CHAPTER 5

Soil Carbon Erosion and Its Selectivity at the Plot Scale in Tropical and Mediterranean Regions

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CONTENTS

5.1 INTRODUCTION

Global warming is one of the greatest challenges of the twenty-first century (Robert, 2001). At the human time scale, climate change is closely linked to the increasing atmospheric concentration of greenhouse gases (GHGs), which are mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (IPCC, 2001). It is estimated that land use and land-use change and forestry (LULUCF) represent 34% of GHG emissions globally, and 50% of GHG emissions in the tropics and subtropics (IPCC, 2001). Due to the importance of carbon (C) fluxes in the processes relating to LULUCF, there is a renewed interest in studies dealing with the effects of land use and management on C balances. However, such studies generally focus on changes in soil and biomass C or on GHG emissions (mainly CO_2), but rarely take into account C fluxes resulting from erosion. In experiments conducted to determine the effects of cropping systems on C budgets, erosion is generally considered as negligible. Several authors have suggested that this assumption is not valid even when experiments are conducted on relatively flat land with slope gradient of less than 1% (Boli, 1996; Roose, 1996). Thus, erosion and eroded C cannot be ignored (Voroney et al., 1981; Gregorich et al., 1998; Mitchell et al., 1998). Indeed, erosion is considered the most widespread form of soil degradation (Gregorich et al., 1998), with water being its most common agent. Land areas affected by water and wind erosion are estimated at 1100 and 550 Mha respectively (Lal, 2003); those affected by tillage erosion are not precisely known, but are equally important (Govers et al., 1999). Additionally, as soil organic carbon (SOC) has a low density and is concentrated near the soil surface, it is one of the first soil constituents removed by erosion (Roose, 1977; Lowrance and Williams, 1988). Furthermore, erosion is one of the only soil processes that can remove stable soil SOC in large quantities (Starr et al., 2000).

Soil erosion consists of detachment, transport, and deposition of soil particles (Roose, 1981; Lal, 2001). The main mechanisms of water erosion detachment are disintegration of soil aggregates by slaking, cracking, dispersion, and shearing by raindrop impact or runoff. Particles are transported by runoff and splash resulting from the raindrop impact (Lal, 2001). The shearing and transport capacities of runoff increase with the increase in slope length and steepness. Water erosion then transforms from sheet (interrill) erosion, in which detachment and transport are caused by raindrops and shallow surface flow, to rill erosion, dominated by runoff concentrated into discernible channels (Jayawardena and Bhuiyan, 1999). As surface soil is enriched in SOC, its erosion also results in SOC erosion. The carbon enrichment ratio (CER) is defined as the ratio of SOC content in sediments to that in the topsoil (0 to 10 cm depth in general) (Roose, 1977).

The quantification of SOC erosion requires the quantification of soil losses and the determination of sediment SOC content. Soil losses may be assessed at different scales: catchment ($> 10^4$ m^2), plot (10 to 10^4 m^2) and microplot (< 10 m^2) (Mutchler et al., 1988; Hudson, 1993). Catchments are generally heterogeneous in terms of soil and land management, and the contributions of the spatial subunits are often difficult to distinguish (Roose, 1981; Le Bissonnais et al., 1998). Measurements at the microplot scale underestimate soil losses because runoff flow cannot gain velocity and concentrate on a short slope (Le Bissonnais et al., 1998). At the intermediate plot scale, slope length is sufficient for runoff to concentrate, and most of the sedimentation is avoided as long as slope gradient and soil surface roughness are uniform. Additionally, such plots can be easily established in homogeneous edaphic and vegetal conditions. Consequently runoff plots have been widely used for erosion studies (Mutchler et al., 1988; Roose and Sarrailh, 1989; Hudson, 1993). Other methods based on ^{137}Cs analysis and measurement of magnetic susceptibility have also been used to estimate soil redistribution over the landscape. In addition to being innovative and sophisticated, these methods provide pluri-decennial balances of soil movements. Nonetheless, these methods are not the most suitable to assessing water erosion and the effects of some of its determinants (e.g., land management). Moreover, variability in ^{137}Cs assessment from noneroded references remains an important concern as regards the first method, as well as variability in parent materials (with different magnetic properties) regarding the second one (Sutherland, 1996; De Jong et al., 1998).

The objective of this paper is to collate and synthesize data of numerous experiments regarding the effect of land use and management on SOC losses by water erosion in runoff plots representing a wide range of tropical and Mediterranean environments, with a range of climate, slope, soil, and management conditions. Factors affecting CER of sediments are also discussed.

5.2 SITES, MATERIALS, AND METHODS

5.2.1 Sites

Table 5.1 and Table 5.2 present the location, altitude, slope gradient, annual rainfall, soil type, topsoil texture (stoniness and clay content), topsoil SOC content, and land use of the 54 runoff plots under study in tropical and Mediterranean regions, respectively. Tropical regions may be divided into three groups: humid West Indies, humid West Africa, and subhumid West and Central Africa.

In the humid West Indies (2200-mm yr^{-1} rainfall), seven runoff plots were established near St. Joseph in Martinique. Soils are very acidic and clayey Inceptisols developed from volcanic ashes on steep slopes (10 to 40%). Uncultivated areas are forested (Khamsouk, 2001).

In the humid West Africa (1400- to 1900-mm yr^{-1} rainfall), six runoff plots were established in Adiopodoumé (Roose, 1979b), Azaguié (Roose and Godefroy, 1977), and Divo (Roose, 1981), in southern Ivory Coast. Soils are acidic and well-drained sandy loam Ultisols developed from sands, schist, or granite on half orange-shaped hills. Uncultivated areas are forested.

In the subhumid West and Central Africa (600- to 1300-mm yr^{-1} rainfall, concentrated within few months), 18 runoff plots were established in Korhogo (Roose, 1979a) and Bouaké (Roose, 1981) in northern Ivory Coast, Gonsé (Roose, 1978) and Saria (Roose, 1981) in western Burkina Faso, Djitiko in southwestern Mali (Diallo, 2000), Séfa in southwestern Senegal (Roose, 1967), and Mbissiri in northern Cameroon (Boli, 1996). Soils are either sandy Ultisols, Inceptisols, and Alfisols developed from granite and sandstone on long slopes (declivity < 3%) below residual hills with ironstone, or Alfisols with Vertic properties developed from schist in plains. Uncultivated areas are under bush or woody savannas that are traditionally burnt during the dry season.

In the Mediterranean regions, 23 runoff plots were established near Médéa, Mascara, and Tlemcen in northwestern Algerian highlands (Arabi, 1991; Roose et al., 1996; Morsli et al., 2004). Total annual rainfall is low (350- to 550-mm yr^{-1}) but intense rain storms often occur at the end of the summer. Soils are Mollisols, Inceptisols, and Vertisols developed on steep slopes (10 to 40%), with high clay and calcium contents, and often containing a high proportion of gravels and stones. Uncultivated areas are generally covered by matorral due to grazing by sheep and goats.

In total, 54 runoff plots established represent a wide range of land uses and vegetation covers: uncultivated plots with little disturbance (i.e., forests or savannas) or some disturbances (i.e., burnt savanna or matorral used as rangeland); plots previously cultivated but now under fallow, or orchard and vineyard; cultivated plots based on cropping systems involving either intensive tillage and some organic inputs (cereals e.g., maize *Zea mays*, cotton *Gossypium sp.*), direct drilling with residue mulch (idem.), or infrequent tillage with large biomass (banana *Musa sp.*, sugar cane *Saccharum officinarum*); and bare tilled soil as baseline for soil erodibility assessment.

5.2.2 Measurement of Soil Erosion

Most runoff plots were 100-m^2 in area (20 × 5 m), except in Martinique where cultivated plots were 200 m^2 (20 × 10 m), and in Médéa (Algeria) where plot area ranged from 80 to 220 m^2. Each runoff plot was surrounded by half-buried metal sheets and fitted out with a collector draining runoff and sediments into tanks arranged in series. The first tank trapped coarse sediments (aggregates, gravels, coarse sands, litter). When full, the overflow moved through divisors into two tanks in series, which were used to measure the runoff amount and suspended sediments (the third tank was necessary for rainfall events resulting in large runoff volume).

Wet coarse sediments were collected in the first tank after each rainfall event or sequence of events, and weighed. The weight of dry coarse sediments was either determined by oven drying of aliquots, or by using calibration curves drawn up by weighing increasing amounts of dry topsoil in a bucket filled up with water. These different determinations were supposed to give equivalent

Table 5.1 Description of the Runoff Plots Established in Tropical Regions (Soil Properties Refer to 0 to 10 cm)

Location		Altitude m	Slope %	Rainfall mm yr^{-1}	Soil Type	Gravels %	Clay %	Land Management or Vegetation Cover	Soil OC g kg^{-1}	Erosion Mg ha^{-1} yr^{-1}	Eroded OC kg ha^{-1} yr^{-1}	CER	Years
St Joseph Mart.[1]	14°40'N, 61°00'W	70	10	2220	oxic Dystrudept	0	68	bare tilled soil	15.1	85.8	1249	1.0	2
St Joseph Mart.[1]	14°40'N, 61°00'W	70	10	2220	oxic Dystrudept	0	68	pineapple, ridged	16.2	17.2	294	1.1	2
St Joseph Mart.[1]	14°40'N, 61°00'W	70	10	2220	oxic Dystrudept	0	68	banana, mulched	17.9	0.5	12	1.5	2
St Joseph Mart.[1]	14°40'N, 61°00'W	70	10	2220	oxic Dystrudept	0	68	sugar cane, mulched	16.5	0.1	2	1.7	2
St Joseph Mart.[1]	14°40'N, 61°00'W	70	10	2220	oxic Dystrudept	0	68	flat pineapple, mulched	16.7	0.0	1	2.1	2
St Joseph Mart.[1]	14°40'N, 61°00'W	70	25	2220	oxic Dystrudept	0	68	bare tilled soil	17.0	127.5	2274	1.0	2
St Joseph Mart.[1]	14°40'N, 61°00'W	70	40	2220	oxic Dystrudept	0	68	bare tilled soil	18.8	147.4	2999	1.1	2
Adiopodoumé IC[2]	05°20'N, 04°08'W	30	7	1900	typic Hapludult	0	11	maize	10.8	99.1	1982	1.9	2
Adiopodoumé IC[2]	05°20'N, 04°08'W	30	11	1800	typic Hapludult	0	13	forest	18.6	0.1	13	14.0	10
Adiopodoumé IC[2]	05°20'N, 04°08'W	30	65	1800	typic Hapludult	0	15	forest	21.8	0.5	42	4.3	10
Azaguié IC[3]	05°33'N, 04°03'W	80	14	1640	typic Kandiudult	0	13	forest	11.3	0.2	12	7.0	7
Azaguié IC[3]	05°33'N, 04°03'W	80	14	1640	typic Kandiudult	0	15	banana	19.1	1.8	105	3.0	7
Divo IC[4]	05°48'N, 05°18'W	<100	10	1400	oxyaquic Kandiudult	0	26	forest	12.4	0.1	8	4.9	7
Korhogo IC[5]	09°25'N, 05°39'W	390	3	1280	typic Kandiustult	69	16	bush savanna (burnt)	15.8	0.1	5	3.4	8
Korhogo IC[5]	09°25'N, 05°39'W	390	3	1280	typic Kandiustult	69	16	maize	8.1	5.4	63	1.5	8
Séfa Sénégal[6]	13°10'N, 15°30'W	<50	2	1200	typic Kandiustalf	0	10	peanut, rice, sorghum	4.6	9.3	73	1.7	9
Bouaké IC[7]	07°46'N, 05°06'W	370	4	1200	typic Kandiustult	15	6	woody savanna	15.8	0.1	2	2.6	4
Djitiko Mali[8]	12°05'N, 08°25'W	350	2	1080	typic Haplustalf	0	25	old (bush) fallow	11.0	4.8	125	2.4	1
Djitiko Mali[8]	12°05'N, 08°25'W	350	2	1080	typic Haplustalf	0	25	maize/cotton plowed	6.9	18.4	330	2.6	1
Djitiko Mali[8]	12°05'N, 08°25'W	350	2	1080	typic Haplustalf	0	25	maize/cotton no-tilled	8.9	7.4	154	2.3	1
Djitiko Mali[8]	12°05'N, 08°25'W	350	2	1080	vertic Haplustept	0	26	old (bush) fallow	38.4	1.7	190	2.9	1
Djitiko Mali[8]	12°05'N, 08°25'W	350	2	1080	vertic Haplustept	0	26	maize/cotton plowed	38.1	14.1	280	0.5	1
Djitiko Mali[8]	12°05'N, 08°25'W	350	2	1080	vertic Haplustept	0	26	maize/cotton no-tilled	40.5	6.0	358	1.5	1
Mbissiri Cam.[9]	08°23'N, 14°33'E	370	2	860	typic Haplustalf	0	7	cotton plowed (recent)	3.5	8.7	90	3.0	1
Mbissiri Cam.[9]	08°23'N, 14°33'E	370	2	860	typic Haplustalf	0	7	idem with manure	3.0	12.2	111	3.0	1
Mbissiri Cam.[9]	08°23'N, 14°33'E	370	2	860	typic Haplustalf	0	7	cotton minitilled (recent)	5.0	6.0	57	1.9	1
Mbissiri Cam.[9]	08°23'N, 14°33'E	370	2.5	860	typic Haplustalf	0	8	cotton plowed (old)	3.0	40.4	160	1.3	1
Mbissiri Cam.[9]	08°23'N, 14°33'E	370	2.5	860	typic Haplustalf	0	8	idem with manure	3.0	15.2	85	1.9	1
Mbissiri Cam.[9]	08°23'N, 14°33'E	370	2.5	860	typic Haplustalf	0	8	cotton minitilled (old)	3.0	2.4	12	1.8	1
Gonsé BF[10]	12°22'N, 01°19'W	300	0.5	700	kanhaplic Haplustalf	0	8	woody savanna (burnt)	5.5	0.2	9	10.7	6
Saria BF[11]	12°16'N, 02°09'W	300	0.7	640	typic Plinthustalf	0	13	young grass fallow	4.7	0.5	9	3.6	3

[1] Khamsouk (2001), Blanchart et al. (this issue); [2] Roose (1979b); [3] Roose and Godefroy (1977); [4] Roose (1981); [5] Roose (1979a); [6] Roose (1967); [7] Roose (1981); [8] Diallo et al. (2004); [9] Boli (1996), Bep A Ziem et al. (2004); [10] Roose (1978); [11] Roose (1981).

Abbreviations for locations: Mart. Martinique; IC Ivory Coast; Cam. Cameroon; BF Burkina Faso.

Table 5.2 Description of the Runoff Plots Established in the Mediterranean Regions (Algeria; Soil Properties Refer to 0 to 10 cm)

Location		Altitude m	Slope %	Rainfall mm yr^{-1}	Soil Type	Gravels %	Clay %	Land Management or Vegetation Cover	Soil OC g kg^{-1}	Erosion Mg ha^{-1} yr^{-1}	Eroded SOC kg ha^{-1} yr^{-1}	CER	Years
Médéa[1]	36°14'N, 02°51'E	900	14	550	typic Haploxerert	4	64	improved cereals	5.2	0.0	0	1.8	5
Médéa[1]	36°14'N, 02°51'E	900	14	550	typic Haploxerert	4	65	cereal with legume	6.8	0.0	0	1.3	5
Médéa[1]	36°14'N, 02°51'E	900	40	550	typic Haploxeroll	16	43	matorral with shrubs	9.6	0.1	1	2.1	5
Médéa[1]	36°14'N, 02°51'E	900	40	550	typic Haploxeroll	16	50	idem but regrassed	7.1	0.0	0	3.1	5
Médéa[1]	36°14'N, 02°51'E	900	35	550	typic Haploxerept	0	51	orchard on bare soil	7.1	1.4	16	1.6	5
Médéa[1]	36°14'N, 02°51'E	900	35	550	typic Haploxeroll	20	39	vineyard, cereal, legume	8.2	0.1	1	1.2	5
Mascara[2]	35°20'N, 00°17'E	640	20	470	typic Haploxeroll	0	17	rangeland (matorral)	10.2	1.6	42	2.5	1
Mascara[2]	35°20'N, 00°17'E	640	20	470	typic Haploxeroll	0	17	cereals	10.3	0.8	22	2.7	1
Mascara[2]	35°20'N, 00°17'E	640	20	470	typic Haploxeroll	0	17	bare tilled soil	10.0	8.5	136	1.6	1
Mascara[2]	35°20'N, 00°17'E	640	20	470	typic Haploxeroll	0	17	protected fallow	12.3	0.5	24	3.9	1
Mascara[2]	35°20'N, 00°17'E	670	40	470	vertic Haploxeroll	0	57	rangeland (matorral)	11.3	1.2	31	2.3	1
Mascara[2]	35°20'N, 00°17'E	670	40	470	vertic Haploxeroll	0	57	cereals	11.6	1.1	25	2.0	1
Mascara[2]	35°20'N, 00°17'E	670	40	470	vertic Haploxeroll	0	57	bare tilled soil	10.2	6.8	95	1.4	1
Mascara[2]	35°20'N, 00°17'E	670	40	470	vertic Haploxeroll	0	57	protected fallow	12.3	0.6	21	2.8	1
Tlemcen[2]	34°50'N, 01°10'W	450	21	450	typic Haploxeroll	46	20	bare tilled soil	18.6	3.9	78	1.1	1
Tlemcen[2]	34°50'N, 01°10'W	450	21	450	typic Haploxeroll	46	20	rangeland (matorral)	23.0	0.7	28	1.7	1
Tlemcen[2]	34°50'N, 01°10'W	450	21	450	typic Haploxeroll	46	20	protected fallow	33.3	0.7	34	1.4	1
Tlemcen[2]	34°50'N, 01°10'W	450	15	420	vertic Haploxeroll	7	50	bare tilled soil	8.0	1.8	19	1.3	1
Tlemcen[2]	34°50'N, 01°10'W	450	15	420	vertic Haploxeroll	7	50	cereals/rangeland	9.3	1.6	27	1.8	1
Tlemcen[2]	34°50'N, 01°10'W	450	15	420	vertic Haploxeroll	7	50	fertilized cereal (contour)	10.3	1.6	33	2.0	1
Tlemcen[2]	34°50'N, 01°10'W	450	10	360	typic Haploxerept	42	37	bare tilled soil	6.3	3.2	31	1.6	1
Tlemcen[2]	34°50'N, 01°10'W	450	10	360	typic Haploxerept	42	37	rangeland (matorral)	6.8	1.8	26	2.1	1
Tlemcen[2]	34°50'N, 01°10'W	450	10	360	typic Haploxerept	42	37	protected fallow	9.4	1.0	18	1.9	1

[1] Arabi (2004); [2] Morsli et al. (2004).

results. Suspended sediment concentration in runoff was assessed by flocculation and oven drying of aliquots collected in the second tank or in every tank, and was used in conjunction with the runoff amount to determine the weight of dry suspended sediment (runoff amount was assessed by measuring the volume of water in each tank and multiplying it by the coefficients depending on the number of divisors). Erosion (Mg ha^{-1} yr^{-1}) was calculated as the sum of dry-coarse and dry-suspended sediment amounts for all rainfall events over the year.

5.2.3 Sediment and Soil Analysis

The SOC contents of coarse and suspended sediments were determined separately, on individual samples resulting from "representative" rainfall events, or more frequently, on composite samples resulting from all events that occurred over a given period (e.g., month or season). Topsoil samples (0 to 10 cm) were also collected for SOC analysis. The SOC content was determined using either the Walkley and Black method (Ivory Coast, Senegal, Burkina Faso) or dry combustion in an Elemental Analyser (Martinique, Mali, Cameroon), after possible destruction of carbonates by hydrochloric acid (HCl), or using the Anne method (Algeria) (for these methods, see Nelson and Sommers, 1996). It was assumed that the three methods would give equivalent results. Eroded SOC (kg C ha^{-1} yr^{-1}) was defined as the sum of coarse sediment SOC and suspended sediment SOC over one year.

The gravel content (> 2 mm) of topsoil was determined by dry sieving of air-dry samples. Particle-size analysis of air-dry topsoil samples (< 2 mm) was determined by a combination of dry sieving and sedimentation (pipette method), after destruction of the organic matter and total dispersion (Gee and Bauder, 1986). The clay fraction was defined as < 2 μm.

5.3 RESULTS

5.3.1 Erosion

In general, soil erosion ranged from 0 to 150 Mg ha^{-1} yr^{-1} (Table 5.1 and Table 5.2). The maximum erosion rate was ca. 10 Mg ha^{-1} yr^{-1} in Mediterranean areas, 40 Mg ha^{-1} yr^{-1} in subhumid areas, 100 Mg ha^{-1} yr^{-1} in humid African areas, and 150 Mg ha^{-1} yr^{-1} in humid West Indies areas. It increased with increase in annual rainfall. Similarly, maximum erosion was 40 Mg ha^{-1} yr^{-1} for slope < 5%, 100 Mg ha^{-1} yr^{-1} for 5 to 15% slope, 130 Mg ha^{-1} yr^{-1} for 15 to 30% slope, and 150 Mg ha^{-1} yr^{-1} for 30 to 65% slope. Therefore, maximal soil erosion also increased with increase in slope gradient. In addition to climate and slope gradient, land use also had an important influence on erosion. Soil erosion was divided into the following groups:

- Under 2000-mm yr^{-1} rainfall, bare tilled soils eroded at a rate of 80 to 150 Mg ha^{-1} yr^{-1}, which was also the case under maize for a sandy soil on 7% slope
- Under rainfall > 860 mm yr^{-1}, conventionally tilled cereals and cotton on slope < 3% eroded at a rate of 9 to 40 Mg ha^{-1} yr^{-1} (9 to 20 Mg ha^{-1} yr^{-1} in general), as did pineapple (*Ananas comosus*) on 10% slope (clayey soil)
- Maize and cotton grown with reduced or no till under rainfall of 860 to 1300 mm yr^{-1} and bare tilled soils in Mediterranean regions eroded at a rate of 2 to 9 Mg ha^{-1} yr^{-1}
- Under Mediterranean climate, cultivated plots and rangelands eroded at a rate of 0.7 to 2 Mg ha^{-1} yr^{-1}, as did a banana plantation on a sandy soil with 14% slope in Ivory Coast
- Under all eco-regions, forest, savanna, fallow, and crops with thick mulch (sugar cane, pineapple, banana) eroded at a rate of ≤ 0.7 Mg ha^{-1} yr^{-1}, as did Mediterranean rangelands and cultivated plots on clayey or stony soils (≥ 40% clay or gravels)

Of the 54 plots under study, three fallows (two in Mali and one near Tlemcen, Algeria) did not fit this pattern, and eroded at a rate of 1 to 5 Mg ha^{-1} yr^{-1} (instead of ≤ 0.7 Mg ha^{-1} yr^{-1}). This trend was probably related to previous cropping history, burning, and grazing systems. In general, cultivated plots lost less than 40 Mg ha^{-1} yr^{-1} (and generally less than 20 Mg ha^{-1} yr^{-1}) and plots under natural vegetation less than 5 Mg ha^{-1} yr^{-1} (and generally less than 2 Mg ha^{-1} yr^{-1}).

5.3.2 Eroded Carbon

In general, eroded SOC ranged from 0 to 3 Mg C ha^{-1} yr^{-1} (Table 5.1 and Table 5.2), and its variations with regard to annual rainfall, topography, and vegetation were similar to those for erosion. Indeed, maximum eroded SOC increased with increase in annual rainfall: it was 140, 360, 2000, and 3000 kg C ha^{-1} yr^{-1} in Mediterranean, subhumid African, humid African, and humid West Indies eco-regions, respectively. Maximum eroded SOC also increased with increase in slope gradient, and was 360, 2000, 2300, and 3000 kg C ha^{-1} yr^{-1} for slope < 5%, 5 to 15%, 15 to 30%, and 30 to 65%, respectively. The magnitude of eroded SOC was influenced by vegetation and land management, and can be divided into the following groups:

- Under 2000-mm yr^{-1} rainfall, bare tilled soils (and maize on a sandy soil with 7% slope) eroded SOC between 1000 and 3000 kg C ha^{-1} yr^{-1} (median 2130 kg C ha^{-1} yr^{-1}), and the rate corresponded to the maximum erosion
- Under rainfall > 860-mm yr^{-1}, cereals and cotton on slope < 3%, pineapple on 10% slope (clayey soil), banana plantation on 14% slope (sandy soil), and several Mediterranean bare plots eroded SOC between 50 and 400 kg C ha^{-1} yr^{-1} (median 105 kg C ha^{-1} yr^{-1}); among row crops (cereals, cotton) it was not possible to separate conventional and conservation tillage into two different classes (as had been done for erosion classes), though at a given site conservation tillage generally resulted in less eroded SOC than conventional tillage
- Under Mediterranean climate, cultivated plots, rangelands, and some bare plots eroded SOC between 15 and 50 kg C ha^{-1} yr^{-1} (median 26 kg C ha^{-1} yr^{-1}), in accord with a similar erosion class
- Under all eco-regions, forest, savanna, fallow, and crops with thick mulch (sugar cane, pineapple, banana), as well as Mediterranean rangelands and cultivated plots on clayey or stony soils (≥ 40%), eroded OC < 15 kg C ha^{-1} yr^{-1} (median 10 kg C ha^{-1} yr^{-1}), in accord with a class of minimum erosion rate

Of the 54 plots under study, five fallows did not fit this pattern: two burnt fallows in Mali lost SOC between 100 and 200 kg C ha^{-1} yr^{-1}, and three grazed fallows in Algeria lost SOC between 18 and 25 kg C ha^{-1} yr^{-1} (instead of < 15 kg C ha^{-1} yr^{-1}). Additionally, one forest plot from Ivory Coast lost OC at 42 kg C ha^{-1} yr^{-1}. Moreover, Mediterranean bare tilled soils were separated into two classes (this separation was not clearly defined), whereas conventional and conservation tillage could not be separated. Thus the relationship between land use and eroded SOC was less defined than that reported between erosion and land use.

In general, cultivated plots lost SOC at a rate of less than 400 kg C ha^{-1} yr^{-1} (median 90 kg C ha^{-1} yr^{-1}; 110 and 20 kg C ha^{-1} yr^{-1} for tropical and Mediterranean areas, respectively), and those under natural vegetation less than 50 kg C ha^{-1} yr^{-1} (median 10 kg C ha^{-1} yr^{-1}).

5.3.3 Relationship between Eroded SOC, Erosion, and Topsoil SOC Content

Eroded SOC was strongly correlated with erosion, but this relation was markedly influenced by the few highly erodible plots, and became weaker when they were not taken into account (Table 5.3). A correlation existed between eroded SOC and the product of erosion multiplied by topsoil SOC content (0 to 10 cm), which became much closer than the former when highly erodible plots were not taken into account. Except for the few highly erodible plots, eroded SOC was better

Table 5.3 Correlations between Eroded OC, Erosion, and Topsoil OC Content (0 to 10 cm)

Plots under Consideration	Correlation between Eroded OC and Topsoil OC	Correlation between Eroded OC and Erosion	Correlation between Eroded OC and Erosion × Topsoil OC
All 54 plots	$r = 0.157$, $p > 0.1$	$r = 0.979$, $p < 0.001$	$r = 0.976$, $p < 0.001$
The 50 plots having eroded OC < 400 kg C ha^{-1} yr^{-1} (erosion < 80 Mg ha^{-1} yr^{-1})	$r = 0.409$, $p < 0.01$	$r = 0.631$, $p < 0.001$	$r = 0.739$, $p < 0.001$
The 46 plots having eroded OC < 200 kg C ha^{-1} yr^{-1}	$r = 0.116$, $p > 0.1$	$r = 0.633$, $p < 0.001$	$r = 0.904$, $p < 0.001$

correlated with the product erosion × topsoil SOC than with erosion only. In contrast, eroded SOC was weakly correlated with topsoil SOC.

5.3.4 Carbon Enrichment Ratio of Sediments (CER) as Affected by Erosion and Eroded SOC

In general, CER ranged from 0.5 to 14 (one conventionally tilled maize/cotton plot in Mali yielded 0.5). The highest CER (> 3.0) values were always measured on plots with low erosion (≤ 0.5 Mg ha^{-1} yr^{-1}) and the smallest CER (1.0) on plots with high erosion (> 20 Mg ha^{-1} yr^{-1}). However, the relationship between erosion and CER was not unique, as low CER values were also observed on plots with low erosion (Figure 5.1a):

- Plots with erosion < 1 Mg ha^{-1} yr^{-1} had CER between 1.2 and 14.0
- Plots with erosion between 1 and 20 Mg ha^{-1} yr^{-1} had CER between 1.1 and 3.0
- Plots with erosion > 20 Mg ha^{-1} yr^{-1} had CER between 1.0 and 2.0

More precisely, the five erosion groups (i.e., > 80, 9 to 40, 2 to 9, 0.7 to 2, and < 0.7 Mg ha^{-1} yr^{-1}) had average CER of 1.2 (±0.4), 1.9 (±0.9), 1.7 (±0.4), 2.2 (±0.5), and 3.9 (±3.4), respectively. A similar relationship was observed between eroded SOC and CER (Figure 5.1b). The four eroded SOC groups (i.e., 1000 to 3000, 50 to 400, 15 to 50, and < 15 kg C ha^{-1} yr^{-1}) had average CER of 1.2 (±0.4), 1.9 (±0.8), 2.3 (±0.8), and 3.9 (±3.7), respectively. Linear correlations computed between CER and erosion or eroded SOC were not significant, but they were significant between Ln (CER) and Ln (erosion) or Ln (eroded SOC) ($r = 0.482$, $p < 0.001$, and $r = 0.295$, $p < 0.05$, respectively; Figure 5.1c and d). In general, erosion selectivity for SOC (expressed by CER) increased with a decrease in erosion and eroded SOC.

5.3.5 CER as Affected by Land Use

The preferential removal of SOC was also related to land use. The CER values > 3.0 were observed under forest, savanna, or fallow only, and 12 out of the 15 plots (i.e., 80%) under natural vegetation had CER > 2.4. For these 15 plots, mean CER was 4.6 (±3.5) and median CER 3.4. Mean and median CER were 7.5 (±4.5) and 6.0 under forest, 4.2 (±3.2) and 3.0 under woody savanna or bush fallow, and 2.7 (±1.0) and 2.8 under grass fallow or herbaceous savanna, respectively. In contrast, most of the plots (80%) with CER ≤ 1.1 corresponded to bare tilled soils. Of the eight bare plots, four had CER of 1.0 to 1.1, and four of 1.3 to 1.6. For these bare plots, mean CER was 1.3 (±0.2) and median CER 1.2. Mean CER was 1.0 for bare tilled soils in Martinique, which lost large amount of soil and SOC (> 80 Mg ha^{-1} yr^{-1} and > 1000 kg C ha^{-1} yr^{-1}, respectively), but it was 1.4 for Algerian soils, where soil and SOC losses were much less (2 to 9 Mg ha^{-1} yr^{-1} and 20 to 140 kg C ha^{-1} yr^{-1}, respectively). Plots under cultivation or used as rangeland had CER of 1.1 to 3.0, mean CER was 2.0 (±0.5) and median CER was 1.9. It was difficult to distinguish subgroups:

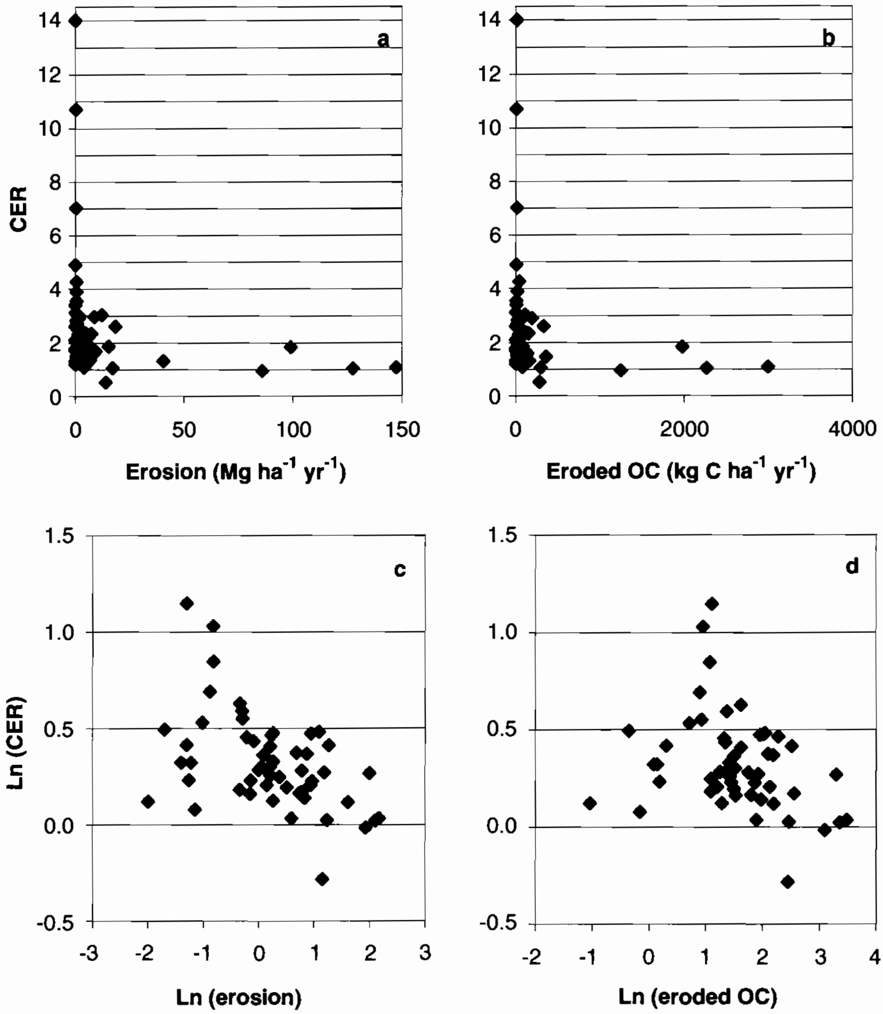

Figure 5.1 Relations between carbon enrichment ratio of sediments (CER) and erosion or eroded OC on the 54 runoff plots under study.

- Fifteen plots under conventionally tilled row crops (cereals, cotton) had CER of 1.1 to 3.0; mean CER was 1.9 (± 0.6) and median was 1.8 (Mediterranean orchard on bare soil was included in this group due to its poor surface cover during the rainy season)
- Four plots under no-till row crops (a fifth plot with contour tillage was included in the same subgroup) had CER of 1.5 to 2.3, and mean and median CER were 1.9 (±0.3)
- Four plots where cultivation practices involved thick mulching had CER ranging from 1.5 to 3.0; mean CER was 2.1 (± 0.7) and median was 1.9
- Six Mediterranean rangelands had CER of 1.7 to 2.5, and mean and median CER were 2.1 (±0.3)

Considering 54 plots, CER values were finally divided into three groups according to land use: bare tilled soils (mean CER 1.3); cultivated plots and rangelands (mean CER 2.0); forest, savanna, and fallows (mean CER 4.6; 2.7 for grass fallow, 4.2 for woody savanna and bush fallow, 7.5 for forest). Mean and median CER did not differ within bare plots and within cultivated plots and rangelands, but the difference was more marked under forest, savanna, and fallow, due to the presence of extreme (i.e., more variable) CER values.

5.3.6 The CER as Expressed by the Relation between Eroded SOC and the Product Erosion × Topsoil SOC

The CER of sediments was also assessed through the relationship between eroded SOC and the product erosion × topsoil SOC content. The eroded SOC is defined as the product of erosion multiplied by SOC content of sediments. Thus plotting eroded SOC against erosion × topsoil SOC is similar to plotting erosion × sediment SOC against erosion × topsoil SOC, and the slope of the regression lines corresponds to the ratio sediment SOC/topsoil SOC (i.e., CER). Plotting eroded SOC against erosion × topsoil SOC produced the following regression equations (Figure 5.2, which includes three scale levels):

- For bare tilled soils, slope of the regression line was 1.1 ($r = 0.999$, $p < 0.001$)
- For cultivated plots and rangelands, the slope was 1.8 ($r = 0.990$, $p < 0.001$; $r = 0.996$ when excluding ridged pineapple from Martinique)
- For forests, savannas, and fallows, the slope was 2.6 ($r = 0.975$, $p < 0.001$), but 2.7 ($r = 0.986$) when excluding one outlier (protected fallow near Tlemcen, Algeria); this group could be further divided into three subgroups:
  - For grass fallow, slope of the regression line was 1.7 ($r = 0.240$, $p > 0.1$); excluding one outlier (protected fallow near Tlemcen, Algeria, where CER was 1.4), the slope was 2.6 ($r = 0.395$, $p > 0.1$)
  - For woody savanna or bush fallow, the slope was 2.7 ($r = 0.992$, $p < 0.001$)
  - For forest, the slope was 4.4 ($r = 0.927$, $p < 0.1$)

Within each group, slope of the regression line was often close to mean or median CER, especially for bare and cultivated plots and rangelands. The difference between mean (or median) CER and slope may be explained by the smaller CER of plots having greater SOC losses, which had more influence in the determination of regression equations (whereas all plots had the same weight when calculating means or medians). Thus slopes of the regression lines tended to be smaller than mean and median CER.

5.4 DISCUSSION

5.4.1 Erosion

The importance of rainfall and slope in water erosion is widely recognized (Wischmeier and Smith, 1978; Roose, 1977; 1996; Lal, 2001), despite some contradictions with regard to the effects of slope steepness (Roose et al., 1996; El-Swaify, 1997; Lal, 1997; Fox and Bryan, 1999). The effect of land use on erosion has also been extensively reported (Wischmeier and Smith, 1978; Roose, 1996; Lal, 2001). Considering the 54 runoff plots in tropical and Mediterranean regions, five erosion groups were distinguished: 80 to 150 Mg ha^{-1} yr^{-1} for bare tilled soils in very humid regions; 9 to 40 Mg ha^{-1} yr^{-1} for conventionally tilled cereals and cotton in humid and subhumid regions; 2 to 9 Mg ha^{-1} yr^{-1} for no-tilled cereals and cotton in subhumid regions and bare tilled soils in Mediterranean regions; 0.7 to 2 Mg ha^{-1} yr^{-1} for crops and rangelands in Mediterranean regions; ≤ 0.7 Mg ha^{-1} yr^{-1} for forests, savannas, fallows, and crops with thick mulch.

The data presented were in agreement with those published in the literature. In Malaysia, Hashim et al. (1995) reported more than 100 Mg ha^{-1} yr^{-1} of erosion on bare tilled soils (3000-mm yr^{-1} rainfall, 18% slope). In Cabo Verde, Smolikowski et al. (2001) estimated erosion of 84 Mg ha^{-1} yr^{-1} on bare tilled soil, and 34 and 0.1 Mg ha^{-1} yr^{-1} under maize-bean association without and with mulch cover, respectively. Though annual rainfall was less (300-mm yr^{-1}), high rainfall erosivity and steep slope gradient (45%) resulted in high erosion rates similar to those presented herein (> 80, 9 to 40 and ≤ 0.7 Mg ha^{-1} yr^{-1}, respectively). In northern Cameroon, Thébé (1987) reported

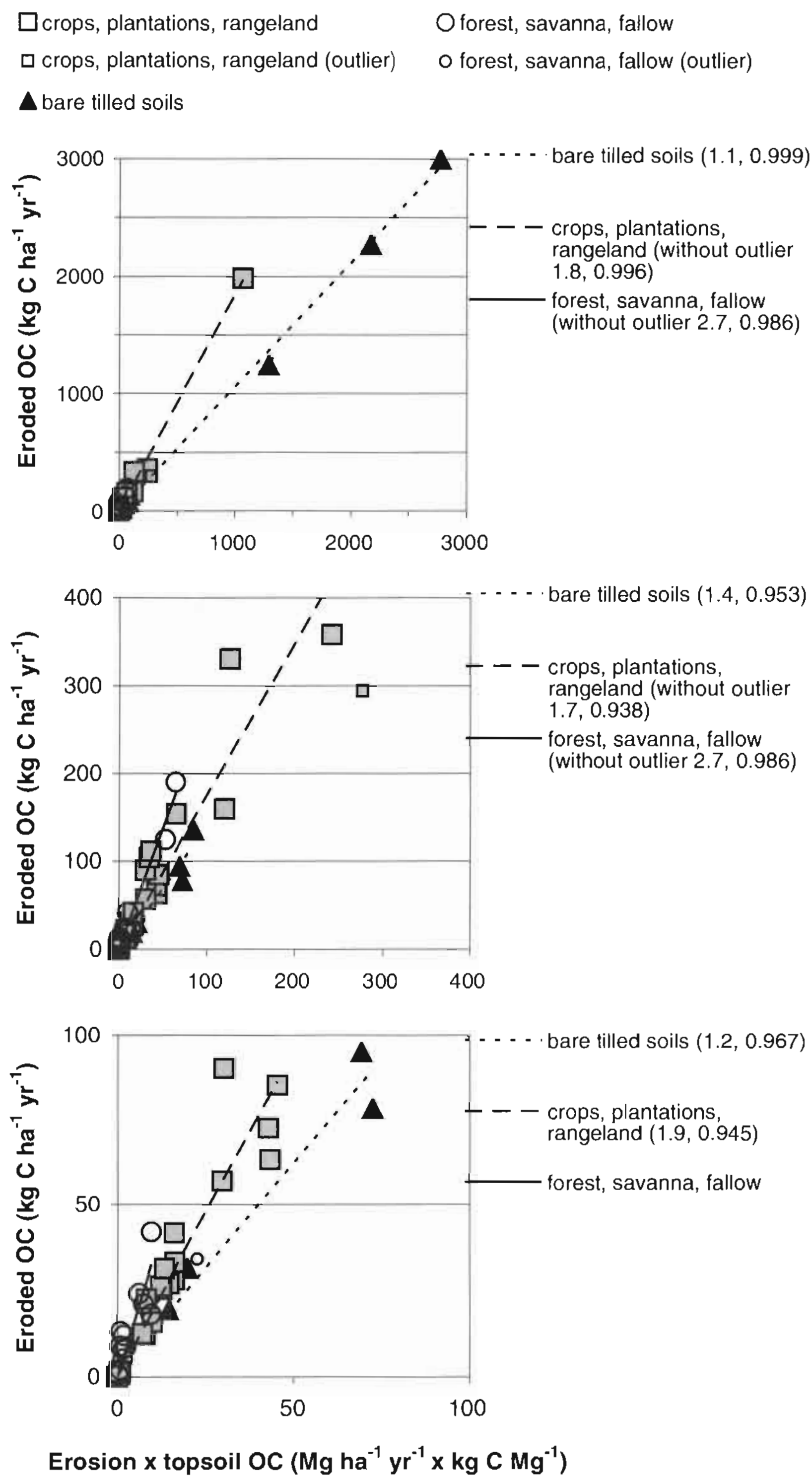

Figure 5.2 Relation between eroded OC and the product erosion-topsoil OC (0 to 10 cm) at three scales (data into brackets are slopes of the regression lines and correlation coefficients).

erosion rates of 11 and 21 Mg ha^{-1} yr^{-1} under conventional cultivation, within the range of present data (9 to 40 Mg ha^{-1} yr^{-1}). In the southern U.S. (1400-mm yr^{-1} rainfall), mean erosion measured in runoff plots (5% slope) by McGregor et al. (1999) was 48.5 and 5.2 Mg ha^{-1} yr^{-1} under conventionally and no-tilled cotton, respectively, and was consistent with present data for cotton in Cameroon (for slope < 3% and rainfall < 1300 mm yr^{-1}, 9 to 40 and 2 to 8 Mg ha^{-1} yr^{-1} under conventionally and no-tilled cotton, respectively). In Nigeria (1400-mm yr^{-1} rainfall, 1 to 15% slope), Lal (1997) measured mean erosion under no-till maize-legume rotations (two cropping seasons per year) between 0.5 and 2.2 Mg ha^{-1} yr^{-1}. Perhaps due to better soil cover over the year, this rate was less than the present data for no-till plots under row crops in subhumid areas with one rainy season (2 to 8 Mg ha^{-1} yr^{-1}). Additionally, Lal (1997) underlined the interest of creating rough soil surface (e.g., by residue mulching and no-till) in order to control erosion. In the Australian contour bay catchments (550-mm yr^{-1} rainfall, 2% slope) studied by Carroll et al. (1997), erosion under row crops was threefold greater for conventional than for zero tillage (4.0 vs. 1.4 Mg ha^{-1} yr^{-1}). Though these values were somewhat more than those in the Mediterranean cropped plots (< 2 Mg ha^{-1} yr^{-1}), perhaps due to a scale effect, they confirmed that reducing tillage also reduced erosion. In Syria, erosion measured by Shinjo et al. (2000) on runoff plots under matorral (280-mm yr^{-1} rainfall, 4 to 19% slope, 40 to 45% clay) ranged from 0.1 to 0.3 Mg ha^{-1} yr^{-1} when the plots were grazed, and from 0.0 to 0.1 Mg ha^{-1} yr^{-1} when they were protected from grazing. This was less than in the Mediterranean rangelands (0.7 to 1.8 Mg ha^{-1} yr^{-1}) and protected fallows (0.1 to 1.0 Mg ha^{-1} yr^{-1}), perhaps due to higher annual rainfall (360-550 mm) and either smaller clay content or greater slope gradient in these plots. In semiarid Spain (360-mm yr^{-1} rainfall, 23% slope), Castillo et al. (1997) measured 0.1 Mg ha^{-1} yr^{-1} erosion under natural shrubland vegetation and 0.3 Mg ha^{-1} yr^{-1} on a counterpart plot where vegetation had been removed but litter left intact. These values were comparable to the present data under protected fallows in Mediterranean areas (0.1 to 1.0 Mg ha^{-1} yr^{-1}).

5.4.2 Eroded SOC and Carbon Enrichment Ratio of Sediments (CER)

The data from 54 runoff plots were divided into four eroded OC groups: 1 to 3 Mg C ha^{-1} yr^{-1} for bare tilled soils in very humid regions; 50 to 400 kg C ha^{-1} yr^{-1} for cereals and cotton in humid and subhumid regions, and some bare plots in Mediterranean regions; 15 to 50 kg C ha^{-1} yr^{-1} for crops, rangelands, and other bare plots in Mediterranean regions; < 15 kg C ha^{-1} yr^{-1} for forests, savannas, fallows, and crops with thick mulch. This grouping indicates that in plots vulnerable to erosion, eroded SOC may be the same order of magnitude as the changes in SOC, especially under row crops in tropical areas. In their review on SOC dynamics under no-till, Six et al. (2002) reported that SOC increase for 0 to 30 cm depth was 325 ± 113 kg C ha^{-1} yr^{-1} under no-till systems in tropical regions (i.e., within the range of eroded SOC in the present cereal and cotton plots, which was 50 to 400 kg C ha^{-1} yr^{-1}). The relative importance of eroded SOC in C budgets is generally more on tilled plots because (1) SOC is generally lesser than on no-till plots (Balesdent et al., 2000) and (2) changes in SOC are either positive but generally less than on no-till plots, or negative. This observation confirms that eroded SOC cannot be neglected when conditions accentuate soil erosion risk (Voroney et al., 1981; Gregorich et al., 1998; Mitchell et al., 1998). In contrast, under forest, savanna, and crops with thick mulch, eroded SOC is small and negligible compared with changes in SOC resulting from large residue biomass.

The data from 54 plots is grouped into three CER classes: bare soils with CER ranging from 1 to 1.6 and averaging 1.3 (1.0 in the tropics, 1.4 in Algeria); cultivated plots and rangelands with CER ranging from 1.1 and 3.0 and averaging 2.0; forests, savannas, and fallows with CER of > 2.4 and averaging 4.6 (2.7 in grass fallows, 4.2 in woody savannas and bush fallows, and 7.5 in forests).

The distinction between conventional and no-till row crops was not possible for both eroded SOC and CER though it was relevant to erosion: no-till resulted in less erosion than conventional tillage, but the effect of tillage on eroded OC and CER was not clear. This trend indicates that the processes involved in SOC enrichment of sediments did not depend on tillage, and to a larger extent, on cropping system. However, it is likely that under no-till a noticeable proportion of eroded SOC consisted of coarse plant debris or litter, which may have been trapped by obstacles on the hillside and not transported to long distances. Thus SOC erosion under no-till may be considered less severe than under conventional tillage though the present data at the plot scale were not explicit. Determining the size distribution of organic matter in sediments may help verify this assumption. Additionally, measurements at the hillside scale may reveal differences in eroded SOC between conventional and no-till cultivation that were not apparent on 100-m^2 plots.

Comparison with published data was not easy due to the scarcity of references regarding SOC erosion at the plot scale in tropical and Mediterranean regions. On clayey Inceptisols in Colombia (2000-mm yr^{-1} rainfall, 7 to 20% slope), eroded SOC measured on runoff plots by Ruppenthal et al. (1997) averaged 5700 kg C ha^{-1} yr^{-1} on bare tilled soil and 200 kg C ha^{-1} yr^{-1} on cassava plots with forage legume intercropping whose effect on eroded SOC was not clear. These losses were more than those reported herein especially for bare soil, probably due to the very high SOC content (60 g C kg^{-1} in 0 to 20 cm). However, CER did not differ significantly among treatments and averaged 1.0, indicating that erosion was not selective for SOC probably due to strong soil aggregation and steep slope. On sandy Alfisols in Zimbabwe (500-mm yr^{-1} rainfall, 5% slope), measurements carried out on runoff plots by Moyo (1998) on bare tilled fallow, conventional and no-till maize showed erosion rates of 81.8, 34.3, and 0.2 Mg ha^{-1} yr^{-1}, eroded SOC of 210, 180, and 5 kg C ha^{-1} yr^{-1}, and CER of 1.1, 1.5, and 6.6, respectively. On bare soil, erosion was consistent with that of the present tropical plots (> 80 Mg ha^{-1} yr^{-1}), but smaller SOC content in Zimbabwe (< 3 g C kg^{-1}) resulted in smaller eroded SOC. Nevertheless CER was similar to the present data (i.e., close to 1). Data were also consistent with the present report for conventional maize, but for no-till maize there were similar to plots under forest or savanna (CER > 3), indicating the effect of thick mulch cover in no-till in Zimbabwe. Thus in particular conditions (e.g., thick mulch cover), cropping system could have an important effect on eroded SOC and CER. On sandy clay loam Alfisols in India (660-mm yr^{-1} rainfall, 1.5 to 2% slope) cropped with cereals, Cogle et al. (2002) measured eroded SOC ranging from 46 to 178 kg C ha^{-1} yr^{-1} and CER of 1.5 to 4, depending on tillage depth and mulch. Straw mulching decreased eroded SOC but the effect of tillage was unclear, as in the tropical plots under row crops in the present study. Overall, the values presented in this paper were consistent with those measured in Cameroon plots under cotton (57 to 160 kg C ha^{-1} yr^{-1} and $1.9 \leq$ CER ≤ 3.0 for 2% slope and 860-mm yr^{-1} rainfall). On clayey Alfisols in Kenya (1000-mm yr^{-1} rainfall, 30% slope), eroded SOC measured on runoff plots by Gachene et al. (1997) was 650 and 2370 kg C ha^{-1} yr^{-1} for conventional-till maize with and without fertilizers, respectively. This rate was much higher than in most cereal plots in tropical areas (50 to 400 kg C ha^{-1} yr^{-1}), though erosion data were consistent (7 and 29 Mg ha^{-1} yr^{-1}, respectively, vs. 9 to 40 Mg ha^{-1} yr^{-1}). The difference may be explained by rather high SOC content (ca. 30 g C kg^{-1} at 0 to 10 cm) and erosion rates (due to the 30% slope) of Kenyan plots, whereas the cultivated plots with high SOC content generally had low soil erosion. Indeed, CER was 1.3 in both Kenyan plots vs. 1.1 to 3.0 in the present cultivated plots, indicating that sediments were not particularly enriched in SOC on Kenyan steep slopes. In Malaysia (3000-mm yr^{-1} rainfall, 18% slope), Hashim et al. (1995) studied 1000-m^2 plots in cocoa plantations with possible legume cover crop on soils derived from sandstone and shale (20% clay). Erosion was ten times smaller with than without cover crop; but CER was 1.6 and 1.4, respectively, i.e., in the range for the cultivated plots reported herein, and confirmed the limited influence of cultivation practices on CER.

From these references and from the present data, it is concluded that land use has more influence on erosion than on eroded SOC and on CER. In similar climate, soil and slope conditions, land uses that increased soil OC generally reduced erosion, due to better soil aggregate stability and better infiltration (Barthès et al., 2000; Roose and Barthès, 2001). Because an increase in topsoil SOC content also increases sediment SOC content, it results in low soil losses and high SOC content, and the impact on eroded SOC and CER is not evident because of increase in both soil and sediment SOC. Thus differences in land use that affect SOC only are perhaps not sufficient to clearly affect eroded SOC and CER, though they affect erosion. Land use affects eroded OC and CER through effects on preferential erosional processes (e.g., due to change in soil surface cover). Indeed, the three classes consisting of (1) bare soil, (2) cultivated and rangelands, and (3) virgin soils and fallows, differed in soil surface cover and in eroded SOC and CER. To a larger extent, important differences in climate, slope, and soil conditions (texture especially) may also affect erosion selectivity along with eroded SOC and CER, as indicated e.g., by lower CER on bare soils in Martinique (high erosivity) than in Algeria (low erosivity).

5.4.3 Erosion Selectivity and Preferential Removal

Erosion is a selective process that removes the smallest or lightest soil particles faster than sand and gravels (Roose, 1977; Gregorich et al., 1998; Starr et al., 2000). Indeed, sheet erosion is generally selective because shallow runoff can only transport small or light particles usually produced by macroaggregate disintegration, such as organic particles, clay and silt, or microaggregates (Roose, 1996; Wan and El-Swaify, 1997; Cogle et al., 2002). Sheet erosion also results in selective deposition, which occurs when the flow velocity decreases due to vegetation, litter, surface roughness, or decrease in slope angle. Raindrop splash can transport larger or heavier particles such as sands, in all directions (including upslope), but is not considered an important interrill transport process under normal field conditions (Sutherland et al., 1996; Wan and El-Swaify, 1998). Sheet erosion is however less selective in some cases, especially on steep slopes with well-aggregated soils, e.g., with high clay or organic matter content, such as volcanic soils (De Noni et al., 2001; Khamsouk, 2001) or Vertisols with high calcium content (Roose, 2004). Indeed, on steep slopes, stable macroaggregates can be displaced by shallow runoff flows, resulting in comparable sediment and topsoil composition.

Rill erosion is less selective due to the greater shearing and transport capacities of concentrated runoff flow, which can incise and scour the whole topsoil; thus sediments and topsoil do not differ much in composition (Roose, 1977; Wan and El-Swaify, 1997). However, it results in selective deposition: stones and gravels first, followed by sands, and finally fine particles along the flood plains (Roose, 1996).

Thus the selectivity of erosion for SOC decreases with increase in soil losses (Avnimelech and McHenry, 1984; Sharpley, 1985; Cogle et al., 2002). Low soil loss results from sheet erosion only, which affects SOC-rich top layers mainly and transports small or light particles preferentially, organic matter. Consequently sediments are enriched in SOC. In contrast, high soil loss also involves rill erosion, which affects subsoil layers with less SOC and can transport heavier (and less organic) particles, thereby decreasing the sediment enrichment ratio. CER may be of < 1 when erosion affects soil layers that contain less SOC than the reference layer (i.e., 0 to 10 cm). In general, factors that decrease runoff velocity increase the erosion selectivity (e.g., thick litter and mulch). In contrast, factors that increase runoff velocity decrease erosion selectivity (e.g., bare soil surface or steep slope).

5.4.4 Relationship between Erosion, Eroded SOC, and CER

The relationship between erosion and eroded SOC is generally recognized (Gregorich et al., 1998) and is evident from the fact that eroded SOC is included in sediments. The influence of topsoil SOC content (in addition to that of erosion) is also evident because topsoil provides the materials that are eroded, although this relationship has never been explicitly described. The present data indicate that taking erosion and topsoil SOC into account allows a better prediction of eroded SOC than considering erosion only, especially with regards to the principal land uses.

At the watershed scale and considering individual events, Starr et al. (2000) suggested a power law relationship between erosion and eroded SOC (eroded SOC = $a \times \text{erosion}^b$). Such a relationship was not observed with the present data. Starr et al. (2000) also reported a logarithmically linear but inverse relationship between erosion and CER, which was also the case with the present data (Figure 5.1c). Sharpley (1985) reported a similar relationship from rainfall simulations on 2-mm sieved topsoil samples. The fact that investigations at very different scales (individual events on watersheds, annual rainfall on runoff plots, simulated rainfall on sieved samples) result in a comparable relationship between erosion and CER validate the general trend.

5.5 CONCLUSION

On the basis of the data from 54 plots, five erosion classes were defined as follows: bare soil in very humid regions (maximum); conventional-tillage row crops in humid and subhumid regions; no-till row crops in subhumid regions and bare soil in Mediterranean regions; crops and rangelands in Mediterranean regions; and forest, savanna, fallows, and crops with thick mulch (minimum). In contrast, only four eroded SOC classes (conventional-tillage and no-till plots behaving similarly) and three CER classes (bare soils, crops and rangelands, forest, savannas, and mulched crops) were identified. Factors that affected soil erosion did not necessarily affect carbon erosion or the enrichment ratio. In particular, changes in topsoil SOC did not clearly influence changes in eroded SOC or CER, which required changes in erosion selectivity (e.g., resulting from changes in soil surface cover or roughness). Indeed, erosion selectivity for SOC was low on bare soils (CER $\leq$ 1.6), especially in humid conditions (CER $\leq$ 1.1), indicating that subsoil layers contributed to sediment production by rill erosion, or intact aggregates were eroded. In contrast, erosion selectivity for SOC was high on plots covered by thick litter (2.4 $\leq$ CER $\leq$ 14.0), suggesting the preferential removal of organic particles by sheet erosion. The preferential removal of SOC was intermediate under cultivation and rangeland (1.1 $\leq$ CER $\leq$ 3.1).

The annual SOC losses by water erosion generally ranged between 50 and 400 kg C ha^{-1} yr^{-1} in tropical regions and between 15 and 50 kg C ha^{-1} yr^{-1} in Mediterranean regions under cultivation and rangeland. This is the same order of magnitude as annual changes in SOC, indicating that on plots vulnerable to erosion, SOC erosion cannot be neglected when assessing carbon balances at the plot scale. Eroded SOC was less (< 15 kg C ha^{-1} yr^{-1}) under mulch farming and under forest, savanna, and fallows, where the soil surface is covered by litter. In such conditions, eroded SOC is generally negligible as compared to SOC input as residues or litter. Besides losses of SOC in sediments, soluble SOC is also lost in water runoff. Preliminary and partial data indicated that runoff SOC was generally 4 to 20 times less than eroded SOC, but that it could sometimes be of the same order of magnitude such as under mulched crops in very humid conditions (Roose, 2004). This observation underlines the need for complementary research taking into account all SOC losses resulting from water erosion. The same preliminary data also indicate the need for studying losses of soluble SOC through deep/vertical drainage, which can be 30 to 75 kg C ha^{-1} yr^{-1} in plots where eroded SOC is less than 15 kg C ha^{-1} yr^{-1}.

Nested studies on plots and watersheds are also necessary to determine the fate of SOC removed from plots, which does not necessarily reach the river. Such studies may address specific questions with regard to the differences in eroded SOC or CER among land use and management (e.g., between conventional and no-till farming).

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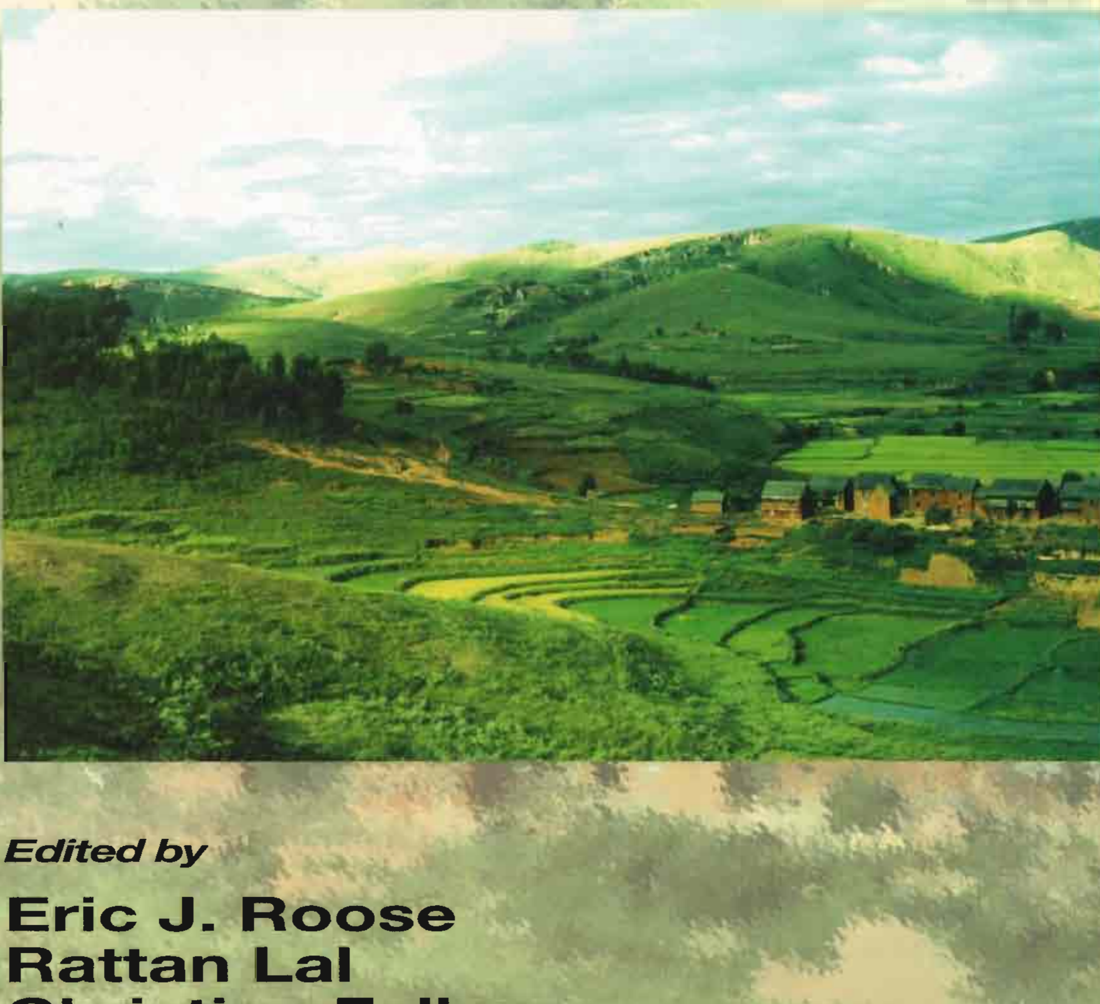

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On the cover: A typical landscape of red ferrallitic soils on the high plateau of central Madagascar near Antananarivo during the rainy season. The hilltop is covered by overgrazed grassland deeply eroded around the cattle trails which join the village 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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Environmental Science & Technology

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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