreatophyte condition, present in plants from arid regions, induces them to take water from almost unattainable zones at very deep phreatic levels.

The association of annual plants with woody shrubs has been recognized as to have higher organic soil contents, to trap windblown seeds and to protect the seeds or seedlings from predation (Fowler, 1986).

The general vegetation distribution is controlled by precipitation, and at the same time, distribution and amount of precipitation affects the development and distribution of vegetation, which also modifies the atmospheric energy and the storage of water (Xue, 2006; Dekker et al., 2007). Under some circumstances herbaceous layer productivity is lower under tree canopies than in nearby open grasslands, whereas in other instances grassland productivity is higher under tree canopies (Belsky et al., 1989). Studies suggest that tree canopies may improve the water - status of understory species. Native species such as *Prosopis laevigata*, *Acacia farnesiana*, *Opuntia* sp., and even for *Opuntia imbricate*, contribute to the development of surface vegetation. The combination of canopy cover and the greatest development of surface vegetation in the rainfall period, when soils are more susceptible to soil erosion, diminish the erosive effect of precipitation at the highest intensities. Therefore some trees of semiarid environments like adult *Acacias* are considered as nurse plants for understory native species (Yang et al., 2009).

Figure 5 shows the dynamics of vegetation leaf area index (LAI) for four species and their understory. It is clearly observed that once precipitation falls in those areas, ground cover increases significantly. However, canopy cover of *Opuntia imbricate* and *Opuntia* sp. does not increased significant in comparison with *Acacia* and *Prosopis*, because the morphology of its rackets.

Some morphometric characteristic of the four main types of vegetation patches in semiarid Cadereyta, are listed in Table 1.

Currently, trees in semi-arid regions are viewed as having the potential to increase crop productivity (agroforestry), to increase the forage production, to improve soil fertility and to reverse or at least stop desertification (Beslky et al., 1989).

On the other hand, plants of *Prosopis* and *Acacia* possess nitrogen-fixing bacteria in their root systems that accumulate nitrogen under the canopy soils. These trees tend to propagate in overgrazing soils (Tapia-Pastrana et al., 1999) and become free of grass competition (Mooney et al., 1977). These trees can be optimal for reforestation and for sustainable use in arid and semiarid zones (El-Keblawy & Ksiksi, 2005; Deans et al., 2003; Álvarez-Yépiz et al., 2008).

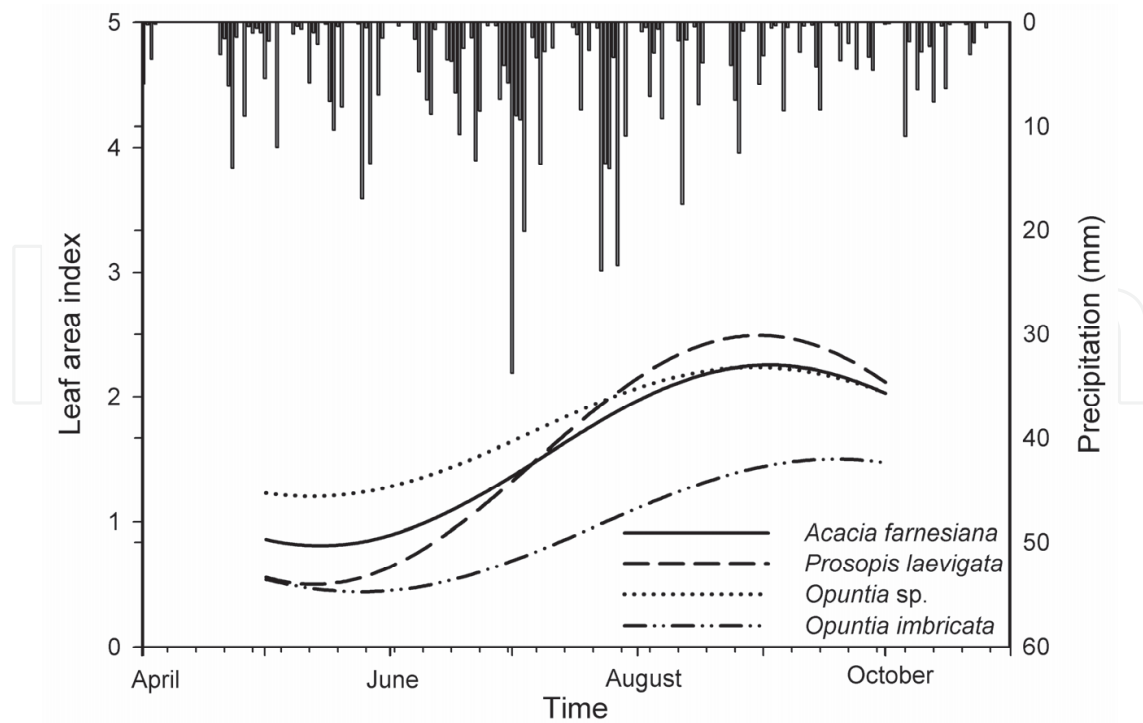


Fig. 5. Canopy and surface LAI dynamics in native plants at a semiarid environment during the rainfall season in Cadereyta, Queretaro, Mexico.





	<i>Opuntia imbricata</i>	<i>Prosopis laevigata</i>	<i>Acacia farnesiana</i>	<i>Opuntia sp</i>
				
Plot Area (m ²)	13.00	9.00	8.00	9.00
Total Height (m)	0.67	2.05	2.57	3.08
Trunk height (m)	0.20	0.69	0.86	0.45
Canopy cover (%)	23.60	60.00	53.50	86.70
Ground cover (%)	22.10	35.30	36.60	76.90

Table 1. Characteristics of the vegetation patches studied (Vásquez-Méndez et al., 2010).

4. Rainfall-runoff relationships

The relationships between rainfall and runoff processes that result in erosion at a given location are generally complex (Bedford & Small, 2008). Prediction of runoff and soil loss is important for assessing soil erosion hazard and for determining suitable land uses and soil conservation measures for a catchment (Bedford & Small, 2008). Soil erosion by water occurs as a result of the detachment of soil particles by raindrops and runoff (Kim & Gilley, 2008). The most known and widely used parameter to predict the erosive potential of raindrop impact and to reflect the amount and rate of runoff generated by erosive storms is the rainfall erosion index, also known as rainfall erosivity or R-Factor of the Universal Soil Loss Equation or USLE (Wischmeier & Smith, 1978).

The smaller amount of rainfall in semi-arid areas compared with that in humid climates does not mean a corresponding low level of soil erosion by water. Indeed rainfall erosion can be higher in semi-arid areas than in any other climatic zone. This is also because there is poor protective vegetative cover, especially at the beginning of the rainy season. Some of the soils common in semi-arid areas are particularly vulnerable, either because they have poor resistance to erosion or because of their chemical and physical properties (Schlesinger & Pilmanis, 1998).

Spatial patterns of soil properties are linked to patchy vegetation in arid and semi-arid landscapes. The patterns of soil properties are generally assumed to be associated to the ecohydrological functioning of patchy dryland vegetation ecosystems (Bedford & Small, 2008). Researchers, such as Ares et al. (2003) and Bautista et al. (2007), have found an inverse relationship between water runoff and the scale of heterogeneity of a vegetation mosaic. They have suggested that the landscape scale characteristics, such as topography, constrain the plant spatial pattern at finer scales. More runoff is produced as the vegetation cover is more disperse or bare areas increase, since their soils are susceptible to develop physical and biological crusts (Rango et al., 2006).

Amount of runoff per event in four native species and a control (bare surface), as evaluated in USLE-type plots is presented in Figure 6. Runoff decreases considerable when a greater vegetation cover is present. Bare or nearly bared surfaces always produced greater amounts of runoff.

In a more specific analysis (Figure 7), an inverse relationship between runoff and leaf area index, both canopy and ground, was found for the studied species and their fertility island. The results demonstrate the positive effect of native vegetation by diminishing the runoff processes in a considerable way.

The contribution of different layers of vegetation (canopy, understory, and lower vegetation), is significant, by diminishing the kinetic energy of rainfall against soil and intercepting precipitation, promoting infiltration. Runoff decreased from 87 to 98% from the total rainfall amount due to canopy cover (Vásquez-Méndez et al., 2010).

Sealing soils occur when soil surface is unprotected against precipitation effects and wetting and drying occurs quickly. Rainfall impacts consolidation the surface, resulting in pressure and erosion by splash of soil particles (Ries & Hirt, 2008). The consequences of sealing and crusting soil are the reduction in hydraulic conductivity, increased in horizontal flow (runoff), the inability of soil gas exchange (Li et al., 2005; Ries & Hirt, 2008). When these conditions exist, depending on the vegetation cover area, runoff coefficients fluctuate from 8 to 60% (Al-Qurashi et al., 2008), and total runoff can increased up to 80 and 90% in sealed soils (Ries & Hirt, 2008, Vásquez-Méndez et al., 2010). Bare surfaces decrease infiltration, for sealing soils (Ruan et al., 2001; Chen et al., 2008).

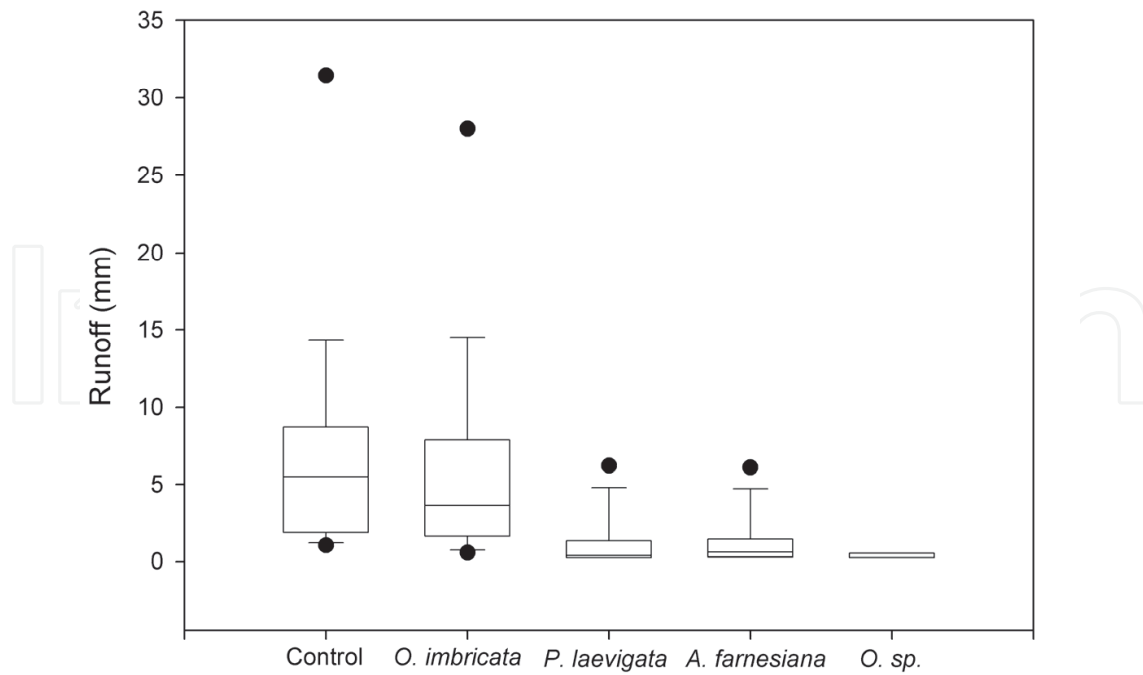


Fig. 6. Box plot of runoff by native vegetation in a semiarid environment of Central Mexico (Vásquez-Méndez et al., 2010).

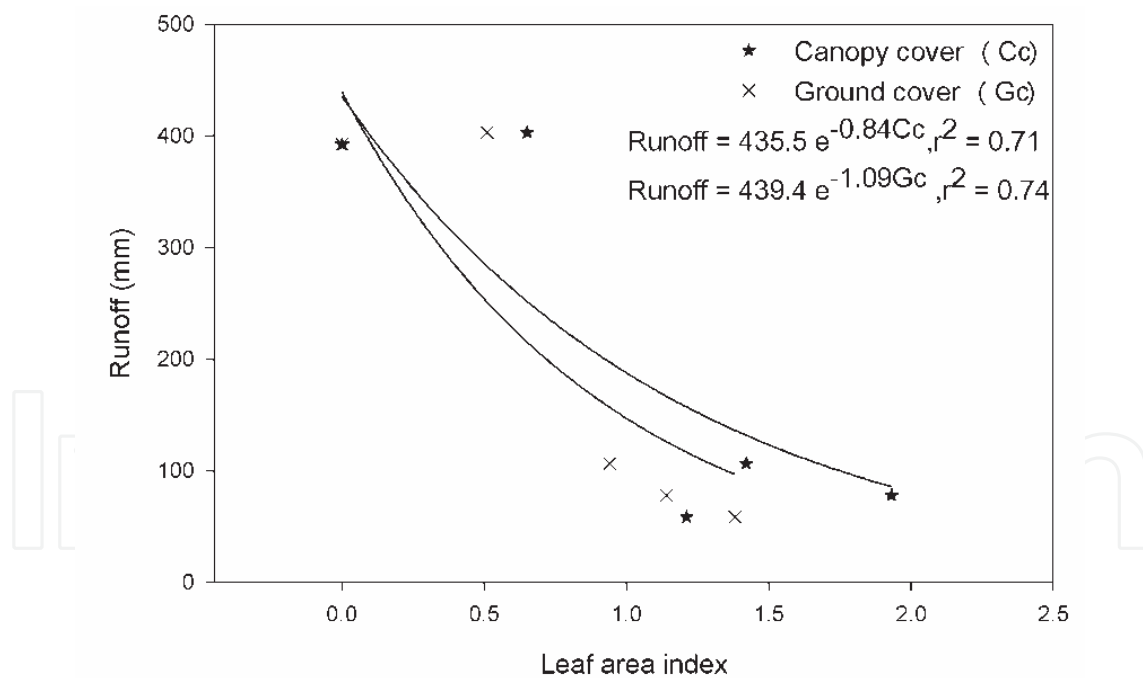


Fig. 7. Typical behavior between runoff and leaf area index of native vegetation in a semiarid environment of Central Mexico.

5. Soil erosion

Erosion, the detachment of particles of soil and surficial sediments and rocks, occurs by hydrological (fluvial) processes of sheet erosion, rill and gully erosion, and through mass

wasting and the action of wind. Erosion, both fluvial and eolian (wind) is generally greatest in arid and semi-arid regions, where soil is poorly developed and vegetation provides relatively little protection. Where land use causes soil disturbance, erosion may increase greatly above natural rates.

Soil erosion, continues to be a primary cause of soil degradation throughout the world, and has become an issue of significant and severe societal and environmental concern (Wei et al., 2007). About 80% of the world's agricultural land suffers moderate to severe erosion, and 10% suffers slight to moderate erosion (Pimentel et al., 1995). Erosion by water and wind adversely affects soil quality and productivity by reducing infiltration rates, water-holding capacity, nutrients, infiltration rates, water-holding capacity, organic matter, soil biota and soil depth.

The removal of vegetation is the main cause of soil degradation in semiarid areas (Castillo et al., 1997). Changes in soil properties induced by vegetation removal modified the runoff and soil erosion response in a semiarid area of Spain. Total runoff was significantly greater when vegetation was removed (48.8 mm) as compared to undisturbed conditions (34.9 mm). Runoff ratios between the disturbed and natural plots increased with time from 1.4:1 in 1990 to 2.5:1 in 1993. Vegetation removal increased the soil losses by 127% compared the undisturbed conditions. The annual soil loss ratio between the disturbed and natural plots increased from 1.6:1 in 1989 to 4.2:1 in 1993. The observed increase in surface runoff and soil loss was attributed to a progressive deterioration of soil physical properties. Bulk density increased by 8.4% (from 1.55 to 1.68 Mg m⁻³), total organic carbon was reduced from 4.0 to 2.6% and the percentage of stable aggregates decreased from 81.6 to 56.3% in the disturbed area. There was no evidence of vegetation recovery, suggesting that reduced vegetal cover might lead to irreversible soil degradation in semiarid areas.

The relationship between erosion and vegetation cover have been shown from various researchers (Stocking & Elwell, 1976; Evans, 1980) that erosion declines exponentially as vegetation in cover increases. One particularly important interaction is how, during rainstorms, patches of vegetation serve as surface obstructions that slow and trap runoff, sediments, and nutrients from open interpatch areas (Schlesinger et al. 2000) due to their sufficient stem and biomass densities.

Soil loss from vegetation patches of *P. laevigata*, *A. farnesiana* and *O. sp.*, was significantly smaller as compare to a bare surface area and an area with *O. imbricata*, with low vegetation cover.

The maximum values of soil loss were 1275, 1366, 120, 130 and 21 kg ha⁻¹, while the soil loss cumulative correspond to values of 3520, 3913, 240, 177 and 38 kg ha⁻¹ for bare surface, *Opuntia imbricate*, *Prosopis laevigata*, *Acacia farnesiana* and *Opuntia sp.*, respectively (see Figure 8). Corresponding values of soil loss were 97%, 93% and 99% with respect to the bare surface of vegetal species of *Acacia farnesiana*, *Prosopis laevigata* and *Opuntia sp.*

6. Interception

Interception is defined in three different ways: i) Interception storage (L), is considered the amount of rainfall which is temporarily stored on the land and evaporated shortly after and during the rainfall event. ii) Interception flux is considered the amount of intercepted water, which is evaporated in a certain time (LT⁻¹). iii) Interception process (I) (LT⁻¹) is considered as the part of the rainfall flux which is intercepted on the wetted surface after which it is fed back to the atmosphere. The interception process is equals to the sum of the change of interception storage and the evaporation from this stock (Gerrits et al., 2007).

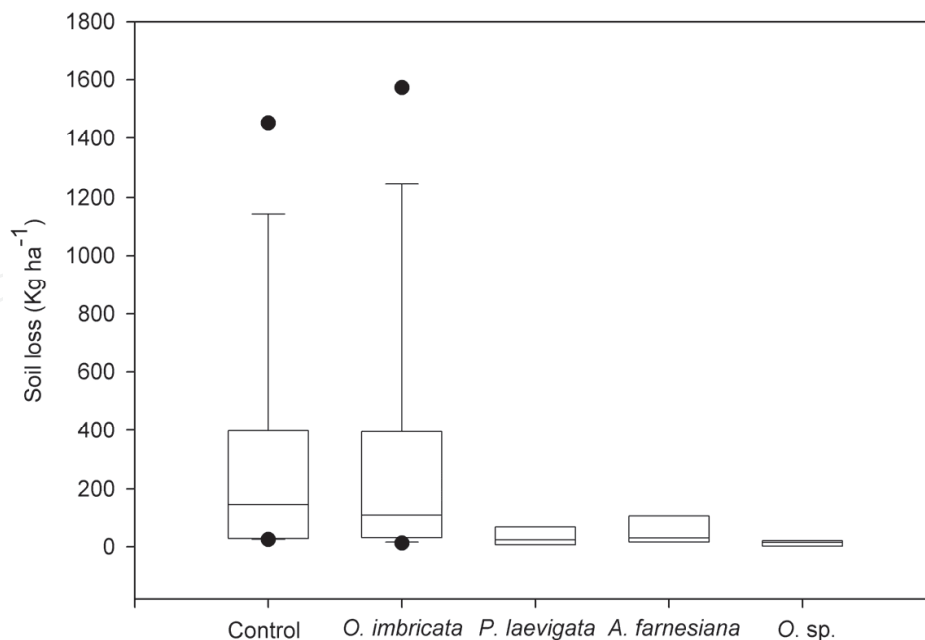


Fig. 8. Box plot of soil loss by native vegetation in semiarid environment (Vásquez-Méndez et al., 2010).

It appears that on average interception can amount to 10-50% of the precipitation (Calder, 1990; Gerrits et al., 2007; Wang et al., 2007). Therefore, knowledge about the process of interception is important (Gerrits et al., 2007). The canopy interception process, which is a basic process controlling interactions of precipitation with plant canopies, plays an important role in the water resources cycle of forest watersheds and isolated environments. This rainfall distribution affects the runoff generation and flow concentration.

Interception, a process affecting the availability of water in the hydrological cycle, is often considered as the trapping, storage and disposition of materials on the vegetative surface of plants, or as the process of aerial redistribution of precipitation by vegetation. Rainfall interception includes the processes that result from the temporary storage of precipitation by the tree canopy. Water can either evaporate directly to the atmosphere, absorbed by the canopy surfaces, or ultimately transmitted to the ground surface (Xiao et al., 2000). Thus, interception can be described as the difference between gross rainfall (PG) and throughfall (T). There are two principal ways in which the physical and physiological characteristics of plants can influence the hydrological cycle. These effects can be separated broadly into the effects vegetation has on water delivered as precipitation on the quantity and distribution of that water to the soil, and on the amount and distribution of water that is removed from soil and subsoils (Wang et al., 2005). The first influence is to a large extent a physical one, whereas physiological characteristics determine the way plants remove water from the soil. The interception processes determine water losses from vegetation canopies wetted by rain (Wang et al., 2005).

Rainfall interception processes is considerable in the tree or shrub canopies at semiarid and arid environments. Plant communities have a positive response to intercept rainfall water through their leaves, branches and trunks. Mastachi-Loza et al. (2010) and Nívar & Bryan (1994) registered that canopy of native vegetation (Prosopis and Acacia trees) can intercept up to 20 to 30% of the rainfall.

Infiltration rates in arid and semiarid depend on factors like vegetation cover, rainfall amount, intensity, and duration, soil type and moisture, slope degree, and land use (Salas, 2000; Wilcox et al., 2003). Soil water infiltration rates are greater under canopies as a result of the soil protection from raindrop impact and compaction by the addition of organic matter from plants, improving soil crumb structure (Salas, 2000; Rango et al., 2006). Trees are a principal factor to increase organic material levels, to moderate soil temperature and to improve soil moisture, resulting in a higher infiltration rate beneath the canopy cover (Gutiérrez, 2001; Zehe, 2008).

7. Vegetation-soil interaction

The typical soils of arid and semiarid environment are poor in fertility. However, when native vegetation is still present, the properties of soils are positively enhanced. Table 2 shows the behavior of fertility of soils in three different native plant species and at bare surfaces. Organic matter in surface with vegetation cover is improved by 100% beneath canopy of *Prosopis* and *Acacia*.

	Bulk Density	Sand	Silt	Clay	Organic Matter	N	K	Ca	Mg	Na	Fe
	g cm ⁻³	%				ppm					
Without Vegetation	1.38	65.12	12.88	22.00	0.88	4.53	586	2404	308	22.8	6.35
<i>Cilindropuntia imbricate</i>	1.39	76.56	7.44	16.00	0.67	3.78	516	2144	289	1.17	6.53
<i>Prosopis laevigata</i>	1.31	75.56	8.44	16.00	1.98	5.29	769	2996	308	1.17	9.66
<i>Acacia farnesiana</i>	1.32	80.56	7.44	12.00	1.57	9.06	500	1501	213	1.17	33.3

Table 2. Soil characteristics comparing three different plant species of native vegetation.

Soils under trees canopies in semi-arid environments are often more fertile than soils from the surrounding grasslands. Quantities of mineralizable nitrogen, phosphorous, potassium, calcium, organic matter, and the microbial biomass, are significantly higher in soils beneath the canopy than in the open area (Belsky et al., 1989).

Soil characteristics shows are better beneath species vegetation in comparison with bare surface, found up to twice of organic matter, minor values of bulk density, greater values of hydraulic conductivity that foster the increase in infiltration rates (Vásquez-Méndez et al., 2010).

8. Final remarks

Precipitation is one of the most important climatic variables to characterized arid and semiarid environments, especially in these environments precipitation varied from year to year. In Cadereyta, Querétaro, México it was found that maximum rainfall occurs in July and August months, besides that erosivity was major to in comparison with the rest of the year.

Vegetation cover is a very important factor to diminish runoff quantity, and native vegetation of semiarid areas contributes to protect the soil against rainfall erosivity and surface sealing phenomena.

For some insects and epiphytes, trees are the minimum habitat unit and can be considered islands, because, like islands, there are discrete ecological units with fixed borders surrounded by different environment (Flores-Palacios & García-Franco, 2006). In pastureland trees are often isolated and distant from other trees.

Some phreatophytes, especially in drier regions, have extensive, subsurface lateral roots to take advantage of any light rainfall that might occur. Such subsurface root systems help to stabilize the soil. The aerial system too has a role in reducing wind erosion and ameliorating the microclimate although information on changes in humidity and temperature is generally lacking (Wickens, 1995).

The indirect contribution of native species to soil fertility is two-fold. First, there is a contribution through nitrogen is probably minimal since the foliage on the ground probably undergoes two periods of rapid degeneration (Wickens, 1995). Along with the improvement in soil fertility, soil physical and micro-climate conditions, the trees play an important role in soil binding processes and the reduction in the eroding action of both water and wind (Pimentel et al., 1995).

The amount and seasonality of rainfall is also reflected in the amount of vegetation cover within the increase of vegetation (surface and canopy). The annual distribution of vegetation has a tendency to increase shortly after the first rains, as in all arid and semiarid environments. However, there was a greater contribution of shrubs or beneath the surface patches of vegetation with a greater coverage area of vegetation.

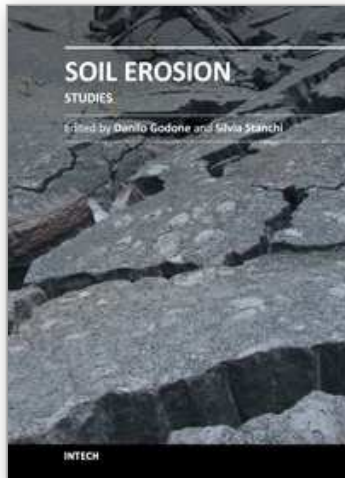
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Soil Erosion Studies

Edited by Dr. Danilo Godone

ISBN 978-953-307-710-9

Hard cover, 320 pages

Publisher InTech

Published online 21, November, 2011

Published in print edition November, 2011

Soil erosion affects a large part of the Earth surface, and accelerated soil erosion is recognized as one of the main soil threats, compromising soil productive and protective functions. The land management in areas affected by soil erosion is a relevant issue for landscape and ecosystems preservation. In this book we collected a series of papers on erosion, not focusing on agronomic implications, but on a variety of other relevant aspects of the erosion phenomena. The book is divided into three sections: i) various implications of land management in arid and semiarid ecosystems, ii) erosion modeling and experimental studies; iii) other applications (e.g. geoscience, engineering). The book covers a wide range of erosion-related themes from a variety of points of view (assessment, modeling, mitigation, best practices etc.).

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Rebeca Vásquez-Méndez, Eusebio Ventura-Ramos, Klavdia Oleschko, Luis Hernández-Sandoval and Miguel Angel Domínguez-Cortázar (2011). Soil Erosion Processes in Semiarid Areas: The Importance of Native Vegetation, *Soil Erosion Studies*, Dr. Danilo Godone (Ed.), ISBN: 978-953-307-710-9, InTech, Available from: <http://www.intechopen.com/books/soil-erosion-studies/soil-erosion-processes-in-semiarid-areas-the-importance-of-native-vegetation>

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
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InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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