Agriculture, Ecosystems and Environment 130 (2009) 23–30

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

The influence of traditional steep land agricultural practices on runoff and soil loss

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ARTICLE INFO

Article history:
Received 29 June 2008
Received in revised form 13 November 2008
Accepted 13 November 2008
Available online 23 December 2008

Keywords:
Shifting cultivation
Slash-and-burn
Runoff
Soil loss
Guarapuava-Brazil

ABSTRACT

The erosion of soil from subsistence agricultures on lands with steep slopes and shallow soil is poorly documented, particularly in Brazil. This paper details the hydrological and soil loss responses to traditional agriculture (shifting agriculture) of a steeply sloped sector (32° incline) classified by FAO has having Regosol soil. This sector is in Guarapuava, Brazil and is covered by a shallow, clayed soil that originates from basalt rock. All measurements were carried out between May 2003 and April 2004. Three replicate plots were established at three randomly selected land sites, which were under different phases of the rotational cycle: burned, fallow or shrubs. A total of 76 natural rainfall events were measured throughout the study period and the accumulated precipitation was 1538.9 mm. Rainstorms ≥30 mm were important for runoff and soil loss. The average runoff (expressed as a proportion of the total rainfall) over the 12-month investigation period for each of the three sites was determined to be 2.4%, 1.0%, and 1.4% for burned, fallow, and shrubs, respectively. The response to rainfall during the measurement period differed completely at each site. The average soil loss was as follows: for shrubs, fallow, and burned sites, average loss was 1.2 t/(ha year), 5.1 t/(ha year), and 6.1 t/(ha year), respectively. The results suggest that fire and traditional agriculture tillage practices affected the topsoil. Shifting cultivation patterns in the steeply sloped sectors cause a succession of high, intermediate, and low soil loss regimes, which are important for understanding contemporary landscape dynamics and land degradation in the Guarapuava region.

1. Introduction

Geomorphological processes are affected by both landforms and land use. Soil erosion is an important process in geomorphological research. Land use and soil tillage have been recognized as factors that control soil loss in an agricultural landscape (Braudy, 1989; Battany and Grismer, 2000; Morgan, 2005).

Agriculture is also responsible for on-site and off-site effects on the landscape. The major on-site effects are related to soil degradation, and include increased bulk density, reduced aggregate stability, and depletion of nutrient and carbon content (Morgan, 2005). The main off-site effects are related to the delivery of sediments and nutrients to stream channels (Walling, 2003).

Most research on soil erosion and soil conservation is carried out on commercial agricultural systems, because of their economic importance worldwide. Kang et al. (2001) claimed that most soil erosion research is limited to gentle slopes that generally have less than 15% inclines. Bryan (2000) suggested that there are gaps in recognizing the hydrological and geomorphological behavior of some soils, especially of shallow soils on steep slopes.

Likewise, few studies have been conducted either on steep hill slopes that are covered by shallow soils, or in the marginal land that is managed for agricultural production in the rotational land system. Despite this fact, the effect of subsistence agriculture on land degradation has nonetheless been observed worldwide (Stocking, 1983; Tiessen et al., 1992; Turkelboom et al., 1997; Hamandawana et al., 2005; Tenge et al., 2005; Styger et al., 2007).

Traditionally, shifting cultivation cycles used fire to clear brushes and weed. Consequently, this system (slash-and-burn process) has many implications, especially on soil degradation. For example, Alegre and Cassel (1996) suggested that a modification of soil's physical and dynamical properties occurred, and Tiessen et al. (1992) and Denich et al. (2005) highlighted the effects on nutrient dynamics and soil organic matter. Furthermore, Borggaard et al. (2003) suggested that reductions in the fallow period could be followed by reductions in biomass yield, nutrient accumulation, and total productivity, such that the fallow period must be long enough for adequate re-establishment of these soil properties.

Soil loss from subsistence agricultures on steep slopes is poorly documented, particularly in Brazil, in contrast to commercial

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doi:10.1016/j.agee.2008.11.009

agriculture, which applies advanced technologies. Also, more information regarding post-fire consequences for soil loss and runoff is needed.

Research concerning soil loss has been well-documented in many countries across the world. In China's Loess Plateau, Chen and Luk (1989) reported average soil loss rates of 150 t/(ha year), reaching a maximum of 390 t/(ha year). Tangtham (1991) reported that, in areas with steep slopes of 20–80% in Thailand, the soil loss could vary between 5 t/(ha year) and 90 t/(ha year). In Bangladesh, Borggaard et al. (2003) indicated that, with shifting agriculture, soil losses could vary from 11.5 t/ha to 41 t/ha. In Brazil, however, the soil loss from subsistence agricultures on steep slopes is poorly documented.

Measurements were carried out to appraise the effects of a 3-year land rotation system on land use dynamics and soil loss in Guarapuava, Brazil. The objectives of this study were to (1) compare runoff rates and soil loss from three fields that were under different phases of the rotational cycle, (2) assess the effects fire (slash-and-burn) on hydrological responses and soil loss, and (3) estimate the soil loss rates and compare the values to shallow soil.

2. Materials and methods

2.1. Characteristics of the study site

The Guabiroba catchment is located in the Third Paranaense Plateau in the Jordan Valley, a tributary of the Iguaçu River, in South-Central Parana State, Gurapuava, Brazil (Fig. 1). The catchment has an area of 23.6 km^2. Geologically, the site is located in the Parana Sedimentary basin, and the predominant rock is basalt, belonging to the São Bento Group of the Mesozoic, formed 145 Ma (Petri and Fúlfaro, 1983). The altitude ranges from 1280 m on the divide to 980 m (a.s.l.) at the outlet of the catchment.

The steep slopes $\geq 17^\circ$ (30%) are generally straight or convex, and they occupy 20.3% of the catchment area. In these sectors, the length of the hill slopes is short (less than 100 m). The soil is shallow (<0.50 m) and has many stones and much gravel scattered over the topsoil.

The soil is classified as a Regosol by the FAO, and the main clay mineral is kaolinite, with gibbsite also present (Melfi and Pedro, 1977, 1978). At soil depths between 0 m and 0.40 m, the clay quantity is 33%, silt is 22.5%, and sand is 44.5%. With increasing weathering depth, especially in rock fractures (0.70 m), clay increases to 63%, and silt and sand decrease to 20% and 17%, respectively (Thomaz, 2005). Hence, due to the steep slope and soil shallowness, the soil becomes susceptible to erosion.

According to Köppen (1948), the climate is classified as Cfa mesothermic subtropical wet. The average temperature in the hottest month is 20.8 °C (January), and the coldest month is 12.7 °C (July), with an average annual temperature of about 17 °C. The average annual precipitation totals 1953.8 ± 389.7 mm, with the minimum and maximum recorded as 1261.1 mm (1985) and 3168.4 mm (1983), respectively. The precipitation is distributed throughout the year, with an average of 149 ± 20 rainfall days, and the average annual evaporation is 835.1 ± 123.9 mm (long term 1976–2002) (Instituto Agronômico do Paraná, 2002).

Fig. 1. Location of the study area and the experimental site (ES).

Box 1. Soil characteristics and vegetative cover throughout the experiment.

Site characteristics	Burned	Fallow	Shrubs
Soil type	Regosols (FAO classification)	Regosols	Regosols
Slope angle	31.5°	32°	32°
Surface stoniness (%)	15–20	30	15–20
Org. C (0–20 cm) (%)	4.2	n.d.	4.2
Sand (0–20 cm) (%)	43	n.d.	43
Silt (0–20 cm) (%)	23	n.d.	23
Clay (0–20 cm) (%)	34	n.d.	34
Bulk density (0–5 cm) (g cm^3)	0.87 ± 0.15 (*n* 28)	1.02 ± 0.11 (*n* 28)	0.84 ± 0.1 (*n* 28)
Total porosity (0–5 cm) (%)	67.3 ± 5.7% (*n* 28)	61.5 ± 4.3% (*n* 28)	68.5 ± 3.4% (*n* 28)
[a]Soil water retention capacity	Low	Low	Low
Vegetation cover (onset) (%)	Bare (ash and residual burned)	30	90
Vegetation cover (6 months after) (%)	30	50	90
Vegetation cover (12 months after) (%)	70–80	80	100
General characteristic	This site was burned and left in fallow during the measurements. The fire was not homogeneous in the area. It was possible to observe some remaining patches with leafs, twigs and trunks over the topsoil. Meanwhile, other patchy the superficial material had been burned, leaving only the ash layer and the mineral topsoil horizon.	This site remained in fallow for 7 years (1995–2001). It was subsequently deforested, burned, and cultivated with maize in 2002. The plots were set after the maize harvest, approximately 8 months post-fire.	This site was deforested, burned, cultivated with maize and left in fallow in 2001. During the experiment, the land was covered with shrubs displaying a canopy of up to approximately 3-m height. Additionally, the topsoil was covered with a layer of litter 7.8 ± 1.8 t/ha (*n* 15). The main shrubs were predominantly from *Miconia candolenna* and *Bacharis* spp. Only plot 1 was totally covered with grass (*Andropogon icanus*). This species of grass enhanced the runoff in this plot.

[a] Based on Empresa Brasileira de Pesquisa Agropecuária (1979), n.d. (not defined).

The land occupation history in the middle South Paraná State has had a strong relationship with the exploitation of natural resources (Chang, 1988). Today, agriculture is a significant economic activity in the Guarapuava region, showing two major characteristics. Firstly, there is a modern commercial agriculture that uses high technology for soybean, maize, oat and barley production. Secondly, there is a subsistence agriculture that produces mainly maize and bean and occupies the shallow soils located on steep slopes.

2.2. Measurement design

The three chosen land sites (burned, fallow, and shrubs) are representative of shifting cultivation patterns throughout the Guabiroba catchments, as well as the upper Jordan River. The phases of land use in subsistence agriculture in the Guarapuava region are slashing–burning–growing–fallow–re-establishment (full cycle). After slashing and burning, the vegetation area is cropped for only 1 year, and the fallow period is around 3–5 years (Thomaz, 2005).

The plot dimensions (experimental unit) to measure overland flow, infiltration, and erosion were varied. Plots were constructed in accordance with the research purpose. Morgan (2005) argues that there is no instrument standardization in soil erosion research. Although, according to Morgan (2005), plots of 10 m length are necessary for soil erosion research, since this length represents a distance sufficient for catching runoff while also allowing rill development. The short lengths of 1 m^2 plots (small plots) does not allow for observing slope effects on flow velocity and rill formation; therefore, only infiltration and rainsplash erosion could be measured. Romero-Díaz et al. (1999) noted that plots are disconnected from the natural hillslope, which could avoid sediment replacement from upslope. Also, evidence from Phillips (1999) suggests that some parameters, such as precipitation intensity, infiltrability and soil physics, could have major effects on plot scales. In contrast, Battany and Grismer (2000) suggested that results from small plots (on the order of 1 m^2) could be comparable to those from larger plots (30–40 m^2). Notwithstanding these limitations, Hudson (1993) recommended that small plots be used in exploratory soil erosion studies and in experimental designs that seek to compare the effects of land use systems.

Data were collected in nine plots, with three replicates for each land use type. The bounded plot dimensions were 2 m^2 (2 m × 1 m). Each plot was chosen at random and was established adjacent to the other plots, with approximately 10–20 m between sites. Plots on burned and shrubs-filled sites were set in adjacent fields, while fallow plots were set around 200 m away, but in the same geomorphological unit.

The burned site represents the first 6 months to 1 year after slash-and-burn, with minimal soil protection from vegetation. The fallow site approximates the onset of the second year in the land rotation system, i.e. the phase following the harvest. In this period, the land is left fallow for field re-establishment. The shrubs represent the third year in the land rotation system, with significant soil protection by vegetation regeneration. The general characteristics of each site and of the experimental design are summarized in Box 1.

Measurements were taken at three sites (burned, fallow and shrubs), and a bounded plot approach was used to assess the runoff and soil loss for the different land use stages. Every plot was coupled to a sediment Gerlach trough (Gerlach, 1967), which was connected to a 100-l drum. These procedures permitted all runoff and soil loss to be collected.

Measurements were carried out from May 2003 to April 2004. During this period, 76 natural events (storms) occurred. The runoff and soil lost were collected after the storms. The soil from the trough was dried (24 h at 105 °C) and weighed. The runoff accounts for water running off the plot as a percentage or mm of the total volume of water entering by rainfall. The runoff volume from the

Table 1
Daily rainfall amounts and intensities recorded in 30 min during the experiment.

Date	Daily rainfall (mm)	Intensity (*I*30)	Date	Daily rainfall (mm)	Intensity (*I*30)	Date	Daily rainfall (mm)	Intensity (*I*30)	Date	Daily rainfall (mm)	Intensity (*I*30)
5/2/2003	12.0	7.0	09/26/03	59.5	17.0	12/14/03	32.0	10.0	02/15/04	29.0	6.0
05/23/03	36.0	18.0	09/27/03	10.3	3.0	12/16/03	9.5	3.0	02/19/04	8.5	n.d.
6/3/2003	18.0	5.0	10/10/2003	40.5	18.0	12/17/03	6.8	3.0	02/20/04	14.3	7.0
6/5/2003	20.8	n.d.	10/11/2003	23.5	4.0	12/20/03	19.5	17.0	02/23/04	17.0	n.d.
6/6/2003	46.6	9.0	10/21/03	6.5	2.0	12/21/03	51.5	20.0	3/9/2004	9.0	3.0
6/8/2003	16.0	13.0	10/22/03	7.0	2.0	12/22/03	5.5	3.0	3/10/2004	4.5	4.0
6/9/2003	1.8	1.0	10/27/03	61.0	14.0	12/23/03	8.0	3.0	3/12/2004	14.4	6.0
06/19/03	2.3	n.d.	11/1/2003	3.9	2.0	12/30/03	12.5	9.0	03/15/04	63.5	6.0
7/7/2003	61.0	5.0	11/3/2003	4.3	4.0	1/1/2004	17.0	6.0	03/18/04	11.4	11.0
7/9/2003	16.6	n.d.	11/7/2003	5.0	3.0	1/8/2004	11.0	6.0	03/20/04	21.0	7.0
07/16/03	90.5	62.0	11/13/03	56.0	22.0	1/9/2004	4.5	4.0	4/3/2004	15.8	5.0
8/7/2003	17.5	6.0	11/17/03	61.0	13.0	1/11/2004	15.0	8.0	4/5/2004	9.9	7.0
08/15/03	3.6	4.0	11/19/03	18.0	11.0	01/22/04	28.5	28.0	4/6/2004	7.5	2.0
08/16/03	4.5	4.0	11/24/03	9.9	5.0	01/25/04	24.5	7.0	4/7/2004	13.0	8.0
08/25/03	10.1	2.0	11/25/03	39.5	26.0	01/29/04	5.9	4.0	04/16/04	6.7	2.0
9/8/2003	16.5	4.0	11/28/03	9.5	3.0	01/30/04	6.0	6.0	04/20/04	73.0	24.0
9/9/2003	1.0	1.0	12/5/2003	7.0	3.0	2/1/2004	11.3	8.0	04/23/04	17.0	10.0
9/10/2003	22.5	3.0	12/9/2003	33.5	n.d.	2/5/2004	5.3	2.0	04/24/04	3.0	n.d.
09/16/03	9.0	2.0	12/12/2003	35.5	13.0	2/6/2004	10.9	6.0	04/30/04	18.5	n.d.

n.d.: no data.

drum was measured, and a well-mixed sample of suspended sediment was collected, filtered, dried and weighed. Both samples (trough and drum) were then added to obtain the total amount of soil loss. The measurement takes account the storm event-basis over 24 h.

The total accumulated precipitation was monitored daily by an automatic meteorological micro-station (WM-918 *Electronic Weather Station*). The station was set to determine rainfall intensity every 30 min (*I*30 maximum rainfall intensity registered in 30 min) and to measure the total rainfall over 24 h.

The development of vegetation was measured at the beginning, at 6 months, and at the end of the experiment. Vegetation was visually evaluated, and photographs of each site were taken, to verify assessments of vegetative cover. The photographs were evaluated visually without any auxiliary image processing software.

The data were inspected for homogeneity of variance (normalized) and were transformed (square root). The average of each site was compared with *F*-tests (runoff and soil loss). The level of significance for all tests was 0.05%. Simple regression relationships (coefficients of determination) between total rainfall and runoff, maximal 30-min intensities and runoff, total rainfall and soil loss, runoff and soil loss, and maximal 30-min intensities and soil loss were calculated. The analysis seeks to determine the role of independent variables such as total rainfall, intensity, and runoff in determining other dependent variables that correlate to soil loss.

3. Results and discussion

3.1. Rainfall characteristics and runoff

Rainfall is one of the most important physical parameters affecting soil erosion in the subtropical region (Guarapuava-Brazil). Therefore, its characteristics are essential in understanding runoff and soil loss. During the monitoring period, 76 natural rainfall events were recorded. Daily rainfall amounts were divided into alternating light rain (≤20 mm), moderate rain (≤40 mm) or heavy daily rainfall (≥40 mm) regimes. Table 1 displays daily rainfall amounts and rainfall intensity per 30 min (*I*30). The total rainfall accumulated was 1538.9 mm, and the average intensity was 8.41 mm (*I*30). The highest rainfall intensity occurred in July 2003, and was 62 mm (*I*30). The experimental year was dry in comparison to the historical rainfall average (1953 mm). This pattern might have changed the rainfall characteristics and affected runoff and soil loss in the study area.

Precipitation events less than 20 mm were the most frequent (69.8%) of all recorded. Despite this, they accounted for a total accumulated rainfall of only 529.5 mm (34.4%). In contrast, events greater than 40 mm were less frequent, constituting 14.5% of the events (11 events). These events were responsible for 664.1 mm (43.3%) of the total precipitation of 1538.9 mm. The highest rainfall events took place less frequently. In addition, even events with ≥30 mm had a significant role in hydrological response and soil loss, as further explained in the text.

There were significant differences in runoff average between burned and fallow sites ($P < 0.05$). There were, however, no significant differences between fallow and shrubs sites ($P > 0.05$) or between burned and shrubs sites ($P > 0.05$).

After clearing and burning, the surface of the burned site became homogeneous, displaying low runoff variation in comparison to the other sites (Table 2). The average runoff in burned sites was 35.5 ± 2.7 mm (mean ± S.D.), and the average runoff coefficient was 2.3% (expressed as a proportion of the total rainfall). Nevertheless, in 71.1% of events (54 events) the runoff coefficient during the measurement period did not exceed 1.0%. A noticeable rise in runoff

Table 2
Monthly runoff in plots with different land use.

Rainfall			Burned		Fallow		Shrubs	
Month	mm	%	Runoff		Runoff		Runoff	
			mm	C.V.	mm	C.V.	mm	C.V.
May	48.0	3.1	7.2	38.7	1.4	87.1	1.3	64.9
June	105.4	6.9	2.3	28.6	1.7	82.4	1.0	53.5
July	168.1	10.9	9.3	14.4	2.6	54.2	3.2	46.2
August	35.7	2.3	1.1	41.2	0.5	24.5	0.6	54.3
September	118.8	7.7	4.7	30.2	1.0	100.3	1.9	74.2
October	138.5	9.0	1.4	35.6	1.1	99.4	2.1	62.7
November	207.1	13.5	3.2	26.6	2.3	44.9	3.0	66.7
December	221.3	14.4	2.4	35.1	2.1	63.3	3.2	57.3
January	111.9	7.3	1.3	54.9	0.9	89.6	1.5	46.6
February	96.2	6.3	0.6	39.8	0.3	84.0	1.0	39.4
March	123.8	8.0	0.8	24.3	0.6	72.9	1.1	37.6
April	164.3	10.7	1.5	36.5	1.5	77.5	1.9	60.2
Total	1538.9	100.0	35.5	–	16.0	–	21.7	–

The runoff is based on the average of three replicates plots per site, C.V. (coefficient of variation).

Table 3
Rainfall characteristics, runoff and soil loss according to land use phase.

Daily rainfall class (mm)	Accumulated daily rainfall (mm)	Average of rainfall intensity (I30)	Burned		Fallow		Shrubs	
			Runoff (mm)	Soil loss (kg/ha)	Runoff (mm)	Soil loss (kg/ha)	Runoff (mm)	Soil loss (kg/ha)
1–9.9 [a](29)	176.1	3.2	0.4	282.2	0.2	[b]1060.1	1.2	150.7
10–19.9 (24)	353.4	7.5	5.0	760.9	2.5	[b]1245.6	4.3	234
20–29.9 (6)	139.8	9.2	1.8	121.9	1.0	292.7	1.7	62.7
30–39.9 (6)	205.5	16.8	8.5	1351.4	3.0	681.4	3.5	176.8
≥40 (11)	664.1	19.1	19.8	3600.4	9.3	1825.0	11.0	556.8
Total (76)	1538.9	-	35.5	6116.8	16.0	5104.8	21.7	1181.0

The runoff and soil loss are based on the average of three replicates plots per site.
[a] Number of rainfall per class.
[b] The soil loss was influenced by spontaneous movement.

was observed immediately post-fire at burned sites, followed by a continuous decrease in runoff (Table 2).

At the fallow site, the runoff averaged 16.0 ± 7.6 mm, and the average runoff coefficient was only 1.0%. In addition, in 69.7% of events (53 events) the runoff coefficient did not exceed 0.5%. In turn, the average runoff at the shrubs site was 21.5 ± 11.7 mm, while the average runoff coefficient reached 1.4%.

At the burned site, we observed variability in the hydrological response, and the relationship between precipitation and runoff was less strong (r^2 = 57.2%) than for the fallow and, especially, the shrubs site. After the strong disturbance of the topsoil, stemming from the burning, this site became unstable, and high runoff was observed.

At the fallow site, the relationship between rainfall and runoff input was r^2 = 79.3%. The response was similar to that at the shrubs site, but the runoff generation trend at the fallow site decreased slightly as the experiment progressed. However, the variation was higher than observed at the burned site, with the fallow tending to show runoff similar to the shrubs site. The fallow site was cleared and burned 8 months earlier than burned site, which could decreased the onset effects of the fire.

The runoff volumes were positively related to the rainfall at shrubs site (r^2 = 86.7%), which indicates that the runoff rose with increasing precipitation. However, a disturbance in the topsoil did not occur, and, consequently, trends in the hydrological response pattern, such an increase or decrease in the runoff, were not observed during the experiment. Furthermore, at this site, the rainfall was intercepted by the cover of shrubs and by litter.

3.2. Rainfall characteristics and soil loss pattern

Rainfall events over 30.0 mm are important due to their physical characteristics, especially rain intensity and total volume. Rainstorms ≥30.0 mm were significant to both the hydrological response and to the soil loss at every site (Table 3). These events accounted for around 870.0 mm (56.5%) of the total rainfall (1538.9 mm) for the period. They are characterized by short duration and high intensity. It was observed that, on average, 54.3% of the total rainstorms lasted between 30 min and 90 min, and, as a result, their physical characteristics reflected soil loss. Both runoff and soil loss tended to increase progressively according to rainfall class. However, the runoff effect on soil loss was markedly different in each land use (Fig. 2).

An important increase in the runoff and soil loss was observed for rainfall classes over 30 mm. For events of over 30 mm, the response was greatest at the burned site. The soil loss at the burned site reached 4951.8 kg/ha (81.0%), and the runoff reached 79.7%. The lowest amount of soil loss occurred at the fallow site, with 2506.4 kg/ha (49.1%); however, the runoff (76.9%) at this site was similar to that at the burned site. Shrubs displayed 66.8% runoff and 733.6 kg/ha (62.1%) of total soil loss recorded as a result of these events.

The rainstorm effect was more significant in the first 6 months of measurement, particularly at the burned site where 70.4% (4306.3 kg/ha) of the total soil was lost over 7 events. Although the 11 events occurred in the remaining period (November–April) contributed just 11.0% (671.7 kg/ha) to the total soil loss at the site. The effect of rainstorms on soil loss decreased throughout the experiment at every site. It is probable that the effects of rainstorms (≥30.0 mm) on both runoff and soil loss were due to more total rainfall amounts than to intensity (I30), with the rain causing soil saturation, resulting in enhanced runoff (Table 3).

Regression relationships between rainfall and soil loss, runoff and soil loss, and intensity in 30 min and soil loss are displayed in Table 4. The coefficient of determination between rainfall and soil

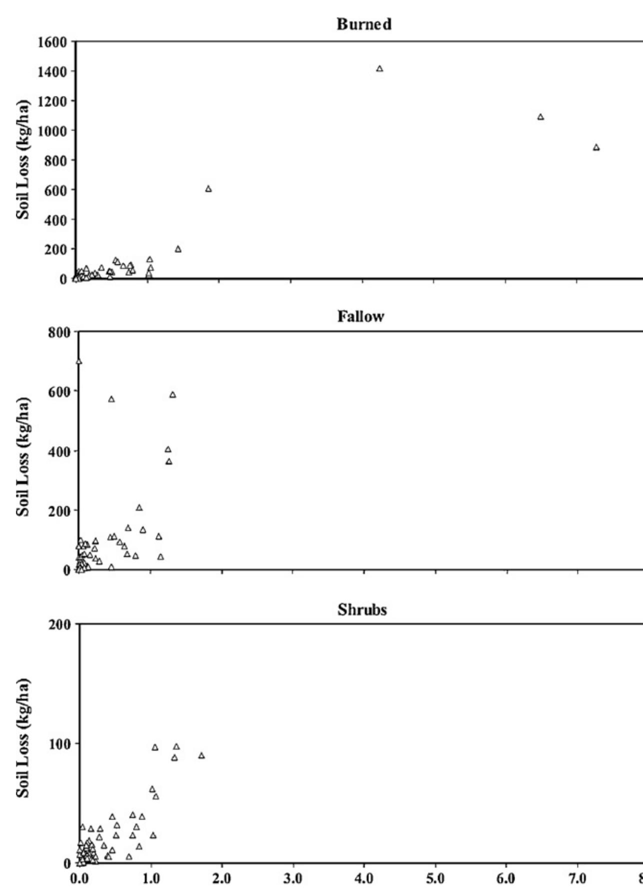

Fig. 2. Relationship between runoff and soil loss for each land use.

Table 4
Regression relationship (coefficient of determination r^2%) for some hydrological parameters in each site under different land use phase.

Land use	Rainfall–soil loss	Runoff–soil loss	[a]I30–soil loss
Burned	43.7[b]	81.8[b]	27.3[b]
Fallow	28.9[b]	57.1[b]	65.8[b]
Shrubs	52.8[b]	74.6[b]	42.1[b]

[a] Maximum rainfall intensity registered in 30 min.
[b] Coefficient of regression significant at 0.05% level Test *F*.

loss was low at the fallow site. In general, the average coefficient of determination was higher between runoff and soil loss than between *I*30 and soil loss, especially at the burned site.

The results suggest that the runoff mechanism is more important than rainfall intensity in understanding the soil loss on steep hill slopes, particularly post-fire (Fig. 2). Also, in the soil in the study area is shallow, with low capacity for water retention (see soil characteristics Box 1). As a consequence, the soil has a propensity to become saturated, especially during extended heavy precipitation events. When the effect of fire on runoff is ignored, soil saturation appears to be an important mechanism for runoff production, as well as for soil loss.

The evolution of soil loss in the experiment was entirely different at each site (Table 5). Despite strong fluctuations, there was a trend of increasing soil loss in the onset of the experiment; in later phases, a noticeable decrease in soil loss occurred, especially at burned and fallow sites.

The burned site showed a noticeable increase in soil loss at the beginning of the experiment. A total of 4008.0 kg/ha (65.5%) of the total soil was lost in the first 4 events, and this indicates the impact of burning. Even more notably, the event that occurred on 05/23/2003 (36 mm, *I*30 18.0 mm) was 1 month post-fire and was responsible for 1096.4 kg/ha of loss. This single event led to soil loss from the burned area that was approximately equal to the total loss observed in the shrubs area for the whole year (1181 kg/ha for the shrubs site).

At the burned site, 69.4% (4245.8 kg/ha) of the removal was concentrated in three separate months: May, July, and September (Table 5). After these months, this site had a gradual reduction in soil loss because of the emergence of naturally growing vegetation. For example, in the month of May, 1 month after the fire, a significant soil loss of 1142.8 kg/ha (18.7%) (Table 5) occurred, despite only 48 mm of rain (3.1% of the total period). This is in stark contrast to the remaining period between October 2003 and April 2004 (7 months), when soil loss of 1429.5 kg/ha (23.4%) was measured. The accumulated precipitation in these months was 1062.9 mm, or around 69.5% of the total rainfall for the entire period.

Fallow land lost 2634.0 kg/ha (51.6%) over five total events, although the contribution from the middle to the end phases of the experiment was an important contributor to the total soil loss. The fallow site had the highest soil loss in the three consecutive months of July, August, and September (Table 5). The total accumulated loss during this period was 54.9% of the total annual loss (2803.2 kg/ha). August, despite being a month of low rainfall (35.7 mm), had a significant soil loss of 574.8 kg/ha (11.3%). A similar phenomenon was also observed in September, with a monthly loss of 701.6 kg/ha (13.7%). In both cases, the soil loss stemmed largely from shallow soil flux (spontaneous flux).

The material in soil flux is a mix of soil, gravel, branches, small twigs and leaves. The "steady" small-fan deposits were formed by overland flow. This process occurred at the fallow site and could have been triggered in many ways (e.g. biogeomorphologic agents, tillage practices and fire). Nevertheless, soil flux did occur following a dry period: 35 days in August and 14 days in September. Presumably the induced instability was due to superficial moisture loss. In a short drought period, loss of superficial wetness causes topsoil shrinkage. This process could modify the surface where superficial material deposits rest, causing instability, and therefore, movement. In addition, the process is facilitated by inclines of 60%. Soil flux was important for the fallow site since at least 28% (1434.4 kg/ha) of the total soil loss came from this process.

From October to April, the fallow site registered 1602.9 kg/ha (31.4%) of loss, an amount slightly higher than that at the burned site (1429.5 kg/ha, 23.4%). During this time, the soil loss at fallow and burned sites tended to be similar, indicating a reduction post-fire effects and an increase in ground protection conferred by spontaneous vegetation growth at both sites.

In contrast, the soil loss at the shrubs site progressed throughout the experiment, although there was a considerable concentration at the beginning of the measurement. Around 85.5% of the total rainfall events at this site accounted for soil loss ranging from 0.0 kg/ha to 25 kg/ha, totaling 421.6 kg/ha, or approximately 35.7% of the total annual soil loss. In six major events, the soil loss was above 50 kg/ha, totaling 491.0 kg/ha (41.6%).

Soil loss at shrubs reached 37.5% (442.5 kg/ha) of the total annual amount Only during spring (September–October–November) (Table 5). At this site, a more constant rhythm of removal over longer periods was observed despite the concentration of soil loss in these 3 months.

After 6 months of measurement, the topsoil covering in each area had completely changed. It was noted that soil protection had a significant role in the study area, particularly at shrubs site. In all the sites (burned, fallow and shrubs), the soil loss was increased at the onset of the experiment compared to the final periods. The different phases of recovering vegetation at each site markedly influenced different patterns of soil loss. Around 6 months after the beginning of the experiment, vegetative coverage at the shrubs site included almost the entire topsoil and canopy, while the burned area had approximately 40% covering and the fallow around 60–70%. The significance of canopy protection and its effects on soil loss reductions have been reported in many other studies (Romero-Díaz et al., 1999; Vacca et al., 2000; Kang et al., 2001; Kimoto et al., 2002).

3.3. Considerations of soil loss rates and soil degradation

The average soil loss at the burned site was 6116.7 ± 3418.4 kg/(ha year), and the average soil loss at the fallow site was

Table 5
Monthly soil loss according to land use phase.

Rainfall			Soil loss					
Month	mm	%	Burned		Fallow		Shrubs	
			kg/ha	C.V.	kg/ha	C.V.	kg/ha	C.V.
May	48.0	3.1	1142.8	34.0	410.4	89.9	105.0	70.1
June	105.4	6.9	259.2	37.2	285.1	52.5	80.7	20.8
July	168.1	10.9	1563.8	29.6	1032.8	29.2	206.3	45.9
August	35.7	2.3	182.3	27.2	574.8	93.0	98.1	77.2
September	118.8	7.7	1539.2	91.1	1195.6	80.3	138.3	54.3
October	138.5	9.0	285.6	62.6	233.8	72.9	131.4	76.1
November	207.1	13.5	494.5	56.5	419.0	65.6	172.8	33.6
December	221.3	14.4	273.6	59.8	367.3	73.5	111.2	70.8
January	111.9	7.3	97.7	86.2	350.3	94.0	38.6	79.8
February	96.2	6.3	80.1	75.0	73.9	75.1	37.3	91.7
March	123.8	8.0	82.6	82.2	67.0	78.0	20.8	92.5
April	164.3	10.7	115.5	91.7	94.9	78.7	40.6	93.5
Total	1538.9	100.0	6116.8	–	5104.8	–	1181.0	–

The soil loss is based on the average of three replicates plots per site, C.V. (coefficient of variation).

5104.8 ± 1717.4 4 kg/(ha year), while the average of soil loss at the shrubs site was only 1181.0 ± 390.1 kg/(ha year). The soil losses at burned and fallow sites were similar ($P > 0.05$); in contrast, the shrubs site differed markedly from the burned and fallow sites ($P < 0.05$).

With the shrubs site, the soil loss could be considered very slight (<2 t/ha), while in burned and fallow sites, the soil loss tended to be slight (2–5 t/ha) or moderate (5–10 t/ha) (Morgan, 2005). Therefore, the soil loss at the study area was above the tolerance limit for shallow soil. According to the FAO (1967), the tolerance limit accepted for soil loss from shallow soil landscapes is between 2 t/(ha year) and 4 t/(ha year) (Regosols, FAO classification).

In the study area, land rotation systems which use fire for clearing and which have land sitting fallow for 3–5-year periods, might be agriculturally unsustainable. The unsustainable nature of this type of shifting agriculture is confirmed by studies from the Bolivian Highlands (Grau and Brown, 2000) and from Bangladesh (Borggaard et al., 2003).

The authors recommend that the fallow period should be no shorter than 10 years (10–12 years or up to 15–20 fallow years) (Tiessen et al., 1992; Grau and Brown, 2000; Borggaard et al., 2003). However, a fallow period longer than 10 years can lead to increased runoff, as well as to soil loss, when the field is used again. Therefore, the increase of available material (fuel) for burning would be great. This may intensify the fire and damage the topsoil. Benevides-Solorio and MacDonald (2001) have reported that most studies concerning wildfire or prescribed fire indicate that the greatest increase in runoff and soil loss occurs within the first 1 or 2 years after the fire.

Furthermore, many studies suggest that the soil loss rates return to the pre-disturbance conditions around 3–9 years after burning. Thus, the entire influx of nutrients, organic matter, and aggregate stability into the soil re-establishment could be lost (Shakesby et al., 1996, 2000; De Bano, 2000; Benevides-Solorio and MacDonald, 2001; Úbeda and Bernia, 2005). More research must be done to verify the relationship between the length of the fallow period and runoff and soil loss in lands under shifting cultivation.

It is not the main goal of this study to reduce the soil loss on lands in the subsistence rotation system. However, at least two recommendations could be made. Following the manual harvest of maize, plant stalks stand in erect positions, because the farmers do not spread the crop residue on the surface. Consequently, if the crop residue was left scattered on the surface, it could offer the topsoil considerable protection, especially during the recovery phase.

Also, farmers could use stone fence contours. Silva and Silva (1997) note that the use of stone barrier contours was efficacious for soil retention, as well as for improvements in soil qualities, such as soil depth, porosity, water supply, organic mater and fertility.

4. Conclusions

At the burned site, fire-induced soil disturbances caused an imbalance in the water penetration into the topsoil and, as a result, even the low rainfall events produced significant runoff. Therefore, the fire had a significant influence on topsoil, causing soil loss and hydrological changes in the burned site. The amount of soil loss at the burned site could have been higher if the usual tillage practices had been followed. Practices such as planting, manual tillage, hoe usage, and maize harvesting did not occur at this site. The major effect on runoff and soil loss could be considered to be fire, especially at the onset of the experiment, because it caused a reduction in topsoil cover, an increase in bare soil, the sealing of soil pores by ash, and the enhanced provision of easily removed soil.

The fallow site was affected by soil flux movements, which constituted an important component of soil loss. The plots at this site were installed after the maize harvest. During the harvest processes, much disturbance occurred, due to farmer foot traffic, which was necessary to carry the crop from the field. These disturbances could have a residual effect on the topsoil, as well as on soil loss.

In all three sites studied, the land use phase (burned, fallow or shrubs) had a significant influence on runoff and soil loss patterns. Furthermore, the recovery of vegetation had a critical effect on soil loss reduction, particularly after rainstorms of as much as 30 mm of precipitation. Indeed, 3 years after burning, recovering shrubs (at the shrubs site) were important for reducing soil loss fivefold in comparison to the other land use phases.

Subsistence agricultural practices have caused episodic changes in soil protection, as well in soil loss. These episodes have tracked the dynamics of the land rotation system, with its phases of clearing, burning, growing, abandonment, and recovery. These shifting cultivation patterns are essential in understanding the contemporary agricultural landscape dynamics and soil degradation in the Guarapuava region.

Acknowledgements

I acknowledge the receipt of Research Doctorate Studentship from the Brazilian Research Council (CNPq–Conselho Nacional de Desenvolvimento Científico e Tecnológico). I thank the farmer Joel Araújo Silvério for collaborating on fieldwork. Also, I acknowledge the useful comments from anonymous referees that help to improve the paper.

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