TOPIC 2
SOIL EROSION

Soil Erosion, Conservation and Restoration: A few Lessons from 50 Years of Research in Africa

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Abstract

For over 7000 years Man has tried to defend land against the combined assaults of rain and runoff energies. Here we relate a few lessons from 50 years of soil research in Africa, where the population has multiplied by five over the last century.

During the colonial period, explorers thought that tropical soils must be very fertile in relation to the dense vegetation of the tropical forest! But after clearing and one or two years of cropping, the yields became very low: the forest was living from its residues. In his book "Afrique, terre qui meurt", J.P. Harroy (1944) described the two main reasons causing the rapid degradation of african soil fertility: the quick mineralisation of soil organic matter under hot climates and the erosion of cultivated soils. In the "ex-Belgian Congo", the agronomists of INEAC developed rotations, legumes cover crops under permanent tree-crops, and a system of cultivation between living hedges producing mulch in order to maintain the humus in the cropped fields. It was also the period of large National Parks creation to preserve the fauna and flora diversity. In francophone Africa, ORSTOM and CIRAD built a first network of runoff plots to estimate the runoff and erosion risks under various crops and vegetal cover. Well known geographers studied various erosion processes in Africa and Madagascar. Hudson in Rhodesia/Zimbabwe developed devices to measure erosion under natural or simulated rainfalls: he established the importance of slope steepness, soil management and mainly vegetation cover. He demonstrated that agriculture intensification does not necessarily increase soil degradation but can improve the soil cover and reduce erosion and runoff by ten times.

Then began a second period (1960-2000) devoted to the quantification of various erosion processes and factors at various scales under the conditions of various production systems. A new set of standardised runoff plots was built in Africa and Madagascar in order to estimate the parameters of the empirical models available, such as the USLE and variants or SLEMSA. It appeared that

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tropical rainfalls are very aggressive, 10 to 100 times more than temperate rains, but tropical soils are very resistant. The low green cover is very efficient and acts like a stone mulch to disperse the rain drops and runoff energy. On the other hand, the topographic factor is very complex because the erosion processes change at around 20 and 40% slope angles. Cultural practices did not reduce erosion on slopes steeper than 20%. Curiously, sheet and rill erosion never exceeded 700 t/ha/year, even with slopes steeper than 80%, because the soils are more resistant (clay, stones). On steep terrains (>25%), rills, gully erosion and various mass movements become much more important than sheet erosion, mainly in Mediterranean mountains where the valleys are deeply embanked. In Algeria, gully erosion varied from 90 to 400 t/ha/year while sheet and rill erosion did not exceed 1 to 20 t/ha/year even on 35% slopes. On the Uluguru Mountains in Tanzania, Rapp et al. (1972) showed the importance of exceptional rainstorms and the protection effect of trees on mass movement and on gullies that were quite stable during normal climatic and cover conditions.

The spatial aspect of local erosion measurements remains difficult. Attempts have been made to evaluate erosion risks using indicators such as erosion typology, macro-aggregates stability, surface features such as % of closed surface (sealing crust, compaction), % of covered surface (by residues, stones, weeds, litter), and the use of radio elements like Cesium-137 or Beryllium-7 combined with GIS technology. But these models or indicators must be validated on the ground, which is long and difficult because of the non-linearity of the impact factors (many interactions). For example, the slope effect depends not only on slope angle, form and length but also on hillslope orientation to the rain direction, and the topographic position in relation to hypodermic (subsurface flow) or superficial drainage. The diversity of processes and other factors leads to difficulties in developing efficient technologies to reduce erosion and strategies acceptable to rural populations.

Erosion is not only the local scouring of a mass of ground with deposition somewhere lower in the landscape; it refers also to a local loss of water, nutrients and organic matter (1 to 500 kg/ha/year on weeded crops). Even if the ground mass scoured is limited, selective losses of clay and soil organic matter by sheet erosion accelerates the degradation of the potential soil productivity. Therefore, rural communities have progressively developed over the centuries various strategies (26 observed in the Moroccan mountains) well adapted to their conditions in order to manage water and soil nutrients on steep hillslopes. They sometimes accepted local degradation of areas difficult to manage (stony soils on the hill top) in order to promote production in better field conditions (fertile colluvial soils in the valleys). Some traditional systems have been abandoned during the last century, not because of their inefficiency but in relation to socio-economical changes: heavy maintenance work, better salaries in towns, emigration and accompanying shortage of young workers in the villages.

From the industrial period, during the economic and environmental crises, modern strategies were developed that favoured rural hydraulic equipment. Since 1860 in Europe, foresters developed the restoration of overgrazed mountainous terrains (RTM) in the Alps and Pyrenees (terracing, gully restoration and reforestation of the high valleys). In 1930 in the Great Plains of the USA, agro-

nomists developed the Soil and Water Conservation Service, which proposed volunteer technical and financial help to farmers to help them properly manage drainage of their fields (graded terraces). Finally, in 1940, a mixture of both strategies was tested on millions of ha around the Mediterranean basin, mainly by foresters, but with limited success.

During a workshop in Puerto-Rico in 1987, the reasons behind these mechanical approaches were analysed and a new participative strategy (Land Husbandry) was proposed and tested in a dozen countries. It takes into better account farmer constraints and uses farmer experience to introduce new farming systems to best utilize the land and labour while reducing runoff and erosion risks. Instead of terracing, which did not improve soil productivity, this strategy tested on the farmer's fields biologic techniques improving infiltration, deep rooting, soil cover and porosity and nutrients available for plants. Soil conservation is perceived as a part of modern technologies able to increase yields and farmer benefits. Conservation Agriculture is only a part of Land Husbandry, which takes care of the entire landscape.

Soil was considered as a non-renewable resource by soil scientists and soil restoration was left to foresters who planted trees on degraded soils with limited success. But African farmers have developed various technologies to restore soil production not only with various fallows but also with complex systems that are able to restore soil productivity in one year. One such example is the Zaï system, which includes: i) a runoff management system (stone bund) to capture a part of it, ii) a deep tillage of the bottom of a basin to restore macro-porosity and infiltration, iii) one or two handfuls of manure or compost to revitalise the humus, stabilise the structure and increase the soil pH above 5 (to suppress aluminium toxicity), iv) complement nutrients to plants (P and N, chiefly) to insure good yields. This system could be adapted to each ecologic situation like precision agriculture, minimum tillage, and direct drilling under the litter of cultivation residues/legumes cover.

Keywords: Erosion, Africa, soil conservation, fertility restoration.

Introduction

Since the Earth first appeared, mountains have been shaped by erosion and for over 7000 years Man has tried to defend land against the assaults of rain and runoff energies (Loudermilk, 1953). Rural communities have developed numerous traditional strategies, not only to preserve their soil and water resources but also to improve their soil fertility (Roose et al., 2002). In Africa, explorers looking at the luxurious vegetation of the forests thought that tropical soils should be very fertile. But after clearing and one or two years of cropping, yields declined quickly; the tropical forests were living on their own residues. Harroy (1944) wrote a book "Afrique, terre qui meurt" in which he described two causes of soil degradation in tropical countries: rapid mineralization of organic matter under wet and hot climates, and erosion of plowed bare soils exposed to the high kinetic energy of tropical storms. Although erosion effects were described very early, scientific studies began only after 1950.

During half a century, research studies in Africa were very abundant because under these aggressive climates, erosion problems were numerous for sustainable agriculture, river management, and reservoir siltation. At present more than 600 researchers in teams have participated in "The Francophone Erosion Network", WASWC, ESSC and ISCO. It is thus impossible to make an exhaustive review of soil erosion literature. Because of this amount of literature, only those carried out in northern, western, central Africa and Madagascar on water erosion will be reviewed.

Period of erosion risks exploration (1940-60)

In the "ex-Belgian Congo", geographers and agronomists of INEAC (Institut d'Etudes Agronomiques du Congo) observed the degradation of soils when they were tilled, bare and exposed to the energy of sun and rainfall. They developed cover crops, permanent crops, cropping between trees lines and leguminous bushes. In a larger setting, the political leaders created National Parks for biodiversity and soil protection (Harroy, 1944).

In French-speaking Africa, Fournier (1960) produced a first map of erosion hazards based on climatic and topographic indexes. He managed the first network of runoff plots in half a dozen of countries from Senegal to Madagascar to quantify runoff and erosion risks under various cropping systems (Fournier, 1967). Fauck (1956) studied the effects of heavy mechanization on the fragile Alfisols of Senegal over soil structure stability, runoff and erosion. Tricart (1953) distinguished natural and anthropic erosion processes in Madagascar: he insisted on the non-linear reaction of erosion to rain erosivity, slope and cover. Bailly et al. (1976) compared erosion under various forested ecosystems with various cropping systems in Madagascar, Burkina Faso and Niger.

In Rhodesia (now Zimbabwe), Hudson (1958, 1971) developed a large number of experiments at various scales to measure runoff and erosion under various vegetal covers, slopes, soils, and tillage managements. Under natural or simulated rainfalls he proved that it is possible to reduce erosion by a factor 100, and runoff by 10, if the soil surface is well covered. He concluded that intensification of agriculture is not necessarily more degrading to the soil than extensive systems. Beginning with the Bennett (1939) mechanical approach, Hudson (1992) was a fervent supporter of the biological approach to soil and water conservation (Land Husbandry) as proposed by Shaxson et al. (1989) and Shaxson (1999).

Quantifying erosion and modelling (1960-2000)

After a period of basic descriptions of various erosion processes, scientists began to quantify erosion at various scales from runoff plots (100 m^2) to micro watersheds (a few ha) and to large basins of thousands of km^2. Here we review sheet and rill erosion in runoff plots and the main parameters used for the model USLE (Wischmeier and Smith, 1960, 1978), the most commonly used in Africa to predict erosion risks and to propose soil conservation management.

Sheet and rill erosion

A network of more than 400 runoff plots was progressively developed and their management was standardized:

- In North Africa: Heusch, Laouina; FAO in Morocco (1970-2000); Cormary and Masson, Pontanier and Delhoume (1965-80) in Tunisia; Roose, Arabi, Mazour, Morsli and Brahamia in Algeria (1990-2000),
- In Western Africa: Fauck (1956) and Charreau (1969) in Senegal; Roose in Côte d'Ivoire and Burkina (1964-80); Azontonde (1993) in Benin; Diallo in Mali (1998-2000); Lal in Nigeria (1976-81),
- Central Africa: Boli (2000-2005) in Cameroon; Combeau and Quantin in the RCA (Republique de Centre Afrique) (1965-60); Dunne (1979) and ICRAF in Kenya; Hurni et al. (1981) in Ethiopia; Elwell and Stocking (1970-80) in Zimbabwe;
- In Madagascar: CTFT, IRAT & ORSTOM (1960-76).

From this network, we will summarise the main results on the USLE parameters.

Rainfall erosivity (R = 100 to >1000): the sheet erosion cause

Hudson (1958) demonstrated that the main cause of sheet erosion is the kinetic energy of raindrops. He proposed a rainfall index taking into account the kinetic energy of rains with an intensity higher than 25 mm/hour, the limit of the beginning of the runoff on the very stable Oxisols of Rhodesia. On this basis, Stocking and Elwell (1976) drew a map of rainfall erosivity in Zimbabwe.

In the Côte d'Ivoire, Roose (1977) compared various rain erosivity indexes to soil losses on the runoff plots of Abidjan's Ultisols. He confirmed the usefulness of the Wischmeier index ($R = Ec.I_{30}$) taking into account the importance of the total amount, the kinetic energy of all the rains > 10 mm and the maximum intensity during 30 minutes (Wischmeier and Smith, 1960), which are related to soil moisture and runoff volume. Calculating this index for 20 stations with records of more than ten years, Roose observed that the Ram (ten year average index) is simply related to the ten-year average amount of rains (Ham) in western Africa:

$$Ram = Ham \times a$$

where a = 0.50 in rolling plains, 0.60 near the ocean, 0.25-0.30 in tropical mountains of Cameroon, Rwanda and Burundi, and 0.1 on Algerian Mediterranean mountains. From these data it appears that tropical rainfalls are much more intense and energetic than rains in the tropical mountains, in temperate regions and even in Mediterranean areas. Roose drew a map of isoerodent lines in western and a part of central Africa; rainfall erosivity ranges from 100 in Sahelian areas, 300 to >600 in the Sudanian savannah, and to more than 1000 in subequatorial forests. The erosivity of tropical storms can be 10 to 20 times more erosive than temperate rainfalls.

Soil erodibility (factor K = 0.01 to 0.40)

In the 1950's, European universities taught that tropical soils are very fragile: the data measured on runoff plots have shown that it is not always the case:

- many tropical soils are less fragile than some temperate soils, but tropical rainstorm erosivity explains why there is so much erosion in Africa;
- there is a large variability between soil types, from K= 0.01 to 0.40;
- even if soils have not been classified on parameters included in soil erodibility (Roose and Sarrailh, 1989; Roose 1981, 1996), we found that:
  - Ferrallitic soils (Ultisol or Oxisols) are very resistant: from K= 0.01 to 0.20 if basalt, granite or schist;
  - tropical Ferruginous soils (Alfisols) are less resistant after 2 years of cropping (K=0.2 to 0.3);
  - Calcic Vertisols are very stable (K= 0.001 to 0.010) but sodic Vertisols are very fragile (K>0.40);
  - Lithosols rich in gravels or rocks on the surface are very stable (K= 0.01 to 0.10);
  - Brown Calcic mediterranean soils are especially resistant if they have many rocks on the topsoil;
  - red leached Fersiallitic mediterranean soils (terra rossa) are the most fragile for sheet and linear erosion (K=0.20);
- the soil erodibility index is not stable: it varies with soils characteristics, rainfall seasons, organic carbon evolution and elements tilled out of deep horizons by deep plowing (clay, rocks, $CaCO_3$, iron and aluminium hydroxydes), but some tests like macro-aggregate water-stability are efficient to estimate present soil erodibility (Barthès and Roose, 2002).

Improving tropical soil erodibility is very difficult because SOM declines very fast (50% in 4 years after clearing in sandy soils). Much biomass is needed to increase the SOM content by 1%, and that reduces soil erodibility by 15% only on sandy clay topsoils (Roose, 1996). Clearing stones off the topsoil increases erodibility, but leaving a stone mulch on the soil surface decreases the risks of splash and gully formation, maintains a good infiltration rate and protects aggregate stability. A good compromise for farmers is to take off the big stones impeding tillage and seedling growth, to bring them on stone bunds, and maintain the little stones on the soil surface as a mulch. Deep plowing may temporarily improve runoff infiltration and moisture storage under stone crusts, but its favorable influence is very transitory on unstable soils.

The vegetal cover (factor C = 1 to 0.001): the main parameter for soil conservation

Compared to a bare plot, the cover of the main crops in Africa reduces erosion risks by 20 to 60%, in relation to cultural practices increasing green cover growth. The C factor decreases down to 1% under perennial crops with green-cover or prairie/leguminous fallows, and 1/1000 for forests and mulched crops (Roose, 1981; Mietton, 1988).

This is the main parameter available to reduce erosion risks: early and densely plantation, mixed cropping, agroforestry, balanced fertilization, leguminous short fallow, mulching, crop residues and weeds management, living hedges, etc. in order to dissipate rainfall and runoff energy on hillsides (Roose, 1977; Roose, 1996).

Bushfires in Africa have a tremendous effect on runoff for the first storms when the vegetation is burnt just before the rainy season. Three years of protected fallow was sufficient to increase bush vegetation and pedo-fauna activities, drastically increasing the infiltration capacity, the vegetation cover and limiting soil losses (Roose, 1996).

Hudson (1958) made a nice demonstration of the impact of drop energy and their interception possibilities on a 4% slope with a stable Oxisol. A simple mosquito gauze at 15 cm over the soil surface was as efficient as a meadow to reduce erosion to 1% and runoff to 10% of what is observed on a bare runoff plot. The cover of the low canopy seems to be more important than the vegetation type and even more than roots (which are more efficient against linear erosion). Subsequentally Elwell and Stocking (1976) developed a cover index. In Zimbabwe, as long as the crop cover was more than 70% of the soil surface, there was no risk of dangerous erosion even if runoff was significant.

In northern Cameroon, Boli et al. (1993) compared the influence of crop residue management (tilled in, exported, mulched & manure) to a plastic net taut 15 cm above the surface of a sandy ferruginous soil during 4 years on a rotation cotton-maize adequately-fertilized 2% slope. Manure and crop residues plowed in during 4 years had no significant effect on runoff and erosion. A plastic net increased runoff and erosion significantly as compared to hay mulch because the sandy soil became crusted and compacted simply by water moistening and running over the topsoil. The influence of mulching is thus dependent on soil aggregation stability and the nature of the mulch: plastic or stone mulches are less efficient on runoff than natural litter.

In Morocco, Laouina (1992) showed that erosion remained moderate (<2 t/ha/year) in Mediterranean mountains when the soil surface was covered by litter, dense bush, grass or rocks. However, as soon as the soil was plowed for annual crops with clean weeding, erosion could increase to over 20 t/ha/year on 20% slopes during rainy years. The main difference between natural forests and grazed degraded forest is the abundant runoff where animal hooves have compacted the topsoil (Sabir et al., 1994): overgrazing can lead to gullies on the way from the grassland to the watering points (Fotsing and Tchawa, 1994).

The topographic factor (SL = 0.1 to 20): an important but difficult factor

In the USLE empirical model of Wischmeier and Smith (1978), only slope angle (2 to 25%) and slope length were taken into account ($L^{0.5}$). It is clear that the slope influence has multiple interactions with slope shape, topographic position on the hillside, drainage in the upper horizons, topsoil surface features, litter, weeds and stones cover, etc. Each erosion process has threshold conditions depending on the soil moisture, etc. Thus the slope factor remains a real problem.

Many authors have established that when slope angle increases, runoff decreases, but soil losses increase exponentially on badly covered fields (Hudson, 1958; Heusch, 1970; Roose, 1977). On mulched plots, erosion remains moderate even on steep slopes (Lal, 1981; Roose, 1981). In Vertisols of Algeria (Roose et al., 1993a), the slope angle (15 to 40%) was determinant neither for runoff nor for erosion: there are interactions with soil types, stone cover, topographic position. In the hills of Rwanda and Burundi, it seems that soil losses on steep cropped slopes are limited to E<700 t/ha/year on 25 to 80% slopes. Above 25% slope, soils are richer in clay or rocks, runoff decreases and soil erosion processes changed from sheet/rill erosion to rill and creeping erosion.

Tillage erosion is very efficient to transform the hilly landscape in terraces (Duchaufour et al., 1996; Ndayizigyié and Roose, 1996; König, 2002).

The slope length effect is not evident as well. Only plots with rills generally lose more soil when the length increases. Where the litter or topsoil roughness dissipates the sheet runoff energy, the influence of slope length on erosion is insignificant (Lal, 1976; Roose, 1996). Thus on the smooth sandy glacis of northern Cameroon, increasing the length (20 to 60 m) or field surface (100 to 1000 m^2) of runoff plots on 2% slopes did not significantly increase erosion (Boli et al., 1993).

The influence of the topographic position at the bottom of the hillside is sometimes more important than the slope steepness in Mediterranean areas. Gullies are sometimes growing from the valley bottom to the hilltop, because they profit from the cumulative runoff, or from the declivity at the riverbed contact provoking riverbed degradation, or because the hypodermic flow springs out on the soil surface (Cosandey and Robinson, 2000; Roose et al.,1993a). In the Ivory Coast, Valentin et al. (1987) showed that the hilltops are covered with very stable red gravelly ferrallitic soils (without rills), but rills and discontinued gullies begin on the fragile ferruginous soils of the hillsides. Large gullies develop in the hydromorphic valley bottoms.

To reduce slope effects, all kinds of terraces, stone bunds, and living hedges are building embankments modifying slope angle and length. It was observed experimentally that embankments are more efficient than ditches: but all these systems are expensive for building (300 to 1500 days of work/ha) and maintenance. The essential task remains: to manage and fertilize the space between these spectacular structures, often useful but not sufficient to efficiently manage waters running along the hillslopes (Roose, 1996; Shaxson, 1999).

Cultural practices to reduce erosion (factor P = 1 to 0.1)

The influence of cultural practices is not negligible. In semi-arid areas and on long glacis of <3% slopes, plowing or ridging on the contour and tied ridging increased the water storage over the soil and the crop yields. In the mountains, however, where cultivated slopes have more than 20 to 60% slope gradients, runoff decreases but soil losses may increase quickly as the processes change from sheet to linear erosion or even creeping. Above 20% slope, cropping on the contour line is less efficient to decrease erosion (Roose, 1996) while vegetation cover becomes more efficient.

In sandy soils of Senegal, Charreau and Nicou (1971) demontrated that plowing in semi-arid areas allowed better rooting and infiltration at the beginning of the cropping season. Lal (1976) near Ibadan, a humid region of Nigeria, observed that tillage degraded soil aggregates of Alfisols but direct drilling in the litter allowed for a more sustainable production of corn, with less runoff and erosion problems.

Boli (Boli et al., 1993; Boli, 1996) in Cameroon and Diallo et al. (1999, 2008) in southern Mali in a Sudanian area on sandy ferruginous soils observed that direct drilling in the litter of a rotation cotton/corn reduced runoff and erosion. Finally, after 4 years, the carbon stock of the topsoil was very low and not significantly different (Roose and Barthès, 2001). Agroforestry and leguminous bush hedges seem very important not only to reduce erosion and stabilise embankments, but also to produce forage and improve the carbon stock and earthworm activity (Ndayizigyié and Roose, 1996; König, 2002; Sabir et al., 2002; Nooren et al., 1995; Blanchart et al., 2004).

Finally, more than 1200 annual erosion data have been obtained on runoff plots but they are so dispersed in Africa that it is difficult to test the validity of various models.

Obviously the USLE model has numerous limitations: average tendencies over 20 years do not answer daily problems, interactions between parameters, slope effect to be modified locally, slope gradient limited between 2 to 20%, and the necessity to include runoff energy in the steepest hillslopes (Roose, 1978). The advantage is that even with "extensive uses", if we have a minimum of representative measurements of the regional situations, we may evaluate the soil losses at the field scale but not at the basin scale. Other models have been proposed such as MUSLE (Williams, 1975), where rainfall energy has been replaced by runoff energy (useful in mountains), RUSLE (PNUD, 2002) in Morocco, and SLEMSA, developed by Elwell (1978) for southern Africa where the interactions between factors have been modified (cultural practices with soil erodibility). Finally all those models are not necessarily more accurate than USLE.

Gully erosion

Although linear erosion is very active on Mediterranean and semi-arid hillsides (see Table 1), studies are much less abundant even for Sudanian savannas (Valentin et al., 1987).

In a tropical semi-arid area of Tanzania, Rapp et al. (1972) showed how exceptional events are important for the development of gullies and slumping that are quasi-stable during normal years.

Stocking (1980) observed different types of gullies progressing in the fragile sodic alluvium of Zimbabwe. Erosion was dependent mainly on the amount of rainfall (P in mm), the watershed area (S in km^2), and the height of the gully head (H in m). The equation is:

$$Gully\ erosion = 6.87 \times 10^{3}\ P^{1,34} \times S \times H^{0,52}$$

In the Algerian mountains, the volume of a network of gullies was measured during three years. Gully erosion varied from 90 to 300 t/ha/year in relation to soil and rocks, slope gradient and distance to the river system, and rainfall amount and distribution during the seasons (Kouri et al., 1997; Roose et al., 2000).

The importance of erosion processes varies very much in the African landscapes. In Mediterranean areas, sheet erosion is limited even on steep slopes according to soil stability, calcium saturated clay content and rock presence (Roose et al., 1993a). In Morocco it was demonstrated in small watersheds that gully erosion is more active than sheet erosion (Heusch, 1970; Naimi et al., 2002; Mouffadal, 2002; Moukhchane, 2002). In Tunisia, Collinet and Zante (2002) have shown how much piping influences gully development in gypsic marl.

In the Sudano-Sahelian area slope gradients are gentle. Crusted topsoils protect against sheet erosion but not against runoff. Gully erosion can be very active even on 1% slopes because sealed glacis produce very significant runoff volumes.

Finally, in landscapes formed in ferralitic areas ("demi-orange") of humid tropical countries, sheet erosion may increase up to 700 t/ha/year on convex hillsides, but runoff decreases when the slope increases. Gully erosion can be very important after denudation, clearing for urbanisation, and can develop on animal paths to springs (Tschotsua, 1993; Duchaufour et al., 1993).

Table 1: Importance of various erosion processes (t/ha/year) as a function of three African landscapes (Roose et al., 2000).

Landscapes	Slope angle	Sheet erosion	Tillage erosion	Gully erosion
* Lowest mountains Mediterranen	10-40%	0.1-20	10-50	90-300
* Long glacis Sudano-Sahelian	1-3%	0.1-35	2-5	20-100
* Convex hillsides, moist tropics	4-30%	0.1-700	10-50	100-500

Mass movements: very few studies

Investigations by Rapp et al. (1972) who studied the Uluguru mountains of Tanzania and by Moeyersons (1989) in Rwanda showed the importance of exceptional rainstorms and earthquakes on slumping. It seems that well-rooted Eucalyptus trees can reduce mass movement in the mountains (along the roads).

Tillage erosion, another type of mass movement, is very active in plowed fields as soon as the slope is steeper than 5%, but very few studies estimated its importance except for Wassmer (1981) in Rwanda and Smolikowski et al. (1998) in the Capo Verde Islands.

Erosion, nutrient losses and carbon sequestration

Erosion not only influences the depth of the topsoil and the volume of sediment transport or siltation in reservoirs, but also losses of water, soil organic carbon (SOC) and nutrients. Many authors have noticed that soil erodibility is negatively related to SOC of topsoil. The richer the topsoil in SOC, the more the aggregates are stable and the higher the infiltration rate (Combeau and Quantin, 1962; Roose and Barthès, 2001; Barthès and Roose, 2002).

Moreover, sediments washed from the plots are richer (1.2 to 3 times) in fine particles, SOC and nutrients (N, cations) than the 10 cm topsoil. Selective sheet erosion is the primary cause of topsoil impoverishment in fine particles and nutrients of numerous sandy African topsoils. Another cause could be the earthworms, termites, etc. digesting fresh and labile soil above the litter of the forests (Roose, 1981; Nooren et al., 1995).

Nutrients losses

In western Africa, losses by runoff and erosion were measured on runoff plots along a catena from sub-equatorial moist forest to Sudano-Sahelian savannas around Ouagadougou in the center of Burkina Faso (Roose, 1981). Even if erosion is selective concerning nutrients, losses are correlated to the topsoil nutrients content and the abundance of soil erosion. Fertilizing at the soil surface significantly increased nutrients loss. Losses increased from a forest losing 50 kg/ha/year to a fertilized maize field (N120, P20, K36) losing 90 t/ha/year. Nutrient losses increased from 14 to 1866 kg/ha/year of carbon, 1.5 to 185 kg of nitrogen, 0.1 to 33 kg of phosphorus, 0.8 to 70 kg of calcium, 0.3 to 35 kg of magnesium and 0.6 to 54 kg/ha/year of potassium. Sheet erosion seriously impoverished this plowed field in clay, SOC and nutrients.

Stocking (1988) in Zimbabwe computed that losses in carbon, nitrogen and phosphorus from runoff plots on the main soils and land uses of this country exceeded US$ 1.5 billion per year. On cultivated fields, losses by erosion varied from US$ 20-50, which is more than fertilizers invested yearly in these fields.

Erosion and drainage losses can be important in soil degradation of tropical cultivated soils. They are one more reason to protect soils where rainfalls are abundant. But if rainfalls are abundant during some weeks of the year, it may happen that erosion losses are reduced but drainage losses increased. That was the case in the Mbissiri station in northern Cameroon where no tillage in mulched fields decreased erosion (25 to <5 t/ha/year) and runoff (25 to 10%) but increased nitrogen leaching and required a supplement of 20 kg/ha fertilizers to correct the deficiencies in N of leaves of a cotton/maize rotation (Boli, 1996).

Carbon losses at the field and hillside scale

A number of studies have been carried out on carbon losses by various erosion processes in tropical and Mediterranean areas.

Comparing biomass production (1 to 20 t/ha/year), the losses of particulate carbon by erosion are moderate: 1 to 50 kg/ha/year in well-protected areas (forests, prairies, savannas, mulched crops, cover crops), but they can reach 50 to 500 kg/ha/year under weeded crops and up to 2t/ha/year on bare soils in very rainy countries and steep slopes. Dissolved carbon losses by drainage and runoff increased from 1 to 600 kg C/ha/year with the drainage volume from the Sahel to the Equatorial forest. Only sheet erosion on gentle slopes is really carbon selective (1.3 to 3 and sometimes 10 times the content of the topsoil). Where rills are numerous, C losses are a function of erosion volume and 10 cm topsoil C content (Roose and Barthès, 2001).

Comparing carbon sequestration potential of soils (0.1 to 2.5 t/ha/year), losses by drainage and erosion are of the same order. Thus farmers have an interest to develop cultural systems concerning the soil to reduce SOC and nutrients losses, to increase soil aggregation, maintain SOC stock and better nourish the crops (nitrogen fixation and water storage).With intensive agroforestry systems, the available biomass and the SOC stock increases, the leaching by drainage is reduced and nutrients are more available for plants (N fixation, P assimilable, pH slightly acid, etc.) (Boye and Albrecht, 2002; König, 2002; Sabir et al., 2002).

At the level of hillslopes, eroded carbon meets various traps: dense vegetation, concave slopes, permeable soils, embankments, living hedges, filtering stony obstacles, and swampy prairies along the rivers. Diallo et al. (2000) found that soil losses from all the fields of a basin are 20 times the sediment delivery at the outlet of this basin (103 km^2) of southern Mali.

An important part of the ground that we thought eroded by rainfalls, are in reality pushed by tillage practices to the embankments or to the colluvium at the bottom of hillslopes. It is more a local mass movement than a real carbon sequestration process, except if this humus buried under the plowed topsoil will take longer to be mineralized (Wassmer, 1981; Roose, 1996). Livestock grazing compacts the topsoil, increases runoff and gully development and transfers biomass from the grasslands to the fields around the parks (Nyssen et al., 2002; Coelho et al., 2002). More important is the erosion rate; the deeper the incision in the soil cover, the less the selectivity ratio. The carbon content is important in the sediments (Lal, 2002; Roose, 2002).

In little hilly dams of Tunisia, the majority of the sediment carbon comes from vegetation and topsoil cover (Albergel et al., 2002). In contrast, in large rivers most of the carbon is soluble and comes from drainage waters and weathering of carbonates or silicate rocks. Particulate eroded carbon is trapped upstream and soluble humus acids are used for development of plankton and algae in the rivers (Meybeck, 2002; Probst, 2002).

Soil restoration

For soil scientists, water and soils are non-renewable resources. It is evident that if the thin topsoil over a hard calcareous or granitic rock is eroded, it will not be possible to restore the soil in a single lifetime because it takes 1000 to 3000 years to weather 10 cm. However, some soft rocks such as limestone, argillite, loess, schist, volcanic ashes and basalt can be weathered in 10 to 20 years. Some farmers from Haïti and northern Cameroon have traditional systems to accelerate soil formation with fire, special plants, manure and terraces (Seignobos, 1998).

The restoration of the productivity of degraded soils is traditionally made during a long fallow and bush fire, but some special systems have been developed in Sudano-Sahelian areas of Western Africa such as the Zaï (Roose et al., 1993b; Roose, 1996).

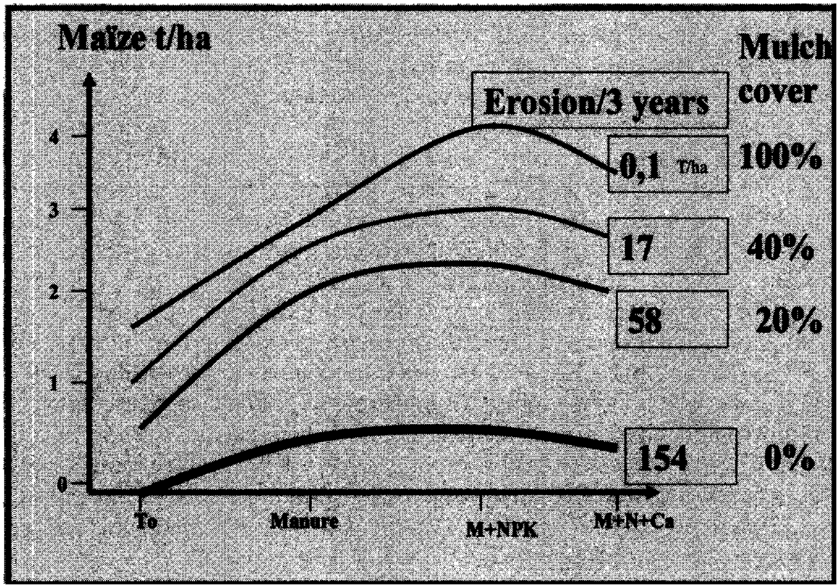

Fig. 1: Effects of preceding sheet selective erosion accumulated over 3 years and 3 restoration systems on the grain yield of maize (t/ha/year). Importance of the mulched surface on erosion and on the future production of maize grain. IRAZ research station of Mashitsi near Gitega, Burundi: 8 runoff plots on 10 % slope, very acid ferrallitic soil (Ultisol).

The case of a sandy-clay Ultisoil of Burundi (Rishirumuhirwa, 1993)

The problem was to improve the soil productivity on tropical mountains of central Africa where 250 to 800 inhabitants must survive on very poor ferrallitic soils (pH<4, Al toxicity, N+P+K+C deficiencies). During 3 years, 8 runoff plots were tested using 4 treatments with 2 repetitions (Fig. 1):

- a bare tilled fallow with 0% of mulch, accumulated 154 t/ha, i.e. around 10 mm of sheet erosion;
- a mulched plot cultivated with 100% of herbaceous mulch, accumulated only 0.1 t/ha;
- a dense banana tree plantation (3 x 3 m) with 40% of mulched residues accumulated 17 t/ha;
- a low density plantation (5 x 5 m) with only 20% mulch accumulated 54 t/ha, i.e. about 4 mm of erosion.

During a fourth year, each plot was divided into 4 subplots planted in maize; 1 subplot to observe the after-effect of accumulated erosion (the topsoil memory), and 3 subplots with soil restoration systems: with 20 t/ha of fresh farm manure = the traditional local system, with 10 t of manure with a complement of NPK necessary to produce 4 t of grains, and 10 t of manure + NPK + 500 kg/ha of dolomite to reduce the soil acidity.

Selective sheet erosion after-effect: The grain production decreased from 15 quintals/ha for mulched plot (such as after deforestation), to <10 quintals/ha for banana plantations and 0 kg for the most eroded plot. The topsoil has a memory of degradation from selective sheet erosion. Even if 10 mm of topsoil thickness is very thin, it significantly decreased maize production.

Soil productivity restoration: With 20 t/ha of farm manure, the yield increased from 0.5 t/ha on eroded plots to 2 t/ha on banana plantations and to 3 t/ha on completely mulched plots. Here it seems best to give limited amounts of manure to the best uneroded fields, but the families living on 0.5 ha have very little manure. Hence we tested 10 t/ha/year of manure + mineral complement NPK. The yield on the degraded soil remained at 0.5 t/ha, but on partially mulched banana plantations the maize grain yield attained 3 t/ha. For an entirely protected plot, the grain yield reached 4 t/ha (very good given that the soils are so poor). In that optimal field it was possible to feed 1600 people/km². Finally, we added 500 kg/ha of dolomite to improve the pH and to reduce the soil aluminium toxicity, but the grain yield decreased, possibly because the calcium saturation of the drainage reduced the already very low assimilable phosphorus.

In conclusion, in the first year of cropping on that sandy clay Ultisol, the yield multiplied by 6 to 8 times when the soil was well aggregated and the nutrients sufficient for crop growth.

The case of a sandy Alfisol sealing in the Sahelian area of Burkina Faso (Roose et al., 1993b)

A population of 50 to 150 inhabitants/km² must survive on <5 ha/family of very unstable and poor (C, P, N deficient) ferruginous soils with erratic rainfalls (600 to 300 mm in 4 months) during the hot season and 5 to 6 dry months. Because the topsoil is sandy loam and poor in SOM with very fragile aggregates, after tillage the soil is rapidly covered with an impermeable sealing crust and most of the rainfall runs off away from the cultivated fields. After 10 to 15 years the plowed areas are completely degraded, the humiferous horizon scoured by runoff, and the topsoil closed by a thick erosion/deposition sealing crust. These abandoned degraded fields, termed "Zipelle", covered more than 20% of the hilltop, the hillside or alluvial soils of the valleys of the Mossi Plateau.

A traditional rehabilitation system of the abandoned fields has been developed on the Sudano-Sahelian areas of Africa from the Dogon hills of Mali, the glacis of the Mossi plateaus in Burkina Faso, Niger, Tchad, Tanzania, and even in the dry earths of Madagascar. The Zaï system consists of digging basins of 20 cm deep and 40-60 cm diameter every meter in alternate rows, to prepare the ground in crescent-shapes downstream, to mix 1 or 2 handfuls of dry manure (3 t/ha) in the bottom of the basin and to plant 12 to 20 seeds of sorghum or millet before the beginning of the rainy season. At the first storm, the runoff from the crusted area corresponded to 5 times that of the basins, and the nutrients available were concentrated in the basins around the clumps of sorghum plants. This system can store enough water in the soil to resist 3 weeks of drought.

Various studies have shown that with a minimum of manure or compost and a complement of NPK, it is possible to produce 8 to 15 quintals/ha of sorghum grains, as much as in the best fields (Roose et al., 1993a). The standard degraded field with plowing only produced 150 kg/ha of grains, basins + runoff produced 400 kg, basins with 3 t/ha manure produced 800 kg and basins + manure + NPK produced more than 1500 kg/ha of grain, enough to feed 6 persons on one ha, i.e. ten times the yield of the standard conventionally plowed fields. This demonstrated that in the Sahelian area, nutrients are as deficient as water storage. Nevertheless in one year it is possible to restore the productivity of a degraded field with labour, deep tillage, manure or compost, fertilizers and an adequate system to decrease runoff energy and to store the runoff in basins and soils. The system of Zaï was described in detail in another paper (Roose et al., 1993b) but this complex system has socio-economic requirements (labour, manure, stone lines and fertilizers) and climatic limits (rainfall between 350-850 mm) corresponding to the Sudano-Sahelian area of Africa and Madagascar. The Zaî system is a more complex and efficient system than tied ridging because it restores biodiversity, soil fauna, and creates an agro-sylvo-pastoral system in semi-arid areas.

In conclusion, it is possible to quickly restore soil productivity, but requires 5 steps:

1. Because eroded soils have a high rate of runoff, the first step is to develop a system of runoff management (stone bunds, living hedge + basins);
2. Because degraded soils are compact and instable, it is necessary to plow them deeply and to stabilize them with organic matter or calcium carbonate;
3. Because the vitality of the mineral horizons is very low as compared to the humic horizon, it is important to bury compost or manure with a large diversity of microbes and mycorrhizes able to dissolve the soil's nutrients;
4. Because the degraded soils are generally very poor, it is important to restore nutrients to the plants when the crops are deficient and not to the soil, which cannot store them efficiently;
5. If the soil pH is too low (<5), it is imperative to increase the pH to over 5 in order to decrease aluminium toxicity.

Conclusions and perspectives

Numerous studies have been made in Africa concerning various erosion processes and their parameters in different ecological zones. We propose three possibilities for measurement technology, to be applied and analyzed for soil productivity restoration over the next ten years.

Technologies for measurement

No measurement technology is perfect. Researchers must select a body of technologies adapted to problems to be solved and to human and financial conditions.

In Africa two approaches can be defined:

- Very simple tools were developed to evaluate erosion processes and risks in the landscape: cheap techniques adapted to labour availability, geomorphological observations, simple reference marks (nails, pins, trees roots, stones, soil surface features), long-term measurements on runoff plots and gullies, interviews with old people and, more recently, manual irrigators to evaluate infiltration rate on steep slopes and indicators on surface features, soil characteristics and aggregation stability (Sabir et al., 2002).
- More recently, sophisticated technology has been developed to reduce the research duration in the field. It began with rainfall simulators tests (50 to 1 m²), (Lafforgue and Naah, 1976; Lafforgue, 1977; Roose and Asseline, 1978; Collinet and Valentin, 1979; Casenave and Valentin, 1989; Sabir et al., 2002). Planchon (1991) developed studies on hillslope sediment traps and models of gully growth. Hydrologists have measured fine particles in suspension (MES) without explaining the scale effect between local sediment yield and the global budget of sediment delivery. The scale effect is now assessed by GIS crossing various indicators such as aggregate stability and surface features (Diallo et al., 2000). Geomorphologists have drawn maps of erosion processes based on the analysis of aerial photographs, and then regional repartition of processes on satellite imagery. Currently little drones are equipped with special cameras to monitor the surface features of fields from 50 to 200 m altitude. (Asseline and De Noni, 2000).

Finally, various isotopes such as Cesium-137 may help to calculate the balance between sedimentation and erosion along hillslopes and the origin of the sediments in a watershed (Moukhchane, 2002; Huon and Valentin, 2002).

Two problems remain: validation of the models and representativity of local observations.

Erosion processes

Most erosion research has been directed towards sheet and rill erosion, which are the first steps of soil degradation by erosion. Africa currently produces more than 1200 yearly data sets from runoff plots in relation to various parameters: soil erodibility, cropping systems, slope gradient, and rainfall erosivity. In our opinion, it is now important to move from soil degradation process and mapping of risks to studies on sustainable systems to increase productivity at the rate of population growth (doubling in 20 years) (De Noni and Roose, 1998).

As farmers deforest steeper slopes, it is now important to study gullies, tillage erosion, and various mass movement processes. We need data to predict silting rates of reservoirs. The origin and the parameters of the various soil erosion processes must be studied locally, but also the efficiency of soil restoration systems and the valorization of sediments for fruit, forage and wood production. In the Moroccan mountains the traditional Mediterranean forest has been completely destroyed, but a new agro-forestry system is developing with crops growing under olive trees. No one knows the impact of such an evolution of the landscape on floods, sediment yields and sediment delivery.

Validation of water and soil fertility management: efficiency, acceptability, profitability.

For 50 years, mechanical techniques of soil and water conservation (SWC) have been proposed internationally but without validation. Many SWC projects were found to be neither efficient nor acceptable by farmers (Hudson, 1991).

More recently, biological techniques have been tested to be efficient in runoff plots such as living hedges (never adopted by farmers outside the projects), mulching in the Sahel (less profitable than extensive stock farming), and direct drilling into the litter (but there is no litter left at the beginning of the rainy season in the semi-arid areas) (Shaxson et al., 1989).

Many soil conservation systems have been found to be efficient to reduce erosion and runoff. Nevertheless, they cannot increase the yield of poor soils typical in Africa.

For the future it is suggested to cross biomass and water and soil management with some additional mineral fertilisation to correct the nutrition of crops (mainly N, P) (Roose, 1996; Zougmore et al., 2002).

To improve systems accepted and developed by farmers themselves, we need to return to traditional approaches to manage water, biomass and soil fertility resources. Reij et al. (1996) studied their diversity in Africa, then the World Overview of Conservation Approaches and Technologies (WOCAT) project analysed their efficiency in the world (Hurni, 1986; Liniger et al., 1998). We now to develop a soil and water management manual for Morocco based on improved traditional systems as observed in the mountains of each agro-ecosystem (Roose et al., 2008).

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