CHAPTER 9

Carbon, Nitrogen, and Fine Particles Removed by Water Erosion on Crops, Fallows, and Mixed Plots in Sudanese Savannas (Burkina Faso)

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9.1 INTRODUCTION

In tropical zones, and particularly in subhumid areas such as Sudanese savannas, erosion and runoff are important factors of degradation of the cultivated soils and cause declines in crop yields (Lal, 1975, 1983; Roose, 1981; Pieri, 1991). In Sudanese areas of West Africa, many studies have analyzed the process of erosion and characterized the soil losses (Roose, 1981; Pontanier et al., 1986; Collinet, 1988; Mietton, 1988; Casenave and Valentin, 1989; Fournier et al., 2000). On a bare plot, the "splashing" effect of an intense rain on an uncovered soil dissociates soil skeleton and soil plasma, causing a waterproof surface crust. A diffuse runoff evacuates released materials. Downstream, a sheet flood occurs, developing both sheet erosion and regressive erosion like small stairs. Furthermore, linear erosion and gullies can appear when runoff concentrates. Even on low slopes (< 1%), the soil losses are high, around 10 t ha^{-1} yr^{-1}. Little research has evaluated the losses in fine particles, nutrients, and carbon (C) at the plot level (Roose, 1981; Bep A Ziem et al., 2002). However these elements represent the principal losses for the farming systems and for the environment. Moreover, erosion is potentially a cause of C loss, to be taken into account in the strategies of environmental management on a global scale.

In the soils of the Sudanese savannas, C, nitrogen (N), and fine particles are highly related, physically or not. Soil organic C fractions of slow turnover and N soil reserves are aggregated to fine particles (Feller, 1995). Consequently, losses of stabilized soil organic C will be explained largely by fine particle losses and will be parallel to N losses. Yet, N and fine particles are highly subjected to fertility status of soils. Consequently, managing soil organic C should be related to management of N and fine particles. Hence, studying C losses of savanna-cropped soils should be related to a study of N and fine particle losses.

The existing data have to be brought up to date, taking into account the dynamics of the farming systems in the expanding cotton belts of Sudanese savannas. Here there is evidence on the best nonsloping soils of the lowlands that the old cereal farming systems in shifting cultivation (pearl millet, *Pennisetum glaucum,* and sorghum, *Sorghum bicolor*) have made way for ploughed, ridged, and fertilized cotton, sorghum, and maize through permanent cropping. Temporary cropping and fallowing remains only on the lands of secondary interest like the sandy or gravelous upland soils (Serpantié, 2003). These soils are most susceptible to erosion. Two principal ways of management of land against erosion exist, depending on whether land use is homogeneous or not.

9.1.1 Homogeneous Land Use

This chapter does not consider contour hydraulic treatments (micro-dams, stone lines, stone walls, terraces), which are rare in this zone because they require too heavy investments for peasants without external aid (Van Campen and Kebe, 1986) and show little adaptation to the large surfaces that are cropped in cotton zones. Therefore this chapter focuses on agricultural treatments. Tillage reduces runoff temporally but increases its turbidity, maintaining high soil losses (Roose, 1973; Collinet, 1988; Maass et al., 1988). Comparing crops of tilled sorghum and fallows in Saria (Burkina Faso, 0.7% slope), Roose (1993) found 7.3 t ha^{-1} yr^{-1} soil losses under sorghum, 0.51 t ha^{-1} yr^{-1} under herbaceous fallow, and 0.17 t ha^{-1} yr^{-1} under shrubby fallow. The least erosive cropping methods like contour ridges are unfortunately unsuitable. Continuous rectilinear ridges with a light incline (1% on average), frequently used by farmers, are easier to build. They drain excess water, which is common in the Sudanese climate, and reduce the risks of transverse gullies that can appear because of lateral collection of runoff in the case of almost-contour ridges (Nimy, 1999). Mulching-based cropping systems, tested in the wet tropics, strongly reduce erosion (Blancaneaux et al., 1993), but are poorly suited to prevailing Sudanese conditions: freely grazing herds in the dry season, and a short growing season. Thus for the moment, few antierosive agricultural treatments seem to be perfectly appropriate to the Sudanese cotton zones.

9.1.2 Heterogeneous Land Use

A proper study scale is essential for the assessment of soil losses. The farmer may find it beneficial to reduce displacements of nutrients and fine elements, and to preserve them within his own land, but not necessarily to retain them at the same place where erosion occurs. The same conditions occur for C, for which it is important to know the starting and destination places. Local losses are partly recoverable on differently treated contiguous spaces. One can thus assume that variations of cropping practices along a slope will reduce the global erosion of the hill slope. To verify this, the erosion effects of a heterogeneous method of managing a hillside must be characterized, and the balance of erosion must be checked, on a given scale. Such a structured landscape has already been recommended by Wischmeier and Smith (1978) in order to reduce erosion, but in reference to models like buffer strip cropping adapted to mechanized open-fields. Their adaptation to the Sudanese conditions, including different crops, narrow "grass strips" and "hedges," has already been documented (Roose, 1967; Roose and Bertrand, 1971; Boli et al., 1993; Albergel et al., 2000), but not sufficiently concerning fine and organic elements. It would also be advisable to study composite modes of hillside management, such as the crop–fallow mosaics of the natural landscapes of Sudanese uplands, where grass and shrubs represent more cover than in the case of grass strips and hedges.

9.1.3 Adaptation of the Method

Currently, empirical studies on erosion under natural rain using the 'USLE' scale (plot area of 100 m^2 and slope length of 20 m; Wischmeier, 1974), or rainfall simulation on a smaller area (Collinet, 1988) are related to the measurement of a potential of diffuse erosion, which is firstly due to primary rain erosion. However, on a larger area, other erosion processes occur. On the one hand, it is advisable to take into account longer slopes, particularly for the study of grass strips. This more closely accounts for the real conditions of the farmers' fields (Boli et al., 1993). On the other hand the "small water-catchment" scale, carried out on natural water catchments, does not provide a precise account due to the differences in soils and local parameters of rain and catchment geometry between experimental catchments.

In recent experiments conducted in Burkina Faso (Bondoukui), Fournier et al. (2000) studied runoff and erosion during natural rains, under conditions of farming systems of the cotton zones. This original experiment included plots of great length (50 m) and very small width (3.2 m), in opposition to the classical pattern of experimental plots. Ridges inclined in the direction of slope (1% slope) channeled runoff on four interridges of 80 cm each, reproducing farmers' practice. Channeling runoff made it possible to work on experimental plots of very low width since it eliminated "edge-effects." The treatments reproduced the principal land-use classes of the Sudanese uplands (5- to 10-year cropping after clearing, short fallow, long fallow) and principal land-use associations, i.e., crop upstream, grass fallow downstream, and a broad grass strip.

Our research used the same device, though it focused more specifically on the assessment of fine particles, C, and nutrients, in order to evaluate the effects of land use on erosion on a qualitative level. Therefore, the objectives of the present chapter are: (1) to assess erosion of C, N, and fine particles on homogeneous land use modes; and (2) to compare them with results obtained on heterogeneous land-use mode.

9.2 MATERIALS AND METHODS

9.2.1 Site of Study

The experiments were carried out in the area of Bondoukui (11°49'N, 3°49'W; altitude 360 m) in the west of Burkina Faso. In this area, the climate is Sudanese with a wet season of 5 months, a dry season of 7 months, and an average annual rainfall of 850 mm. On deeper soils, the cropping system combines cereals (maize or sorghum) with a commercial crop (cotton) in 2-year rotations, during 10 years after clearing a 10- to 20-year fallow. The average technical system involves: ridged plowing (for cotton and maize), sowing on ridges, low mineral fertilization, manual weeding, and a new ridging of lines around 50 days after sowing.

9.2.2 Experimental Device

Two blocks were built in May 1997 on a sandy plateau covered with ferruginous tropical eluviated soils (luvisol; FAO) on a 1% slope.

The first experimental block included eight isolated plots, measuring 50 m × 3.2 m, marked by ridges and metal sheet reinforcements. They were laid out on a well-draining soil till 80 cm deep. Three plots were studied for the purposes of this research. The treatments were:

- Plot in homogeneous land use "CROP": annual cotton/corn biennial rotation on ridges. Before the experiment, the plot was cultivated for 8 years since clearing. Another plot, 20-m long, was coupled with this plot in 1999.
- Plot in homogeneous land use "GFAL": grass fallow of 1 or 2 years protected against cattle, excluded in 1999 (cotton on mulch), and on which old ridges remained.
- Plot in composite land use "CROP/GFAL": at the upper part of the plot, a 40-m-long subplot with a biennial rotation of cotton/corn on ridges (like CROP), and at the lower part of the plot, a 10-m-long subplot with permanent meadow, not grazed in the wet season. It contained *Andropogon gayanus* sown in 1997, whose residues remained on the soil in the dry season, without burning (except accidentally in 1999). As compared with classical grass strip treatments, this composite plot had a higher grass area/plot area ratio (1/5 against 1/20 in the classical case).

The second experimental block included three plots, only one of which was retained for this research. They were laid out on a hydromorphic eluviated soil well drained and only tilled to 35-cm depth. The plot in homogeneous land use "SFAL" was a 15-year dense shrubby fallow. The plot dimensions were 25 m × 6.5 m.

9.2.3 Cropping Systems

Previous ridges remained at the beginning of the rainy season. The cultivated plots were ploughed by animal traction (10 to 15 cm deep, ripple relief) in direction of slope at the beginning of the wet season. At that time, only the lateral ridges were manually reconstructed. After sowing cotton or maize on lines and after preemergence chemical weeding, two manual hoe weedings progressively reconstructed the three central ridges on sowing lines, principal ridging occurring 50 days after sowing. Fertilizer was brought twice: 100 kg ha^{-1} of NPK (14-23-14) in holes after the first weeding, and 50 kg ha^{-1} of urea (46% N) in holes after ridging. The plots were protected from fire and grazing. In 1999 however, the strips of *Andropogon gayanus* (CROP/GFAL) burned accidentally, and SFAL burned in 1998 and 1999. GFAL never burned.

9.2.4 Field Measurements

Each block included a recording rain gauge collecting rain at a 1-m height, making it possible to calculate the maximum intensity of rain into 15 or 30 min (I_{15}, I_{30}). Each plot was equipped with a downstream concrete surface for reception of runoff, followed by a tank for the coarse sediment decantation, of a calibrated runoff divisor (thin blade, cut up in multiple "V"), and one or two barrels for the reception of a sample of water downstream from the central V. By gauging from the various containers and maximum level of water measured on divisor blades, runoff amount and maximum runoff intensity were estimated after each rain throughout the years 1998 to 2001.

For the coarse sediment measurement, the tank was allowed to settle, clear water was manually drained, and the bottom was collected, dried, and weighed. The barrels containing samples of runoff including fine sediments mainly were vigorously mixed without any flocculating agent in order not to modify the composition of the aqueous solutions, then sampled (0.66:l per barrel). Each sample was filtered with the filter paper (about 15 μm pores). Already filtered but still tinted water was again sampled and filtered under aspiration with the micro-filter (0.2 μm pores). The coarse sediments of the tank constituted the "carriage" while the filtered sediments of barrels added to the micro-filtered ones constituted the "suspension" (fine erosion). The final micro-filtrated water was intended to an analysis of soluble minerals.

One of the problems arising from the measurement of erosion under natural rains is the catastrophic nature of the erosive events of rare recurrence. In the present case, light overflows occurred from the barrels of reception during some rainy periods in 1999. Fortunately, the presence of a 20-m-long cultivated plot in which barrels did not overflow and in which runoff was usually identical to that of the 50-m-long cropped plot ($R_{50m} = 1.03\ R_{20m} + 0.50$, with $r^2 = 0.93$; R_{50m} and R_{20m} in % of rainfall) helped estimate the probable quantities of runoff on the 50-m-long cropped plot. Erosion was appreciated on the barrels of the 50-m-long plot, with a possible slight overestimation due to a decantation effect during overflow.

9.2.5 Analyses of the Samples

The particle-size and chemical analyses of sediment samples were carried out by compartment. The samples of coarse carriage were analyzed for all the events from 1999 to 2001. The small samples of filtered suspensions collected on filter papers in 1998 and 1999 were gathered on each plot according to the amount of soil losses (< 1 t ha^{-1}, 1 to 10 t ha^{-1}, > 10 t ha^{-1}) and were analyzed for C and N. However there was not enough suspension to determine particle-size distribution for each plot and for each type of event. So it was measured for each group of events on gathered samples from several plots, therefore achieving the minimal quantities needed for the laboratory. In order to assess the annual fine particle losses, this average particle-size distribution was affected to soil loss quantity for each event according to its group. Micro-filtrates, presumed to have a content of 100% of fine dispersed particles (fine silt, clay, and organic colloids), were not analyzed. Micro-filtered water and the rainwater were analyzed for N some events during the year 1999.

Organic C and total N in coarse sediments and in soils were determined following the Walkley and Black method (Nelson and Sommers, 1996) and the Kjeldhal method (Bremner, 1996), respectively. Total C and N in fine sediments were determined by dry combustion using a CHN Elemental Analyser (Nelson and Sommers, 1996). Mineral N (NO_3^-, NH_4^+) was also determined in micro-filtered water (Mulvaney, 1996). Particle-size analysis of air-dried 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). Physical measurements were carried out *in situ*: bulk density (150-cm^3 cylinder, eight samples); steady state infiltration under a sheet of water was measured with the double ring method of Fournier (1998), using a central ring with 1-m^2 diameter and two replicates per treatment. The sampling of soils for analysis (eight subsamples within the blocks) was made on May 1998 and infiltration measurement on May 2000.

Table 9.1 Topsoil Properties (0 to 10 cm depth) and *in situ* Measurements in the Experimental Plots

	Block 1	Block 2
Clay (< 2 μm; %)	5.9	3.0
Fine silt content (2 to 20 μm; %)	3.8	8.6
Coarse silt content (20 to 50 μm; %)	17.0	20.9
Fine sand content (50 to 200 μm; %)	39.5	31.5
Coarse sand content (200 to 2000 μm; %)	33.8	36.0
Bulk density	1.58	1.58
Total porosity (% in 150 cm^3)	39.0	40.1
Water-stable aggregates (%)	4.9	7.5
Infiltration in CROP (mm h^{-1})	250	—
Infiltration in GFAL (mm h^{-1})	250	—
Infiltration in CROP/GFAL (*A. gayanus*) (mm h^{-1})	500	—
Infiltration in SFAL (mm h^{-1})	—	120
C content (g kg^{-1})	2.3	6.6
N content (g kg^{-1})	0.3	0.6
C/N ratio	8	11
pH in water	5.8	6.5
pH in KCl	4.9	5.3

9.3 RESULTS

9.3.1 Physical Properties of the Experimental Soils

Table 9.1 shows that the soils from the two blocks had comparable particle-size distribution and porosity, except that topsoil clay content was twice lower in Block 2 (15-yr shrubby fallow) than in Block 1 (cultivated for several years). Infiltration was also two times less in the soil of Block 2, though it was better protected by litter, biologically and chemically richer, and better aggregated. This lower infiltration could result from the higher silt/clay ratio, which is an indicator of plugging. Indeed, the hydromorphic pseudo-gley layer was deeper in Block 1 (80 cm) than in Block 2 (35 cm). It could thus be assumed that runoff was caused mainly by soil saturation in Block 2 (in wet years especially), and by surface crusting in Block 1. Within Block 1, where the soil was already very permeable, the perennial grass cover (*Andropogon gayanus*) in CROP/GFAL resulted in a two times greater infiltration (under a sheet of water) than in CROP and GFAL.

9.3.2 Effects of Rainfall Erosivity and Soil Moisture on Runoff and Soil Losses

Table 9.2 presents the annual runoff rate and erosion for each plot over the experimental period. It clearly shows the dramatic effects of high annual rainfall on runoff and erosion: indeed, when compared to averages over the years 1998, 2000, and 2001, the year 1999 had a 50% higher annual rainfall, but runoff was multiplied by 2 to 4, and erosion by 3 to 18, depending on the plot. Years 1998, 2000, and 2001 were characterized by a total rainfall ranging from 680 to 850 mm, lower than or equal to the mean annual rain in Bondoukui (850 mm). The rain intensity was low (only three to four rains with I_{30} higher than 50 mm h^{-1}, one higher than 80 mm h^{-1}), and rains were spaced out so that soils remained dry, producing little runoff and erosion. In contrast, annual rainfall was 1155 mm in 1999 (wettest year of the decade), with seven rains having I_{30} higher than 50 mm h^{-1} (including two higher than 80 mm h^{-1}). Several events occurred when the soils were already very wet, even saturated by a temporary water table in the case of plot SFAL, resulting in great runoff and abundant erosion. The dramatic effect of intense and repeated rains has already been reported (Roose, 1977; Wischmeier and Smith, 1978). Erosion was more affected by wet conditions

Table 9.2 Annual Runoff and Erosion on the Experimental Plots

Period	Plot	Occurrence of Fire	Rain (mm yr^{-1})	Annual Runoff Rate (%)	Maximum Runoff (%)	Coarse Carriage (t ha^{-1} yr^{-1})	Fine Suspension (t ha^{-1} yr^{-1})	Total Erosion (t ha^{-1} yr^{-1})
1998	$CROP_{50m}$		846	20	70	0.9	3.4	4.3
	CROP/GFAL		id	2	23	0.1	0.1	0.2
	GFAL		id	0	0	0.0	0.0	0.0
	SFAL	fire	899	13	51	0.6	0.8	1.4
1999	$CROP_{50m}$		1155	38	90	6.2	30.6	36.7
	$CROP_{20m}$		1155	40	99	9.2	16.4	25.6
	CROP/GFAL	fire	1155	22	83	0.7	8.3	8.9
	GFAL		1155	nd	nd	nd	nd	nd
	SFAL	fire	1098	18	73	0.4	5.1	5.5
2000	$CROP_{50m}$		800	24	68	1.5	8.4	10.0
	CROP/GFAL		800	4	21	0.0	0.8	0.8
	GFAL		800	2	8	0.2	0.0	0.2
	SFAL		666	2	16	0.0	0.0	0.0
2001	$CROP_{50m}$		680	26	52	4.0	11.2	15.3
	CROP/GFAL		680	8	21	0.1	0.5	0.6
	GFAL		680	2	10	0.0	0.0	0.0
	SFAL		652	2	8	0.0	0.0	0.0
Average over 1998, 2000, and 2001[a]	$CROP_{50m}$		775	23 a	63 a	2.1 a	7.7 a	9.9 a
	CROP/GFAL		775	5 b	22 b	0.1 b	0.5 b	0.5 b
	GFAL		775	1 b	6 b	0.1 b	0.0 b	0.1 b
	SFAL		739	6 b	25 b	0.2 b	0.3 b	0.5 b
Weighted average over four years[b]	$CROP_{50m}$		814	25	66	2.5	10.0	12.6
	CROP/GFAL		814	7	28	0.2	1.3	1.3
	GFAL		814	nd	nd	nd	nd	nd
	SFAL		775	7	30	0.2	0.8	1.0

Note: nd: not determined.

[a] Averages over 1998, 2000, and 2001 were compared using a Student t-test; within a column, two different letters mean that the difference was significant at $p < 0.05$.

[b] Weighted averages over four years were calculated as the sum of data relating to 1999 with a 0.1 coefficient (as 1999 was the wettest year of the decade) and averages over 1998, 2000, and 2001 with a 0.9 coefficient.

than runoff: on CROP treatment for example, runoff rate was 1.7 times higher but erosion 3.7 times higher in 1999 than during the three other years, on average.

9.3.3 Effects of Treatments on Runoff and Erosion, Quantitative Approach

The years 1998, 2000, and 2001 were used as experimental replicates to study usual climatic conditions ("modal erosive years"). In such conditions, the effect of complete cropping on runoff and erosion was clear: mean annual runoff rate and erosion were significantly higher on CROP than on the three other plots (23 vs. 1 to 6% and 9.9 vs. 0.1 to 0.5 t ha^{-1} yr^{-1}, respectively; $p < 0.05$). When compared with the three other plots, CROP had a 4 to 18 times higher mean annual runoff rate but a 20 to 150 times greater erosion, thus erosion was much more affected by complete cropping than runoff. Runoff and erosion did not differ significantly between CROP/GFAL, GFAL, and SFAL, though they tended to be higher on CROP/GFAL and SFAL than on GFAL (5 to 6% vs. 1% and 0.5 vs. 0.1 t ha^{-1} yr^{-1}, respectively). Runoff and erosion on CROP/GFAL were thus significantly smaller than on CROP (they were divided by 5 and 20, respectively) but not significantly greater than on GFAL. Therefore, introducing a 10-m-long grass strip at the downstream part of a cultivated plot was very effective for water and soil conservation, the data indicated that it absorbed most of the runoff and trapped most of the sediments produced by the upper part of the plot. The fire that occurred on SFAL in 1998 had noticeable effects: indeed, in the absence of fire (years 2000 and 2001, and GFAL in 1998), runoff and erosion were similar and small in GFAL and SFAL (2% and 0.2 t ha^{-1} yr^{-1}, respectively), whereas fire (SFAL in 1998) resulted in strong increases in runoff and erosion (13% and 1.4 t ha^{-1} yr^{-1}, respectively, i.e., at least seven times more than in the absence of fire).

Runoff and erosion were much higher in the wettest year of the decade (1999). Annual runoff rate reached 20% on SFAL and CROP/GFAL, 40% on CROP, and maximum runoff rate more than 70%, due to topsoil saturation. Erosion reached 36.7 t ha^{-1} yr^{-1} on CROP. Even under such climatic conditions, the grass strip in CROP/GFAL was effective in reducing runoff and soil loss (which were two and four times smaller than in CROP, respectively), though an accidental burning in the dry season of 1999 probably reduced its effectiveness.

9.3.4 Erosion, Qualitative Approach

9.3.4.1 Coarse Sediment Load or "Carriage"

The "carriage" (eroded coarse particles and soil aggregates trapped in the tank) generally represented a low proportion of total erosion (≤ 50%), during the wet year especially (< 20%). It was less than 1 t ha^{-1} yr^{-1}, except on CROP (Table 9.2).

Its contents in C and N were small (3 to 4 g C kg^{-1} and 0.2 to 0.3 g N kg^{-1}), but close to those measured in the topsoil (0 to 10 cm depth). Its C/N ratio ranged from 12 to 16 and was higher than in the topsoils (8 to 11), suggesting that the carried organic matter contained a high proportion of fresh organic residues. These carried materials could thus be considered as a mixture of soil aggregates, washed sands, and litter fragments. Carriage increased at the beginning of the rainy season and more particularly after plowing. In the same way, some cases of strong erosions in C corresponded to erosive rains occurring on tilled soils in the course of the rainy season (weeding, ridging), causing a facilitated mobilization of aggregates. The small runoffs on tilled soils showed high levels of turbidity.

The carriage (more important after plowing) could form a deposit not far from the eroded place. Thus this coarse erosion, of low content in fine particles and in C and N, was not really worth fighting against. However, it increased a lot in the case of highly erosive events and could be exported in lowlands.

9.3.4.2 Suspension (Collected with Filters)

The fine elements in suspension represented the major eroded fraction: it generally accounted for more than 50% of total annual erosion, and more than 70% on CROP. It seemed advisable to separate the solid fractions collected on filter paper (weighed and analyzed) from the fractions collected on micro-filter (weighed but not analyzed).

The filtered residues mainly consisted in fine elements (< 20 μm), except for the most erosive rainfall events: indeed, fine particles represented 76, 79, and 36% of the particles collected on the filter papers for events resulting in < 1, 1 to 10, and > 10 t ha^{-1} erosion, respectively (Figure 9.1). These rates were much higher than those measured in the topsoil (10 to 12%), indicating that suspensions were particularly enriched in fine particles. In the same way, suspension were enriched in C (30 to 55 g kg^{-1}) and N (1.5 to 4 g kg^{-1}) compared to the topsoils (2.3 to 6.6 g C kg^{-1} and 0.3 to 0.6 g N kg^{-1}). These sediment contents in C and N decreased, just as the content in fine particles, with the importance (and the scarcity) of the erosive event. It suggested that runoff produced by the most erosive events could erode soil layers that were deeper and contained less C and N than superficial layers affected by less erosive events. The C and N contents of filtered suspensions were generally lower for CROP than for CROP/GFAL and SFAL, probably due to the presence of litter and enriched upper soil layer on the latter plots. Additionally, considering the

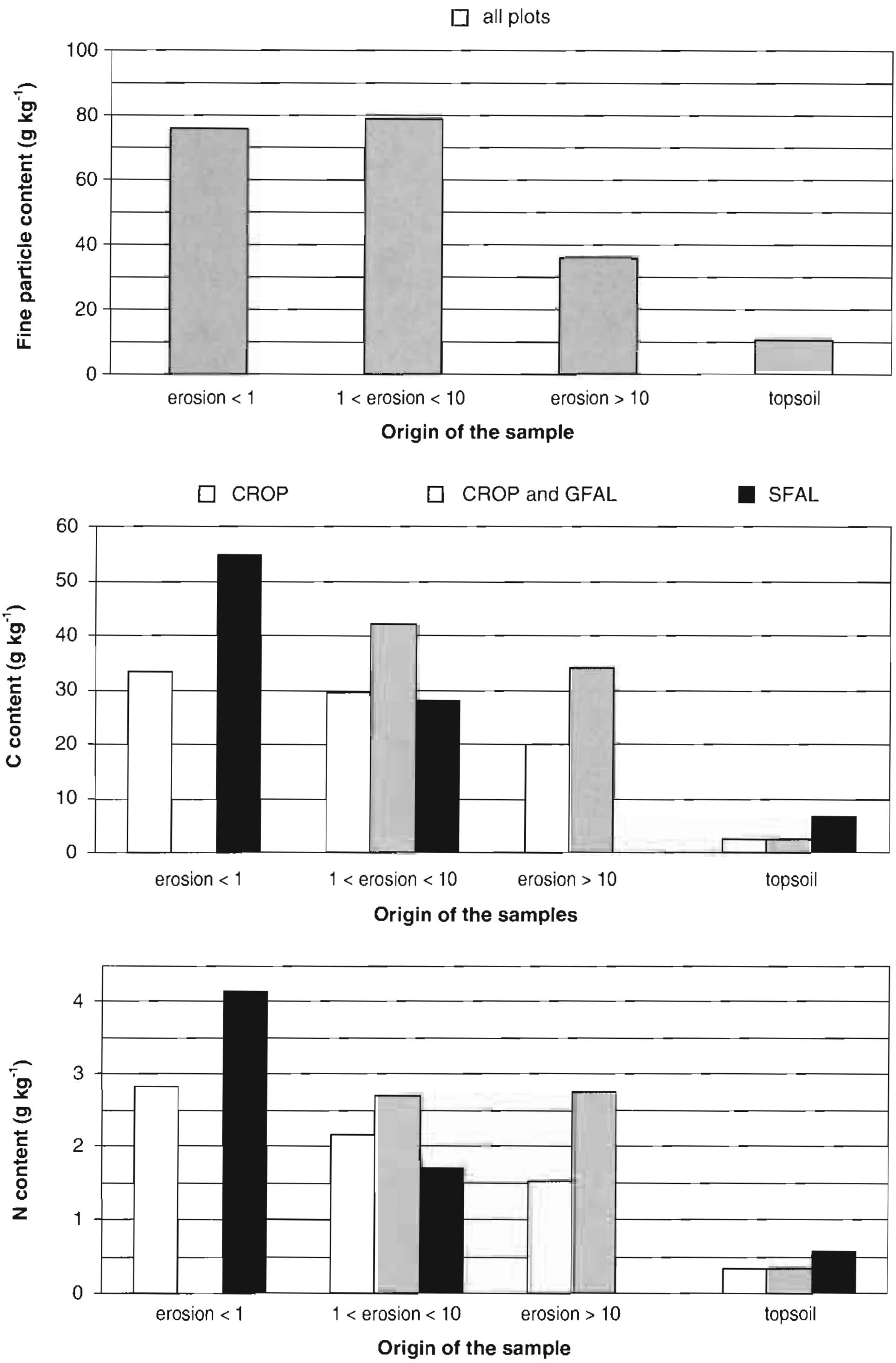

Figure 9.1 Contents in fine particles, carbon, and nitrogen in suspensions filtrated with filter paper, gathered from groups of erosive events (< 1, 1 to 10, and > 10 t ha^{-1} yr^{-1}), and in the topsoil (0 to 10 cm depth).

whole of the analyzed suspensions, the ratios of C content to clay content and of C content to fine particle content were rather constant (ca. 0.090 and 0.035, respectively), highlighting the close relationship between C and fine particles.

The colloidal and very fine eroded fractions, collected by micro-filtration but not analyzed, represented small sediment amounts (0.12 t ha^{-1} in 2000 on CROP). However, these very fine particles, which crossed the pores of the filter paper (15 µm) but were retained by the 0.2-µm pores of micro-filters, must be taken into account in an assessment. Indeed, the very fine particles (fine clay) are rare in the soils under study, but are associated to a fine and processed organic matter. The constant ratio between C and fine particle content allowed the estimation of C content in micro-filtrated suspension. Finally, the amount of C in this fraction remained low, like the C eroded in carriage: on CROP, the mean annual erosion of C for 1998, 2000, and 2001 reached 243 kg C ha^{-1}, of which 11 kg C ha^{-1} (estimate) were related to the micro-filtrated residues and 5 kg C ha^{-1} to carriage (see below).

9.3.4.3 C and N Dissolved in Rains and in Micro-Filtrated Water Samples

Rainwater contents in N-NO_3^- and N-NH_4^+ were determined for seven rainfall events in June and July 1999 (Figure 9.2). They were 0.218 (±0.089) mg N-NO_3^- l^{-1} and 0.122 (±0.089) mg N-NH_4^+ l^{-1}, equivalent to a gain of 4 kg N ha^{-1} yr^{-1} for the year under study (1155 mm yr^{-1}). In general rainwater N-NO_3^- content was slightly higher than N-NH_4^+ content, except for one event where they reached 0.4 and less than 0.05 mg l^{-1}, respectively.

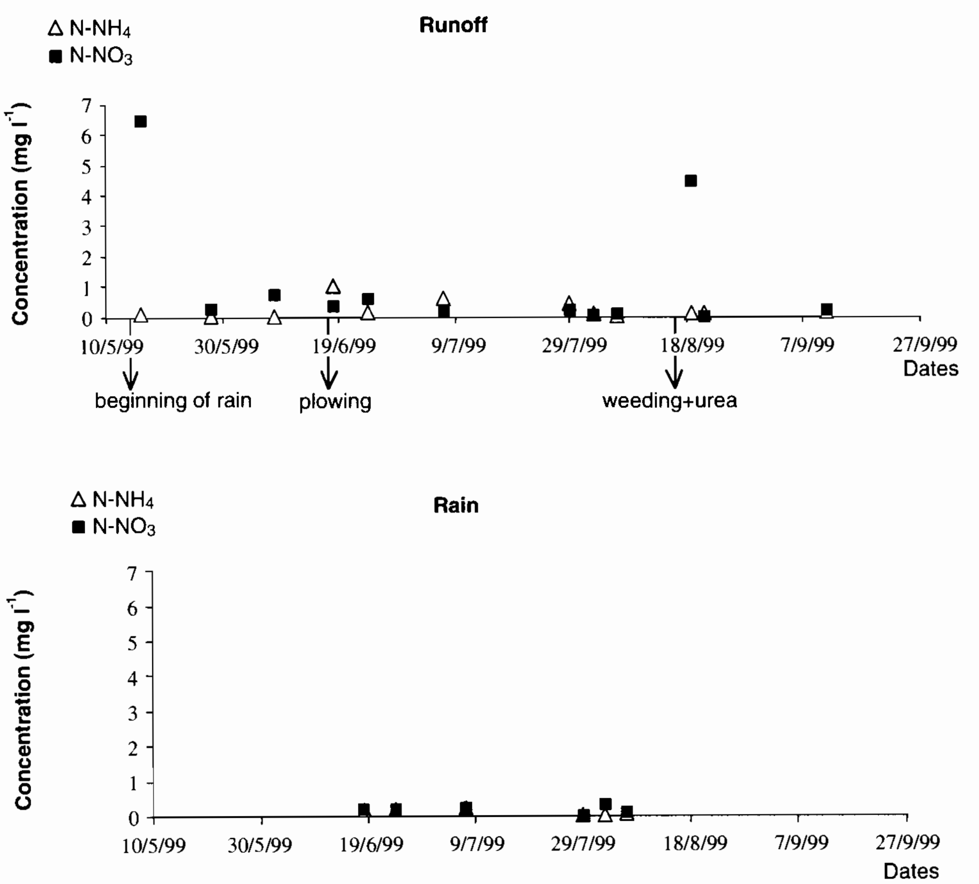

Figure 9.2 Contents in N-NO_3^- (nitrates) and N-NH_4^+ (ammonium) of micro-filtrated runoff water (CROP plot, year 1999).

Runoff contents in N-NO_3^- and N-NH_4^+ were determined for 12 events from May to September 1999, and varied according to the season (Figure 9.2). Runoff content in N-NO_3^- was high at the beginning of the rainy season (6.5 mg l^{-1} on May 16), then it decreased strongly (< 1 mg l^{-1} from the end of May to mid-August) until fertilization with urea, which corresponded to another peak (4.4 mg l^{-1} on August 19), followed by another strong decrease (< 0.5 mg l^{-1} from August 20 to mid-September). Runoff content in N-NH_4^+ was very low at the beginning of the rainy season (< 0.2 mg l^{-1} from May to mid-June), increased just after plowing (1.0 mg l^{-1} on June 18), then decreased and remained low (< 0.5 mg l^{-1} from June 24 to the end of July, and < 0.2 mg l^{-1} in August and September).

Thus runoff was enriched in nitrates at the very beginning of the rainy season and just after fertilization (urea), and in ammonium just after plowing, otherwise its N-NO_3^- and N-NH_4^+ contents were slightly richer than concentrations in rainwater. For the year under study, losses in N dissolved in runoff could therefore be roughly estimated at 3 and 6 kg N ha^{-1} yr^{-1} for fallows (20% runoff) and crops (40% runoff), respectively. The soluble C in runoff was not measured due to its small concentration. It could however be estimated from N determinations and data in the literature: in Saria (central Burkina Faso), Roose (1981) reported C/N ratios in runoff water from 0.2 (crops) to 0.6 (fallows). Using these values, losses of soluble C in runoff could be roughly estimated at ca. 1 and 2 kg C ha^{-1} yr^{-1} for crops and fallows in 1999, respectively (Roose reported 5.4- and 1.1-kg ha^{-1} yr^{-1} losses of C dissolved in runoff on cereal and savanna plots, respectively).

9.3.5 Carbon, Nitrogen, and Fine Particle Losses by Erosion

For each event the suspension was multiplied by the average content of the type of erosive event on the considered plot, thus giving an assessment of the global quantity of C, N, and fine-exported elements (Table 9.3). This process, however, limited the precision of the study because the composition of the erosion could have evolved during the season or between years in the same manner as the content of the carriage.

In rather dry years (1998, 2000, and 2001), total annual eroded C ranged from 100 to 350 kg C ha^{-1} yr^{-1} on CROP, and from 0 to 50 kg C ha^{-1} yr^{-1} on the other plots. In 1999 (wet year), it reached 770 kg C ha^{-1} yr^{-1} on CROP, and 160 to 350 kg C ha^{-1} yr^{-1} on the other plots. Suspensions represented the major eroded fraction (> 50% in general) and their C content was much higher than that of coarse sediments (ca. 10 times more). As a consequence, suspensions generally accounted for more than 90% of total eroded C. Eroded C was much greater in 1999 than in drier years (i.e., 3, 10, and 23 times greater on CROP, SFAL, and CROP/GFAL, respectively). In 1998, 2000, and 2001, mean annual eroded C (total) was significantly and much greater on CROP than on the other plots ($p < 0.05$), but did not differ significantly between CROP/GFAL, GFAL, and SFAL. Similar relationships were found for mean carriage C, suspension C, total eroded N, eroded clay, and eroded fine silt. In 1999 (wet year), carriage C, suspension C, eroded C, eroded N, eroded clay, and eroded fine silt were also greater on CROP than on the other plots, but differences between plots were smaller than in 1998, 2000, and 2001 (drier years). The grass strip was effective in reducing C and N erosion, especially in rather dry years: when compared with CROP, annual eroded C and N on CROP/GFAL were 93 to 94% smaller in average in 1998, 2000, and 2001, and 55 to 62% smaller in 1999 (despite an accidental burning in the dry season of 1999).

9.4 DISCUSSION

9.4.1 Validation of Experimental Data on Erosion

Methods of measures used in this study were not the standard ones used in West Africa. Low width of plots is often criticized, even in case of ridging (Boli et al., 1993). However the results of

Table 9.3 Losses in Carbon, Nitrogen, Clay, and Fine Silt on the Experimental Plots

Period	Plot	Carriage C (kg C ha^{-1} yr^{-1})	Suspension C (kg C ha^{-1} yr^{-1})	Total Eroded C (kg C ha^{-1} yr^{-1})	Total Eroded N (kg N ha^{-1} yr^{-1})	Total Eroded Clay (t ha^{-1} yr^{-1})	Total Eroded Fine Silt (t ha^{-1} yr^{-1})
1998	CROP	3	105	108	8.4	1.1	1.4
	CROP/GFAL	0	4	4	0.3	0.1	0.1
	GFAL	0	0	0	0.0	0.0	0.0
	SFAL	3	44	47	3.5	0.1	0.1
1999	CROP	11	760	771	58.0	7.2	10.1
	CROP/GFAL	2	346	348	22.1	2.5	4.1
	GFAL	nd	nd	nd	nd	nd	nd
	SFAL	2	157	159	10.1	1.5	2.4
2000	CROP	5	265	270	20.6	2.9	3.9
	CROP/GFAL	0	25	25	2.1	0.3	0.3
	GFAL	1	0	1	0.1	0.0	0.0
	SFAL	0	0	0	0.0	0.0	0.0
2001	CROP	8	342	350	27.0	3.5	5.2
	CROP/GFAL	0	16	16	1.4	0.2	0.2
	GFAL	0	0	0	0.0	0.0	0.0
	SFAL	0	0	0	0.0	0.0	0.0
Average over 1998, 2000, and 2001[a]	CROP	5[a]	237[a]	243[a]	18.7[a]	2.5[a]	3.5[a]
	CROP/GFAL	0[b]	15[b]	15[b]	1.3[b]	0.2[b]	0.2[b]
	GFAL	0[b]	0[b]	0[b]	0.5[b]	0.0[b]	0.0[b]
	SFAL	1[b]	15[b]	16[b]	1.2[b]	0.1[b]	0.1[b]
Weighted average over four years[b]	CROP	6	289	296	22.6	3.0	4.2
	CROP/GFAL	0	48	48	3.4	0.4	0.6
	GFAL	nd	nd	nd	nd	nd	nd
	SFAL	1	29	30	2.1	0.2	0.3

Note: nd: not determined.

[a] Averages over 1998, 2000, and 2001 were compared using a Student t-test; within a column, two different letters mean that the difference was significant at $p < 0.05$.

[b] Weighted averages over four years were calculated as the sum of data relating to 1999 multiplied by 0.1 (as 1999 was the wettest year of the decade) and averages over 1998, 2000, and 2001 multiplied by 0.9.

the present study were close to those of other studies. On a field cultivated in a prolonged way (CROP), the erosion measured in dry or normal years ranged from 4 to 15 t ha^{-1} yr^{-1}. This was consistent with data reported by Roose (1993) on cultivated ferrugineous soils in central Burkina Faso (Saria, 800 mm of annual rain, 0.7% slope), where erosion amounted to 3 to 20 t ha^{-1}·yr^{-1} on 20-m-long plots. In northern Cameroon (1000- to 1500-mm annual rainfall, 1 to 2% slope), Boli-Baboulé et al. (1999) measured erosion between 10 and 15 t ha^{-1} yr^{-1} for cotton-maize rotations involving plowing on recently cleared plots. In similar conditions but in southern Mali, Diallo et al. (2000) reported 18 t ha^{-1} yr^{-1} erosion. This confirmed the interest of plots with low width but great length, which were used in the present study.

In the wettest year of the decade (1999), erosion in CROP increased considerably: 37 t ha^{-1} on a 50-m-long plot, and 26 t ha^{-1} on a 20-m-long plot. Surprisingly, the cumulated runoffs were similar: 464 and 434 mm for the 20- and 50-m-long plots, respectively. The difference in soil losses could be attributed to a bias involving the relative concentration of suspensions by decantation of the overflowed barrels of the 50-m-long plot. Actually several differences appeared between plots, even when barrels did not overflow (Figure 9.3). The runoff events produced similar erosion on both plots when runoff maximal intensity was under a threshold. The difference between the two plots became positive when the peak of runoff exceeded a certain value, then increased with increasing runoff intensity. The erosion was less selective, too. It suggested that linear erosion

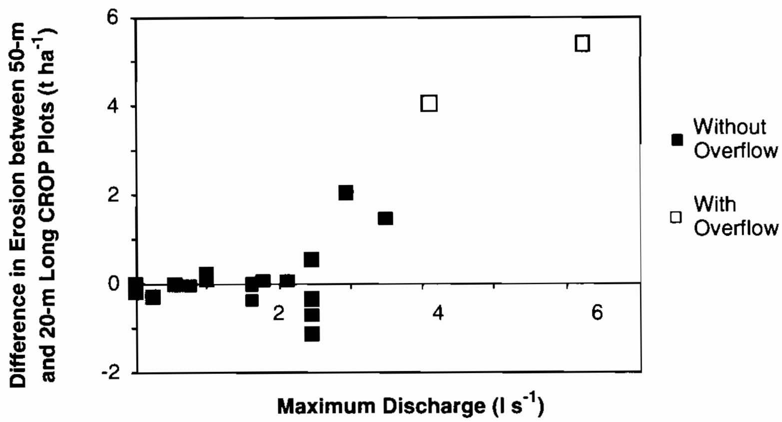

Figure 9.3 Difference in erosion between 50-m- and 20-m-long CROP plots, in relation to maximal discharge on the 50-m-long plot.

be added to sheet erosion on long ridged plots, as observed by Poesen and Bryan (1990) in experimental conditions.

The measurements of erosion were thus coherent. Major erosion in 1999 on the plots of 50 m was due to a combination of several factors: very humid climate, two exceptional erosive events with $I_{30} > 80$ mm h^{-1}, saturation of soils, especially on SFAL. In addition, the length of the slope and ridged relief determined some linear erosion under high rainfalls.

9.4.2 Physical Composition of the Eroded Soils and Consequences

The erosion sediments were separated in two classes: coarse carriage sediments and fine particles in suspension, including micro-particles. Solutes in runoff represented another source of loss. Carriage represents the coarse eroded fractions (litters, sands, and aggregates), which progress by saltation and are deposited in plane anfractuosities or on the zones of deceleration or spreading out of the sheet of runoff, for example on grass strips. This coarse erosion, which accounted only for 20% of the soil losses and 2% of C loss, was measured at the exit of the plots and thus classically considered as a soil loss. It seems also to take part in soil degradation (Collinet, 1988). However, these coarse sediments are poor in nutrients, fine particles, and C, and they settle not far from the eroded zone, in the first anfractuosities or obstacles, reducing the damages due to this type of erosion. This minimal distance covered by coarse sediments undoubtedly explains the relative scarcity of the "alluvial cones" in the current landscapes of cultivated savanna (compared with the Sahel landscapes) and thus gives the impression of small erosion to observers. This carriage is easily retained along bush hedges and narrow grass strips, which gives the illusion of high erosion control effectiveness of these hedges. If there were no strips, the same carriage would be retained in the water-furrows and other hollows.

The coarse particles contrast with suspensions, which accounted for 80% of erosion and primarily consisted in fine particles (75% of fine elements rich in organic matter and nutrients). Though we analyzed gathered samples, the results were consistent with those of Droux et al. (2000), which showed a composition of 50% clay and 40% silt in suspension in the water of Dounfin (Mali) draining into a water catchment of 17.5 km^2. These materials are a remote exportation and give sedimentation on the zones of spreading rivers, which, with a high flood risk, are seldom cultivated or used as pastures. Considering that eroded soils were sandy, the results confirmed the high selectivity of erosion in Sudanese cropping conditions. The selectivity of this rain erosion has often been observed in savanna regions (Roose, 1973; 1981; 1996; Lal, 1983) as well as in temperate grasslands (Fullen et al., 1998). This selective erosion is particularly detrimental for the farmer and the environment because it results in impoverished soil on the slopes. Organic matter being strongly associated or juxtaposed with fine elements, consequently fine elements and C have the same dynamics.

9.4.3 Carbon Losses and Carbon Selectivity

The C losses by erosion measured by Roose (1981) under sorghum in central Burkina Faso (Saria, 800-mm annual rainfall) amounted to 150 kg C ha^{-1} yr^{-1}, and to 9 kg C ha^{-1} yr^{-1} under savanna. Under cotton and maize, Boli-Baboulé et al. (1999) found 85 to 160 kg C ha^{-1} yr^{-1} in northern Cameroon, and Diallo et al. (2000), 330 kg C ha^{-1} yr^{-1} in southern Mali. In the present study, mean weighed annual eroded C was 296 kg C ha^{-1} yr^{-1} under cotton or maize, and 30 kg C ha^{-1} yr^{-1} under fallow. All these results presented the same order of magnitude.

As regarded C selectivity, the C enrichment ratio (CER, ratio between C content in sediments and in topsoils) was higher in the present experiment (10 for CROP) than in cited experiments (generally 1.5 to 3 for crops). For fine particles and N, enrichment ratios of sediments reached 6 and 6.8 in CROP, respectively, confirming that the selectivity of erosion was very high in the present experiment. The main erosion fraction was suspension sediments. Considering that the soil had been cropped for 7 years at least, it was particularly subjected to disaggregation and dispersion of its small particles, which were rich in C even if the soil was poor. In SFAL, the CER reached 5, which was consistent with values of 3 to 10 under natural vegetation given by cited experiments.

The loss of 1 or 2 kg C ha^{-1} yr^{-1} as C dissolved in runoff was the same order of magnitude as data reported by Roose (1981) in comparable conditions (5.4 and 1.1 kg C ha^{-1} yr^{-1} under cereals and savanna in central Burkina Faso, respectively). This fraction was negligible, however it was likely to be displaced at very long distances, exactly like the micro-particles and colloids fractions difficult to filter and also difficult to settle (less than 11 kg ha^{-1} yr^{-1} according to the results of the present study).

9.4.4 Possible Reasons for Constant Erosion over Years

Yet how does one explain the constant character of the erosion year after year? One could think that, once the fine surface was impoverished by rain erosion, the "sandy mulch" would protect the soil against rain. In the fallow, a cover of grass is apparently enough to fix this sandy mulch, producing a sorted micro-layer on the soil surface, known as "ST3" crust (coarse sands on surface, fine sands in the middle, clay and fine silt film underneath; Casenave and Valentin, 1989). In reality, fine materials extracted and transported by termites in these grasslands lead to an increasing of fine particle content in the topsoil. In the crops, termites in dry season and tillage in wet season (plowing, two or three weedings, ridging) regularly shift and reorganize the soil while bringing on the surface fine particles and associating them with organic matter. Tillage exposes the soil to strong erosion during erosive rainfalls, while the soil is in a fragmentary state. This homogenization results in constant erosion over years, impoverishing the soil gradually. During a cycle of fallow–cropping, a significant variation of the fine particles content has been measured in the 0 to 20 cm depth layer (synchronic measurements; Serpantié, 2003). Between the clearing of fallow and the end of the cropping phase, the fine particle content decreases in the soil (variation of 35 g kg^{-1}). During fallow, it increases. However it would be advantageous to undertake a global assessment of the fine particles because the textural variation remains small compared to the quantity of eroded fine elements. It is also necessary to take into account precisely the sedimentary contributions, which occur in fallow placed downstream from crops.

9.4.5 "Fallow" Effect

In normal or dry years, in unburned and ungrazed fallows, erosion was reduced by a factor of 10 to 20 with respect to cropped plots. The present results thus confirmed those of Roose (1993) and Diallo et al. (2000). Burning the shrubby fallow clearly promoted the runoff and erosion, worsening in the wettest year of the decade. The protective effect of the fallow vegetation increased during the rainy season in direct relationship to the installation and the growth of the herbaceous cover. Runoff and erosion were reduced under fallow, but the fallow also absorbed runoff coming from the upslope. Thus, in normal and dry years, the *Andropogon gayanus* large strip, which represented only 20% of the CROP/GFAL plot, could absorb almost all the runoff and all the solid erosion resulting from the upstream crop. The excess rain and accidental fire in 1999 limited its effectiveness. This confirmed the first results obtained by Fournier et al. (2000). Perennial grass fallow and mulch produced an obstacle and thus reduced the velocity of the runoff sheet and increased its thickness. This surface water flow also infiltrated quickly into the largest pores (in particular the macropores placed in relief on the grass tuft; Planchon and Janeau, 1990). This hypothesis was confirmed by the high infiltration capacity of the perennial grass cover under a sheet of water, on the soil of Block 1 (Table 9.1). What was the origin of such a functional macroporosity under *Andropogon gayanus*? There were no worm casts or fauna pores emerging in the surface. In the present case, the renewal of rooting (thick roots of *Andropogon gayanus*, which fasten the tuft to soil) created the macroporosity. The soil was preserved by its good structural state under tufts (Diallo et al., 1998). In the present experiment (Block 1), this effect of overinfiltration was perfectly expressed because the soil was well drained but easily encrusted in surface and packed under the plowed layer. Only the surface layer was thus opposed to the infiltration, from which came the great "*Andropogon*" effect. On a poorly drained soil, such as the soil of Block 2 (plot SFAL), or on the silty soils of the plains, the "*Andropogon*" effect would be less obvious as suggested by the tests of infiltration of the present study. On these soils, a rate of absorbing fallows of 20% of land should be insufficient. Absorption effect was not at its optimum in 1999 because of an accidental burning of the herbaceous cover and mulch and also due to the existence of runoff resulting from soil saturation by water.

9.4.6 Impact of Soil Erosion

The assessment of erosion in terms of economical and environmental impact is still greatly lacking. Forgetting the scaling factor is a classical mistake. It is often thought that erosion plays a significant role lower production. The N losses are indeed of the same order and magnitude as the deficit of N of the mineral crop balance, which is 25 kg N ha^{-1} yr^{-1} for a cotton-sorghum rotation in Bondoukui (Serpantié, 2003). It is thus a fact that erosion reduces locally the fertility. However this can be compensated by the participation of sedimentation and regeneration of the downstream fallow land, which will be later put into cropping. With annual losses averaging 250 kg C ha^{-1} and 20 kg N ha^{-1}, ordinary erosion locally appears like a dead loss, benefiting downstream sites. However, its impact on the farming system and environment is lower in a cropping system where crops are mixed with fallows, as compared to a completely cropped landscape.

A different conclusion is reached in wet years, because C and N losses are much more severe (770 kg C ha^{-1} and 58 kg N ha^{-1}), even in landscapes including fallows. In such climatic conditions, cultivated soils are brutally impoverished if they are recently tilled and very incompletely covered. It is a dramatic loss because this C is soil organic matter, therefore is a stable organic matter compared with fresh organic residues.

9.5 CONCLUSION

In the Sudanese cotton zones, the selective erosion of the surface layers removes fine particles, C, and nutrients from cultivated plots to downstream areas. Protected fallows (unburned and ungrazed) located on the same slope are potential reception areas, if the soil is well drained. Consequently, according to the type of landscape and to possible burning and grazing of these fallows, erosion can be strongly modified as compared with measurements made on plots managed in a homogeneous way. This process of spatial redistribution of surface water and "fertility" by erosion and sedimentation has only been briefly described in studies (Vallet, 1999). In the process of restoration of the soil fertility by fallows, sedimentation is thus an important process to take into account, though generally forgotten.

In regards to the erosion control, organic matter and nutrient losses over long distances can be reduced by an adequate distribution of fallows or artificial meadows within the cultivated fields or hillsides. Modeling should take into account this process of absorption on various types of soil, and the pattern of land use (in chess-work, in strips). Classic grass strips, which are insufficient to control the runoff losses and the erosion of fine elements (Boli et al., 1993), should also be considered again with larger strips and according to draining capacity of soils. In case of less-filtering soils, and taking into account wet years, erosion could be controlled by a higher proportion of areas covered by perennial grass fallows (Serpantié and Madibaye, 1999; Fournier et al., 2000), by covering practices (mulch, cover crops, associated crops, Mucuna, Cucurbitacea, etc.), reduction of tillage by the employment of weed-killer, hydraulic micro-dams (stone lines). Further research should also consider other linked questions: water-catchment scale (in order to appreciate the complex effects of such associations of crops and fallow), farm or social organization for efficient erosion control, and consequences of strong infiltration on the chemical evolution of the soils.

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

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SOIL EROSION AND CARBON DYNAMICS

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

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

Features

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

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

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