CHAPTER 11

Organic Carbon Associated with Eroded Sediments from Micro-Plots under Natural Rainfall from Cultivated Pastures on a Clayey Ferralsol in the Cerrados (Brazil)

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CONTENTS

11.1 INTRODUCTION

Transformations in land use since the 1950s have affected large areas of the tropics. Conversion of native vegetation to cropping and pastures has been widespread in all biomes of the tropics (humid forests, savannas, volcanic areas, etc.). Among these conversions, monocultures of cultivated pastures with exotic species cover large areas, especially in tropical South America, where pastures cover more than 120 million hectares (Mha). The introduction of pastures has two main objectives: to provide resources for extensive cattle production, and to secure ownership of the land.

In Brazil, the Cerrado region (the savanna biome) covers 22% of the territory, and cultivated pastures with exotic grass species represent 49.5 Mha (Sano et al., 2000). A high proportion of these plant-soil systems is relatively unproductive or in decline. Low productivity pastures are characterized by low liveweight gains during the wet season (from 1000 to 1200 mm) and liveweight losses during the dry season (4 to 6 months) (Rolón and Primo, 1979). Decrease in productivity is due to inadequate cattle and pasture management, and soil factors (Balbino et al., 2002). Soil carbon content (‰) and total carbon stocks are among the main factors that integrate the effects of management when vegetation and tillage are changed. Hence soil carbon is one of the most important indicators affecting soil quality (Doran et al., 1994). Since the 1970s, many experiments on major tropical soil types have indicated that yield decline is caused by soil loss due to erosion (Stocking, 2003). Conversely, Gitz and Ciais (2003) have shown through modeling that changes in land use can cause emission of CO_2 into the atmosphere. Reduction in pasture productivity is generally caused by chemical alterations in the soil (Gijsman and Thomas, 1996), and by the adverse effects of animal trampling on soil physical properties (McCalla et al., 1984; Holt et al., 1996) and especially soil compaction (Willatt and Pullar, 1983; Chanasyk and Naeth, 1995; Greenwood et al., 1997).

The Ferralsols (Latossolos, according to the Brazilian classification) represent 46% of the Cerrado area. The top few cm of soil of low productivity pastures in these soils have extremely low porosity. Soil structure is a strong platy from the surface to 3 cm depth, followed by a combination of compact clods of 1 to 5 cm in size, and clods organized in very porous agglomerated micro-aggregates (Balbino et al., 2002). In addition to research on conservation tillage and cropping systems, there is a need for information on soil loss under a wide range of soil–plant systems. One of the hypotheses concerning pasture decline processes relates to the loss of water and soil caused by runoff, and consequently, loss of organic carbon (C). The infiltration capacity of pasture is, in general, higher than that of arable land. Experimental data on runoff and soil losses exist in the region at scales ranging from 10-m^2 plots (Dedecek et al., 1986; Leprun, 1994; Santos et al., 1998) to a whole watershed (Silva and Oliveira, 1999). However, losses of organic carbon associated with water erosion have rarely been assessed in this region.

This paper presents the results of an experiment carried out under natural rainfall on 1 m^2 erosion micro-plots on a clayey Ferralsol in the Brazilian central plateau, in order to assess runoff, soil losses, and carbon losses under *Brachiaria* pastures. The short-term effects of renewed pastures on runoff, erosion, and eroded C are also discussed.

11.2 MATERIAL AND METHODS

The experimental site was located on a farm at 1000 m above sea level on the Brazilian central plateau (15°13'S, 47°41'W) in an EMBRAPA Cerrados–IRD–Fazenda Rio de Janeiro station. The soil is a homogeneous dark red, clayey Ferralsol with 55 to 65% clay in the upper layers (< 35 cm) and more than 70% in the lower layers (> 55 cm; Table 11.1). The topsoil layer (0 to 0.02 m) has a mean bulk density of 0.9 Mgm^{-3} and a mean C content of 24.2 mg g^{-1}.

The mean annual rainfall is 1200 mm, and the rainy season lasts 7 months from the end of September to the beginning of April. The mean annual temperature is 22°C and those of the coldest and warmest month are 20°C (July) and 23°C (October), respectively.

Table 11.1 Particle Size Distribution, Bulk Density, and Organic Carbon Content (SOC) of the Ferralsol under Study (Mean Data of Experimental Site)

Depth	Clay g 100 g^{-1}		Coarse Sand g 100 g^{-1}		Fine Sand g 100 g^{-1}		Silt g 100 g^{-1}		Bulk Density g cm^{-3}		SOC mg C g^{-1}	
m	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0–0.02	53.4	3.7	3.7	0.8	25.2	5.4	13.4	4.9	0.90	0.09	24.2	4.0
0.05–0.15	62.1	4.3	3.5	1.0	13.9	3.4	14.8	3.3	1.13	0.09	19.3	2.7
0.25–0.35	65.8	4.9	3.8	0.8	14.2	3.6	11.8	4.4	1.13	0.15	12.7	2.1
0.55–0.65	70.7	4.1	2.6	0.5	13.3	3.0	9.7	3.1	1.10	0.15	8.4	1.6
0.85–0.95	71.3	2.9	2.6	1.2	14.1	3.8	8.8	3.4	1.06	0.14	6.7	1.1
1.15–1.25	71.0	3.3	2.1	1.0	14.6	2.9	9.2	3.1	1.02	0.09	5.4	0.8

Note: SD: standard deviation. n = 9 for particle size distribution, n = 54 for bulk density for the 0.0 to 0.02 m depth layer, and n = 9 for the other layers.

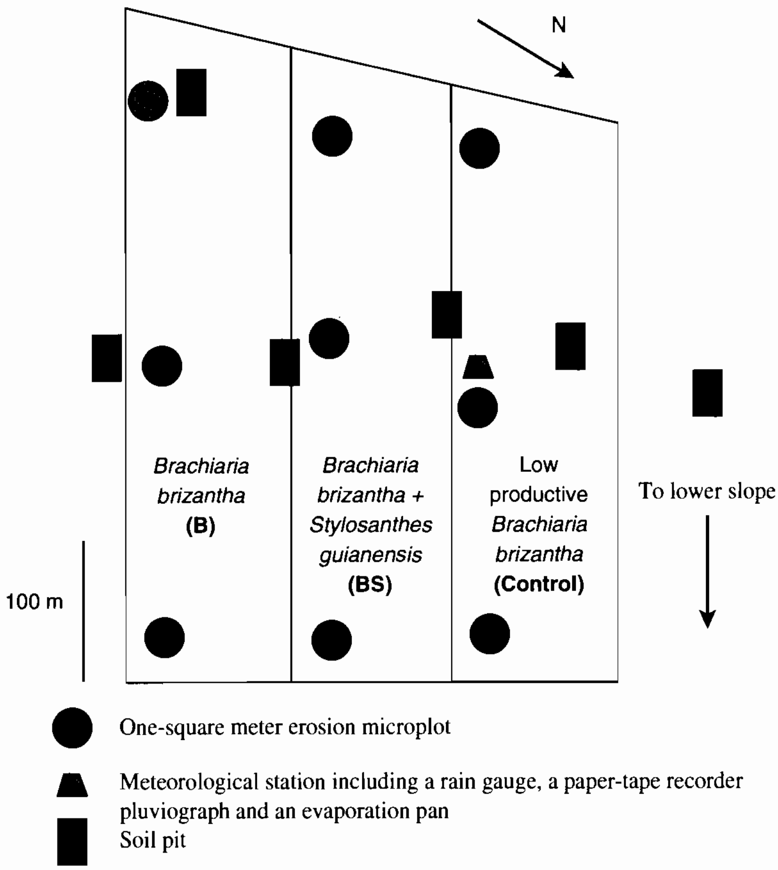

Figure 11.1 Experimental site EMBRAPA Cerrados — IRD — Fazenda Rio de Janeiro (Goiás, Brazil).

Three treatments compared during the first rainy season (Figure 11.1) included:

- Control: a 10-year-old pasture of *Brachiaria brizantha* cv *Marandu*, characterized by a low productivity
- Treatment B: a 21-month-old pasture of the same *Brachiaria*, and restored
- Treatment BSG: a 21-month-old pasture involving the same *Brachiaria* along with a legume *Stylosanthes guianensis* var. *vulgaris*, cv *Mineirão*

The last two treatments, restored pastures, applied to the same pasture as the control, were established in 1999. Soil tillage included disking to 15-cm depth (twice at right angles) to improve germination of *Brachiaria* seeds present in the soil, sowing of the legume, and spreading fertilizer. The fertilizer application was at 40 kg ha^{-1} of phosphorus as triple superphosphate and 74 kg ha^{-1} of sulfur as flower of sulfur. Due to the large plot size (5 ha) and the relative homogeneity of soil and pastures, treatments were not replicated.

Each plot was 400- to 500-m long and had a 3.5% slope. In March 1999, three 1-m^2 erosion micro-plots were demarcated within each plot, at low, middle, and upper positions. These micro-plots were delineated by a frame buried approximately 5 cm into the soil. Runoff generated within the frame border was routed through a pipe into belowground collection tanks. At this 1-m^2 scale, the beginning of runoff process can be observed. Moreover, under the pastures cover, any gully erosion was determined by the nature of nonaggressive rainfalls. However, slope runoff coefficients extrapolated to the watershed scale overestimated watershed runoff (Harms and Chanasyk, 2000). The research on the scale effect on runoff has shown that the sheet flow decreases with an increase in surface area for a given rainfall amount (Molinier et al., 1989). The biomass in micro-plots was cut regularly when it reached 30 cm height.

During the 2000–2001 season, all three treatments (B, BSG, and Control) were managed uniformly so that their effects could be compared. During the 2001–2002 season, only two treatments (B and BSG) could be compared because the control was managed differently: complete cutting (but without disturbing the soil surface and the roots), and leaving soil surface bare throughout the rainy season in order to evaluate the effects of the absence of plant cover (bare soil under control).

Runoff and sediments were collected twice a week between October and May during two successive rainy seasons, from 2000 to 2002. After filtration through 0.2 μm membranes, the sediments were dried at 65°C and weighed. In addition, topsoil in micro-plots was sampled from 0 to 0.20 m in January 2001 and from 0 to 0.02 m at the end of the rainy season of the same year. Particle size distribution was done on the soil of these two layers and on the sediments from the bare soil, but not on the sediments from the pastures due to their small weight. It was measured after dispersion using NaOH, following routine procedures for Ferralsols in Brazil (EMBRAPA, 1997).

Soil and sediment carbon contents were determined by the wet oxidation method (Walkley and Black, 1934, modified by EMBRAPA, 1997). When a runoff event did not produce enough sediment for a C analysis, we assumed that sediment C content was similar to that of the preceding event. The rainfall was recorded weekly on the site by a recording rain gauge.

Statistical analysis was done by Student unpaired *t*-tests where differences in mean runoff coefficient (%), soil losses (g m^{-2}), sediment C (mg C g^{-1}), soil organic carbon (SOC) content, (mg C g^{-1}), SOC stock of the layer 0 to 0.02 m (g C m^{-2}) and SOC losses (g C m^{-2} yr^{-1}) between plots were tested. No assumptions were made on normality and variance equality (Dagnélie, 1975).

11.3 RESULTS AND DISCUSSION

11.3.1 Rainfall, Runoff, and Soil Losses

Total rainfall was 1101 mm during the 2000–2001 season, and 1304 mm during the 2001–2002 season (Figure 11.2). Compared to other tropical areas, rainfall was not very erosive, since only six daily rainfalls exceeded 50 mm during these two seasons, and the intensity of only seven rains exceeded 50 mm h^{-1} in 30 min.

For a given treatment and landscape position, during the first season, the annual runoff coefficient (RC: annual runoff/annual rainfall, in %) ranged between 0.1 and 0.5% in B and BSG and between 0.8 and 1.9% in the control (Table 11.2). The significant difference between the control and B and BSG may be explained by the ground cover, which was 70 to 80% for B and BSG and 50 to 55% for the control. During the second season, the RC in B and BSG ranged between approximately the same values (0.1 to 0.6%) with slight variations among the micro-plots. The RC was 9% on bare soil micro-plots in the absence of grass cover. Averaged over the two seasons, the RC, which ranged from 0.1 to 0.3%, was not significantly different among the two restored treatments.

Annual soil losses ranged between 43 and 119 g m^{-2} yr^{-1} under pasture during the first rainy season (with 1100-mm annual rainfall), but did not differ significantly among the three treatments though they tended to be more in the control (Table 11.2). During the following season (with 1300-mm annual rainfall), soil losses in B and BSG were similar, but higher than the first season. They were often maximum on the low and minimum on the middle position of the slope (except B). No significant difference was observed between the B and BS treatments. Soil losses were 2073 g m^{-2} yr^{-1} on bare soil.

At this scale, under pasture, few data exist on runoff and soil losses for this region. However Castro et al. (1999) observed a RC of 6%, and 20 g m^{-2} of soil loss on no-till and mulched 1-m^2 plots, under natural rainfall on a clayey Ferralsol in southern Brazil. At another scale, Dedecek et al. (1986) measured soil losses up to 53 Mg ha^{-1} yr^{-1}, in 77-m^2 bare soil plots of a Ferralsol in the same region. Thus, the

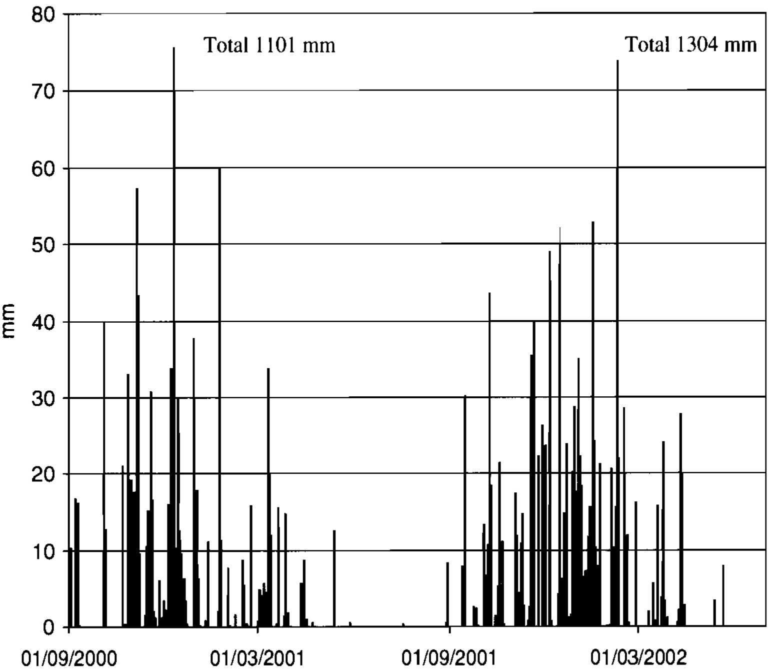

Figure 11.2 Daily rainfall (mm) during the two rainy seasons from 2000 to 2002.

Table 11.2 Runoff Coefficient (RC) in % and Soil Losses in g m^{-2} on 1-m^{-2} Plots

	2000 to 2001				2001 to 2002			
	RC		Soil Losses		RC		Soil Losses	
Plot	Mean	SD	Mean	SD	Mean	SD	Mean	SD
B	0.1 a	0.1	43 a	6	0.3 a	0.3	124 a	40
BS	0.2 a	0.2	72 a	63	0.2 a	0.2	123 a	74
Control	1.3 b	0.6	119 a	92	—	—	—	—
Bare soil under control	—	—	—	—	9.0 b	0.4	2073 b	475

Note: SD: standard deviation. Within a column, data followed by the same letter are not significantly different ($p < 0.05$).

present data confirmed the major effect of plant cover, with the two kinds of pasture rehabilitation, on runoff generation on these Ferralsols, which are clearly sensitive to erosion as shown by the control bare soil. The present results also indicated that legume introduction in the renewed pasture did not significantly affect soil erosion.

11.3.2 Organic Carbon Concentration in Sediment

For a given treatment, landscape position, and year, sediment C content ranged between 21 and 27 mg C g^{-1}, except in the middle slope position of the control plot where it was 31 mg C g^{-1} during the 2000–2001 season (under pasture) and 40 mg C g^{-1} during the 2001–2002 season (bare soil). But the treatment means, which ranged between 23 and 30 mg C g^{-1}, did not differ significantly (Table 11.3). In comparison, for small pastured watersheds, Owens et al. (2002) observed values ranging from 52 to 72 mg C g^{-1}.

However, sediment C content tended to be somewhat more during the 2001–2002 season than during the 2000–2001 season (+5% on average). This may be explained by the fact that there was an incomplete amount of litter/waste during the first season, part of it having been accidentally

Table 11.3 Organic Carbon Contents in the Sediments (mg C g^{-1}) and the Soil Layers (SOC) 0 to 0.02 m and 0 to 0.10 m, and Carbon Enrichment Ratio

Plot	Sediment C mg C g^{-1} 2000 to 2001 Mean	SD	Sediment C mg C g^{-1} 2001 to 2002 Mean	SD	SOC 0 to 0.10 m mg C g^{-1} Mean	SD	C Enrichment Ratio Reference Layer 0 to 0.10 m 2000 to 2001	2001 to 2002	SOC 0 to 0.02 m mg C g^{-1} Mean	SD	C Enrichment Ratio Reference Layer 0 to 0.02 m 2000 to 2001	2001 to 2002
B	23.6 a	0.9	24.1 a	2.7	18.2 a	2.7	1.3	1.3	22.1 a	0.8	1.1	1.1
BS	23.0 a	1.8	24.7 a	2.1	20.9 a	2.2	1.1	1.2	23.6 a	1.6	1.0	1.0
Control	25.4 a	5.0	—	—	21.8 a	1.7	1.2	—	26.9 a	3.1	0.9	—
Bare soil under control	—	—	30.4 a	8.1	21.8 a	1.7	—	1.4	26.9 a	3.1	—	1.1

Note: SD: standard deviation. Within a column, data followed by the same letter are not significantly different ($p < 0.05$).

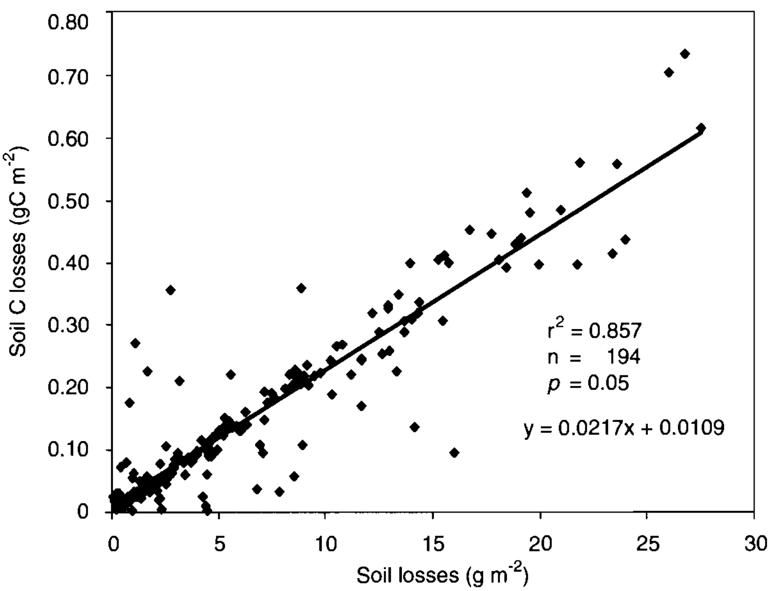

Figure 11.3 Relationship between the soil carbon mass associated to sediments and soil losses under pastures (2000 to 2002).

removed during the first samplings. The SOC content in the micro-plot topsoil (0 to 0.02 m) ranged from 21 to 29 mg C g^{-1}, and was thus similar to sediment C contents. Correlation between topsoil and sediment C contents was stronger in the 2001–2002 season ($r^2 = 0.64$, n = 9) than in the 2000 –2001 season ($r^2 = 0.47$).

11.3.3 Organic Carbon Mass Associated with Sediments and in the Topsoil

Soil carbon losses depended strictly on soil losses because C content in the topsoil (0 to 0.02 m) varied little. Considering each runoff event under pasture during these two rainy seasons, the mass of C associated with the sediment (g C m^{-2}) was strongly correlated with the mass of sediment (g soil m^{-2}) ($r^2 = 0.86$, n = 194; Figure 11.3).

Two years after pasture restoration, in May 2001, the mean SOC stock in the 0 to 0.02 m layer was 384, 432, and 499 g C m^{-2} in B, BS, and the Control, respectively (Table 11.4). Although the control had a C stock 30% and 15% higher than B and BSG, respectively, these differences were not significant. Nevertheless, differences may be explained partly by the lower SOC content in B and BSG treatment. The disk plowing in 1999 to 15 cm depth in B and BS treatments may have

Table 11.4 Soil Organic Carbon (SOC) Losses of Micro-Plots (g C m^{-2} yr^{-1}) and SOC Stock of Layer 0 to 0.02 m (g C m^{-2})

	SOC Stock 0 to 0.02 m		SOC Losses 2000 to 2001		SOC Losses 2001 to 2002	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
B	384 a	19	1.0 a	0.2	3.0 a	1.1
BS	432 b	18	1.7 a	1.5	3.1 a	2.1
Control	499 ab	97	2.7 a	2.0	—	—
Bare soil under control	499 ab	97	—	—	61.8 b	9.4

Note: SD: standard deviation. Within a column, data followed by the same letter are not significantly different ($p < 0.05$).

accentuated mineralization of organic matter, a dilution of the surface organic matter by the mechanical effect of disking, and also on the soil bulk density, which was lower in treatment B. Additionally, the SOC stock at 0 to 0.02 m depth was 13% more in B than in BSG, and this difference was significant (due to small standard deviations).

Considering the 0 to 0.20 m layer, these differences were smaller or nonexistent, the C stocks being 3.9, 4.6, and 4.5 kg C m^{-2} in B, BS, and Control, respectively (data not shown). Under 12-year-old pasture on Brazilian Ferralsols of the same type, Chapuis-Lardy et al. (2002) observed a C stock of 5.4 kg C m^{-2} for the 0 to 0.2 m layer.

For a given treatment and year, C losses ranged between 1.0 and 3.1 g eroded C m^{-2} yr^{-1} under pastures, and were more in the 2001–2002 than in the 2000–2001 season in B and BSG treatments (Table 11.4). In contrast, on bare soil, C losses were twenty times greater (61.8 g eroded C m^{-2} yr^{-1}) than under pasture during the second rainy season (Table 11.4). Moreover, if we consider separately the runoff events on bare soil for lower and upper slope positions, where mean sediment C content was 25.8 mg C g^{-1}, C losses were strongly correlated with soil losses ($r^2 = 0.99$, n = 86). For the middle slope position, where sediment C content was 39.6 mg C g^{-1} in bare soil, C losses were also strongly correlated with soil losses ($r^2 = 0.995$, n = 42). On this last landscape position, soil losses were the lowest and sediment C content was the highest of all measurements.

Finally, on the 1-m^2 scale, mean annual C losses under pastures represented 0.5% of the SOC stock in the 0 to 0.02 m soil layer, whereas under bare soil they represented 12% of the SOC stock. These data provide some new insights into C fluxes in managed tropical grassland. Representing relatively small quantities of the SOC, the C associated with the eroded sediment may be of some importance in the organic matter redistribution over the landscape down slope. For example, at another scale, on small watersheds in Ohio (< 0.8 ha), Owens et al. (2002) reported mean eroded C losses of 12.7 to 24.0 kg eroded C ha^{-1} yr^{-1} depending on tillage practices (13.8 kg eroded C ha^{-1} yr^{-1} for no-tillage). On 100-m^2 runoff plots from tropical and Mediterranean regions, Roose (2004) reported C losses ranging from 0.1 to 50 kg eroded C ha^{-1} yr^{-1} in well-covered plots (forest, savanna, etc.), 50 to 350 kg eroded C ha^{-1} yr^{-1} under row crops, and up to 3000 kg eroded C ha^{-1} yr^{-1} for bare fallows on steep slopes in very humid regions. In Kenya, Zöbisch et al. (1995) arrived at similar conclusions; on 23-m^2 plots, they observed during a rainy season 773 and 53 kg eroded C ha^{-1} lost on bare fallow and maize–beans rotation, respectively.

11.3.4 The Enrichment Ratio

The enrichment ratio is defined as the ratio of the concentration of any given component in the eroded materials to that in the contributing soils. It is greater than one when the sedimentary materials are enriched. For the two rainy seasons under study, the organic carbon enrichment ratio was more than one for all treatments, considering the 0–0.10 m soil depth layer as a reference (Table 11.3). Then, it ranged between 1.1 and 1.3 under pastures, and was 1.4 in the control bare soil. Considering the 0 to 0.02 m soil depth, the enrichment ratio was close to one. In the control bare soil, the particle size distribution showed that the amounts of clay and silt in sediments ranged from 500 to 690 and 120 to 230 g kg^{-1}, respectively, depending on the micro-plot considered, whereas they were 560 and 110 g kg^{-1} soil in the 0 to 0.02 m layer and 630 and 160 g kg^{-1} in the 0 to 0.10 m layer (data not shown). The small depletion of clay particles in this Ferralsol upper layer was a consequence of sheet erosion over time. De Jong and Kachanovski (1988) reported that about 50% of SOC losses in Canadian grassland sites were due to erosion. But in other cases, for well-managed pastures, the SOC content is generally conserved. For example, Fisher et al. (1994) observed an increase in soil C content to 1-m depth under *Brachiaria humidicola* on a "Llanos" soil in Colombia. Chapuis-Lardy et al. (2002) reported that pastures increased the storage of C in the topsoil of Ferralsols compared to the native Cerrado ecosystems. But under low productivity cultivated pastures, C storage may be lower than in native fields (Da Silva et al., 2004).

11.4 CONCLUSION

At the 1-m^2 scale of this study, runoff under pasture was small, and was significantly smaller in the restored pastures than in the degraded control pasture. Similarly, soil and carbon losses under pasture were small, and were smaller in the restored pastures than in the control, but the differences were not significant. In contrast, runoff, soil, and carbon losses were much greater in control bare soil than under pasture. Considering events individually, eroded C was strongly correlated with soil losses. The C enrichment ratio was about one considering the 0 to 0.02 m soil depth layer, and ranged between 1.1 and 1.4 considering the 0 to 0.10 m soil layer. However, there was no significant differences in C stock between restored and control pastures in the 0.02 m soil layer. The level of eroded C by sheet erosion under experimental pasture conditions was small (0.5% of the initial C stock in the 0.02 m soil layer), but was larger (12%) in the bare soil.

The plant cover in the restored pastures was very efficient in reducing runoff and sediment loss for most rainfall events compared to the control, a 10-year-old *Brachiaria brizantha* pasture. However, differences were small and generally not significant among both renewed pastures with regard to runoff, soil losses, and eroded C.

The erosion of C was a selective process because it was limited to the top soil. There were no rills. The eroded C may be of some importance in the redistribution of soil organic matter over the landscape. However, this process is probably not the main factor responsible for pasture decline in this region.

The data presented allows the assessment of the effect of the pasture restoration on runoff and carbon associated with sediment losses under natural rainfall and runoff conditions. Further investigations are needed to study the sustainability of the restored pastures beyond two successive rainy seasons for numerous runoff and erosion events.

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On the cover: A typical landscape of red ferrallitic soils on the high plateau of central Madagascar near Antananarivo during the rainy season. The hilltop is covered by overgrazed grassland deeply eroded around the cattle trails which join the village and the springs in the valley. The hills lose carbon, nutrients, soil, and water, but might be nourishing the rice paddies below.

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SOIL EROSION AND CARBON DYNAMICS

In addition to depleting nutrients necessary for healthy crops, soil erosion processes can affect the carbon balance of agroecosystems, and thus influence global warming. While the magnitude and severity of soil erosion are well documented, fluxes of eroded carbon are rarely quantified. **Soil Erosion and Carbon Dynamics** brings together a diverse group of papers and data from the perspectives of world-renowned soil scientists, agronomists, and sedimentologists to resolve whether soil erosion on carbon is a beneficial or destructive process.

This book collects quantitative data on eroded organic carbon fluxes from the scale of the agricultural plot to that of large basins and oceans. It quantifies the magnitude of eroded carbon for different soil management practices as compared to normal carbon sequestration and discusses the fate of the eroded carbon and whether or not it is a source or sink for atmospheric CO_2. Finally, the book offers data reflecting the impact of soil erosion on soil, water, and air quality. Other important topics include solubilization, carbon transfer, and sediment deposition, as well as carbon dioxide emissions, global warming potential, and the implications of soil erosion on the global carbon cycle and carbon budget.

Features

- Defines basic concepts and general approaches to the global carbon cycle, carbon sequestration, erosion, and eroded carbon
- Addresses the great debate on "missing" or "fugitive" carbon
- Includes arguments and data that support contrasting viewpoints on the effects of the carbon cycle
- Offers a meaningful look at the impact of soil erosion on the global carbon cycle and the global carbon budget
- Covers solubilization and carbon transfers in rivers and deposition in sediments
- Addresses the impact of soil erosion on crop production systems
- Elucidates the CO_2-to-carbon relationship and organic carbon fluxes

Based on the first symposium of the international colloquium *Land Uses, Erosion and Carbon Sequestration* held in Montpellier, France, **Soil Erosion and Carbon Dynamics** provides data that link soil erosion to the global carbon cycle and elucidates the fate of eroded carbon at scales ranging from plot to watershed.

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