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Soil erosion under different management of coffee plantations in the Venezuelan Andes

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Abstract

In the Venezuelan Andes the traditional way of cultivating coffee has been beneath shade, using the variety *Coffea arabica var. arabica*. However, since 1975 the government has promoted a change from this type of cultivation to 'sun coffee' which implies the elimination of shade trees and the replacement of old coffee trees with varieties such as *C. arabica var. bourbon* and *var. caturra*. In order to analyze the possible consequences of this change to the soil erosion in the sloping coffee plantation, a study was carried on in the region of Canaguá, in the State of Mérida. The results were obtained from studying the successive loss of the mineral fraction and runoff, measured in plots situated in (1) a 16–17 year old shade plantation, (2) the same plantation in the first and second years following its transformation to a 'sun plantation', and (3) a seven to ten year old sun plantation. The results show that: (a) Despite the larger losses in the sun plantation, both types of management show very low erosion after the plantation has become established, (b) the loss of the mineral fraction less than 4 mm represents the greatest difference between erosion in the sun and shade plantation in full production, (c) the losses of < 4 mm fraction during the first year following implantation of sun coffee are four times greater than those found in the old shade plantation, and (d) there is a positive relation between erosion and human activities within the plantation, contrasting with a non significant correlation between erosion and runoff and rainfall erosivity.

Keywords: Erosion; Anthropic erosion; Coffee; *Coffea arabica*; Andes; Venezuela

1. Introduction

Since the second half of the 19th century, the success of the plantations of *Coffea arabica var. arabica*, known as 'shade coffee', in Venezuelan Andes has been deter-

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mined by the low investment requirements, the ability to maintain soil fertility and the high quality product. Coffee planted beneath shade has always been considered as an example of 'rational' utilization of the environment mainly because of 'highly soil protective' qualities such as permanent cover and thick litter (Coste, 1969; Jimenez and Gómez-Pompa, 1982; Vishveshwara and Jacob, 1983; Haarer, 1984; Hoffmann et al., 1987).

The replacement of these plantations with the vars. *bourbon*, *caturra*, *catuai*, *mundo nuevo*, etc., known as 'sun coffee', has caused preoccupation as they require high investment inputs, tend to be a monocrop and management practices result in unprotected soil, which is more susceptible to erosion.

C. arabica var. arabica, the first variety introduced in Latin America and, perhaps, the first to be cultivated in the world, requires little direct sunlight and should be cultivated in shady environments, except in very cloudy regions. Trees from the original forest are often replanted in these plantations, but shade can also be provided by fruit trees such as citrus trees, avocados, bananas, etc., which increase the diversity of the farm products. The trees above the coffee plants also increase soil cover and provide a thick layer of litter. These plantations do not require fertilization for their maintenance, although the use of fertilizers increases their productivity. All the coffee varieties are perennial, but this variety is particularly long lived when used as a well maintained crop, and it can be profitable for up to 50 years.

After the creation of the Fondo Nacional del Café (FONCAFE, National Coffee Foundation) in 1975, the government promoted the replacement of the shade variety by the sun varieties, in order to increase coffee production as the sun varieties are on average three times more productive. Sun varieties require direct sunlight for their development and, as a consequence, the coffee producers use wide spacing between plants, leaving more bare soil. The application of fertilizers is necessary to reach and maintain commercial production. These varieties are only productive for approximately 17 years, which is less than half that of the shade variety.

However, an analysis of the consequences of implanting a new technological program, in particular the ecological impact, has not been carried out, so we start a study on water balance, litter dynamics, nutrient balance and erosion, for several years, will enable an evaluation of interannual environmental variations (Hurni, 1983; Roose, 1981).

In relation to the impact on erosion caused by the change from shade to sun coffee plantations it has been suggested that: (1) Soil is more susceptible to erosion due to a lesser plant cover and a higher human disturbance, and (2) the most critical period in coffee plantation (the establishment phase) occurs approximately every 17 years in the sun coffee and only every 50 years in the shade coffee plantations (Sanchez, 1976; Van Putten, 1985; Rice, 1990; Ataroff and Monasterio, 1996a). In this paper, the results of the analysis of erosion during four years of sun coffee plantations in full production, two years of shade coffee and the first two years of transformation of a shade coffee plantation to a sun coffee plantation are presented.

2. Study area

A farm was selected in Canaguá (08° 08′N, 71° 18′W), one of the principal coffee growing regions of Mérida State, in the Venezuelan Andes. Two different types of plantations management could be found here, one cultivating sun coffee of the *bourbon* and *caturra* varieties, with a density of 3100 plants ha^{-1}, and the other growing shade coffee (*var. arabica*) with a density of 4300 plants ha^{-1} beneath the shade of *Inga oerstediana*. The latter was later transformed into a sun coffee plantation with the *caturra* variety, with a density of 3300 plants ha^{-1}. These plantations are adjacent and have the same slope of 31°. These plantations are at an altitude of 1730 m with a substrate fundamentally composed of schists and lightly metamorphosized sandstones (Mucuchachi Formation) above which a thin, sandy, Typic Humitropept soil has developed, with a rooting depth of 30 cm. This area has an annual rainfall of 1779 mm (Table 2) and an annual temperature of 18°C and corresponds to the upper limit of a seasonal montane forest (Sarmiento et al., 1971). The pattern of annual rainfall can be divided into two distinct periods: rainy, from April to October, and dry, between November and March (Fig. 1).

The phenology of the vegetation is of particular importance because it is related to effective precipitation and the agricultural activities. During the dry season the coffee fruits are maturing and harvest takes place, plants gradually lose their leaves (all coffee varieties and *Inga oerstediana*), and at the end of this period the cover is minimal. The plantations are usually fertilized before floration and the development of new leaves is initiated by the beginning of rainy season. The fruits develop throughout the rainy season and the coffee producers fertilize the soil on one or two occasions during this period to aid fruit production. The plantation is weeded before maturation of the fruits to

Table 1
Seasonality of erosion (t ha^{-1}), with number of human activities (*I*) in the coffee plantations

Season	Shade coffee (16 years)			Shade coffee (17 years)			Sun coffee (1 year)			Sun coffee (2 years)		
	< 4 mm	> 4 mm	*I*	< 4 mm	> 4 mm	*I*	< 4 mm	> 4 mm	*I*	< 4 mm	> 4 mm	*I*
Rainy	0.49	0.91	2	0.20	0.05	0	2.97	3.10	6	0.40	0.75	1
Dry	0.30	0.10	2	0.23	0.17	1	0.25	0.30	0	1.74	0.60	3
Total/fr.	0.79	1.01		0.43	0.22		3.22	3.40		2.14	1.35	
Total/year	1.80		4	0.65		1	6.62		6	3.49		4

Season	Sun coffee 7 years			Sun coffee 8 years			Sun coffee 9 years			Sun coffee 10 years		
	< 4 mm	> 4 mm	*I*	< 4 mm	> 4 mm	*I*	< 4 mm	> 4 mm	*I*	< 4 mm	> 4 mm	*I*
Rainy	0.46	0.01	3	0.22	0.79	1	0.18	0.05	4	0.18	0.12	1
Dry	1.11	0.24	4	0.51	0.31	3	0.13	0.03	2	0.29	0.15	2
Total/fr.	1.57	0.25		0.73	1.10		0.31	0.08		0.47	0.27	
Total/year	1.82		7	1.83		4	0.39		6	0.74		3

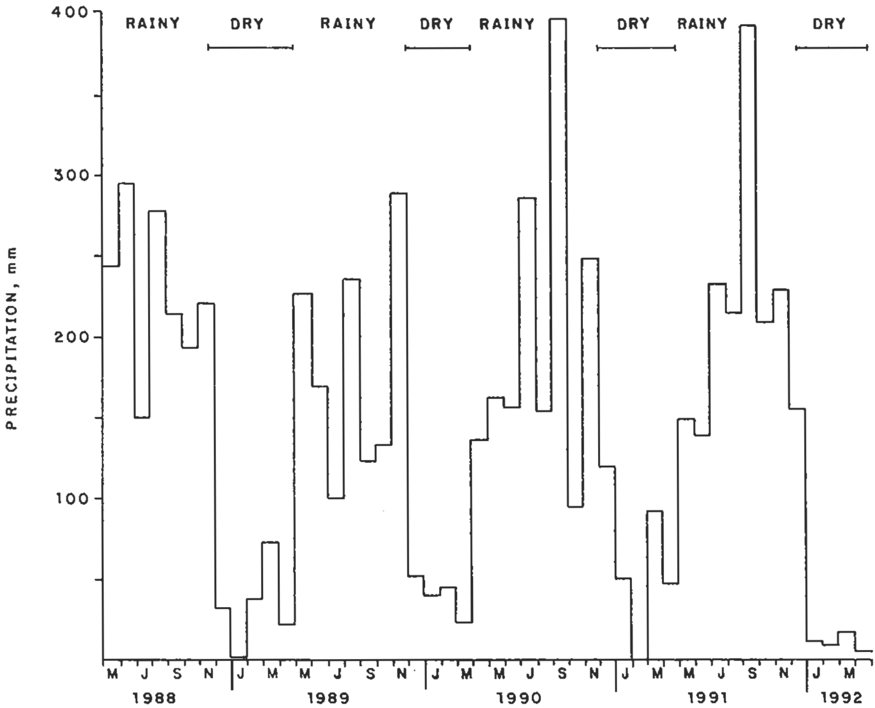

Fig. 1. Rainfall in the plantations studied during the investigation.

avoid species competition, removing ferns and other herbs and incorporating them into the litter.

3. Field methods

A series of devices were installed in both types of coffee plantations at the end of 1987, with the aim of obtaining information on water flow and the loss of mineral soil. An erosion plot of 6 × 2 m was set up in each plantation to measure runoff and erosion (Fig. 2).

All eroded material (in trap channel and collector 1, Fig. 2) was carried to the laboratory and sifted into two categories: material of less than 4 mm and greater than 4 mm.

Measurements were made every ten days in the rainy season (five days during the peak) and every 15 days in the dry season (20 days in January). The first months' data were ignored in case they were altered or affected by the installation of the plots.

In order to analyze the human impact, no agricultural activity was interrupted or modified during the investigation, and all activities were recorded.

Three cylindrical soil samples from three layers (0–10 cm, 10–20 cm and 20–30 cm) were taken in each plantation to measure bulk density, and fine and coarse fraction (<4 mm and >4 mm).

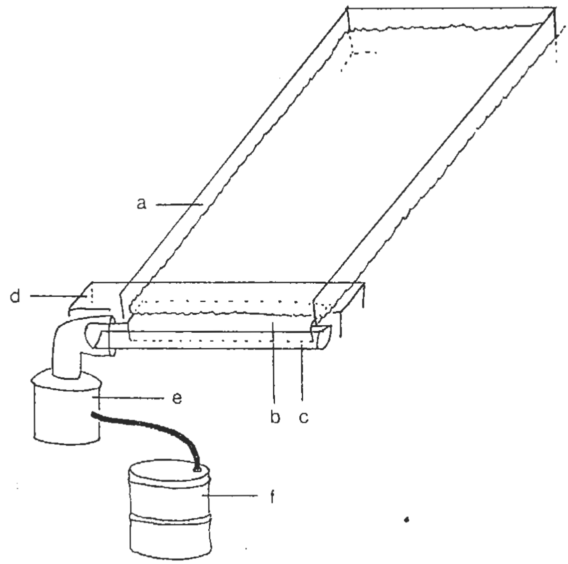

Fig. 2. Configuration of the erosion plot. (a) Side wall, (b) plastic sheeting to direct runoff and eroded material (c) trap channel, (d) protective lid, (e) sediment and runoff collector 1 (25 L), (f) runoff collector 2 (200 L).

A pluviograph with continuous register was installed near the plantations, to obtain data for EI_{30} calculation (Wischmeier and Smith's erosivity factor *R*, Foster et al., 1981).

The data presented here were collected between May 1988 and April 1990 from both sun and shade plantations in full production. In May 1990 part of the shade plantation was converted by the owner to a sun coffee plantation, resulting in the drying out of shade trees and the cutting down of existing coffee plants, after which new plants of the *caturra* variety were planted. This new plantation was studied for the next two years (May 1990–April 1992).

4. Results and discussion

4.1. Magnitude of losses

When comparing the two coffee plantations, sun and shade, in full production during the same time period, a larger loss of mineral fraction was found to have occurred in the sun plantation (Table 1, Figs. 3 and 5). During the first two years of this study, the loss of the fraction < 4 mm in the sun plantation (1.57 and 0.73 t ha^{-1} $year^{-1}$) was twice that of shade (0.79 and 0.43 t ha^{-1} $year^{-1}$, respectively). The greatest importance is given to the fraction < 4 mm for the comparison of the two plantations, because the coarse fraction (> 4 mm) was not the same in the two sites; in the first 10 cm of the soil in the shade plantation the coarse fraction was double that of the sun plantation (2.0 t

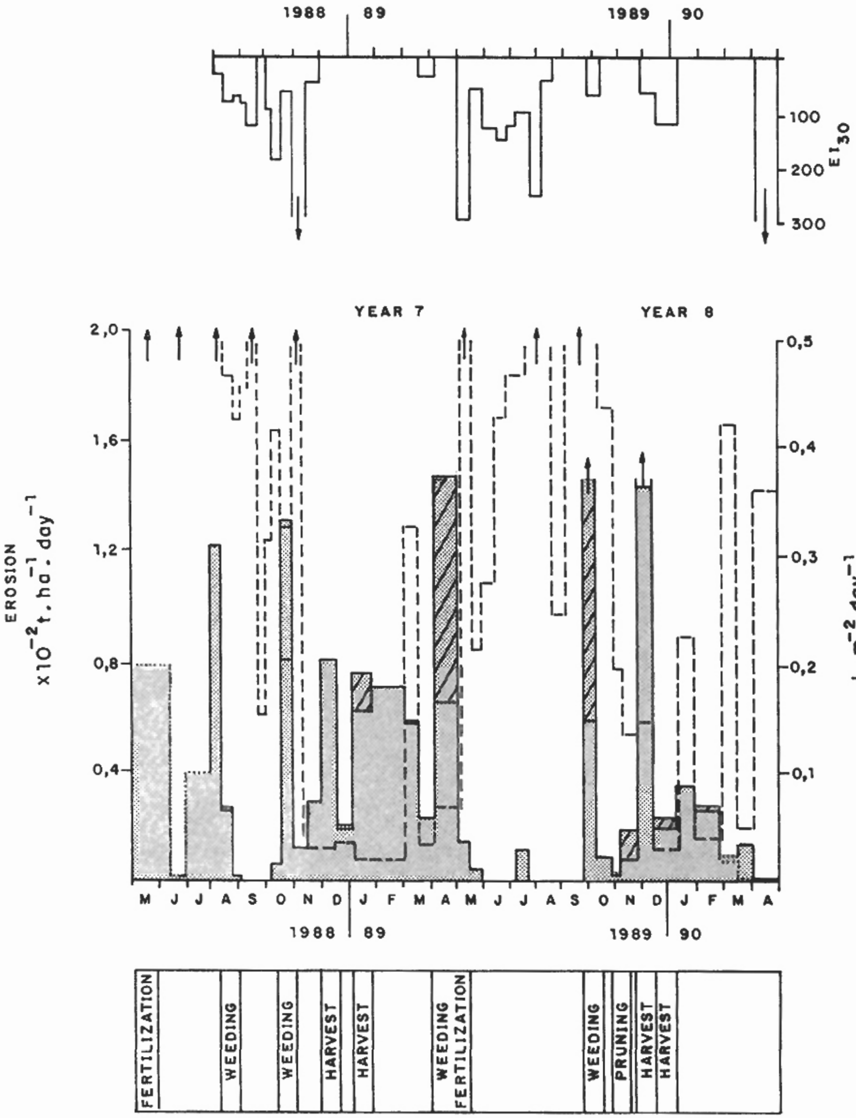

Fig. 3. Erosion in the sun coffee plantation (7 and 8 year old): (1) In the center graph, the relation between erosion (shaded, the striped area indicating the fraction > 4 mm) and the runoff (dotted line); (2) in the upper graph, rainfall erosivity calculated by the index EI_{30} (MJ mm ha^{-1} h^{-1}), and (3) in the lower graph, agricultural activity.

ha^{-1}, 2.3% of total layer, in shade plantation, and 0.90 t ha^{-1}, 1.0% of total layer, in sun plantation) and as a consequence larger losses could be expected to occur without this being an indication that stronger erosive processes are occurring within this plantation. Coarse fraction contributes very little to the maintenance of the agricultural characteristics, and its loss is therefore not as important as the loss of the other fraction.

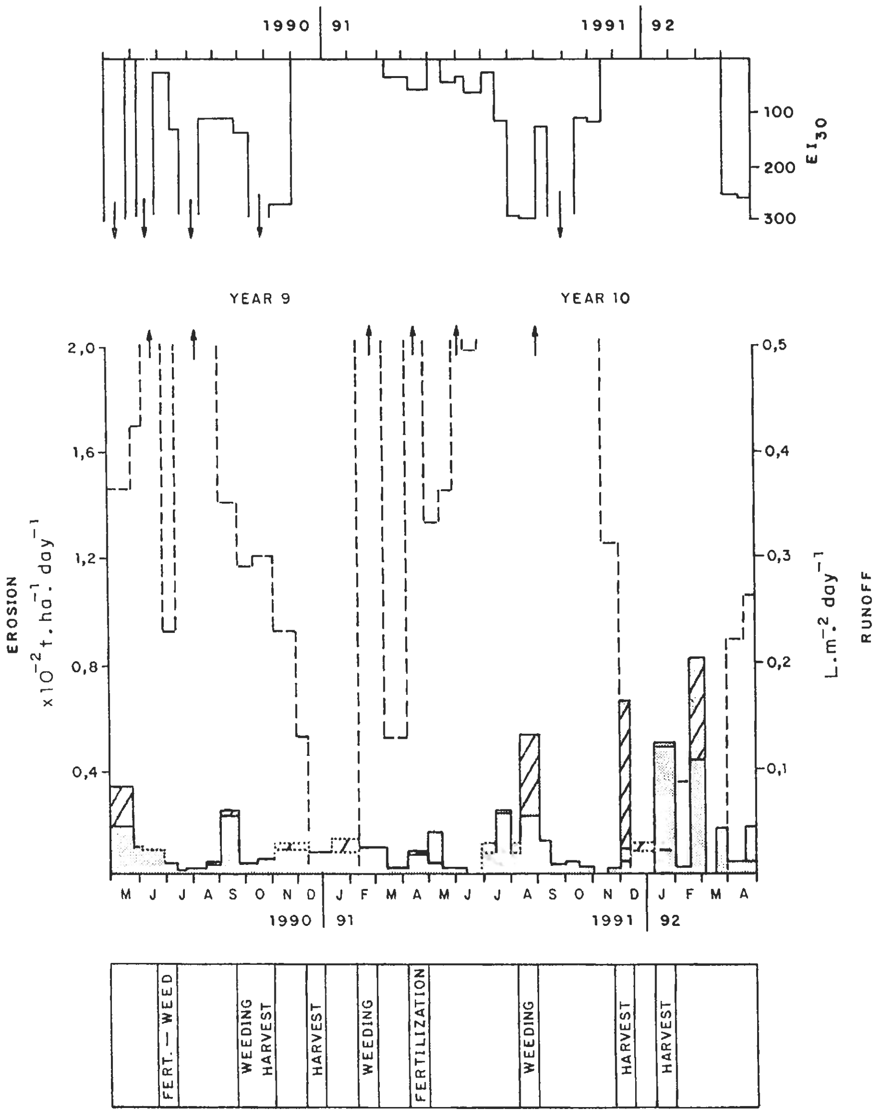

Fig. 4. Erosion in the sun coffee plantation (9 and 10 year old, continuation from Fig. 3): (1) In the center graph, the relation between erosion (shaded, the striped area indicating the fraction > 4 mm) and the runoff (dotted line); (2) in the upper graph, rainfall erosivity calculated by the index EI_{30} (MJ mm ha^{-1} h^{-1}), and (3) in the lower graph, agricultural activity.

Erosion varied greatly between years (Table 1). Average losses of the < 4 mm fraction between May 1988 and April 1990, amounted to 1.15 t ha^{-1} $year^{-1}$ in sun and 0.61 t ha^{-1} $year^{-1}$ in shade plantations, which suggests that it would take 140 years in shade plantations and 79 in sun plantations to erode 1 cm of top soil, considering that 90.89 and 86.01 t ha^{-1} of the < 4 mm fraction are located in the top 10 cm in the sun

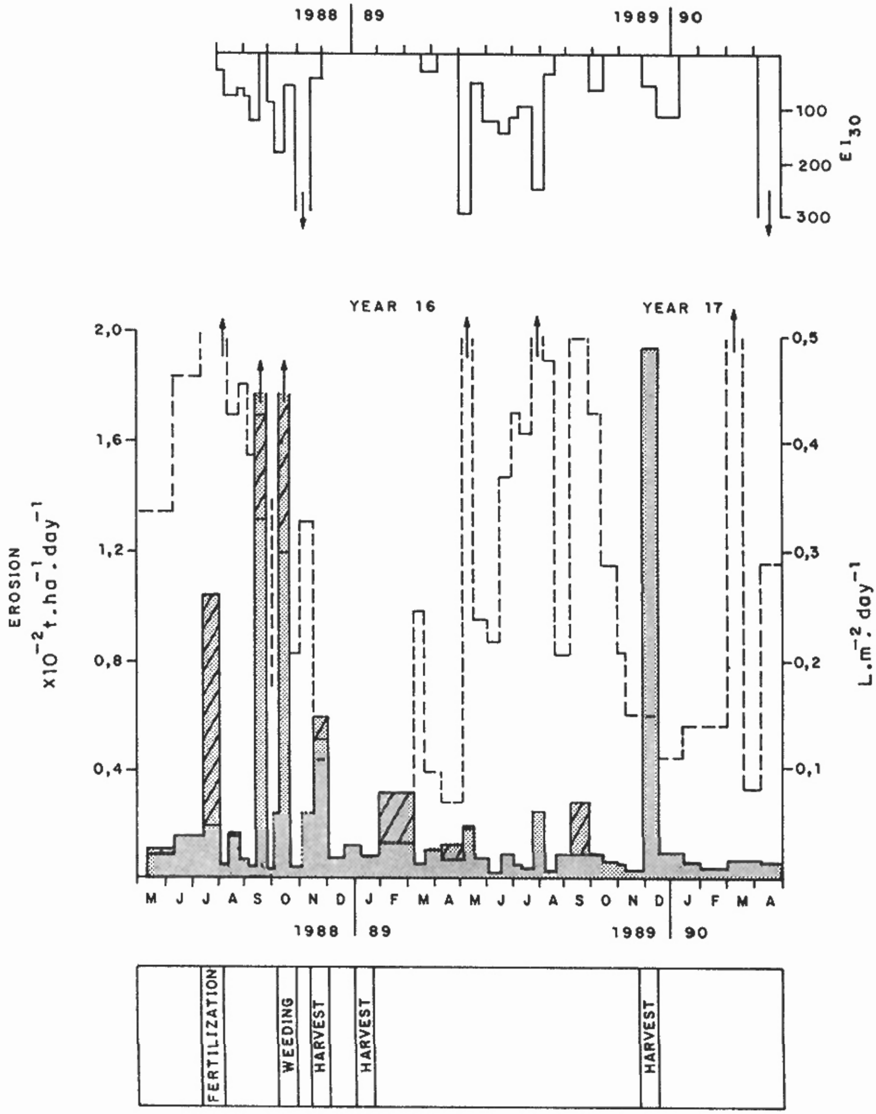

Fig. 5. Erosion in the shade coffee plantation (16 and 17 year old): (1) In the center graph, the relation between erosion (shaded, the striped area indicating the fraction > 4 mm) and the runoff (dotted line); (2) in the upper graph, rainfall erosivity calculated by the index EI_{30} (MJ mm ha^{-1} h^{-1}), and (3) in the lower graph, agricultural activity.

and shade plantations respectively (total soil: 91.82 t ha^{-1} in sun plantation and 88.06 t ha^{-1} in shade plantation).

During the first year of the establishment phase of a sun coffee plantation the disturbance to the system resulted in an important increase in erosion. Firstly, original

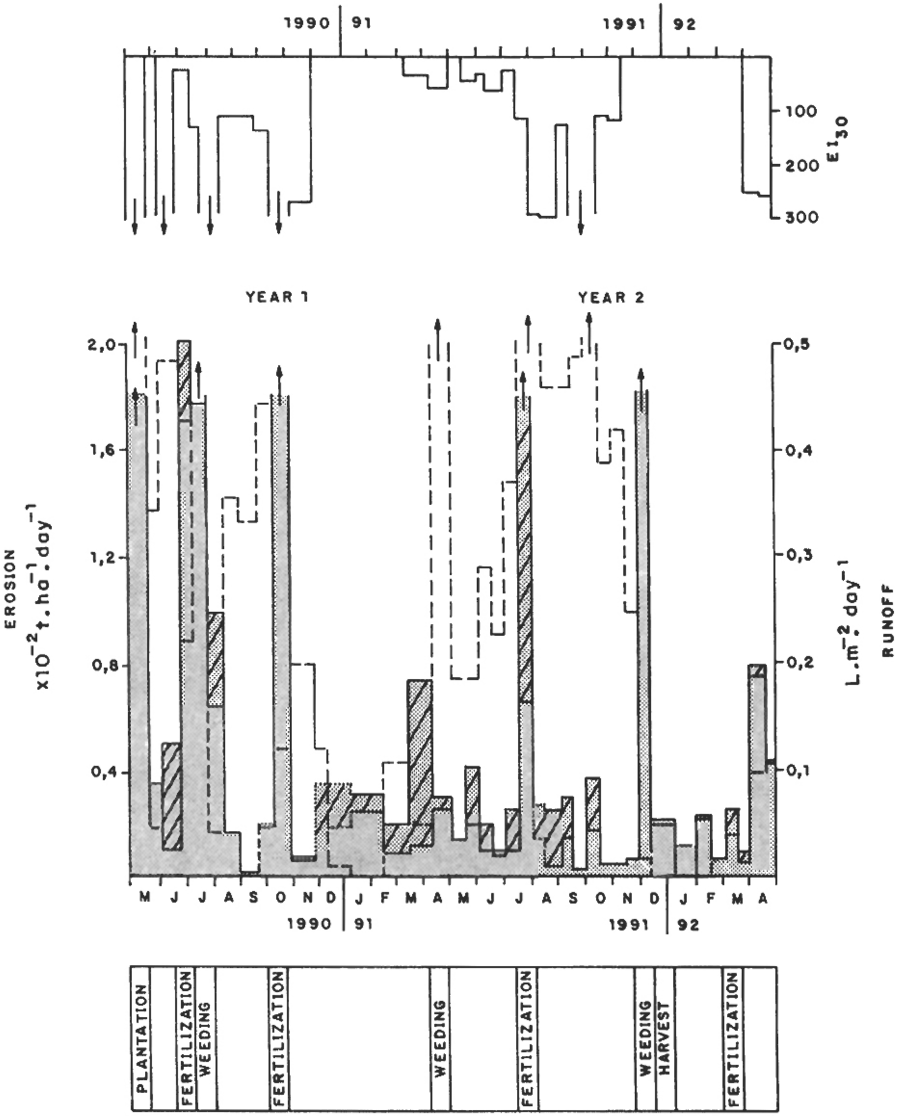

Fig. 6. Erosion in the sun coffee plantation in the first and second year (continuation from Fig. 5): (1) In the center graph, the relation between erosion (shaded, the striped area indicating the fraction > 4 mm) and the runoff (dotted line); (2) in the upper graph, rainfall erosivity calculated by the index EI_{30} (MJ mm ha^{-1} h^{-1}), and (3) in the lower graph, agricultural activity.

vegetation was cut down (which in our case was a shade coffee plantation), secondly, holes were made and small coffee plants were transplanted, thirdly, the new plants were fertilized and finally the area was weeded. The disturbance caused by these activities (especially opening the holes) lasted for several months. More than four times the

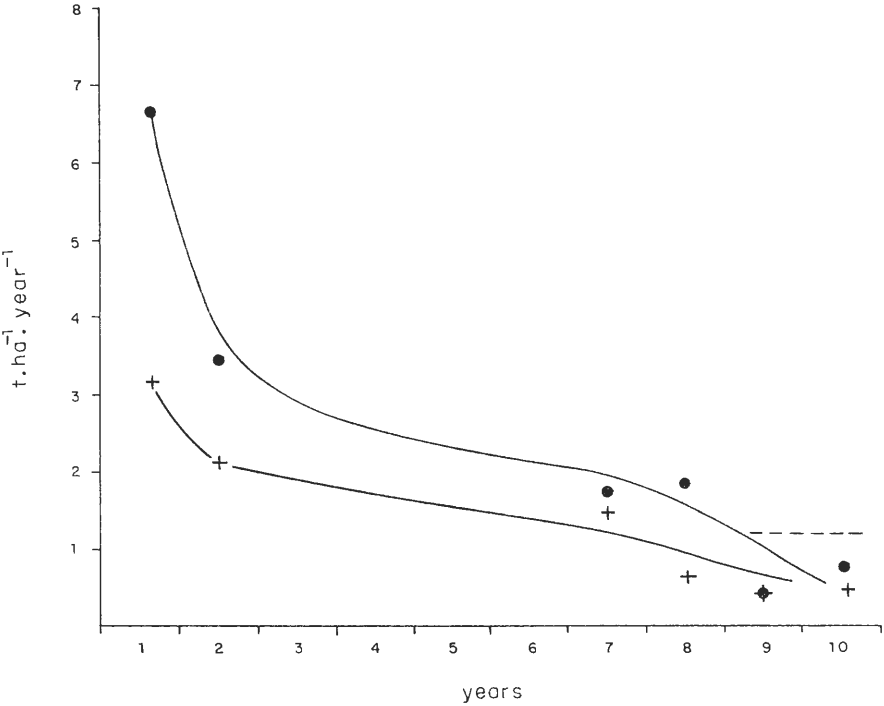

Fig. 7. Erosion in sun coffee plantations of different ages: (·) Total erosion, (+) < 4 mm fraction.

average loss of the mineral fraction < 4 mm in a 7–10 year old sun coffee plantation (0.77 t ha^{-1} year^{-1}) was recorded for the first year of plantation (3.22 t ha^{-1} year^{-1}), and more than six times the average loss if all the mineral fraction is considered. Suarez

Table 2
Seasonality of total precipitation (PT) and runoff (mm). Year: from May to April

Year	Season	PT	Shade coffee (16–17 years)	Sun coffee (1–2 years)	Sun coffee (7–10 years)
1988–1989	rainy	1508	78 (5.2%)		94 (6.2%)
	dry	239	9 (3.8%)		8 (3.3%)
	total	1747	87 (5.0%)		102 (5.8%)
1989–1990	rainy	1452	75 (5.2%)		95 (6.5%)
	dry	301	22 (7.3%)		21 (7.0%)
	total	1753	97 (5.5%)		116 (6.6%)
1990–1991	rainy	1492		82 (5.5%)	110 (7.4%)
	dry	314		12 (3.8%)	26 (8.3%)
	total	1806		94 (5.2%)	136 (7.5%)
1991–1992	rainy	1645		89 (5.4%)	129 (7.8%)
	dry	163		7 (4.3%)	9 (5.5%)
	total	1808		96 (5.3%)	138 (7.7%)

de Castro and Rodriguez (1955, cited in Sanchez, 1976) report that erosion is about three times greater during the establishment phase (1.80 t ha^{-1} compared to 0.60 t ha^{-1} of an established plantation in Colombia).

Considering the total losses, Fig. 7 presents an estimate of the rates of loss that could occur in the first ten years of a sun coffee plantation, with an average for the last four years of 1.20 t ha^{-1} $year^{-1}$ on total erosion and 0.77 on < 4 mm fraction (with annual oscillations due to causes that are analyzed, and that depend on agricultural activities). In agreement with this tendency, a loss of 25.5 t ha^{-1} would occur up to the tenth year, or 15 t ha^{-1} if only < 4 mm fraction is taken into account.

All results show that erosion in established plantations was low. Other authors also report low erosion values for coffee plantations in mountains of tropical America: Lizaso (1980) reports 1.36 t ha^{-1} in the three months with the highest precipitation in the northeast Venezuelan Andes, Renda et al. (1988) studying shade coffee plantations in Cuba, report 0.0035 and 0.0012 t ha^{-1} for 12° and 9° slopes respectively under artificial rain of 25 mm (with 1.60 and 1.85 mm min^{-1}).

4.2. *Erosive mechanisms*

Various factors have been traditionally reported to be fundamentally responsible for erosion in rainy climates: rainfall erosivity, erodibility of the soils, degree and length of the slope, vegetation cover and land use. In this case, the first three factors are the same in both plantation types, and differences in total loss therefore depend on vegetation cover and the type of land management. One presumes that an increase in vegetation cover and litter would reduce the effects of rainfall erosivity, and erosion should be reduced; it could therefore be expected that the shade coffee plantation will show less erosion as it is protected by more vegetation.

The annual rhythm of erosion (Figs. 3–6) shows differences in each plantation. Runoff was lower under shade coffee (Table 2) probably due to a larger interception by foliage and litter and had different patterns than rainfall erosivity (which was low) and runoff. During the first year of establishment runoff was in the same order (Table 2), since litter was still high and infiltration rate was larger. But, correlation between runoff and erosion was not significant neither comparing plantations (shade coffee $R^2 = 0.016$, sun coffee 1–2 years $R^2 = 0.021$, sun coffee 7–10 years $R^2 = 0.002$), nor comparing seasons (rainy season $R^2 < 0.3$ and dry season $R^2 < 0.01$ in all plantations).

On the other hand, the human disturbance caused by agricultural activity was highly related to the magnitude of losses (Figs. 3–6). Differences between erosion (< 4 mm) with and without human activities were significant: shade plantation ANOVA, $F = 6.29$, $P < 0.05$, sun plantation in full production ANOVA, $F = 9.78$, $P < 0.05$, and first year of sun coffee plantation ANOVA, $F = 17.74$, $P < 0.05$.

The analysis of frequency of agricultural activities in the plantations studied indicates that, on average, fertilization occurs once a year in a shade plantation, with one or two harvests depending on the year and just one weeding or pruning (2.5 human activities each year). In the sun coffee plantation the activities are more frequent, with an annual average of one fertilization, two weedings and two harvests (five incursions per year). An increase in human disturbance during the dry season increases mineral fraction losses (Table 1). Agricultural activities include the effects of many people trampling over the field, and in these steep slopes each footstep displaces the first few centimeters of soil when it is predominantly dry.

In well-established plantations, the differences in vegetation cover (82% in the shade coffee plantation and 66% in sun plantation) and litter thickness (1.15 kg dry m^{-2} in shade coffee plantation and 0.36 in sun plantation, Ataroff and Monasterio, 1996b) can be fundamental in determining the magnitude of losses during the dry season when the first few centimeters of soil are dry and the possibility of disintegration is greater. During this period even an isolated light rainfall, after people have walked over the plantation, breaks up the aggregates and the runoff water (only a little amount) drags the material away. This is most frequently observed where the soil is less protected, as in the sun coffee.

During the first year of establishment there were no important activities during the dry season, so the erosion was less in this period (Table 1). The removal of the old coffee plants and the planting of the new ones created an important alteration in the plantation, resulting in immediate large losses, and even greater losses two months later when fertilization and weeding took place (Fig. 6). Five months later a second fertilization caused a further loss. However, during the second year losses were reduced significantly, although they were higher than those registered in a 7–10 years old sun coffee plantation as a consequence of human activities during the dry season.

Agricultural activities explain three of the four peaks of material loss in the shade coffee, six of the seven peaks in the 7–8 year old sun coffee, four of the six peaks in the 9–10 year old sun coffee and six of the eight peaks in the 1–2 year old sun coffee plantation.

5. Conclusions

The current results indicate that despite the larger losses in the sun plantation, both types of management show very low erosion after the plantation has become established. The fine mineral fraction loss (< 4 mm) constitutes the most important difference between the sun and shade plantations, and probably that of the greatest consequence. Over the same period of two years this loss was the double in the sun plantation than in the shade plantation. More than 98% of material from the superficial layer is found in this fraction and this loss may therefore be important for this soil which is only functional for the first 30 cm.

However, until we have an idea of the rates of soil formation for this zone, the values of lost material may be considered low. The maximum rate of mineral fraction loss (presumed to be that of the first year after the transformation from shade to sun) also shows moderate values.

In the zone studied, rainfall erosivity and runoff are low in all plantations types, making the differences in agricultural activities the principal factor in mineral fraction removal. Shade plantations that require less human disturbance have the least erosion.

The erosion values for the coffee plantations in full production correspond to the most favorable conditions for the soil, where minimum disturbance occurs due to: (1)

Sufficient time having passed since the establishment phase (7–10 years for the sun plantation, 16–17 years for the shade plantation) and (2) both being in full production and with equivalent ages with respect to the average life of a producing coffee plantation. In the best of cases, this situation could be maintained until the plantations become old: in 30 years for the shade plantation and six years for the sun plantation. After this period of time it would be necessary to eliminate the old plants and prepare the land for a new plantation, which would provoke an important increase in erosion as already shown. The frequency of this transformation is more than double in sun coffee plantations than in shade coffee plantations.

The importance of water balance appears to be limited with respect to erosion although it is evident that, as a consequence of greater evaporation on the soil surface of the sun coffee plantation, the dryness of the first few centimeters of soil facilitates soil displacement by human footsteps. Those years of greater movement in the plantations in the dry season resulted in higher erosion rates.

Despite the steep slope (31°) runoff is small in proportion to rainfall which hits the soil surface (7.1% of effective precipitation in shade coffee and 8.4% in sun coffee plantation, Ataroff and Monasterio, 1996b) indicating that these soils have a high infiltration capacity, perhaps being more susceptible to mass movements than to superficial laminar erosion.

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