Runoff and soil and nutrient losses in semiarid uncultivated fields[1]

Escoamento, perdas de solo e nutrientes em campos não cultivados em regiões semiáridas

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Abstract - Although water erosion is the principle agent responsible for soil degradation, field data on the impacts of erosion, due to high operational costs and measurement difficulties, are scarce, especially in semiarid regions. In this context, the aim of this study was to evaluate runoff and soil and nutrient losses in uncultivated areas in the semiarid region of the state of Ceará in Brazil. The experiment was conducted in a 20 m² erosion plot that was uncultivated and populated with herbaceous plants. Data were collected during the rainy season from January to May 2009. Monthly water losses from overland flow ranged from 3.4 to 168.9 mm, representing 1.8 to 42.3% of the total monthly rainfall for January and April, respectively. Soil loss from erosion totaled 2,166.6 kg ha^{-1}. In February, soil losses were 834.3 kg ha^{-1}, corresponding to 38.5% of the total value. The rainfall erosivity index (EI_{30}) was 5,716.4 MJ mm ha^{-1} h^{-1}. The observed high variability of soil losses in individual events was influenced mainly by the antecedent soil water content. Although this study used only one year of observations, the findings are important for land use planning, especially in the semiarid region of Brazil, where datasets are scarce.

Key words - Soil-erosion. Sediments (Geology). Arid regions.

Resumo - Embora a erosão hídrica seja a principal agente no empobrecimento dos solos e na contaminação dos recursos hídricos, poucos são as mensurações efetuadas em campo. A baixa disponibilidade de dados obtidos in loco é decorrente do elevado custo e das dificuldades na efetivação destas mensurações, em especial nas regiões semiáridas. Neste sentido, o presente estudo teve como objetivos investigar a ação das erosividades das chuvas sobre o escoamento superficial, bem como as perdas de solo e nutrientes em áreas não cultivadas do semiárido cearense. O experimento foi conduzido em uma parcela de erosão (20 m²) sob condições de áreas não cultivadas com cobertura vegetal composta por extrato herbáceo. Neste estudo foram investigados 37 eventos registrados no período chuvoso de 2009 (janeiro/maio). O acumulado mensal do escoamento superficial variou de 3,4 a 168,9 mm, correspondendo a 1,8 e 42,3% da precipitação total mensal, para janeiro e abril, respectivamente. As perdas de solo para todo o período estudado foram de 2.166,6 kg ha^{-1}, com destaque para o mês de fevereiro com perdas de 834,3 kg ha^{-1}, correspondendo a 38,5% do valor total. O índice de erosividade (EI_{30}) da chuva foi de 5.716,4 MJ mm ha^{-1} h^{-1}. A alta variabilidade nos valores de perda de solo por eventos isolados foi influenciada principalmente pela umidade antecedente do solo. Os resultados obtidos nesse trabalho, embora iniciais, são valiosos para a gestão e planejamento adequado de uso da terra, principalmente em regiões semiáridas onde essas informações são mais escassas.

Palavras-chave - Solos-erosão. Sedimentos (Geologia). Regiões áridas.

Introduction

Soil erosion is one of the most challenging global environmental problems. The United States maintains the largest dataset on soil erosion, which uses a patterned methodology. In Europe, erosion data comes from a series of research projects based on different methodologies, and only a portion of them used experimental erosion field plots under conditions similar to those used in the United States (CERDAN et al., 2010). These datasets contain important information on actual erosion rates. Soil erosion investigations are typically conducted in experimental plots with different characteristics. Variations in scale and differences in the factors investigated can determine the quality of the erosion dataset. Studies using different plot sizes can help to identify natural variability (BAGARELLO; FERRO, 2004; BOIX-FAYOS et al., 2007).

Land use plays an important role in the control of the erosion process (AGUIAR et al., 2006; DASS et al., 2011; SANTOS et al., 2000). Removing vegetation can significantly reduce water infiltration rates and increase surface runoff and erosion. Although soil erosion results in the loss of soil fertility, land degradation and water pollution, the amount of information on erosion under field conditions is limited. Researchers from different parts of Brazil have commented on the scarcity of data in related to erosion (ALBUQUERQUE et al., 2002; BERTOL et al., 2004; FRANCO et al., 2002; SANTOS, 2009).

Among the major factors influencing soil erosion, rainfall erosivity is difficult to predict and control (MARTINS et al., 2003). Accurate estimation of rainfall erosivity requires continuous rainfall data, which is rarely of acceptable spatial and temporal coverage. This limitation is as defined by best land use management practices (ANGULO-MARTÍNEZ; BEGUERÍA, 2009). Rainfall intensity is major component related to soil erosion and sediment yield (MELLO et al., 2003; RODRIGUES, 2009).

Northeast Brazil is the most populated semiarid region in the world, with a population of 51,534,406 habitants (IBGE, 2010). In this area, large quantities of agricultural and forest products are consumed, and to meet demands, vegetation is harvested from the Caatinga Forest without the observation of best management practices, resulting in soil degradation by erosion (ALBUQUERQUE et al., 2002; INÁCIO et al., 2005). Additionally, the effects of rainfall intensity (erosivity process) on erosion in the semiarid region of Brazil have not received sufficient attention. Investigations of long-term flow and erosion processes were initiated in small watersheds in the semiarid region of Brazil, but they were interrupted after a short period of data collection because of high operational costs.

(SANTOS et al., 2007). An understanding of the erosion process in this region requires an evaluation of runoff and losses of water, soil and nutrients in undisturbed soils.

Materials and methods

This study was performed in the Alto Jaguaribe watershed, located between 6°23'38'' and 6°23'58''S and 39°15'21'' and 39°15'38''W at an elevation of 217 m (FIG. 1). The field plot experiment was conducted in the experimental watershed of the Instituto Federal de Educação, Ciência e Tecnologia do Ceará (IFCE), Campus de Iguatu, in Iguatu County, Ceará, Brazil. The experimental plot was monitored during the wet season (January to May) of 2009. The climate in the region is semiarid, with a mean air temperature of 29 °C. Average annual precipitation is 970 mm, and rainfall events are often characterized by short durations and high intensities. Nearly 80% of the total precipitation falls during the summer and fall (January to May). The soils in the area are predominantly Vertisols Ebonics Carbonates, according to Embrapa (1999). The physical and chemical properties of the soil in the field plots are shown in Table 1. The cover vegetation in the experimental plot was mostly grass (*Axonopus purpuni*) and bush (*Hyptis sauaviolens*) species. At the end of the wet season, the soil surface is 100% covered.

The runoff and soil and nutrient losses were measured in a plot that was 2 m wide and 10 m long (20 m²) and located on a fallow slope (FRANCO et al., 2002). The average slope of the experimental plot was 9.8%. The plot was bounded on all sides by galvanized iron (GI) CHAPA that was buried to a depth of 0.15 m to prevent outside influences (FIG. 2). The lower end of the plot was connected to a collector system composed of three galvanized iron tanks with volumes of 30; 100 and 200 L. The first is a multi-slot tank with seven slots. The spout of the first tank was connected to the second and third tanks.

A total of 72 rainfall events were registered, 37 of which produced runoff and sediment yield. Runoff from the experimental plot was recorded daily by measuring the depth of water collected in the runoff collection tanks. To determine soil and nutrient losses, runoff samples were taken from the tanks after agitation in 1-liter bottles. Samples were sent to the Soil and Water Laboratory of the Instituto Federal de Educação, Ciência e Tecnologia do Ceará (IFCE), Campus Iguatu, to quantify the total solids and the amounts of Ca, Na, Mg, SO, K and PO, according to the APHA (1998) methodology. Runoff depth was

Table 1 - Soil physical and chemical properties of the field plot

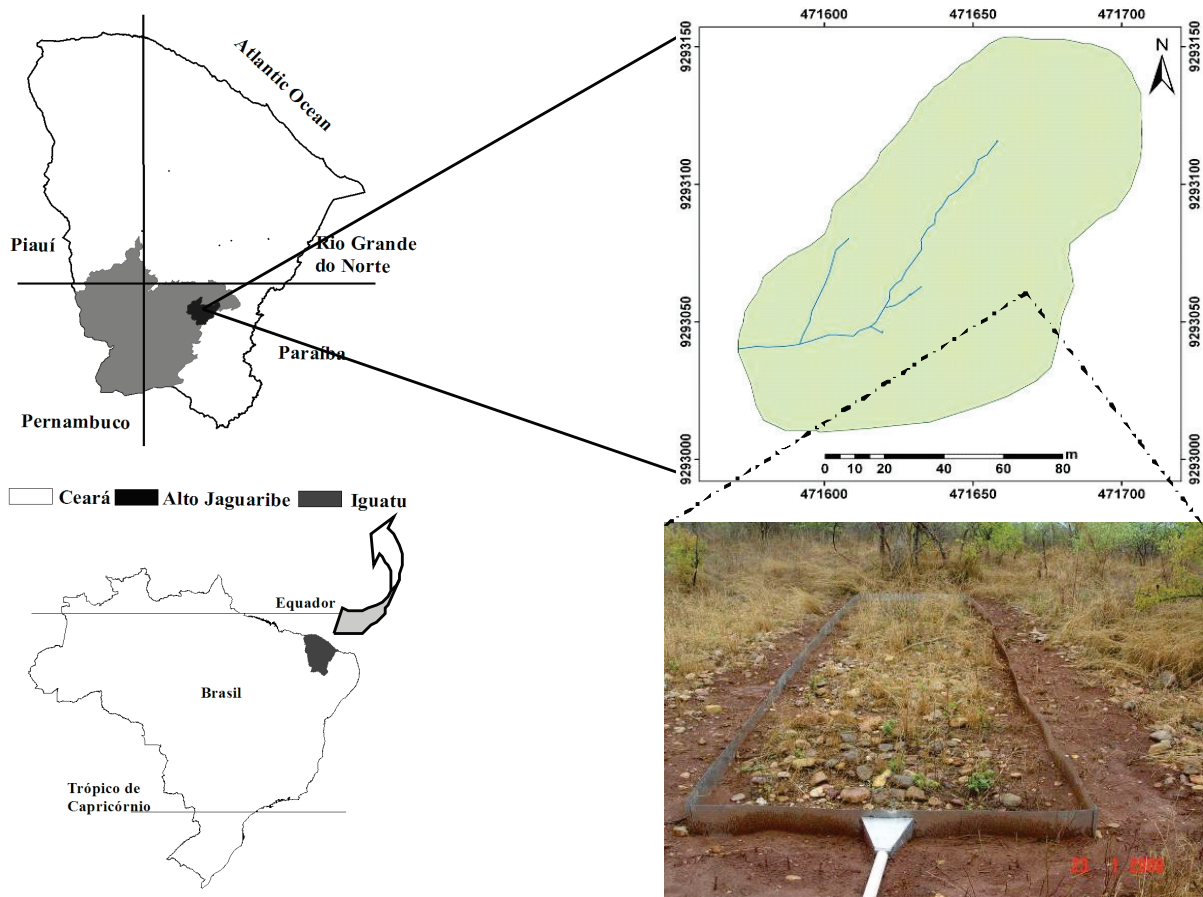| Particle size distribution (%)			Global density	O.M.	P	K$_{sat}$	C/N	EC	pH
Clay < 0.002	Silt 0.002 - 0.05	Sand > 0.05	(g cm^{-3})		(g kg^{-1})	(mm h^{-1})		dS m^{-1}	
11	46	43	1.22	2.03	1.22	5.10	10	0.18	6.8

Figure 1 - Location of the study area in the Alto Jaguaribe watershed, Ceará, Brazil

estimated as a function of the total drainage volume and the plot area, and the soil and nutrient losses were estimated as functions of the total solids and nutrients concentrations in the sampled water.

The rainfall dataset was collected from a rain gauge in the experimental watershed, which recorded values every five minutes. From the daily rainfall dataset, the intensity of events (I) in mm h^{-1} and the maximum 30-min intensity (I$_{30}$) in mm h^{-1} were calculated. The kinetic energy (E) associated with the rainfall in MJ ha^{-1} mm^{-1} was calculated from Equation 1 (WISCHMEIER; SMITH, 1978) and modified according to Foster et al. (1981).

$$E = 0.119 + 0.0873 \text{Log } I \qquad (1)$$

where E is the total storm energy (MJ ha^{-1} mm^{-1}), and I is the rainfall intensity (mm h^{-1}).

The values obtained from Equation 1 were used to calculate the rainfall erosivity index for storms (EI$_{30}$), which is proportional to the product of the total storm energy (E) and the maximum 30-min intensity (I$_{30}$).

Figure 2 - The experimental plot and the multi-slot tank

Results and discussion

The total monthly depth of runoff was 332.3 mm (TAB. 1), representing 31.3% of the total rainfall depth. Although the total rainfall depth (1,062.6 mm) during the studied period was 26.4% greater than the region average, the total depth of runoff was not different from the annual average runoff for the region (SANTOS et al., 2007). Thus, a larger amount of rainfall (depth) did not necessarily indicate a greater runoff depth; rather, runoff depth was more dependent of rainfall intensity.

The percentage of rainfall that became surface runoff was highly variable, ranging from 1.8 to 43.9% from January to May 2009, respectively. In January, which is the beginning of the wet season, the soil was dry and the rate of infiltration was high. In May, when the soil moisture content was high and rainfall events occurred over consecutive days, surface runoff represented 43.9% of total rainfall. The high variability in monthly surface runoff percentages could be related to antecedent soil moisture conditions (BOIX-FAYOS et al., 2007; MELLO et al., 2003).

Table 1 - Monthly rainfall, runoff depth, soil loss and erosivity measured in the field

Month	2009				
	Rainfall	--------------Runoff depth-------------		Soil loss	EI_{30}
	(mm)	(mm)	(%)	(kg ha^{-1})	(MJ mm ha^{-1} h^{-1})
January	193.3	3.4*	1.8*	170.3*	182.2*
February	217.7	77.8	35.7	834.3	1837.0
March	134.4	30.4	22.6	289.6	470.5
April	398.9	168.9	42.3	745.2	2723.8
May	118.3	51.9	43.9	127.2	502.8
Total	1062.6	332.4	31.3	2166.6	5716.4
Standard deviation	111.9	63.5	17.5	332.3	1091.5
CV %	52.7	95.5	59.8	76.7	95.5

* Two events were not recorded (January 30th and 31st events with 76.5 and 11.9 mm of runoff, respectively)

The highest soil loss was observed in February (TAB. 1) when vegetation had not yet fully developed. In this region, the wet season begins in January or February after a long dry season (from June to December). In February, the soil is not yet protected by vegetation. The EI_{30} in February (1,837.0 MJ mm ha^{-1} h^{-1}) was the second highest index registered. Although, the highest rainfall depth, EI_{30} and runoff depth occurred in April, soil loss in this month was lower than that recorded in February. This could be explained by protection from the well-developed vegetation against the direct action of rainfall erosivity (DASS et al., 2011; INÁCIO et al., 2005).

The annual erosivity and total soil loss for the study period were 5716.4 MJ mm ha^{-1} h^{-1} and 2166.6 kg ha^{-1}, respectively, which are within the acceptable limits for soil loss proposed by the FAO (1967). Although the total annual soil loss was similar to previously reported values (AGUIAR et al., 2006; ALBUQUERQUE et al., 2002; MARTIN et al., 2003; RODRIGUES, 2009; SANTOS, 2009), these data were measured in different parts of Brazil, and there was a high variation in the coefficient value (CV) between months. This high CV, which was expected, was attributed to the high spatial and temporal variability of rainfall throughout the year. This indicates that information on annual soil loss should be investigated carefully because processes are not precisely represented.

Although the majority of rainfall and erosivity events occurred in April (FIG. 3), the largest values of I_{30} (the maximum 30-min intensity) and EI_{30} (rainfall erosivity index for storms) were recorded in February. The absolute highest values of I_{30} and EI_{30} were observed on February 18th and measured 76.7 mm h^{-1} and 936.5 MJ mm ha^{-1} h^{-1}, respectively, and the highest value of rainfall occurred on January 22nd, indicating that the highest precipitation value does not necessarily generate the highest rainfall erosivity index.

During the study period, the greatest surface runoff values occurred in the February 18th and April 15th events, and the highest values of soil loss were registered in the February 12th and February 18th events (FIG. 4). Losses prior to April 15th were highly correlated with runoff depth, indicating that surface runoff was the dominant factor. After April 17th, soil losses were independent of runoff depth because the quantity of soil loss was stable at different values of runoff. These observations could be attributed to factors such as rainfall intensity, vegetation coverage and antecedent soil moisture (MARTINS et al., 2003).

Based on the events on March 3rd and 4th, strong relationships were observed between soil loss and the maximum 30-min intensity (I_{30}) and the maximum rainfall erosivity index (EI_{30max}). For the March 3rd event, I_{30max} was 5.1 mm h^{-1}, EI_{30} was 6.2 MJ mm ha^{-1} h^{-1} and the total soil loss was 0.98 kg ha^{-1}. For the March 4th event, I_{30max} was 29.6 mm h^{-1} (480% greater than the previous event), EI_{30} was 121.4 MJ mm ha^{-1} h^{-1} (1,856% greater than the previous event) and the total soil loss was 98.90 kg ha^{-1}, demonstrating the effects on soil loss of surface runoff and disaggregation and transport of soil particles following the impact of raindrops.

The soil loss for the March 18th event, which had an EI_{30} of 177.5 MJ mm ha^{-1} h^{-1} (FIG. 3) and a precipitation

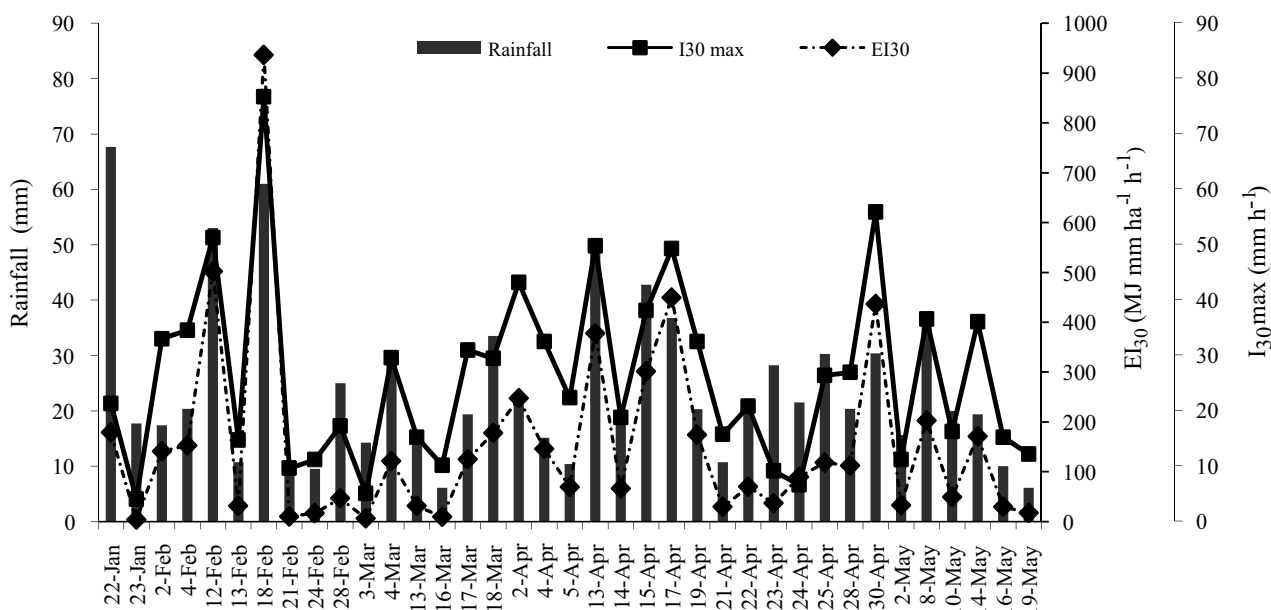**Figure 3 -** Precipitation (PPT), maximum 30-min intensity (I_{30}) and rainfall erosivity index for storms (EI_{30}) in the experimental plot
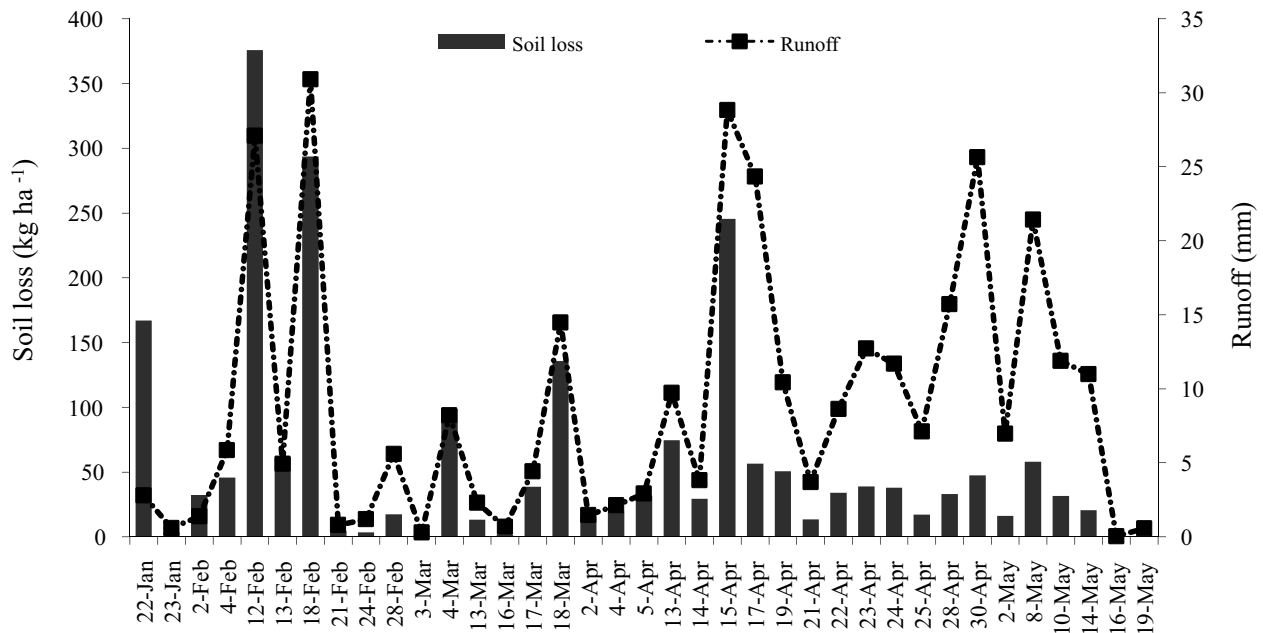
Figure 4 - Soil loss and runoff depth for each event

depth of 33.5 mm and followed 9 days of rain totaling 43 mm, reached 135.7 kg ha^{-1} (FIG. 3). For the subsequent April 2nd event, which followed a fourteen-day dry spell and had a precipitation depth of 22.7 mm and an EI$_{30}$ of 247.3 MJ mm ha^{-1} h^{-1}, the soil loss was 15.6 kg ha^{-1}. Although the number of studied events was small, the results demonstrated the effect of antecedent soil moisture. This could be partially explained by the soil classification (Vertisols Ebonics Carbonates), which showed clay of type 2:1. The rainfall that precedes a given event, which determines the antecedent soil moisture prior to subsequent rainfall events, is strongly related to soil loss (GUADAGNIN et al., 2005).

The influence of vegetation coverage was observed in the events of February 12th and April 13th, which had similar rainfall depths and precipitation amounts during the 3 days before the events of 0 and 20.3 mm, respectively. For the February 12th event, EI$_{30}$ was 501.77 MJ mm ha^{-1} h^{-1}, the total precipitation amount was 50.3 mm and the total soil loss was 375.83 kg ha^{-1}. For the April 13th event, which occurred two months after the development of coverage vegetation, EI$_{30}$ was 377.68 MJ mm ha^{-1} h^{-1}, the total precipitation amount was 50.5 mm and the total soil loss was 74.49 kg ha^{-1}, which was 404.5% less than the amount from the February 12th event and demonstrated the shielding effect of vegetation (DASS et al., 2011).

For the rainfall events of April 2nd, 4th and 5th, EI$_{30}$s were 247.32; 146.05 and 69.56 MJ mm ha^{-1} h^{-1}

(FIG. 3), total precipitation amounts were 22.8; 15.1 and 10.4 mm and total soil losses were 15.63; 19.48 and 31.75 kg ha^{-1}, respectively (FIG. 4). These trends were likely attributable to the progressive degradation and deposition of soil particles on the lower parts of the plot and their transport during the subsequent rainfall events, which had decreasing erosive energies. Among these three events, the April 2nd event registered the highest rainfall depth and the highest maximum rainfall erosivity index, expressing the greater ability to disaggregate soil. Because this event occurred after 14 consecutive dry days, the soil moisture and surface runoff were low (1.46 mm), indicating a limited amount of available energy to transport soil that had been disaggregated by raindrops (ANGULO-MARTÍNEZ; BEGUERÍA, 2009). For the subsequent events (April 4th and 5th), rainfall depths and EI$_{30}$ values were lower, but soil loss was higher because the soil had been disaggregated by previous events. Erosion is a complex process based on soil type and moisture, native vegetation, landscape properties, rainfall intensity and cumulative rainfall amounts (BAGARELLO; FERRO, 2004; CERDAN et al., 2010).

Calcium was the most leached nutrient in the runoff in a given month, with a maximum total amount of 47.33 kg ha^{-1}. The higher values for calcium could be explained by its high concentration in the soil, which was classified as Vertisols Ebonics Carbonates High concentrations of calcium in surface runoff have been found in others studies (LOBATO et al., 2009).

Table 3 - Monthly and total losses of monitored nutrients

Month	Rainfall	Runoff	Ca	Mg	K	PO	SO
	------------(mm)------------		-----------------------------------(kg ha^{-1})-----------------------------------				
January	193.3	3.4	0.062	0.009	0.059	0.004	0.153
February	217.7	77.8	11.600	1.340	1.120	0.020	2.390
March	134.4	30.4	4.583	0.437	0.307	0.021	0.937
April	398.9	168.9	26.619	6.031	2.214	0.181	2.821
May	118.3	51.9	4.462	0.886	2.145	0.005	0.699
Total	1062.6	332.3	47.330	8.700	5.900	0.23	7.000
Total accumulated	1062.6	332.3	68.96				

The losses of K were higher than those of PO because of the higher solubility of K (AGUIAR et al., 2006; BERTOL et al., 2004; SCHICH et al., 2000). The total loss of nutrients was 68.96 kg ha^{-1}, and the individual nutrients were lost in the following order: Ca > Mg > SO > K > PO. Approximately 68.6% of the total loss of nutrients was attributable to calcium, which could be explained by the high concentration of calcium in the soil (LOBATO et al., 2009).

Conclusions

1. The data from this study, although preliminary, are important to the best definitions of land use planning and management, especially in the semiarid regions of Brazil where data on soil loss are scarce. The use of experimental plots facilitated a simplified understanding of individual processes and supported an understanding of the interaction of factors related to erosion;

2. Rainfall intensity, the erosivity index of storms, the antecedent soil moisture and cover vegetation are important factors in the erosion processes. The high variability of individual events is determined by the interactions of these factors, which express the dynamics of the processes;

3. The total soil loss in a plot in the Caatinga forest was 2,166.6 kg ha^{-1}, according to values reported by the FAO for shallow and impervious soils.

Acknowledgements

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