

Influence of Land Use, Soils, and Cultural Practices on Erosion, Eroded Carbon, and Soil Carbon Stocks at the Plot Scale in the Mediterranean Mountains of Northern Algeria

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8.1 INTRODUCTION

Following successive colonizations and the rapid increase of the population in northern Algeria, large forested areas of the mountains were assigned to grazing or cropping. Therefore, various erosion processes have been observed for centuries on the mountains around the Mediterranean basin, from the Roman author Tite-Live to the recent geographers, soil scientists, hydrologists, and agronomists (in Tunisia, Cormary and Masson, 1964; Dumas, 1965; in Morocco, Heusch, 1970; Laouina, 1992; in Algeria, Roose et al., 1993; Kouri et al., 1997). In northern Algeria, mountains are a socioeconomic stake under demographic pressure (Benchetrit, 1972). With the failure of industry, the forests have been overgrazed, cleared, and cropped even on steep hillslopes, resulting in soil degradation and leading to the continuous decrease in cereal production, particularly during the dry years of the 1990s.

Presently, 6 million hectares are affected by an excessive rate of erosion and 120 million tons of sediments are exported yearly by the rivers (Heddadj, 1997). About 20 million m³ of water are replaced each year by sediments in the reservoirs (Remini, 2000). Finally, the population is affected by soil fertility degradation and the scouring of organic topsoil, by gullies on hillslopes and by floods in the plains, and mudflows and landslides occurring both in the countryside and cities. The rainstorm of the November 10, 2001 amounted to 200 mm in 26 hours with an intensity of 75 mm h⁻¹ during 2 hours: more than 850 people died and 5500 houses were destroyed, and mud flows covered many km of drains, streets, and roads around Algiers (newspaper *Liberté*, November 11, 2002). In the semiarid mountains of northern Algeria, even if erosion indicators do not always reach spectacular values, they are linked with the decrease in cereal production, the reduction in soil organic carbon (SOC) in cropped fields, and with the selective depletion of nutrients. The damages are very severe when tilled fields are located on steep hillslopes, as the crop residues are grazed by the herds of goats and sheep, and the fields remain bare after harvest (between May and July) until the next cropping period (between September and January). Cropped vegetation limits erosion only from the spring. In summer the main crops are already harvested, leaving the soil bare and sealed.

SOC plays an important role in soil fertility. It has a major impact on the water budget under perennial crops like vineyards (Pla Sentis, 2002). Moreover, SOC stock can be strongly altered by change in land use (Batjes, 1996). Indeed, after forest clearing and a few years of cropping, the SOC stock decreases by more than 50% (Roose and Barthès, 2001). Lal et al. (2004) observed that SOC loss is caused by plowing, which turns the soil over, making it susceptible to accelerated erosion. Leaving crop residues on the soil surface after harvest increases SOC and controls erosion, but the benefits are lost if the biomass is buried because microorganisms quickly degrade residue carbon into CO₂ (Lal et al., 2004). Additionally, soils constitute a great reservoir of OC (1500 to 2000 Gt C) and are an important sink to control CO₂ fluxes at the global level (Doran et al., 1996; Lal et al., 1998; Lal, 2004; Bernoux et al., this volume; Robert, this volume). Therefore, soil restoration and conservation techniques must aim at increasing SOC stocks to improve soil fertility and mitigate the greenhouse effect (Hien, 2002; Lal, 2002).

The soils of Maghreb were subjected to a rapid land use change during 1990s, especially those in Algeria (Coelho et al., 2002). Considering the effects of these changes in the Tell mountains of northern Algeria, a research program was developed by the Algerian INRF (Institut National de la Recherche Forestière) and the French IRD (Institut de Recherche pour le Développement), to study the influence of land uses and cultural practices on runoff, erosion, soil fertility, and SOC dynamics at the scale of runoff plots (100 to 220 m²). The study included comparisons between traditional and improved land management systems for the principal soils of northern Algeria. The data on runoff and erosion have already been published (Roose et al., 1993; Morsli et al., 2004). This report summarizes these results and focuses on eroded carbon, carbon enrichment ratio of sediments (CER), and SOC storage in the topsoil, which is the most affected by land-use changes and cultural practices. While the research on carbon erosion is scanty in the tropics (Lal, 2002), it is rare in the

Mediterranean region (Arabi and Roose, 2002; Roose and Barthès, this volume). In general, sheet erosion is not as important as gully erosion on the steep hillslopes (Heusch, 1970; Laouina et al., 2000; Roose et al., 2000). Therefore, the carbon enrichment ratio (CER) is of limited value.

8.2 MATERIALS AND METHODS

8.2.1 Description of the Sites

Field experiments were conducted: (1) from 1993 to 1998 in the Beni-Chougran mountains near Mascara, in western Algeria, 200 km away from Algiers (35°20'N, 00°17'E); (2) from 1991 to 2001 in the Tlemcen mountains in western Algeria, 300 km away from Algiers (34°50'N, 01°10'W); and (3) from 1988 to 1992 around Medea in central Algeria, 90 km away from Algiers (36°14'N, 02°51'E). These hilly regions have been severely degraded by a long history of grazing, burning, cropping, and colonization (by Romans, Arabs, Turkish, French; Gsell, 1913). These regions are representative of the Tell mountains with regards to landscape, erosion manifestations (sheet erosion, gullies, floods, and mass movements), and the various programs of soil conservation since 1950s.

The climate is Mediterranean semiarid with cool winter and annual rainfall ranging from 280 to 620 mm, falling mainly during the cool season (October to May), with some short but intensive rainstorms (intensity up to 80 mm h⁻¹ during 30 minutes) during the very hot and dry summer (June to September). Every 10 years an exceptional rainstorm (100 to 200 mm within 3 days) may saturate the landscape and cause severe damages as seen in Algiers on November 10, 2001.

The landscape is mountainous, strongly dissected, with a very dense drainage, convex hillslopes with grazed or cultivated fields covering the whole hills even on the steepest slopes (15 to 40%). Soft rocks (marl, argillite, soft calcareous sandstone) alternate with hard calcareous rocks developing steep slopes and diverse erosion processes. Natural vegetation is mainly constituted by overgrazed scrub (*Olea sp.*, *Quercus sp.*, *Pinus alepensis*, and various bushes), which cover the soil surface partially, by some *Pinus sp.* or *Eucalyptus globulus* plantations, and by overgrazed bush lands. The main crops are cereals (winter or spring wheat, *Triticum durum* and *Triticum aestivum*, respectively and oats, *Avena sativa*), legumes (peas, *Pisum sativum*, chickpeas, *Cicer arietum*), onions (*Allium cepa*), vegetables and orchards of almond trees (*Prunus dulcis*), olive trees (*Olea europaea*), and fig trees (*Ficus carica*), and some contour lines of prickly pears (*Opuntia ficus indica*). If natural conditions played a major role on the development of erosion processes, deforestation, overgrazing, and extensive cultural practices have also accelerated soil degradation.

The plots under study were set up on three soil types representative of the northern mountains of Algeria: (1) clayey brown Vertic soils on marl (vertic Haploxeroll in Mascara and Tlemcen, typic Haploxerert in Medea), hereafter called Vertic soils; (2) brown calcareous soils on sandstone or limestone (typic Haploxeroll in Mascara, Tlemcen and Medea), hereafter called brown calcareous soil; (3) red Fersiallitic soils on sandstone (typic Haploxerept in Tlemcen and Medea), hereafter Fersiallitic soils.

Ten runoff plots were established near Mascara: five on Vertic soils and five on brown calcareous soils. Nine runoff plots were observed near Tlemcen: three on Vertic soils, three on brown calcareous soils, and three on Fersiallitic soils. Twelve runoff plots were observed near Medea: three on Vertic soils, six on brown calcareous soils, and three on Fersiallitic soils.

Some properties of the soils are presented in Table 8.1. These soils are rich in free calcium and magnesium carbonates (10 to 30%) except the Fersiallitic soils. SOC content is generally low (10 to 12 g C kg⁻¹) and decreases with depth. The C/N ratio (10 to 12) indicates that SOC decomposition is fast. Even in the topsoil, nitrogen and available phosphorus are deficient for cereals. The soil pH is neutral to slightly basic. Exchangeable sodium is not negligible in some fragile soils, but the presence of calcium carbonate and of stones in the topsoil increases the soil resistance to rain and runoff erosivity (Roose et al., 1993).

Table 8.1 General Properties of the Soils under Study (Northern Algeria)

	Brown Calcareous (Mascara)		Vertic (Tlemcen)		Brown Calcareous (Tlemcen)		Fersiallitic (Tlemcen)
Depth (cm)	0–15	15–45	0–15	15–45	0–10	10–30	0–10
Carbonates (%)	25.2	32.5	19.6	24.5	10.8	15.4	3.2
Clay (%)	17.2	16.1	57.1	57.2	20.2	28.3	37.3
Silt (%)	56.2	60.4	32.6	33.1	56.2	49.2	20.5
Sand (%)	25.8	23.3	10.1	9.1	22.1	21.5	41.4
Bulk density	1.5	1.6	1.3	1.5	1.1	1.2	1.5
Organic carbon (g kg ⁻¹)	10.4	7.5	11.6	10.8	26.7	18.6	10.4
Total Nitrogen (g kg ⁻¹)	0.9	0.7	1.1	1.0	2.4	1.6	0.9
C/N	11.5	10.7	10.5	10.8	11.1	11.6	11.6
P ₂ O ₅ Olsen (mg kg ⁻¹)	10	4	13	6	nd	nd	nd
pH in water	7.5	7.6	8.2	8.1	7.2	7.5	7.0
Exch. Ca (cmol(+) kg ⁻¹)	20.3	19.2	28.4	26.4	21.3	23.8	21.3
Exch. Mg (cmol(+) kg ⁻¹)	2.8	2.7	10.6	9.4	0.9	1.2	1.6
Exch. K (cmol(+) kg ⁻¹)	0.9	0.8	1.1	1.0	1.1	1.0	1.2
Exch. Na (cmol(+) kg ⁻¹)	0.3	0.3	0.2	0.2	0.3	0.6	0.3
CEC (cmol(+) kg ⁻¹)	24.9	23.8	40.2	38.2	24.9	27.3	27.2

Note: CEC: cation exchange capacity. nd: not determined.

8.2.2 Description of the Treatments

The experimental treatments are representative of the most frequent land uses observed in this region, including traditional practices and some possible improved practices: plowing on the contour and ridging to improve the water storage and soil roughness, fertilizer use to enhance vegetation growth, vegetated fallow protection with the introduction of bushes and trees in the grazing lands, and legume and cereal rotations with recommended fertilizer use under vineyard and orchard. The land uses under study were:

- International standard bare plowed fallow (Wischmeier and Smith, 1978)
- Cereals (winter wheat, oats) alone or in rotation with a legume (broad beans, *Vicia faba*) or with grazed fallow, with up and down or contour tillage, with low or appropriate fertilizer rate
- Peas or chickpeas on ridges
- Grazed fallow (not tilled)
- Protected fallow (neither grazed nor burned)
- Protected fallow with the introduction of legumes
- Grazed scrub land
- Grazed scrub land but protected against fire
- Vineyard (traditional, i.e., bare soil and up and down tillage, or improved, i.e., with cereal-legume association and contour tillage)
- Orchards of apricot (*Prunus armeniaca*; traditional, i.e., bare soil and up and down tillage, or improved, i.e., with cereal-legume association and contour tillage)

Plots were not replicated for specific land use and soil type, but were replicated through the measurement of runoff and erosion over several years.

8.2.3 Measurement of Runoff and Erosion

Runoff and erosion were measured on standard runoff plots 22.2-m long and 4.5- to 10-m wide, set up on representative hillslopes with 12 to 40% slope gradient. The plots were surrounded by half-buried sheets and fitted out with a collector channel trapping the coarse sediments and draining runoff and fine sediments in suspension toward two tanks connected in series. When the first tank (0.2 m³) was full, additional runoff flowed through a divisor (including three to nine

slots) into a second tank having a 0.2- to 1-m³ capacity, depending on the expected runoff volume (Fournier, 1967).

Runoff and erosion were measured from 1993 to 1998 in Mascara, from 1991 to 2001 in Tlemcen, and from 1988 to 1992 in Medea. Rainfall amount was determined using recording gauge rain. Runoff was estimated after each rainfall event by taking into account the volume of each tank and the divisors. It was expressed as annual runoff rate (in % of annual rainfall) and maximum event runoff rate over the period under study (denoted maximum runoff rate, in % of the event rainfall). Erosion was calculated as the sum of coarse sediments trapped in the channel collector and fine particles in suspension sampled from the runoff stored in the first tank. Coarse sediments were collected from the channel, dried, and weighted. Fine suspensions were determined from aliquots collected after homogenization of the runoff in the first tank (without coarse sediments), flocculated using 1 cm³ of an aluminum sulfate solution (5%), dried and weighted. Erosion was expressed on an annual basis (Mg ha⁻¹ yr⁻¹). Accuracy of runoff and erosion measurements was estimated at 10%.

8.2.4 Measurement of Eroded and Soil Organic Carbon

Eroded organic carbon (OC) is the sum of OC in the coarse sediments trapped in the channel and in the fine sediments in suspension in the runoff. Eroded OC (kg C ha⁻¹ yr⁻¹) was calculated as the product of sediment OC content (g C kg⁻¹, i.e., kg C Mg⁻¹) multiplied by sediment amount (i.e., erosion in Mg ha⁻¹ yr⁻¹). Sediment OC content was determined on sediment samples collected after each rainstorm during the seasons 1995 and 1996 in Mascara and 2000 and 2001 in Tlemcen mountains. In Medea, sediment OC content was determined on samples collected from 1988 to 1992.

Soil samples (0 to 10 cm depth) were collected during the dry season (September). Samples for the determination of bulk density were obtained using 250-ml cylinders, with three replicates per plot. Samples for OC determination were composited from eight original core samples per plot. Soil and sediment OC contents (g C kg⁻¹) were determined following the Anne method (Nelson and Sommers, 1996). The SOC stock (Mg C ha⁻¹) at 0 to 10 cm depth was calculated as the product of SOC content multiplied by bulk density. Soluble carbon in runoff water was not determined. The carbon enrichment ratio (CER) was computed as the ratio of OC content in sediments to that in the topsoil (0 to 10 cm depth).

8.3 RESULTS

8.3.1 Rainfalls

During the measurement period, the maximum daily rainfall ranged from 43 to 45 mm in Mascara and Tlemcen to 85 mm in Medea (Table 8.2). The annual rainfall was 470 mm in Mascara in 1995 and 1996 and 422 mm in Tlemcen in 2000 and 2001 (when eroded OC was determined).

Table 8.2 Annual Rainfall (1913 to 1970, 1971 to 2001, and 1991 to 2001) and Maximum Daily Rainfall (1991 to 2001) in Mascara, Tlemcen, and Medea (Northern Algeria)

Location	Annual Rainfall for the Period 1913 to 1970 mm yr ⁻¹	Annual Rainfall for the Period 1971 to 2001 mm yr ⁻¹	Annual Rainfall for the Period 1991 to 2001 mm yr ⁻¹	Maximum Daily Rainfall for the Period 1991 to 2001 mm d ⁻¹
Mascara	511 (143)	380 (102)	289 (85)	43
Tlemcen	496 (100)	347 (110)	331 (100)	45
Medea	618 (180)	510 (170)	461 (167)	85

Note: Figures in parentheses are standard deviations.

In Medea, the annual rainfall ranged from 408 to 621 mm during the 1988 through 1991 period, with an average of 533 mm yr⁻¹. Annual rainfall ranged from 240 to 540 mm in the Tlemcen region during the 1991 through 2001 period. This is 33 to 40% less than the long-term average for 1913 through 1971 (Morsli et al., 2004). The minimum rainfall amount producing runoff ranged from 22 mm d⁻¹ in dry conditions (5 days without rain) to 2 to 4 mm d⁻¹ in humid conditions or on compacted and sealed soil.

8.3.2 Runoff

The mean annual runoff rates were moderate during the dry years under study, with very few abundant storms: mean annual runoff rate ranged from 1 to 7% in Mascara, 2 to 13% in Tlemcen, and 0.4 to 19% in Medea (Table 8.3). On bare soil, it tended to be higher in Medea (10 to 20%) than in Mascara and Tlemcen (4 to 13%), probably due to more annual rainfall in Medea (540 mm yr⁻¹ on average vs. 300 to 400 mm yr⁻¹). There was no distinct effect of soil type: for bare plots, the highest annual runoff rate was observed on the brown calcareous soil in Mascara, on the Fersiallitic soil in Tlemcen, and on the Vertic soil in Medea. However, runoff rate was higher on Fersiallitic than on brown calcareous soils. The effect of slope gradient was also not well defined: on bare soil, annual runoff rate increased with an increase in slope gradient on brown calcareous and Fersiallitic soils, but with a decrease in slope gradient on Vertic soils. Mean annual runoff rate was generally higher on bare soil than on crops, fallows, and scrub. Excluding bare soils, differences in annual runoff rate between treatments were generally small for a given location and soil type in Mascara (nevertheless annual runoff was 25 to 45% more on grazed than protected fallows) and Tlemcen (e.g., mean annual runoff rate on overgrazed and protected scrub was 2.4 and 2.2% on the brown calcareous soil and 11 and 11.2% on the Fersiallitic soil, respectively). In contrast, there was a distinct effect of treatments in Medea, annual runoff being smaller for improved than for traditional practices.

Maximum runoff rate per event (which determines the linear erosion risk) ranged from 10 to 30% in Mascara, 20 to 40% in Tlemcen, and 2 to 80% in Medea. The effects of soil type and slope gradient were slight in general, as maximum runoff rate on bare soil ranged between 32 and 42% (except for one plot in Medea). For a given location and soil type, maximum runoff rate was always higher on bare than on cropped soils, fallows, and scrub. Excluding bare plots, differences among treatments were generally small for a given location and soil type in Mascara and Tlemcen (however maximum runoff rate was twice lower for crops than for fallows on the brown calcareous soil in Mascara). In contrast, maximum runoff rate was particularly low for improved practices in Medea ($\leq 5\%$), probably due to a better soil surface cover. Indeed, runoff risks are significantly reduced when the soil surface is covered by vegetation, mulch, or pebbles (Blavet et al., 2004).

8.3.3 Sheet Erosion

Mean annual erosion was moderate: it was less than 14 Mg ha⁻¹ yr⁻¹, and less than 6 Mg ha⁻¹ yr⁻¹ for 30 out of the 31 plots under study (Table 8.3). Erosion ranged from 0.5 to 5.9 Mg ha⁻¹ yr⁻¹ in Mascara, 0.4 to 3.4 Mg ha⁻¹ yr⁻¹ in Tlemcen, and 0 to 14 Mg ha⁻¹ yr⁻¹ in Medea (0 to 3 Mg ha⁻¹ yr⁻¹ when excluding one plot). Thus it tended to be more in Mascara than in Tlemcen and Medea, and this was confirmed by soil losses measured on bare plots: indeed, mean annual erosion on bare soils in Mascara, Tlemcen, and Medea was 4.0, 2.0, and 2.2 Mg ha⁻¹ yr⁻¹ on Vertic soils, and 5.9, 3.6, and 2.8 to 3.0 Mg ha⁻¹ yr⁻¹ on brown calcareous soils, respectively. For a given location, erosion on bare plots was always smaller on Vertic soils than on Fersiallitic (-41 to -84%) and brown calcareous soils (-21 to -44%) whereas differences between brown calcareous and Fersiallitic soils were less clear. The effect of slope gradient was not well defined: on bare plots, when the slope gradient increased, erosion increased on Vertic and Fersiallitic soils but tended to decrease on brown calcareous soils. The highest soil loss was measured on bare soil with 0% stone cover, but the effect

Table 8.3 Slope Gradient, Stone Cover, Rainfall, Runoff Rates, and Erosion on Runoff Plots Located near Mascara (1993 to 1998), Tlemcen (1991 to 2001), and Medea (1988 to 1992)

Location, Soil Type, and Treatment	Slope %	Stone Cover %	Annual Rainfall mm yr ⁻¹	Rainfall Erosivity U.S. units ^a	Altitude m	Annual Runoff Rate %	Maximum Runoff Rate %	Erosion Mg ha ⁻¹ yr ⁻¹
Mascara, Vertic soil	40	5	306 (97)	46 (15)	670			
Bare soil						3.8 (1.8)	32.6	4.0 (2.3)
Cereals						1.4 (0.9)	22.2	0.9 (0.3)
Chickpeas on ridges						2.1 (0.9)	23.5	1.4 (0.5)
Grazed fallow						2.1 (0.6)	22.1	1.0 (0.3)
Protected fallow						1.7 (0.9)	22.3	0.6 (0.1)
Mascara, brown calc. soil	20	8	306 (87)	46 (15)	640			
Bare soil						6.5 (0.8)	32.3	5.9 (2.7)
Cereals						2.2 (0.7)	13.1	0.7 (0.2)
Peas on ridges						2.0 (0.5)	11.0	0.5 (0.3)
Grazed fallow						3.9 (0.6)	25.2	1.0 (0.5)
Protected fallow						2.7 (1.0)	25.7	0.6 (0.5)
Tlemcen, Vertic soil	15	7	330 (97)	58 (11)	520			
Bare soil						6.2 (2.2)	38.6	2.0 (1.8)
Cer./fall., downslope till.						5.6 (1.8)	30.0	1.4 (1.2)
Fertil. cer., contour till.						4.7 (2.3)	24.0	1.0 (0.9)
Tlemcen, brown calc. soil	21	42	387 (77)	58 (11)	730			
Bare soil						3.9 (1.3)	42.1	3.6 (1.4)
Overgrazed scrub						2.4 (1.6)	19.4	0.5 (0.3)
Protected scrub						2.2 (1.4)	20.0	0.4 (0.3)
Tlemcen, Fersiallitic soil	10	42	411 (76)	63 (11)	980			
Bare soil						12.7 (2.1)	38.0	3.4 (1.4)
Overgrazed scrub						11.0 (3.2)	38.0	1.9 (0.6)
Protected scrub						11.2 (3.4)	30.0	1.4 (0.5)
Medea, Vertic soil	12	4	540 (79)	46 (6)	900			
Bare soil						19.4 (6.8)	80.0	2.2 (2.1)
Cereals/grazed fallow						7.8 (8.0)	14.0	0.4 (0.3)
Fertil. cer.-leg. assoc.						1.2 (1.1)	5.0	0.0 (0.1)
Medea, brown calc. soil 1	40	16	540 (79)	46 (6)	900			
Bare soil						10.5 (5.4)	33.0	3.0 (1.3)
Overgrazed scrub						14.3 (4.8)	24.0	2.0 (0.5)
"Regrassed" scrub						0.6 (0.6)	2.0	0.0 (0.0)
Medea, brown calc. soil 2	35	20	540 (79)	46 (6)	900			
Bare soil						9.9 (3.5)	40.0	2.8 (1.3)
Traditional vineyard						2.1 (1.1)	13.0	0.2 (0.1)
Fertil. vine ^d + cer.-leg.						0.4 (0.4)	3.0	0.0 (0.0)
Medea, Fersiallitic soil	35	0	540 (79)	46 (6)	900			
Bare soil under orchard						18.7 (8.4)	32.0	14.0 (8.3)
Traditional orchard						2.7 (1.3)	8.0	1.2 (0.7)
Orch ^d + cer.-leg., contour						0.7 (0.8)	2.0	0.3 (0.4)

Note: Figures in parentheses are standard deviations. calc.: calcareous; cer.: cereal; leg.: legume; vine^d: vineyard; orch^d: orchard; fall.: fallow; till.: tillage; contour: contour tillage; fertil.: fertilized; assoc.: association.

^a Hundreds of foot-tons per acre times inches per hour (to allow comparison with literature data), which may be converted into MJ mm (ha h)⁻¹ when multiplied by 17.35.

of stone cover was not well defined otherwise. Erosion was always more on bare (2 to 14 Mg ha⁻¹ yr⁻¹) than on cropped soil (0 to 1.4 Mg ha⁻¹ yr⁻¹), fallows (0.6 to 1 Mg ha⁻¹ yr⁻¹), and scrub (0 to 2 Mg ha⁻¹ yr⁻¹). Excluding bare plots, the effect of treatment on erosion followed distinct trends. Indeed, for a given location and soil type, mean annual erosion was always greater on grazed than on protected fallow, or scrub, and for traditional than for improved practices. As compared with conventional systems, improved systems (better fertilization, ridging, intercropping, protected fallow, or scrub) reduced erosion risks by 20 to 30% in Tlemcen and by 75 to 99% in Medea.

Two parameters affected erosion in opposite ways: topsoil properties (texture, stoniness) and slope steepness. Even on steep slopes, soils with high silt content (brown calcareous) were less stable than clayey Vertic soils or stony soils. Similarly, the deep Fersiallitic soils of Medea were more fragile than the stony Fersiallitic soils of Tlemcen, and suffered more erosion when tilled (Morsli et al., 2004). The influence of slope steepness was not evident: in Mediterranean areas, slope position is sometimes more important than slope steepness in case of soil saturation at the bottom of the hillslopes (Heusch, 1970; Roose et al., 1993; Roose, 1996; Mazour and Roose, 2002).

8.3.4 Organic Carbon Content and Stock of Surface Soil

The SOC content (0 to 10 cm depth) was low, and ranged from 6 to 12 g C kg⁻¹ except for brown calcareous soils in Tlemcen where it was 19 to 33 g C kg⁻¹ (Table 8.4). The SOC content of surface soil was 10 to 12 g C kg⁻¹ in Mascara, 6 to 10 g C kg⁻¹ in Tlemcen (excluding the brown calcareous soil), and 7 to 10 g C kg⁻¹ in Medea. SOC content ranged from 8 to 12 g C kg⁻¹ in Vertic soils, 7 to 12 g C kg⁻¹ in brown calcareous soils (excluding Tlemcen), and 6 to 9 g C kg⁻¹ in Fersiallitic soils. Thus location and soil type did not clearly affect SOC content of the surface soil, except that it was two to three times more for Tlemcen's brown calcareous soil than for the other location × soil type combinations. The SOC content of surface soil was more clearly affected by land use. It was lower in bare soils than under corresponding crops, fallows, and scrub (-3 to -44%). It was also lower under grazed than under protected fallows or scrub (-8 to -31% for a given location and soil type), whereas improved cropping systems were not always associated with increasing SOC content (difference in SOC content between improved and traditional systems was 15 to -6%). However, the effect of treatments was often small: for a given location and soil type, the maximum difference in SOC content between treatments was 16 and 23% in Medea and Mascara, respectively, but was 30, 50, and 80% for Vertic, Fersiallitic and brown calcareous soils in Tlemcen, respectively.

Changes in SOC content of the surface soil were measured in Tlemcen from 1991 to 2001 (Figure 8.1). Over the decade, the SOC content decreased markedly in the bare soils (-15% for the Vertic and Fersiallitic soils, -28% in the brown calcareous soil) and under grazed scrub (-14%). In contrast, it increased under protected scrub (12 and 25% for the Fersiallitic and brown calcareous soils, respectively). Changes in SOC content were small under cereals (-1% under cereal/grazed fallow, 7% under fertilized cereal).

SOC stock (0 to 10 cm depth) ranged from 9 to 18 Mg C ha⁻¹ except for the brown calcareous soil in Tlemcen where it was 21 to 37 Mg C ha⁻¹. It was generally higher in Mascara (14 to 18 Mg C ha⁻¹) than in Medea (9 to 12 Mg C ha⁻¹), and Tlemcen (9 to 14 Mg C ha⁻¹ when excluding the brown calcareous soil). Furthermore, for a given location it tended to be higher in brown calcareous than in Vertic soils. SOC stock was lower in bare soils than under cropped, fallows, and scrub (-5 to -44%), and was also lower under grazed than protected fallows or scrub (-4 to -11% in Mascara and Medea, -27 to -28% in Tlemcen). The effect of improved cropping systems on SOC stock was either positive (15% for the wheat in Tlemcen, 12% for the orchard in Medea) or negative (-9% for the cereals and -10% for the vineyard in Medea). The effect of treatments was less in Mascara and Medea than in Tlemcen: for a given location and soil type, the maximum difference in SOC stock among treatments was 12 and 15% in Medea and Mascara, respectively, but was 22 to 44% in Tlemcen.

Changes in SOC stock were measured from 1993 to 1998 in Mascara and from 1991 to 2001 in Tlemcen, for Vertic and brown calcareous soils (Figure 8.2). Over the periods under study, the SOC stock in bare soils decreased by 160 (Tlemcen's Vertic soil), 500 to 700 (Mascara), and 820 kg C ha⁻¹ yr⁻¹ (Tlemcen's brown calcareous soil). Under fallows or scrub, it decreased by 330 to 460 kg C ha⁻¹ yr⁻¹ in grazed plots, but increased by 570 to 750 kg C ha⁻¹ yr⁻¹ in protected plots. In crops, SOC stock decreased under legumes (50 to 80 kg C ha⁻¹ yr⁻¹) but generally increased under cereals (-30 to 180 kg C ha⁻¹ yr⁻¹). As compared with initial stocks, annual SOC change in

Table 8.4 Soil Organic Carbon (SOC) Content, Bulk Density, and SOC Stock at 0 to 10 cm Depth, Sediment Organic Carbon (OC) Content, Carbon Enrichment Ratio, and Eroded OC on Runoff Plots Located near Mascara (1996), Tlemcen (2001), and Medea (1988 to 1992)

Location, Soil Type, and Treatment	SOC Content g C kg ⁻¹	Bulk Density Mg m ⁻³	SOC Stock Mg C ha ⁻¹	Sediment OC Content g C kg ⁻¹	Carbon Enrichment Ratio	Eroded OC kg C ha ⁻¹ yr ⁻¹
Mascara, Vertic Soil						
Bare soil	10.2 (0.3)	1.35	13.8	14.0	1.4	95.2
Cereals	12.0 (0.8)	1.35	16.2	23.0	1.9	25.3
Chickpeas on ridges	11.0 (1.0)	1.32	14.5	27.0	2.5	29.7
Grazed fallow	11.3 (2.0)	1.36	15.4	26.0	2.3	31.2
Protected fallow	12.3 (2.2)	1.31	16.1	35.0	2.8	21.0
Mascara, Brown Calcareous Soil						
Bare soil	10.0 (0.4)	1.51	15.1	16.0	1.6	136.0
Cereals	10.3 (1.0)	1.52	15.7	28.0	2.7	22.4
Peas on ridges	10.3 (1.3)	1.50	15.5	29.0	2.8	17.4
Grazed fallow	10.3 (1.3)	1.53	15.8	26.0	2.5	41.6
Protected fallow	12.3 (1.6)	1.44	17.7	48.0	3.9	24.0
Tlemcen, Vertic Soil						
Bare soil	8.0 (0.3)	1.31	10.5	10.6	1.3	19.1
Wheat/fallow, downslope till.	9.0 (0.3)	1.30	11.7	16.8	1.9	26.9
Fertilized wheat, contour till.	10.3 (0.3)	1.30	13.4	20.6	2.0	33.0
Tlemcen, Brown Calcareous Soil						
Bare soil	18.6 (0.8)	1.12	20.8	20.1	1.1	78.4
Overgrazed scrub	23.0 (1.7)	1.16	26.7	39.0	1.7	27.3
Protected scrub	33.3 (1.2)	1.12	37.3	48.0	1.4	33.6
Tlemcen, Fersiallitic Soil						
Bare soil	6.3 (0.4)	1.49	9.4	9.8	1.6	31.4
Overgrazed degraded scrub	6.8 (0.3)	1.51	10.3	14.5	2.1	26.1
Protected scrub	9.4 (0.2)	1.50	14.1	18.0	1.9	18.0
Medea, Vertic Soil						
Bare soil	nd	nd	nd	nd	nd	nd
Cereals/grazed fallow	7.2	1.30	9.4	10.1	1.4	3.7
Fertilized cereal-legume association	6.8	1.30	8.8	9.0	1.3	0.4
Medea, Brown Calcareous Soil 1						
Bare soil	nd	nd	nd	nd	nd	nd
Overgrazed scrub	6.1	1.70	10.2	18.0	2.9	36.0
"Regrassed" scrub	7.1	1.50	10.7	22.1	3.1	0.4
Medea, Brown Calcareous Soil 2						
Bare soil	nd	nd	nd	nd	nd	nd
Traditional vineyard	8.3	1.20	10.0	8.9	1.1	1.7
Fertil. vine ^a with cereal-legume	8.2	1.10	9.0	9.8	1.2	0.1
Medea, Fersiallitic Soil						
Bare soil under orchard	nd	nd	nd	nd	nd	nd
Traditional orchard	7.1	1.50	10.7	11.4	1.6	13.9
Orch + cereal-legume, contour	8.0	1.50	12.0	13.4	1.7	3.9

Note: Figures in parentheses are standard deviations. nd: not determined; till.: tillage; fertil.: fertilized; vine: vineyard; orch: orchard.

the surface soil was -1.2 to -4.2% in bare soils, -1.2 to -2.8% under grazed plots, 2.3 to 4.1% under protected fallows or scrub, -0.3 to -0.5% under legumes, and -0.2 to 1.1% under cereals.

8.3.5 Eroded Organic Carbon

Except on bare soils where eroded OC was 19 to 136 kg C ha⁻¹ yr⁻¹, it ranged from 0.1 to 42 kg C ha⁻¹ yr⁻¹, which is a moderate level especially considering the slope steepness of some plots (Table 8.4). On bare soils, it was greater in Mascara than in Tlemcen (95 to 136 vs. 19 to 78 kg

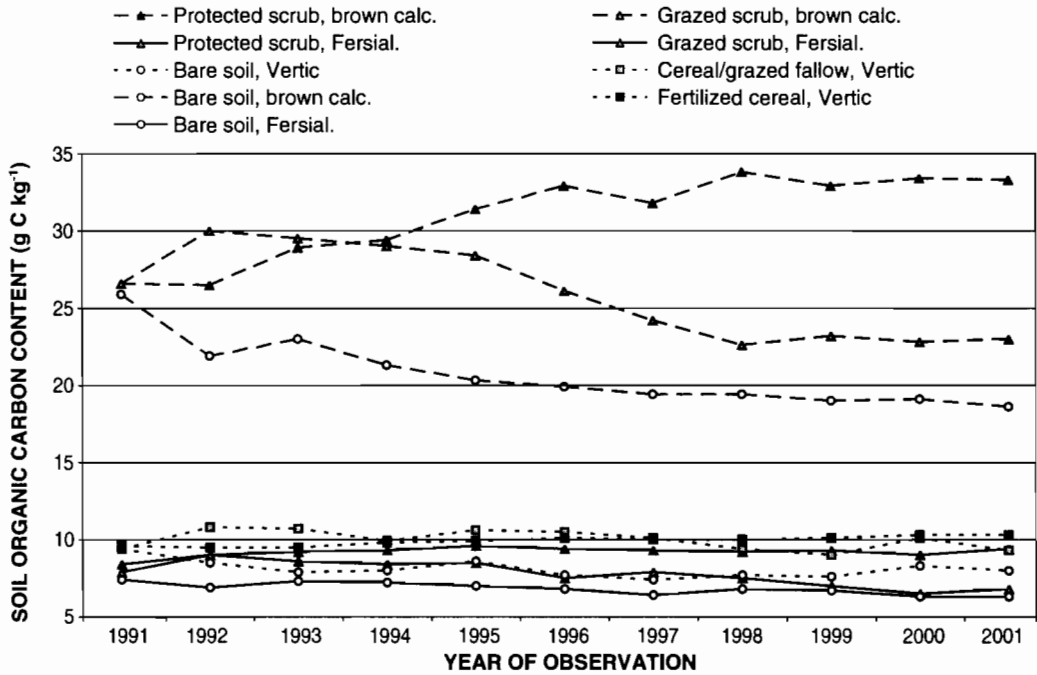


Figure 8.1 Changes in soil organic carbon content at 0 to 10 cm depth in the runoff plots located near Tlemcen (1991 to 2001).

C ha⁻¹ yr⁻¹), but differences among locations were not distinct on vegetated plots (17 to 42 vs. 18 to 34 kg C ha⁻¹ yr⁻¹). The amount of eroded OC was generally less in Medea (0.1 to 14 kg C ha⁻¹ yr⁻¹ except on one overgrazed plot where it was 36 kg C ha⁻¹ yr⁻¹; however, eroded OC was not determined on bare soils). On average, eroded OC was more on brown calcareous than on Vertic and Fersiallitic soils for bare (107, 57, and 31 kg C ha⁻¹ yr⁻¹, respectively) and grazed plots (35, 31, and 26 kg C ha⁻¹ yr⁻¹, respectively). However, soil type had no effect on the amount of eroded OC for protected fallows or scrub (19, 21, and 18 kg C ha⁻¹ yr⁻¹, respectively) and for cereal or legume cropping systems (20 kg C ha⁻¹ yr⁻¹ for both Vertic and brown calcareous soils). Considering vineyards and orchards in Medea, the amount of eroded OC was lesser on brown calcareous than on Fersiallitic soils (< 2 vs. 4 to 14 kg C ha⁻¹ yr⁻¹). For a given location and soil type, eroded OC was generally 20 to 80% more on bare soil than on vegetated plots (except for Tlemcen's Vertic soils where it was 30 to 40% smaller). It was generally 20 to 90% greater on grazed than on protected fallows or scrub (except for Tlemcen's brown calcareous soils where it was 20% smaller). For a given soil and crop type, eroded OC was 70 to 90% lesser for improved than for traditional cropping systems in Medea (cereal, vineyard, and orchard systems), but was 20% more for the improved than for the traditional cereal system in Tlemcen (Vertic soil).

Comparing SOC contents of sediments and topsoil (0 to 10 cm depth), the carbon enrichment ratio of sediments (CER) was more on average for Mascara (2.4) than Tlemcen and Medea (1.7), whereas differences among soil types were small (2.1, 1.9, and 1.8 in average for brown calcareous, Vertic, and Fersiallitic soils, respectively; Table 8.4). With regard to the effect of land use, the mean CER was 1.4 on bare soils (ranging from 1.1 to 1.6) and on vineyards and orchards (1.1 to 1.7), 2.1 on cereal or legume systems (1.3 to 2.8), and on grazed plots (1.7 to 2.5), and 2.6 on protected fallows or scrub (1.4 to 3.9). Excluding vineyards and orchards (Medea), erosion selectivity for OC increased with increase in soil surface cover, from bare plots to protected fallows and scrub lands.

In comparison with the annual change in SOC stock (0 to 10 cm depth), which was computed for Vertic and brown calcareous soils in Mascara and Tlemcen (Figure 8.2), annual eroded OC was negligible on protected fallows and scrub land (< 5% of annual SOC change, which was positive

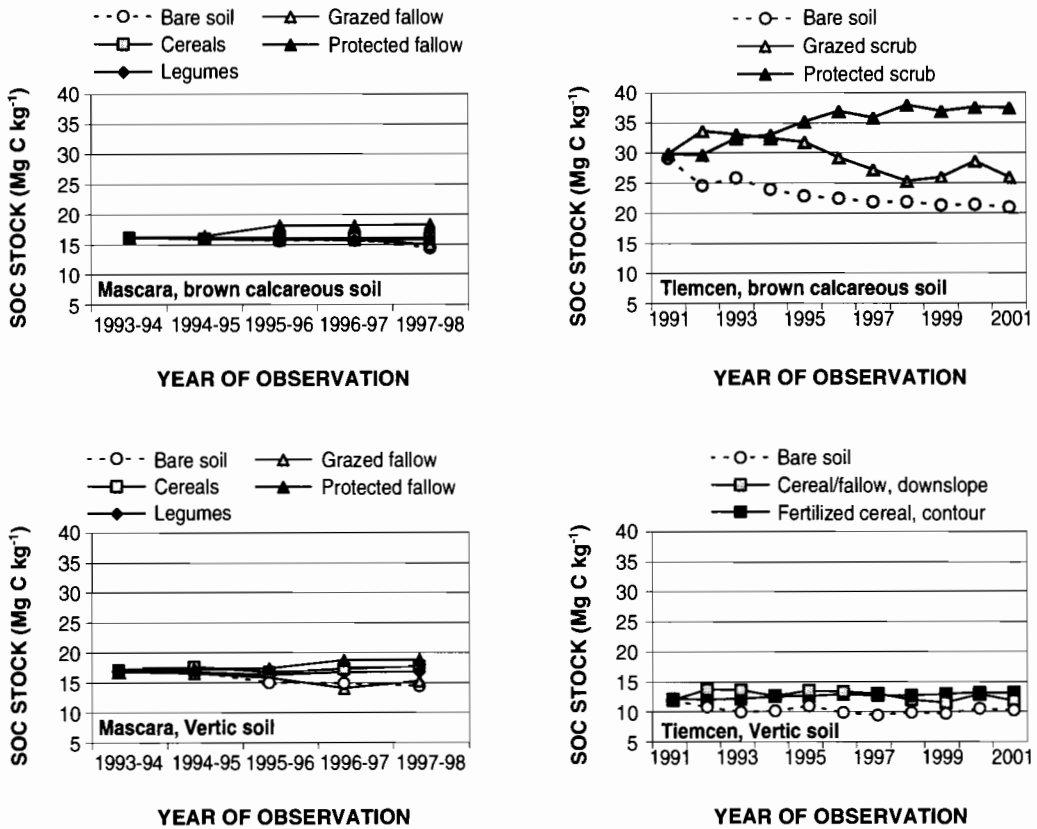


Figure 8.2 Changes in soil organic carbon (SOC) stocks at 0 to 10 cm depth in the runoff plots located on Vertic and brown calcareous soils near Mascara (1993 to 1998) and Tlemcen (1991 to 2001).

in that case). For two out of the three cereal plots on Vertic soils where SOC increased markedly (100 to $180 \text{ kg C ha}^{-1} \text{ yr}^{-1}$), the consequences of SOC erosion (25 to $33 \text{ kg C ha}^{-1} \text{ yr}^{-1}$) were also limited. In contrast, eroded OC contributed greatly to decrease in SOC in some cereal and legume plots (60% for chickpea on Vertic soil and 90% for cereals on brown calcareous soil in Mascara, 180% for traditional wheat/fallow on Vertic soil in Tlemcen). However, loss of eroded OC generally represented a small proportion of decrease in SOC in grazed (7 to 13%) and bare plots (10 to 14% in general, but 26% for the brown calcareous soil in Mascara). Therefore, the consequences of SOC erosion on change in SOC were limited in general and on bare soils, fallows, and scrub especially, but could be high on cropped plots.

For 27 of the 31 plots (eroded OC was not determined for the four bare plots in Medea), annual eroded OC was neither correlated with topsoil OC nor with sediment OC contents, but was correlated with the annual erosion rate ($r = 0.950$, $p < 0.01$; Figure 8.3). It was more closely correlated with the product of erosion multiplied by topsoil OC content ($r = 0.964$), especially when highly erodible plots were not taken into account ($r = 0.908$ for the 24 plots with erosion $< 3.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, vs. $r = 0.711$ for the 27 plots; $p < 0.001$ in both cases). Thus considering topsoil SOC content in addition to annual erosion provided a good prediction of annual eroded OC.

8.3.6 Seasonal Variations in Runoff, Erosion, and Eroded Organic Carbon

Figure 8.4 depicts rainfall amount, runoff rate, erosion, sediment OC content, and eroded OC on a monthly basis from September 1995 to May 1996, for the brown calcareous soil in Mascara (monthly runoff rate is averaged over the period 1993 to 1998). Rainfall and runoff were maximum

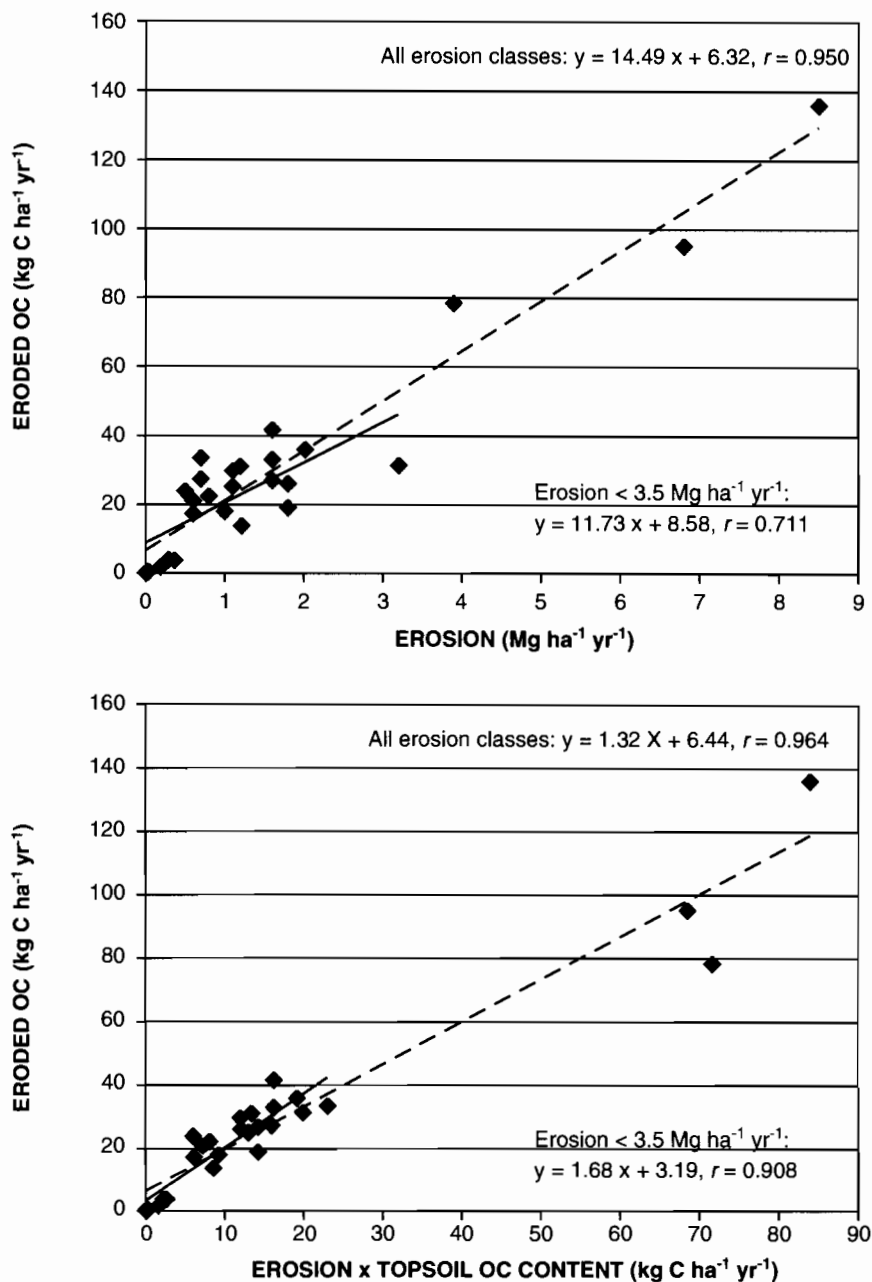


Figure 8.3 Relationships between eroded organic carbon (OC) and erosion, or between eroded OC and the product of erosion multiplied by topsoil (0 to 10 cm depth) OC content, for the runoff plots under study in northern Algeria.

during the winter (rainfall was more than 60 mm month⁻¹ from November to February, and runoff more than 7% on bare soil). The peaks of erosion and eroded OC were observed for a short duration only during November and December. Sediment OC content was low for these both months, but was high in October and between January and March. Indeed, organic residues accumulated on vegetated plots during the summer were eroded by the first rainstorms in autumn, but due to small rainfall amounts, erosion was low and the sediment OC content was high. In November and December, the soil surface being partly covered by vegetation, high rainfall amounts resulted in

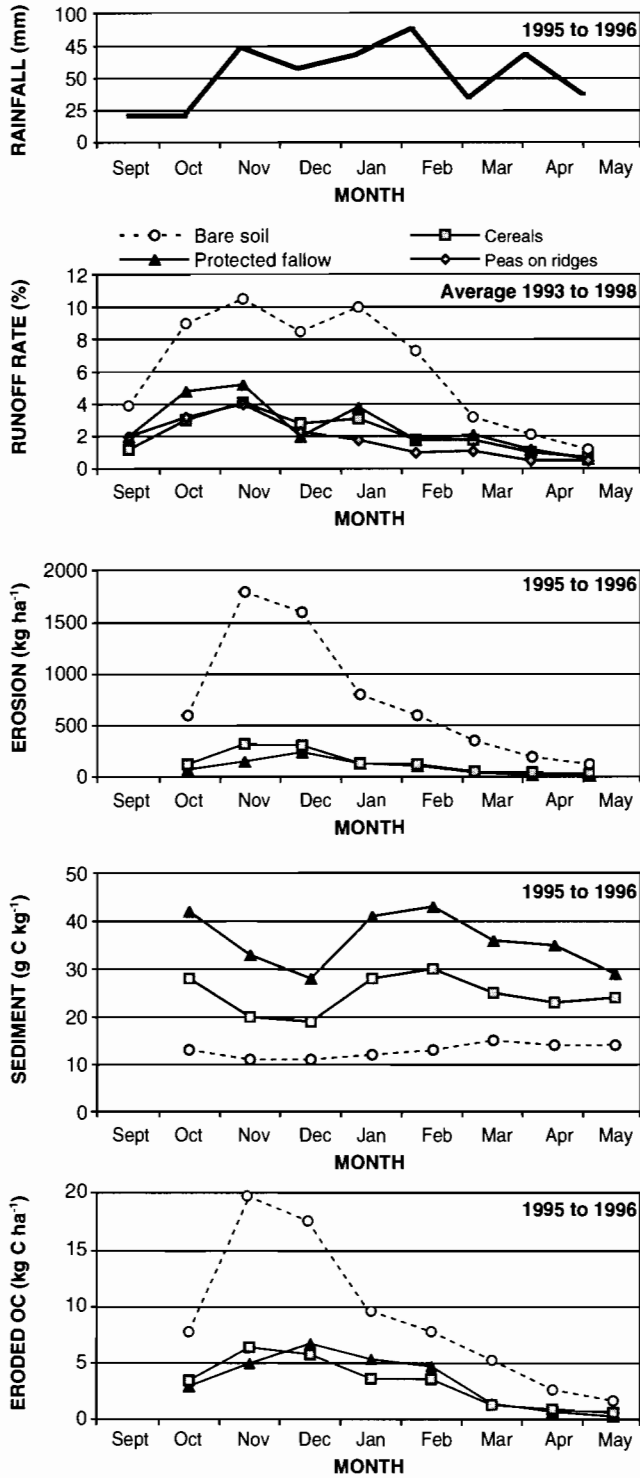


Figure 8.4 Seasonal variations in rainfall, runoff rate, erosion, sediment organic carbon (OC) content, and eroded OC in 1995 to 1996 for Mascara plots (average 1993 to 1998 for the runoff rate).

high soil losses. However, because organic residues had already been eroded, the sediment OC content decreased. In January and February, easily erodible soil particles had already been removed, and despite the high rainfall amounts, erosion decreased, but was more selective for OC. Due to increasing soil surface cover by vegetation, erosion remained low in the spring, but its selectivity decreased resulting in very small OC erosion. Seasonal changes in sediment OC content were less on bare plots due to the absence of vegetation and organic residues, with similar changes in erosion and eroded OC.

8.4 DISCUSSION

8.4.1 Rainfalls

For the study period, annual rainfall in the region was 30 to 40% lower than the long-term average for the 1913 to 1971 period. Storms with high intensities were also few: in 2000 there was only one intense storm with 84-mm hr⁻¹ 30-min intensity. Therefore, the erosivity index of the USLE (Wischmeier and Smith, 1978) was moderate: for the study period, it varied from 30 to 80 U.S. units (hundreds of foot-tons per acre times inches per hour, which may be converted into MJ mm ha⁻¹ h⁻¹ when multiplied by 17.35; this index is expressed in U.S. units to allow comparison with literature data). The ratio of erosivity index to annual rainfall was about 0.10 in the Mediterranean mountainous zone: this is much smaller than in the tropics (0.50) or in tropical mountains (0.25) (Roose, 1996).

Contrary to the general opinion that Mediterranean climate is characterized by erosive rains, these data confirmed those obtained for Medea in Algeria (Arabi and Roose, 1992; Roose et al., 1993) and in Morocco (Heusch, 1970; Arnoldus, 1981). Thus, the principal reasons for the severe erosion of these landscapes are: (1) the weak vegetation cover in these semiarid areas, and (2) the occurrence once in 10 years of one exceptional rainstorm. Such extreme rainstorms completely saturate the thin soils compacted by overgrazing or rendered bare after crop harvest, leading to large amounts of runoff, which, on steep slopes, cause numerous gullies and landslides characteristic of the landscapes (Roose et al., 2000).

8.4.2 Runoff

Annual runoff rates were moderate during the dry period under study (< 20%). However, for Mascara and Tlemcen stations, the maximum (daily) runoff rate was 30 to 40% during exceptional rainstorms saturating the bare topsoil, sealed, compacted, and/or already wet. Similar results were observed on Medea's runoff plots, but the maximum runoff rate was up to 80% for bare plots on Vertic soils (Roose et al., 1993).

Annual runoff rate was correlated with the annual rainfall, as indicated by comparisons made in Tlemcen for bare plots and protected scrub (data not shown). The antecedent soil moisture content was an important determinant of runoff: the runoff began after 22 mm of intense rain when the topsoil was dry (5 days without rain) but after 2 to 4 mm when the soil was wet, compacted or crusted (Morsli et al., 2004; Sabir et al., 2004). These thresholds depended on rainfall (intensity) and soil surface characteristics (initial soil moisture, bulk density, roughness, stone and vegetation cover, macro-aggregation and clods; Sabir et al., 2002).

On bare plowed fallows, even low intensity and amount of rainfall (< 5 mm) produced runoff when rains were successive and the topsoil was wet or sealed. On row-cropped systems, maximum runoff rate occurred between October and January, when the soil surface conditions were susceptible (low vegetation cover, sealing crust, high soil moisture) and the rains were abundant and relatively intense (Figure 8.4). On overgrazed and degraded scrub, runoff events were frequent and large because of a weak tuft vegetation cover, surface crust, abundance of stones, and topsoil compaction

by grazing (Sabir et al., 1994). Grazing lands are an important source of runoff degrading the fields downstream, and causing gullies, landslides, and floods (Roose et al., 2000). Around Tlemcen, runoff occurred for 80% of the rainfall events for bare and already scoured soils covered by grazed scrub or fallows (Mazour, 1992). The runoff generally decreased when these natural fallows were protected against fire and grazing, due to slowly increasing litter and vegetation cover.

8.4.3 Sheet Erosion

All measurements conducted in the Maghreb mountains at the scale of runoff plots have shown that sheet and rill erosion are moderate on the hillslopes (from 1 to 20 Mg ha⁻¹ yr⁻¹): in Algeria, Arabi and Roose (1992), Gomer (1992), Mazour (1992), Brahamia (1993), Roose (1993), Roose et al. (1993), Chebbani (1996), Morsli (1996), Kouri et al. (1997), and Roose et al. (2000); in Morocco, Heusch (1970), Al Karkouri et al. (2000), Laouina et al. (2000), and Moufaddal (2002); and in Tunisia, Masson (1971), Bourges et al. (1977), Delhumeau (1981), and Delhoume (1987). This conclusion was confirmed by the data presented in this chapter.

This low erosion is probably related to low rainfall energy and to soil resistance provided by high contents of clay, exchangeable calcium and stones in the surface soil. Nevertheless the energy of large amounts of runoff on steep slopes causes gullies which are very active during exceptional storms falling on saturated soils during the winter and the spring (Roose, 1991; Roose et al., 1993; Kouri and Vogt, 1994). Indeed, according to Heusch (1970), Demmak (1982), and Moukhchane (2002) sheet erosion represents only a small proportion (0.2 to 10 Mg ha⁻¹ yr⁻¹) of the sediments transported by the wadies (rivers) in the Mediterranean mountains. In these semiarid areas, severe erosion occurs only during exceptional storms cumulating a tremendous runoff energy on steep slopes. The concentrated runoff scarves gullies, increases the flow in wadies, causes floods, embankment degradation, landslides on hillslopes, and rapid siltation of reservoirs (Roose et al., 1993).

The effect of land use on erosion was well defined: improved cropping systems and protection against grazing caused less erosion than traditional cropping practices and grazing. Conservation effective cultural practices like ridging, rough tillage on the contour, appropriate fertilizer rate, and their interactions with the vegetation growth reduced the risks of runoff and erosion. This positive but limited influence of cultural practices in semiarid Mediterranean areas is confirmed by results obtained under natural (Arabi, 1991; Brahamia, 1993; Roose et al., 1993) and simulated rainfalls (Morsli et al., 2002). Higher runoff and soil losses on bare soil and grazed fallow or scrub than on protected scrub have already been reported (Mazour and Roose, 2002).

The influence of slope steepness on sheet erosion is not distinctively observed in the Mediterranean mountains. Heusch (1970) showed for Vertisols on marl in the Pré-Rif hillslopes of Morocco that the slope steepness (12 to 35%) was less important than the position on the toposequence. Indeed, rain falling on these Vertic clayey soils percolated into the cracks and bypassed to the concave or bottom of the hillslopes where it saturated the soil, producing gullies that progressed upslope from the valley to the hilltop. For runoff plots established on a range of soil types near Tlemcen and Medea, Mazour (1992) and Roose et al. (1993) reported that the runoff decreased and the sheet erosion did not increase with increase in slope steepness from 12 to 40%. Nevertheless, the gully erosion increased on steeper slopes, as runoff energy (for detachment and transport) increased with the square of the flow velocity (Roose et al., 2000).

The analysis of the erosion factors showed that the combination of maximum rainfall erosivity and soil erodibility in the cultivated fields occurred at the beginning of the rainy season and during the cool period of winter–spring (Mazour and Roose, 2002). Even if the erosion risks remain moderate according to the tolerable limit, the sheet erosion scours the organo-mineral topsoil, exports selectively the fine or light particles (clay, silts, SOC), and reduces the soil fertility potential, the SOC stock and the potential for SOC sequestration (Meddi and Morsli, 2001; Lal, 2004). Finally, by degrading the topsoil structure, sheet erosion paves the way for rills and gullies (Le Bissonnais, 1996).

8.4.4 Soil Organic Carbon

SOC content of the topsoil (0 to 10 cm depth) was low ($< 12 \text{ g C kg}^{-1}$ in general, and always $< 35 \text{ g C kg}^{-1}$), due to low overall biomass production and residue return, and rapid mineralization, accelerated by erosion. Experiments conducted at the landscape level in the mountains of northern Algeria showed that SOC content varied according to topsoil characteristics such as soil texture ($r = 0.55$), land use, biomass produced, and the landscape position (Morsli, 1996). The SOC content of surface soil was about 10 g C kg^{-1} on the summit and 30 g C kg^{-1} on the fast slopes and valleys. The decrease in SOC content with depth depended on the soil type and was sharp in the brown calcareous soils, but gentle in the Vertic soils due to natural mixing in swelling horizons. These observations confirmed the results reported by Batjes (1996) that SOC content varies at the world level with soil texture and mineralogy.

Land use plays an important role in the variability of SOC and its dynamics (Lal, 2004). For the runoff plots under study, the SOC in the surface soil was lower in bare than vegetated plots (-3 to -44%), and under grazed than under protected fallows or scrub (-8 to -31%). The differences in SOC of surface soil between improved and traditional cropping systems were generally small ($< 15\%$). For the study duration, the SOC of surface soil decreased in bare and grazed plots (-1 to -4% per year), increased under protected fallows or scrub (1 to 3% per year), and changed slightly under crops (-0.5 to 1% per year). Increasing SOC content of surface soil under protected natural fallow (28%) has been reported for the eastern Rif in Morocco (Tribak, 1988). This practice involves large biomass production and residue return, which contribute to the restoration of SOC, soil fertility, and biomass productivity (Sabir et al., 2002; Lal, 2004). However, the restoration is much slower when the fallow is grazed (at an appropriate stocking rate). Improved cropping systems (including appropriate fertilizer rate, intercropping, contour tillage, reduced tillage, etc.) generally result in increasing topsoil SOC, due to increasing biomass production and decreasing OC erosion (Campbell and Zentner, 1993). However, this trend was not clear in the paired plots under study (traditional vs. improved system). On slopes less than 20% , reduced tillage and ridging have a strong influence on soil degradation risks, as they delay the start of runoff, increase infiltration rate, and maintain SOC stock (Sabir et al., 2002). Nevertheless ridges on steep slopes may be broken leading to formation of gullies during intensive rainstorms. However, when it is well managed and on moderate slopes and permeable soils, and tied at 2 to 5 m distance, ridging may effectively reduce erosion and improve infiltration and biomass production (Azontonde, 1993; Roose, 1996; Morsli et al., 2004). Bare soils, overgrazed fallows, and degraded scrub had a high risk of erosion and depletion of SOC stock in the surface layer.

Additional data (not shown) indicated that hill-slope aspect (northern vs. southern slope) had an important influence on SOC content. SOC content was relatively higher on northern than on southern slopes, which received less rainfall, were less covered by vegetation, and were thus more easily eroded (Mazour and Benmansour, 2002).

8.4.5 Eroded Organic Carbon and Erosion Selectivity for Carbon (CER)

For the plots under study, annual erosion of OC ranged from 19 to $136 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ on bare plots compared to 0.1 to $42 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ on vegetated plots. Eroded OC was affected by land use and it was generally more on bare than on vegetated plots, on grazed than on protected fallows or scrub, and on conventional than on improved cropping systems.

Eroded OC contributed to decrease in SOC, but effects on topsoil SOC changes were limited in general, except on some cereal and legume plots. Thus, SOC changes depended primarily on the amount of biomass returned to the soil and on residue decomposition and SOC mineralization, and secondarily on erosion, as reported for tropical areas (Blanchart et al., 2002; Blanchart et al., this volume).

Sheet erosion not only scours the topsoil, it also preferentially removes the fine and light particles (clay, silts, SOC). Compared to the SOC content of 0 to 10 cm depth, sediment enrichment

in OC (CER) ranged from 1.1 to 3.9. It was lower for bare soils, vineyards, and orchards (1.4 on average) than for protected fallows and scrub (2.6 on average), and was intermediate for cropped and grazed plots (2.1 on average). The presence of a thick litter layer reduced the velocity hence the detachment and transport capacities of the runoff flow, but provided easily transportable organic particles. Therefore, sediments from protected fallow or scrub were particularly enriched in OC, as they included relatively less heavy mineral particles and more light organic particles than sediments from bare, grazed, and cropped plots. This effect of litter explains why the increase in topsoil SOC content is generally associated with an increase in CER (Roose and Barthès, this volume). However, ratios of removed OC to topsoil OC were somewhat underestimated, because the dissolved OC in runoff and drainage water were not determined, though it may represent noticeable losses of OC (Blanchart et al., this volume).

The amount eroded OC correlated with erosion, and even more strongly with the product of erosion and topsoil SOC content, especially for plots with erosion rate of $< 3.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (i.e., excluding most of the bare plots). In contrast, the amount of eroded OC did not depend on sediment OC content. Comparing the seasonal variations, Bep A Ziem et al. (2002) reported that eroded OC was more closely correlated with erosion than with sediment OC content. Indeed, most of the OC losses occur during large rainstorms that produce large amounts of sediments with low OC content. Such events produce large runoff amounts that carve rills or gullies in the subsoil where SOC content is low, so that sediment OC content is reduced. In contrast, high sediment OC contents are associated with small soil losses resulting from less erosive rainfall events or from rainfalls that occur when the soil surface is covered by vegetation. Such rains have low runoff energy and erosion affects only the most superficial soil layers, which are the richest in OC, and this results in high sediment OC content (Roose, 1981). In Algeria, the greatest OC losses were measured between November and January, when erosion was maximum and sediment OC content was minimum.

Eroded sediments and OC are partially redistributed in the fields or deposited as colluvium at the foot slopes and in the talwegs (Morsli, 1996). The amount of OC retained on the hillslopes depends on soil surface roughness, topography, and land use. Large sediment deposits have been observed in some parts of the landscapes, and they exert a strong influence on the distribution of soil fertility. Lal (2002) observed that a part of the eroded OC is deposited in the concavity of the hillslopes, where it is somewhat protected, and where it causes strong variations in crop yields. The study of OC dynamics over the landscape is necessary to improve the management of soil potential and to restore SOC stocks, in order to optimize sustainable production and to increase SOC sequestration.

8.5 CONCLUSIONS

The data presented in this chapter show that, at the plot scale (100 to 200 m²), runoff and sheet erosion risks were generally moderate in the semiarid mountains of northern Algeria, even when the fields were cropped on steep slopes (mean annual runoff rate and erosion $< 20\%$ and $< 15 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, respectively). However, a few exceptional rainstorms caused spectacular erosion features: rills, gullies, landslides, and floods. These observations confirm the conclusions of numerous researchers in northern Africa. Nevertheless this moderate erosion degraded the surface soil, depleted soil fertility, and reduced productivity. The losses of eroded OC were also moderate and ranged from 0.1 to 42 kg C ha⁻¹ yr⁻¹ on vegetated plots and 19 to 136 kg C ha⁻¹ yr⁻¹ on bare plots. Losses were influenced by landscape position, soil type, land use, and cultural practices. The eroded OC was generally more on bare than on vegetated plots, grazed than protected fallows or scrub, and improved than traditional cropping systems. Additionally, annual losses of eroded OC correlated with annual erosion, and more closely, with the product of erosion multiplied by topsoil SOC. The data also indicate that sediments were richer in OC than the topsoil (0 to 10 cm depth), and that this enrichment increased with soil surface cover (i.e., bare plots $<$ grazed and cropped plots $<$

protected fallow and scrub). Over the study periods, SOC in the surface layer decreased in bare and grazed plots, increased under protected fallows or scrub land, and changed only slightly under crops. However, the contribution of erosion to annual changes in SOC was limited in general, except on some cereal and legume plots. These results confirm that for most of the land uses, changes in SOC depend primarily on the amount of biomass returned to the soil and on residue decomposition and SOC mineralization, and secondarily on erosion. Such studies, carried out on plots, should be completed by measurements involving complete hillsides, in order to address mechanisms that occur at this scale, such as gully erosion, and sediment and OC redistribution along the slopes.

Considering land management, the results indicate that continuous cultivation did not increase the erosion risks, even under traditional systems. However, bare and compacted soils, abandoned fields, overgrazed fallows, or degraded scrub lands can produce high runoff and increase risk of gully formation and landslides. Ridge cropping and protecting fallows and scrub land can reduce erosion risks and increase the SOC and the biomass production. Use of innovative and improved cultural practices (appropriate fertilizer rate, seed selection, ridging, and adapted cultural practices like crop rotations and intercropping) incorporated in the best traditional farming systems, as land husbandry, increased production (yield of cereals multiplied by 2 to 4 on improved plots), decreased erosion risk, and increased SOC (up to 28% increase) (Roose, 1993). Other antierosive techniques (gully management, stone walls, hedges, planting on the contour, etc.) are effective in trapping sediments and organic matters. The land husbandry approach has demonstrated that it is possible to improve crop production in the hilly regions (intensification and diversification) while enhancing the environment (Arabi and Roose, 1992; Roose, 1993; Mazour and Roose, 2002; Hamoudi and Morsli, 2003). In Algeria, where land use is rapidly changing, the national projects on rural development are based on the land husbandry strategy with the participatory approach (Morsli et al., 2004). Fruit tree plantations, improved cultural practices and water management, agroforestry, and grazing regulation are the most widely used strategies for the rural development. These improved practices have a positive effect on productivity, soil erosion control, and carbon sequestration. Nevertheless, Algeria needs additional research regarding the effects of conservation cultural practices (like no-till and mulch farming) on carbon sequestration and soil productivity.

REFERENCES

- Al Karkouri, J., A. Laouina, E. Roose, and M. Sabir. 2000. Capacité d'infiltration et risques d'érosion des sols dans la vallée des Béni Boufrah — Rif central (Maroc). *Bulletin du Réseau Erosion* 20:342–356.
- Arabi, M. 1991. *Influence de quatre systèmes de production sur le ruissellement et l'érosion en milieu montagnard Méditerranéen (Médéa, Algérie)*. Ph.D. Dissertation, Université de Grenoble, France.
- Arabi, M. and E. Roose. 1992. Water and soil fertility management (GCES). A new strategy to fight erosion in Algerian mountains, in P. G. Haskins and B. M. Murphy, eds., *Proceedings of the 7th ISCO (International Soil Conservation Organization) Conference*, Sydney, 27–30 September 1992, pp. 341–347.
- Arabi, M. and E. Roose. 2002. Influence des systèmes de production et du sol sur l'érosion en nappe et rigole, le stock de carbone du sol et les pertes par érosion en moyenne montagne méditerranéenne du NO de l'Algérie. Communication at the International Colloquium Land Use, Erosion and Carbon Sequestration, Montpellier, France, 23–28 September 2002.
- Arnoldus, H. 1981. An approximation of the rainfall factor in the USLE, in M. De Boedt and D. Gabriels, eds., *Assessment of Erosion*, John Wiley & Sons, New York, pp. 127–132.
- Azontonde, A. 1993. Dégradation et restauration des terres de barre au Bénin. *Cahiers ORSTOM, série Pédologie* 28:217–226.
- Batjes, N. H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47:151–163.
- Benchetrit, M. 1972. *l'érosion actuelle et ses conséquences sur l'aménagement en Algérie*. Presses Universitaires de France, Paris.

- Bep A Ziem, B., Z. B. Boli, and E. Roose. 2002. Pertes de carbone par érosion hydrique et évolution des stocks de carbone sous rotation intensive coton/maïs sur des sols ferrugineux sableux du Nord Cameroun. Communication at the International Colloquium Land Use, Erosion and Carbon Sequestration, Montpellier, France, 23–28 September 2002.
- Bernoux, M., C. Feller, C. C. Cerri, V. Eschenbrenner, and C. E. P. Cerri. 2006. Soil carbon sequestration, in E. Roose, R. Lal, C. Feller, B. Barthès, and B. A. Stewart, eds., *Soil Erosion and Carbon Dynamics*, Taylor & Francis, Boca Raton, FL
- Blanchart, E., E. Roose, B. Khamsouk, M. Dorel, J. Y. Laurent, C. Larré-Larrouy, L. Rangon, J. P. Tisot, and J. Louri. 2002. Comparaison des pertes de carbone par érosion et drainage aux variations du stock de c du sol en deux années: Cas d'une rotation bananiers-cannes-ananas-sol nu sur un nitisol argileux sur cendres volcaniques de Martinique. Communication at the International Colloquium Land Use, Erosion and Carbon Sequestration, Montpellier, France, 23–28 September 2002.
- Blanchart, E., E. Roose, and B. Khamsouk. 2006. Soil carbon dynamics and losses by erosion and leaching in banana cropping systems with different practices (Nitisol, Martinique, West Indies), in E. Roose, R. Lal, C. Feller, B. Barthès, and B. A. Stewart, eds., *Soil Erosion and Carbon Dynamics*, Taylor & Francis, Boca Raton, FL.
- Blavet, D., G. De Noni, E. Roose, L. Maillo, J. Y. Laurent, and J. Asseline. 2004. Effets des techniques culturales sur les risques de ruissellement et d'érosion en nappe sous vigne en Ardèche (France). *Sécheresse* 15:111–120.
- Bourges, J., C. Floret, and R. Pontanier. 1977. *Etude d'un milieu représentatif du sud Tunisien: Citerne Telman, Type Segui, Campagnes 1972–74*. ORSTOM, Tunis.
- Brahamia, K. 1993. *Essai sur la dynamique actuelle dans la moyenne montagne Méditerranéenne: Oued Mina, Algérie*. Ph.D. Dissertation, Université de Grenoble, France.
- Campbell, C. A., and R. P. Zentner. 1993. Soil organic matter as influenced by crop rotations and fertilization. *Soil Science Society of America Journal* 57:1034–1040.
- Chebbani, R. 1996. *Etude à différentes échelles des risques d'érosion dans le bassin Versant de l'Isser (Tlemcen)*. Magister Thesis, INA, Algiers.
- Coelho, C. O. A., A. Laouina, A. J. D. Ferreira, K. Regaya, M. Chaker, R. Nafaa, R. Naciri, T. M. M. Carvalho, and A. K. Boulet. 2002. The dynamics of land use changes in Moroccan and Tunisian sub-humid and semiarid regions and the impact on erosion rates and overland flow generation. Communication at the International Colloquium Land Use, Erosion and Carbon Sequestration, Montpellier, France, 23–28 September 2002.
- Cormary, Y. and J. M. Masson. 1964. Etude de la conservation des eaux et du sol au centre de recherche du génie rural de Tunisie: Application à un projet type de la formule de perte de sol de Wischmeier. *Cahiers ORSTOM, série Pédologie* 2:3–26.
- Delhoume, J. P. 1987. Ruissellement et érosion en bioclimat méditerranéen semi-aride de Tunisie Centrale, in A. Godard and A. Rapp, eds., *Processus et Mesure de l'Erosion*, Editions CNRS, Paris, pp. 487–507.
- Delhumeau, M. 1981. *Recherches en milieu Méditerranéen humide: Etude de la dynamique de l'eau sur parcelles du Bassin Versant de l'Oued Sidi Ben Naceur, Nord Tunisie*. Ministère de l'Agriculture (DRES) and ORSTOM, Tunis.
- Demmak, A. 1982. *Contribution à l'étude de l'érosion et des transports solides en Algérie Septentrionale*. Ph.D. Dissertation, Université de Paris VI.
- Doran, J. W., M. Sarrantonio, and M. A. Liebig. 1996. Soil health and sustainability. *Advances in Agronomy* 56:1–53.
- Dumas, J. 1965. Relation entre l'érodibilité des sols et leurs caractéristiques analytiques. *Cahiers ORSTOM, série Pédologie* 3:307–333.
- Fournier, F. 1967. La recherche en érosion et conservation des sols sur le continent africain. *Sols Africains* 12:5–53.
- Gomer, D. 1992. *Ecoulement et érosion dans des petits Bassins Versants à sols marneux sous climat semi-aride Méditerranéen*. GTZ-ANRH, Algiers.
- Gsell, S. 1913. *Histoire ancienne de l'Afrique du Nord. Volume 1: Les conditions du développement historique. Les temps primitifs. La colonisation Phénicienne et l'Empire de Carthage*. Hachette, Paris.
- Hamoudi, A. and B. Morsli. 2003. Erosion et spécificité de l'agriculture de montagne: réflexion sur la conservation et la gestion de l'eau et du sol en milieu montagneux Algérien. *La Forêt Algérienne* 12:18–25.

- Heddadj, D. 1997. La lutte contre l'érosion en Algérie. *Bulletin du Réseau Erosion* 17:168–175.
- Heusch, B. 1970. L'érosion du Pré-Rif. Une étude quantitative de l'érosion hydraulique dans les collines marneuses du Pré-Rif Occidental (Maroc). *Annales de la Recherche Forestière du Maroc* 12:9–176.
- Hien, E. 2002. Effet de la déforestation et de l'érosion sur le statut organique du sol: cas d'un sol ferrugineux tropical sableux du SO du Burkina Faso. Communication at the International Colloquium Land Use, Erosion and Carbon Sequestration, Montpellier, France, 23–28 September 2002.
- Kouri, L., and H. Vogt. 1994. Gully processes and types in oued Mina basin, Algeria. Communication at the ESSC (European Society for Soil Conservation) Workshop Soil Erosion in Semiarid Mediterranean Areas, 28–30 October 1993, Taormina, ESSC and CSEI, Catania, Italy.
- Kouri, L., H. Vogt, and D. Gomer. 1997. Analyse des processus d'érosion hydrique linéaire en terrain marneux, bassin versant de l'oued Mina, Tell oranais, Algérie. *Bulletin du Réseau Erosion* 17:64–73.
- Lal, R. 2002. Soil conservation and restoration to sequester carbon and mitigate the greenhouse effect, in J. L. Rubio, R. P. Morgan, S. Asins, and V. Andreu, eds., Proceedings of the 3rd International Congress of the ESSC (European Society for Soil Conservation) *Man and Soil at the Third Millennium*, Geofoma Ediciones, Logrono, Spain.
- Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304:1623–1627.
- Lal, R., J. M. Kimble, R. F. Follett, and B. A. Stewart, eds. 1998. *Management of Carbon Sequestration in Soil*. CRC Press/Lewis Publishers, Boca Raton, FL, pp. 37–51.
- Lal, R., M. Griffin, J. Apt, L. Lave, and M. G. Morgan. 2004. Managing soil carbon. *Science* 304:393.
- Laouina, A. 1992. Recherches actuelles sur les processus d'érosion au Maroc. *Bulletin du Réseau Erosion* 12:292–299.
- Laouina, A., R. Nafaa, C. Coelho, M. Chaker, T. Carvalho, A. K. Boulet, and A. Ferreira. 2000. Gestion des eaux et des terres et phénomènes de dégradation dans les collines de Ksar El Kebir, Maroc. *Bulletin du Réseau Erosion* 20:256–274.
- Le Bissonnais, Y. 1996. Aggregate stability and assessment of soil crustability and erodibility. I. Theory and methodology. *European Journal of Soil Science* 47:425–437.
- Masson, J. M. 1971. *L'érosion des sols par léau en climat Méditerranéen. Méthodes expérimentales pour l'étude des quantités érodées à l'échelle du champ*. Ph.D. Dissertation, Université de Montpellier, France.
- Mazour, M. 1992. Les facteurs de risque de l'érosion et du ruissellement dans le bassin versant de l'Isser — Tlemcen — Algérie. *Bulletin du Réseau Erosion* 12:300–313.
- Mazour, M. and M. Benmansour. 2002. Effet de l'exposition des versants sur la production de biomasse et l'efficacité anti-érosive dans le Nord-Ouest algérien. Communication at the International Colloquium Land Use, Erosion and Carbon Sequestration, Montpellier, France, 23–28 September 2002.
- Mazour, M. and E. Roose. 2002. Influence de la couverture végétale sur le ruissellement et l'érosion des sols sur parcelles d'érosion dans des bassins versants du Nord-Ouest de l'Algérie. *Bulletin du Réseau Erosion* 21:320–330.
- Meddi, M. and B. Morsli. 2001. Etude de l'érosion et du ruissellement sur bassins versants expérimentaux dans les Monts de Beni-Chougrane (Ouest d'Algérie). *Zeitschrift für Geomorphologie N. F.* 45:443–452.
- Morsli, B. 1996. *Caractérisation, distribution et susceptibilité des sols à l'érosion (cas des montagnes de Beni-Chougrane)*. Magister Thesis, INA, Algiers.
- Morsli, B., M. Meddi, and A. Boukhari. 2002. Etude du ruissellement et du transport solide sur parcelles expérimentales. Utilisation de la simulation de pluies, in *Actes du Séminaire sur la Gestion de l'Eau*. Université de Mascara, Algeria, pp. 80–88.
- Morsli, B., M. Mazour, N. Mededjel, A. Hamoudi, and E. Roose. 2004. Influence de l'utilisation des terres sur les risques de ruissellement et d'érosion sur les versants semi-arides du nord-ouest de l'Algérie. *Sécheresse* 15:96–104.
- Moufaddal, K. 2002. Les premiers résultats des parcelles de mesure des pertes en terre dans le bassin versant de Oued Nakhla dans le Rif occidental (Nord du Maroc). *Bulletin du Réseau Erosion* 21:244–254.
- Moukhchane, M. 2002. Différentes méthodes d'estimation de l'érosion dans le bassin versant de Nakhla (Rif occidental, Maroc). *Bulletin du Réseau Erosion* 21:255–265.

- Nelson, D. W. and L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter, in D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnson, and M. E. Sumner, eds., *Methods of Soil Analysis: Part 3 — Chemical Methods*, Soil Science Society of America and American Society of Agronomy, Madison, WI, pp. 961–1010.
- Pla Sentis, I. 2002. Soil organic matter effects on runoff and erosion in dryland vineyards of NE Spain. Communication at the International Colloquium Land Use, Erosion and Carbon Sequestration, Montpellier, France, 23–28 September 2002.
- Remini, B. 2000. L'envasement des barrages: quelques exemples algériens. *Bulletin du Réseau Erosion* 20:165–171.
- Robert, M. 2006. Global change and carbon cycle: the position of soils and agriculture, in E. Roose, R. Lal, C. Feller, B. Barthès, and B. A. Stewart, eds., *Soil Erosion and Carbon Dynamics*, Taylor & Francis, Boca Raton, FL.
- Roose, E. 1981. *Dynamique actuelle de sols ferrallitiques et ferrugineux tropicaux d'Afrique Occidentale. Etude expérimentale des transferts hydrologiques et biologiques de matières sous végétations naturelles ou cultivées*. Travaux et Documents ORSTOM 130, ORSTOM, Paris.
- Roose, E. 1991. Conservation des sols en zones méditerranéennes. Synthèse et proposition d'une nouvelle stratégie de lutte antiérosive: la GCES. *Cahiers ORSTOM, série Pédologie* 26:145–181.
- Roose, E. 1993. Water and soil fertility management. A new approach to fight erosion and improve land productivity, in E. Baum, P. Wolff, and M. Zoebisch, eds., *Topics in Applied Resource Management in the Tropics, Vol. 3, Acceptance of Soil and Water Conservation Strategies and Technologies*, Deutsches Institut für Tropische und Subtropische Landwirtschaft, Witzenhausen, Germany, pp. 129–164.
- Roose, E. 1996. Land husbandry: Components and strategy. *FAO Soils Bulletin* 70, FAO, Rome.
- Roose, E., M. Arabi, K. Brahamia, R. Chebbani, M. Mazour, and B. Morsli. 1993. Erosion en nappe et ruissellement en montagne Méditerranéenne Algérienne. Réduction des risques érosifs et intensification de la production agricole par la GCES: synthèse des campagnes 1984–1995 sur un réseau de 50 parcelles d'érosion. *Cahiers ORSTOM, série Pédologie* 27:289–307.
- Roose, E., R. Chebbani, and L. Bourougaa. 2000. Ravinement en Algérie: typologie, facteurs de contrôle, quantification et réhabilitation. *Sécheresse* 11:317–326.
- Roose, E. and B. Barthès. 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. *Nutrient Cycling in Agroecosystems* 61:159–170.
- Roose E. and B. Barthès. 2006. Soil carbon erosion and its selectivity at the plot scale in tropical and Mediterranean regions, in E. Roose, R. Lal, C. Feller, B. Barthès, and B. A. Stewart, eds., *Soil Erosion and Carbon Dynamics*, Taylor & Francis, Boca Raton, FL.
- Sabir, M., A. Merzouk, and O. Berkat. 1994. Impacts du pâturage sur les propriétés hydriques du sol dans un milieu pastoral aride: Aarid, Haute Moulouya, Maroc. *Bulletin du Réseau Erosion* 14:444–462.
- Sabir, M., M. Maddi, A. Naouri, B. Barthès, and E. Roose. 2002. Runoff and erosion risks indicators on the main soils of the Mediterranean mountains of occidental Rif area (Morocco), in *Proceedings of the 12th ISCO (International Soil Conservation Organization) Conference, Sustainable Utilization of Global Soil and Water Resources, Vol. 2*, Beijing, 26–31 May 2002.
- Sabir, M., B. Barthès, and E. Roose. 2004. Recherche d'indicateurs de risques de ruissellement et d'érosion sur les principaux sols des montagnes Méditerranéennes du Rif occidental (Maroc). *Sécheresse* 15:105–110.
- Tribak, A. 1988. *L'érosion du Prérif Oriental. Contribution à l'étude de la dynamique actuelle dans quelques bassins au Nord de Taza (Maroc)*. Ph.D. Dissertation, Université de Grenoble, France.
- Wischmeier, W. H. and D. D. Smith. 1978. *Predicting rainfall erosion losses: a guide to erosion planning*. Agriculture Handbook 537, United States Department of Agriculture, Washington D.C.

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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 CO₂. 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
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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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