Organic matter management for soil conservation and productivity restoration in Africa : a contribution from Francophone research

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Abstract

Soil fertility is closely linked to soil organic matter (SOM), which status depends on input, i.e., mainly biomass management, and output, i.e., mineralization, erosion and leaching. Preliminary results from runoff plots and lysimeters on hillslopes in West Africa indicated that carbon losses by erosion and leaching ranged between 10 and 100 kg C ha^{-1} yr^{-1}, depending on annual rainfall and vegetal cover. Under natural conditions, losses may be low enough to be compensated by aerial deposits. But together with mineralization, erosion can locally be an important cause of SOM decrease in cropping systems where there is poor soil cover, steep slopes and erosive rain conditions.

The effect of previous erosion on cereal production was assessed in case studies from Rwanda, Burundi, Cameroon, and Burkina Faso. On the densely populated hillslopes of Rwanda, hedges and manure reduced runoff and erosion efficiently, but did not succeed in improving grain yields due to P-deficiency of these ferrallitic soils. In Burundi, under similar conditions but under banana plantation, tree density and mulch cover had a strong influence on erosion; this previous erosion had an important effect on the next maize yield, even when the soils were amended with manure, mineral fertilizers and lime. On sandy ferruginous soils of North Cameroon, erosion increased with increasing tillage intensity. Manure application increased grain yield, but burying organic residues did not improve SOM levels and soil resistance to erosion. Mulching and tillage limited to the plant rows protected the topsoil against erosion, but did not clearly increase the yield. Manuring permitted the restoration of soil productivity, but additional mineral fertilizers (P, N) were needed to reach rapidly a high level of grain production. In the same way, experiments conducted with traditional Zaï system for restoring a degraded Entisol in Burkina Faso showed that runoff harvesting and organic matter input were not sufficient with no additional N and P fertilizers. Complementary experiments in Cameroon showed than a 4-mm selective sheet erosion and a 50-mm non-selective de-surfacing resulted in similar yield decline.

Long fallowing, burning and grazing are traditional ways to utilize available biomass in Africa. Considering social habits and technical realities, it seems useful to balance “grazing-manuring” and mulching in order to protect the soil and maintain its productive capacity. Minimum tillage with mulch (crop residues, weeds or legume fallow) is the new trend used for increasing crop production, with the help of herbicides. Agroforestry that produces good-quality litter is also a part of the solution.

Key words: Africa, organic matter management, erosion, carbon losses, restoration of soil productivity, conservation, manure, mulch, hedges, legumes, tillage, fertilizers

Introduction

It is largely recognized that soil organic matter (SOM) increases structure stability (Combeau and Quantin, 1964; Feller and Beare, 1997; Barthès et al., 1999), resistance to rainfall impact (Wischmeier and Smith, 1960; Dumas, 1965; Wischmeier et al., 1971; Hudson, 1973), macroporosity and infiltration rate, mesofaunal activities (Roose, 1976; Lavelle et al., 1992). Plowing in crop residues is generally recommended for maintaining SOM level (Charreau and Nicou, 1971; Pieri, 1989), but more information is needed on optimal SOM management in the tropics (Moyo, 1998; Rishirumuhirwa and Roose, 1998a).

Many authors have shown the positive influence of mulching and minimum tillage for water and soil conservation in tropical areas (Hudson, 1973; Lal, 1975; Boli et al., 1993; Blancaneaux et al., 1993; Roose, 1996; Moyo, 1998). Combeau and Quantin (1964) reported that grass fallows stabilize soil structure and reduce erosion rate in clay Oxisols of Central Africa. Forestry and agroforestry can also increase biomass production and improve soil fertility through litter on the soil surface (Cheatle et al., 1989; Young, 1989; Harmand, 1998). But green manuring with cereals or legumes has limited success in many tropical countries as long as grazing livestock is left in open fields during the dry season (Klein, 1994; Boli and Roose, 1998).

In this paper, we report on SOM losses by erosion and leaching, and on organic matter management in five African countries. The effects of biomass management and tillage on runoff, erosion and restoration of soil productivity were studied in sets of runoff plots. In relation to increasing population, we also questioned whether it was possible to reach sufficient yields with biomass only, or whether additional mineral fertilizers were necessary.

Losses of SOM by erosion in humid and semi-humid tropics

Sheet erosion selectively exports clay, silt, nutrients and SOM from the topsoil (Lal, 1976; Roose, 1977; Gachene, 1989; Belay Tegene, 1990; Kaihura et al., 1998; Moyo, 1998). This selectivity is higher when the soil is well covered by a litter, the slope gentle, and the runoff and erosion rates low. As soon as runoff increases, it coalesces into rills and gullies which scour the whole mass of the upper soil horizons (Roose, 1980).

Carbon deposited by rainfall, lost by erosion, runoff and leaching, and carbon stock in the topsoil were studied by Roose (1980) in three locations on natural and cropped plots (Table 1): (i) Adiopodoumé, near Abidjan, Ivory Coast; twelve runoff plots on sandy clay ferrallitic soils (Ultisols), 7% slope, under sub-equatorial rainforest (rainfall = 2100 mm in ten months); (ii) Korhogo, in northern Ivory Coast; two runoff plots on gravely ferrallitic soils (Oxisols), slopes <3%, in Sudanian savanna (rainfall = 1300 mm in seven months); (iii) Saria, 90 km SE of Ouagadougou, in Burkina Faso; three runoff plots on tropical ferruginous soils (Alfisols on iron pan), slope <1%, in Sudano-Sahelian savanna (rainfall = 800 mm in six months). It may be concluded that: carbon deposited by rains and lost by erosion generally decreased with decreasing annual rainfall; under natural conditions, carbon deposits by rains were somewhat greater than carbon losses by erosion and leaching; carbon lost by erosion was much greater on cropped sites than on natural ones (4 to 20 times); on cropped fields, losses by erosion were 4 to 60 times the amount of rains deposits; and carbon stocks in the topsoil were much greater than erosion losses (20 to 100 times). Further analysis of the data showed that the amount of eroded carbon depended more on erosion quantity than on carbon content of eroded sediments (Roose, 1980).

Many studies have dealt with the effect of erosion on nutrients losses or on soil fertility (Stocking and Peake, 1987; Lal, 1985) and crop production (Kaihura et al., 1998); very few compared carbon losses by erosion to aerial deposits by rains and dust in tropical Africa (Roose, 1980). In southern Zimbabwe, Moyo (1998) reported similar losses of carbon by erosion on runoff plots (5 to 180 kg C ha^{-1} yr^{-1}), comparing mulch ripping to conventional tillage on sandy granitic Alfisols (rainfall = 550 mm); SOM loss was a direct function of soil erosion and runoff (Follet et al., 1987). In Tanzania, Kaihura et al. (1998) showed that topsoil nutrients and organic carbon contents generally decreased with increasing erosion. Compared to SOM mineralization under humid tropical conditions, sheet erosion does not seem to be the main agent of SOM degradation, but erosion can speed up SOM loss during cropping cycles. Ramussen and Albrecht (1998) concluded similarly in semi-arid regions of Pacific Northwest of USA. Farming systems and cultural practices, such as minimum tillage with litter or legume cover, can change erosion rate and SOM balance quite rapidly (Juo and Lal, 1977; Boli et al., 1993). Gregorich et al. (1998) reported that land clearing and cropping decreased SOM by 30%, due to mineralization, but that erosion or deposits might locally result in greater SOM losses or gains. In our African experimental stations, carbon losses were measured on hillslopes, and a part of this carbon was probably deposited at the bottom of the hill, but most was lost in the river.

Case studies

Manure and living hedges in Rwanda's densely populated hills

In Rwanda (250 to 700 inhabitants km^{-2}), each family must produce food crops, energy and forage for five to ten family members and for the livestock, on one hectare of steeply sloping (10 to >60%) acid, P- and N- deficient ferrallitic soils (Roose and Ndayizigiye, 1996). A typical farmer plows small fields by hand. Around the house, he intercrops bananas, beans and sweet potatoes. On 0.3 ha, he spreads 10 t ha^{-1} yr^{-1} of composted manure and crop residues for a maize-bean and sorghum rotation. On 0.1 ha, he maintains coffee trees with a thick mulch of various crop residues. No more manure is available for the remaining land (>0.5 ha), where he therefore plants crops tolerant to acid soils (pH <4.5) such as cassava, sweet potatoes and local vegetables. The family collects all residues from crops, livestock and from the family in a composting pit. In this manner, a maximum of 5–10 m^3 are produced annually (i.e., 1.5 to 3 t yr^{-1} of dry compost) in order to manure 0.1 to 0.3 ha at an application rate of 20 t ha^{-1}. At this rate, only maize and beans can be efficiently produced on these acid soils.

An experiment was carried out by Ndayizigiye (1993) in order to decrease runoff and erosion risks, and improve grain production. Five treatments were tested on nine runoff plots (100 m^2) with a 27% slope: bare cultivated fallow, local cropping system (maize-bean and sorghum rotation) (two replicates), and local cropping system with three types of living hedges (*Leucaena leucocephala, Calliandra calothyrsus* or *C. calothyrsus* associated with *Setaria sphacelata*, each in two replicates). The spacing of the hedge lines was 7 meters. Hedges were pruned four times a year. During the 3-month dry season, the cuttings were used as forage (producing manure) and after planting, they were used for mulching the cropped runoff plots. To maintain food production on cropped plots, 10 t ha^{-1} of farm manure were plowed in at the beginning of each of the first two years, 20 t ha^{-1} the third, and 10 t ha^{-1} of manure, 2.5 t ha^{-1} of dolomite, and 300 kg ha^{-1} of mineral fertilizers (78N, 42P, 42K) the fourth year.

Runoff rate was low but not negligible (2 to 12%; Figure 1a). Erosion, very high on bare fallow (up to 500 t ha^{-1} yr^{-1}; Figure 1b), was half-reduced but remained very high with the regional cropping system (up to 250 t ha^{-1} yr^{-1}); living hedges were efficient enough to limit risks to <2 % runoff and <2 t ha^{-1} yr^{-1} of erosion two years after planting.

Between 10 to 12 t ha^{-1} yr^{-1} of fresh biomass (containing up to 100 kg N, 10 kg P, 40 kg K and 20 to 40 kg Ca and Mg) were produced by hedges. Despite the large amount of buried and mulched organic matter, and the reduced erosion risk, grain yield remained low without mineral fertilizers (0.8 t ha^{-1} yr^{-1}; Figure 1c). This acid, P-deficient soil required mineral fertilizers and dolomite to produce a reasonable yield (Figure 1c).

On a sandy soil of southern Nigeria, Kang et al. (1985) and Kang and Wilson (1987) reported similar results with *Leucaena leucocephala* planted every 5 meters: despite very low runoff and erosion, and high yield of biomass from the 5-yearly prunings, N supply was necessary to get a high maize yield.

Management of manure and banana residues on acid ferrallitic soils of the Burundi Central Plateau

On the Central Plateau of Burundi, the physical and human conditions are quite similar to those of Rwanda described above, with the same problems of erosion risks and productivity restoration, but under banana plantation (Rishirumuhirwa, 1997). Seven 350-m² runoff plots were established in 1989 on a 8% slope and an acid ferrallitic soil (Ultisols), either on bare soil (two treatments) or banana plantation (five levels of banana tree densities and mulch cover, from 20 to 100%). The total erosion during three years decreased from 154 t ha^{-1} on bare fallow to 58 t ha^{-1} for low banana density (20% cover), 17 t ha^{-1} for high density (50% cover), and 0.15 t ha^{-1} for banana plantation entirely mulched (Figure 2a). Mulch cover and disposal were more efficient than banana canopy for reducing runoff and erosion (Rishirumuhirwa, 1997).

After three years of banana cropping, all runoff plots were cleared up and planted to maize in order to evaluate the effect of the previous erosion on the production capacity of this more or less degraded soil (Rishirumuhirwa and Roose, 1998b). Each plot was divided into four subplots, one without any input, the second with manure (20 t ha^{-1}), the third with manure and mineral fertilizers (60N, 40P, 60K), and the fourth with manure, fertilizers and dolomite (0.5 t ha^{-1}).

With no input, the maize grain yield decreased from 1.5 t ha^{-1} on the previously 100%-mulched plot (comparable to the yield measured after the clearing of a long fallow) to

0.8 t ha^{-1} on the previously dense-planted plot, and zero on the bare plot that had been subjected to more than 154 t ha^{-1} erosion (Figure 2b). This direct effect of the previous erosion on yield was explained by topsoil degradation and splash erosion, which decreased infiltration capacity and structural stability (Rishirumuhirwa, 1997).

The restoration sub-trial (manure, fertilizers, liming) showed that within each treatment, the grain yield decreased with increasing previous erosion, i.e., with decreasing previous mulch cover (Figure 2b). Within each previous erosion class, the grain yield was higher with manure and mineral fertilizers than with manure only. Moreover, additional liming did not increase maize production significantly, even though this soil was very acid; the introduction of so much calcium probably disturbed the cation balance and reduced available P, already deficient.

Immediately after treatment, mulch was effective in reducing erosion and maintaining infiltration, and plowing, manuring and mineral fertilizers restored the productivity; but soil characteristics were not significantly improved overall. The application of easily mineralizable manure was not sufficient to increase SOM levels; but its mineralization released nutrients, which increased the pH and supplied the crops (Rishirumuhirwa, 1997). Erosion and runoff were not measured after the third year (because of the civil war). It was therefore not possible to know whether yield increases were due to a fertility effect only, or also to improved soil physical properties. It was clear, though, that organic matter helped mineral fertilizers to be utilized efficiently by maize.

At IITA Station of Ibadan (Nigeria), Lal (1975) showed that surface mulching at the rate of 4 to 6 t ha^{-1} decreased soil temperature, maintained favourable soil structure and infiltration rate, and enhanced microbiological and earthworm activities. Mulch tillage reduced soil erosion to a minimal rate, prolonged the growing period, and increased the yield when sufficient nutrients had been spread: fertilizer requirement was generally higher with mulch tillage than with plowing. At Mbissiri Station (North Cameroon), Boli et al. (1993) showed that mulches (6 t ha^{-1} of grass or 2 t ha^{-1} of crop residues) significantly reduced runoff and erosion on a sandy Alfisol, but that maize yields were not increased because of increasing leaching.

Management of crop residues, weeds, manure and mulch on a sandy Alfisol in North Cameroon

This study was conducted at Mbissiri Station, in the Sudanian savanna of North Cameroon, where average annual rainfall reaches 1250 mm in six months (Boli, 1996; Boli et al., 1998).

Erosion, topsoil carbon content and yields were measured during four years on 57 runoff plots (100 to 1000 m²), on a 1 to 2.5% slope. Three plots were under savanna, as a reference. Thirty-eight plots were on a new manual clearing, divided into three blocks differing in slope angle, in order to compare the effects of tillage (conventional, tied-ridging, minimum or zero tillage), and grass strips on soil conservation. A fourth block of 16 degraded plots was on a 30-year old clearing in order to study restoration of soil productivity; the main treatments were young fallow (grass or legume), conventional tillage with organic management (crop residue removal or incorporation, 3 t ha^{-1} yr^{-1} goat manure incorporation, 6 t ha^{-1} yr^{-1} grass mulch and plastic mulch) and decompaction followed by minimum tillage. All cropped plots were under a cotton-maize rotation with recommended mineral fertilizer input, except one bare tilled plot per block, as an erodibility standard. On the same hillslope, a soil de-surfacing experiment was carried out in order to evaluate the effect of non-selective erosion on maize yield. Six depths of hand-scouring were tested (0, 5, 7.5, 10, 12.5 and 15 cm) on 50-m² plots, with three replicates.

The annual erosion ranged from 0.5 to 3 t ha^{-1} yr^{-1} under savanna or grass fallow, from 3 to 5 t ha^{-1} yr^{-1} under minimum tillage, and from 15 to 25 t ha^{-1} yr^{-1} under conventional tillage. Among the conventionally tilled plots with organic matter management, there was no significant difference in topsoil SOM content, runoff, erosion or yield, except that mulches reduced erosion and somewhat runoff, and that the best yields were always obtained on manured plots. Grass mulch decreased runoff and erosion significantly. Plastic mulch reduced erosion at the beginning of the rainy season only; later on, the aggregates became very fragile, the topsoil became crusted, and runoff was high. The impact of organic amendment on mesofaunal activities and infiltration capacity was evident (Boli et al., 1993).

Figure 3 shows the carbon content of the 10 upper cm during the four years of the study. Burnt fallow had an almost stable carbon content (7 g kg^{-1}). In the conventionally plowed plots, the decrease in carbon content was very fast during the first two years (from 7 to 3 g kg^{-1}) due to a mixing effect and accelerated mineralization by plowing, then reached slowly a minimum level of 2 g kg^{-1}. Under minimum tillage, because the topsoil was less disturbed, the decrease in carbon content was slower, and the minimum level was higher (3 g kg^{-1}).

Soil de-surfacing led to an important decrease in grain yield, by about one-third when 5 cm had been removed, and by more than half when 15 cm, i.e., the entire humic horizon, had been scoured out (Figure 4).

Figure 5 compares total erosion of conventionally plowed plots and minimum-tillage plots over 4 years, and its effect on maize yield during the fifth year (cultural practices, involving plowing, being then the same for all plots). As compared with minimum tillage plots, plowed plots had a decrease in yield of about one third and an erosion increase of about 60 t ha^{-1}, corresponding to a topsoil removing of 4 mm (assuming a 1.5-g cm^{-3} bulk density). The selective sheet erosion, dominant on runoff plots, had thus reduced soil productivity much more than the whole soil removal by non-selective scouring.

Conventional plowing system gave the best grain yield (with manure input), but also the greatest runoff and erosion rate during the four years. Inquiries of farmers revealed that these sandy soils were completely degraded in between 15 years under conventional tillage (Boli et al., 1993). On the contrary, Bonsu (1981), on a shallow clay Alfisol in Ghana, reported that straw mulching and ridging gave the highest yield of millet. Long-term experiments are needed for selecting the most sustainable tillage system and determining the best use of crop residues. Only forest and bush savanna, with their deep-root systems and litter recycling activity, improve soil fertility permanently. Tillage limited to planting rows (20% of the plot surface) and intercropping with deep-rooted legumes (covering more than 50% of the soil surface) might provide a more sustainable system. Azontonde (1993) developed successfully such a system in southern Benin with *Mucuna pruriens* or *Stylosanthes guyanensis.* Lal (1985), at IITA Ibadan Station in Nigeria, on a Paleustalf with a 25-cm deep stone-line, reported a significant effect of erosion on topsoil carbon, N and P contents, pH, total porosity, and finally, on maize grain yield. This yield declined at rates of 0.13 and 0.09 t ha^{-1} cm^{-1} for 10 and 20 cm of scoured soil, respectively. On the same soil, the decline in maize yield caused by sheet erosion on runoff plots (1% slope) was 2.6 t ha^{-1} cm^{-1} of eroded soil (i.e., 16 times more than de-surfacing). This effect of sheet erosion, more drastic at Ibadan than in our experiment, might relate to the presence of a very superficial stone-line.

Micro-watersheds and localized organic matter application in Burkina Faso

The Zaï is a traditional practice commonly used in the Sudano-Sahelian area for rehabilitating degraded fields which have been eroded and completely crusted, with an infiltration too low to sustain vegetation (Roose et al., 1993; Kabore, 1994). The Zaï consists in digging holes during the dry season (30 cm diameter, 15 cm deep, 100 cm spacing), then filling them with one or two handfuls of dry dung (corresponding to 1–3 t ha^{-1} of dry organic matter) and seeding a dozen of sorghum seeds after the first storms; this practice leads to nutrient and runoff concentration around the plants. This complex restoration system has been described in detail by Roose et al. (1993).

Our experiment was carried out in the semi-arid Yatenga region of northern Burkina Faso (400- to 600-mm annual rainfall), on a deep brown Eutropept. Its objective was to compare the yield of sorghum for different treatments: pits alone (sorghum yield: 200 kg ha^{-1}), pits with dry dung (694 kg ha^{-1}), pits with wild legume leaves (395 kg ha^{-1}), with mineral fertilizers (1383 kg ha^{-1}), with dry dung and mineral fertilizers (1704 kg ha^{-1}), and flat conventional tillage without any input (150 kg ha^{-1}).

In this semi-arid area, water harvesting by runoff concentration was not effective without addition of mineral nutrients. The addition of 3 t ha^{-1} of dry dung did not lead to sufficient yield on this P- and N- deficient soil. The highest production of grain (11 times the control) and straw (5 times the control) was achieved with a combination of organic amendment and mineral fertilizers (N and, chiefly, P). Moreover, Zaï made with dry dung led to biodiversity restoration, with development of forage species (Roose et al., 1999).

Recently, Zougmore et al. (2000) came to a similar conclusion: water concentration (by Zaï or half moons) is not sufficient on most of the semi-arid soils, highly N- and P-deficient. On an abandoned Alfisol, the use of composted organic material mixed with powdered carbonatic rock phosphates produced the highest grain yield (1200 kg ha^{-1}), whereas straw mulch with the same P application produced half the yield, and the tilled reference, 12 times less. In the Kitui district of Kenya, pits for soil restoration are semi-circular, and concentrate runoff in half-moon of 5 to 12 m^2; they are very effective in rehabilitating eroded land (Gichangi et al., 1990).

General discussion and prospects: organic matter management in Africa

In Africa, there are numerous traditional practices using organic matter to maintain soil productivity. Analysing their limitations and improving these practices is probably much more efficient than introducing new techniques adapted to other climatic and socio-economic conditions (Roose, 1996).

Burning

Burning is a widespread traditional strategy for clearing large areas from biomass, for grazing and cropping purposes (Levang, 1984). The negative effects of burning have been emphasized by foresters: decrease in biodiversity, especially in the number of tree species, rapid mineralization of biomass and subsequent reduction of litter and SOM in the topsoil, emission of gases (CO_2, N_2O, SO_2), ashes and dust by subsequent erosion (FAO, 1974; Roose, 1978).

More recently, researchers discovered that burning is probably a part of the natural functioning of Mediterranean ecosystems, and that, in Africa and Asia, burning is a complex strategy to transform the natural conditions into more useful agro-pastoral systems (Levang, 1984). Without burning, large parts of African savannas would be presently under dry forest. Burning is often the only way for poor farmers to clear the land, decrease the pressure of pests, increase available P, cations and pH, and reduce aluminium toxicity in acid soils (Jurion and Henry, 1967; Moreau, 1993; Moreau et al., 1998). In Madagascar, burning the hillslopes permits the transfer of runoff and nutrients to the plains below, in order to plant irrigated rice earlier in the year (Rakotomanana, 1995, personal communication). Burning also improves the quality of grasses available for livestock. Thus, burning strategies must be re-examined and adapted to local situations.

Grazing and manuring

Traditionally, farmers use biomass intensively for livestock when the population density is high. Livestock is their insurance and bank: it produces milk, meat and manure. The manure is spread on the fields or concentrated in home-gardens. The commonly used dry manure presents poor qualities, has lost most of its N and K, carries pests, germs and weed seeds, as faeces are not heated up sufficiently to kill these contaminants. Good quality manure is rare in Africa, but its positive influence on yields, its slow release of nutrients and positive effects on pH and other soil properties are well documented (FAO, 1975; Shaxson, 1999). However, 40 to 60% of the carbon and 30 to 50% of the nutrients from the grazed biomass do not return to the soil (Roose, 1996). In addition, available biomass for grazing in Africa allows the manuring of 10 to 30% only of the cropped fields; SOM cannot significantly be increased by such a limited application.

Composting

Compost is “the manure of poor farmers” who possess no livestock. Traditionally, some tribes put their harvest residues and household wastes in pits, previously dug in order to provide building material. Correctly applied, compost can improve locally SOM and fertility (Mustin, 1987; Shaxson, 1999). But this composting is rarely systematic and the residues are not correctly watered. The pit is emptied before each growing season and the mixed material spread on nearby fields: it helps the topsoil to remain fertile for a longer period (Shaxson, 1999), but the fermentation temperature is also too low to suppress weeds, and available quantities of compost are very limited (1 to 3 t ha^{-1} yr^{-1}). Incorrect composting leads to similar losses of carbon and nutrients than manure production with animals, but it produces no meat, and requires a lot of work to collect and chop a large amount of biomass, water it, mix in ashes, clay, phosphate rocks and animal faeces or stable litter (FAO, 1980, 1987; Mustin, 1987).

Compost pits are now recommended near dwellings to accumulate all household wastes, livestock litter and crop residues, as well as domestic waste-waters, in order to increase the quantity (up to 10 t yr^{-1} per farm) and the quality of the compost produced. This requires transportation of biomass to the dwelling and then back to the fields again, transport cart and work (Mustin, 1987). Moreover, manure and compost are often sold for high-value vegetable production in the lowlands during the dry season. Compost may thus maintain soil fertility, but is difficult to obtain in sufficient amount.

Agroforestry

Traditionally, some tree species are preserved when savannas or forests are cleared up (20 to 50 trees producing 0.5 to 3 t ha^{-1} yr^{-1} of nutrient-rich litter), resulting in park savannas, agro-forests or multi-story home-gardens (Jurion and Henry, 1967; Levang et al., 1997). Living hedges are locally used to border farmsteads, protect gardens from livestock, and produce forage and fire-wood. In the mountains of western Cameroon and eastern Africa, where the population density is high (400 to 800 inhabitants km^{-2}), agro-forests and multi-story gardens are numerous around the dwellings. Currently attempts are made to regenerate parks of legumes (like *Acacia albida*) in order to increase the quantity and quality of organic matter available for maintaining soil productivity (Thézé, 1998). In Kenya, ICRAF tried to introduce trees on grass strips or as hedges. Three species survived the heavy Panicum grass competition: *Grevillea robusta, Cassia siamea* and *Leucaena leucocephala*. Four years after hedge plantation, erosion became negligible, and the slope had evolved from 14 to 7% (Kiepe and Young, 1990). But agroforestry practices could lead to problems of rights for using trees (Schrempp, 1990) and competition for light, water and nutrients between crops and trees (Minae et al., 1998); in Africa, further experiments in roots and branches cutting are needed to reduce this competition.

Plowing in crop residues or minimum tilling with mulch cover

During the last 50 years, agronomists from temperate regions have recommended deep tillage to bury crop residues and cereals or legumes as green manure (1 to 7 t ha^{-1} yr^{-1}) in tropical soils (Charreau and Nicou, 1971). In Africa, many difficulties have delayed the adoption of tillage: residues are grazed, used for construction or burnt, credit is not available to buy oxen or tractors and adapted implements (plows, carts). Moreover, oxen are weak when needed for plowing, at the end of the dry season. Finally, when straw (C/N=60) is buried into the soil, its decomposition ties up the available N, inducing crop N-deficiencies; farmers without access to mineral fertilizers cannot compensate for such deficiencies and suffer yield reductions as a direct result of such management.

Mulch provides a good protection against raindrops and runoff energy, limits weeds competition, improves water storage and mesofaunal activity, and releases nutrients progressively. Minimum tillage reduces soil disturbance and denudation, SOM mineralization, and maintains soil cohesion; thus minimum tillage is not adapted to compacted soils, which first require deep tillage. Recent trials on tillage reduced to plant rows, combined with residue mulching or cover crops, showed reduced runoff and erosion risks, maintaining of the topsoil SOM and structural stability, and finally, improvement of the soil and labour productivity (Lal, 1975; Boli et al., 1993). Reduced tillage with mulch cover seems thus more adapted to tropical conditions, as long as biomass remains available for mulching, instead of being burnt or grazed during the dry season.

Fallowing

The traditional long fallow is very efficient in restoring biological, chemical and physical properties of the topsoil (Greenland and Nye 1959; Floret and Serpantié, 1991), but it is frequently no longer possible to wait 10 to 50 years between two cropping cycles, due to population pressure. Expanding cropped areas is difficult in many parts of Africa, where often less than 30% of the land surface is suitable for cropping.

Three solutions seem technically possible to improve fallows: *tree fallows* (leguminous bushes) with intercropping (Harmand, 1998); *short fallows* of natural weeds between crops managed with herbicides, to produce a litter mulch for no-till cropping; *short legume fallows*, which are presently under extension in Latin America and in an experimental phase in Africa (Azontonde, 1993; Sanchez, 1998). In sub-equatorial areas, short legume fallows are effective for maintaining both SOM levels and grain yields (Azontonde, 1993). Where rainfall amount exceeds 1000 mm in six months, leguminous green cover can be relay-cropped with maize. But in Sudano-Sahelian savannas (rain <700 mm in four months), there is no satisfactory solution yet.

Trends for the future

Trends for the future are: reduction of tillage, improvement of manure quality and quantity, development of agroforestry practices, mulching of the soil surface with residues, or introduction of short fallows of weeds or legumes, managed with herbicides.

Problems remaining to be solved

The case studies reported here show the importance of organic matter management combined with mineral fertilization for the restoration of soil productivity under increasing demographic pressure. There does not exist a unique solution under tropical conditions, because ecological and socio-economic conditions are too diverse. Considering the problems to be solved, we suggest four important areas of research.

1. Diagnosis of soil degradation, thresholds and indicators

Soil aggregation, erodibility, infiltration capacity and porosity are depending on SOM. Is it possible to define thresholds of SOM under which the soils are degraded (not functioning correctly)? Are the thresholds related to the clay content only (Pieri, 1989), or also to mineralogy? There is a need for SOM status indicators that can be easily measured in the field.

2. Organic matter quantity

Quantities of organic residues available in tropical countries are not sufficient to increase SOM significantly. By analysing traditional and modern systems leading to SOM increase, we showed that no unique technique could produce enough biomass to feed soil microbes and maintain SOM levels under cropped conditions. The solution may lie in developing combinations of various techniques: manuring and composting a part of the residues, agroforestry, mulching, weeds and leguminous cover-crop management (with herbicides). A supplementation of mineral fertilizers directly available for crops improves SOM management and increases available biomass.

3. Organic matter quality

When fresh legume biomass is buried into the topsoil, mineralization is fast: the final SOM balance may be negative because the microbial population is primed. Positive effects of manure or compost burying on yields are limited to one or two years. Plowing crop residues too rich in lignin leads to N deficiency in crops. Well managed rotation and/or association of pastures and tree-crops, with a variety of residue qualities, may be regional solutions for SOM improvement.

4. Organic matter management

Agronomists have learnt that organic matter must be buried to improve decomposition and humification; but on the other side, recent research showed the interest of covering the soil surface in order to reduce erosion risks in the tropics. Finally, according to each climatic area, is it better to bury or to mulch available organic matter? Are the positive effects of tillage (through weeds and crop residues burying, macroporosity, etc.) greater than their disadvantages (through SOM mineralization increase, aggregate degradation, erodibility enhancement, soil cohesion and infiltration decrease)?

How should trees be installed in farming systems: only on non-arable land, or also on higher-quality cultivated land, where they will produce more wood, litter, forage, fruits, and will partition and enrich the landscape? Multi-story gardens are found in the most densely populated and productive landscapes, where they play an important role in maintaining soil productivity.

How should grass or legumes be installed: fallows, or pasture, in rotation with the cropping system? If crop residues, weeds and legume covers are to be tilled in or maintained as litter on the soil surface, far-reaching changes of African traditions must be accomplished to protect cropped areas from livestock and from fire during the dry season.

References

Azontonde A (1993) Dégradation et restauration des terres de barre (sols ferrallitiques faiblement désaturés argilo-sableux) au Bénin. Cahiers ORSTOM série Pédologie 28 (2): 217–226

Barthès B, Albrecht A, Asseline J, De Noni G and Roose E (1999) Relationships between soil erodibility and topsoil aggregate stability or carbon content in a cultivated Mediterranean highland (Aveyron, France). Communications in Soil Science and Plant Analysis 30 (13–14): 1929–1938

Belay Tegene (1990) Effects of erosion on properties and productivity of eutric Nitosols in Gununo area, Southern Ethiopia. In: Hurni H and Tato K (eds) Erosion, Conservation and Small-Scale Farming, pp 229−242. Bern: Geographica Bernensia

Blancaneaux P, De Freitas PL, Amabile RF and De Carvalho A (1993) Le semis direct comme pratique de conservation des sols des cerrados du Brésil central. Cahiers ORSTOM série Pédologie 28 (2): 253−276

Boli Z (1996) Fonctionnement des sols sableux et optimisation des pratiques culturales en zone soudanienne humide du Nord Cameroun. Thèse Doctorat Université Dijon, France

Boli Z, Roose E, Bep A Ziem B, Sanon K and Waechter F (1993) Effets des techniques culturales sur le ruissellement, l'érosion et la production de coton et maïs sur un sol ferrugineux tropical sableux. Recherche de systèmes de culture intensifs et durables en région soudanienne du Nord-Cameroun (Mbissiri, 1991-1992). Cahiers ORSTOM série Pédologie 28 (2): 309−326

Boli Z, Roose E and Zahonero P (1998) Effets et arrières effets des pratiques culturales sur le ruissellement, l'érosion et la production d'une rotation intensive (coton-maïs) du Nord-Cameroun. Bulletin Réseau Erosion 18: 246−259. Montpellier, France: ORSTOM

Boli Z and Roose E (1998) Degradation of a sandy Alfisol and restoration of its productivity under cotton/maize intensive cropping rotation in the wet savanna of North Cameroon. Advances in GeoEcology 31: 395−401

Bonsu M (1981) Assessment of erosion under different cultural practices on a savanna soil in the northern region of Ghana. In: Morgan RP (ed.) Soil Conservation: Problems and Prospects, pp 247−254. London: Wiley

Charreau C and Nicou R (1971) L'amélioration du profil cultural dans les sols sableux et sablo-argileux de la zone tropicale sèche ouest-africaine: ses incidences agronomiques. Agronomie Tropicale 26 (9): 903−978 and 26 (11): 1183−1247

Cheatle R, Muraya P and Young A (1989) Modelling soil changes under agroforestry. In: Thomas DB, Biamah EK, Kilewe AM, Lundgren L and Mochoge BO (eds) Soil and Water Conservation in Kenya, pp 254−271. University of Nairobi and SIDA

Combeau A and Quantin P (1964) Observations sur les relations entre stabilité structurale et matière organique dans quelques sols d'Afrique Centrale. Cahiers ORSTOM série Pédologie 11 (1): 3−11

Dumas J (1965) Relation entre l'érodibilité des sols et leurs caractéristiques analytiques. Cahiers ORSTOM série Pédologie 3 (4): 307−333

FAO (1974) Shifting cultivation and soil conservation in Africa. FAO Soil Bulletin 24. Rome: FAO

FAO (1975) Organic materials as fertilizers. FAO Soil Bulletin 27. Rome: FAO

FAO (1980) Organic recycling in Africa. FAO Soil Bulletin 43. Rome: FAO

FAO (1987) Soil management: compost production and use in tropical and subtropical environments. FAO Soils Bulletin 56. Rome: FAO

Feller C and Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79: 69–116

Floret C and Serpantié G (1991) La jachère en Afrique de l'Ouest. Colloques et Séminaires. Paris: ORSTOM

Follet RH, Gupta SC and Hunt PG (1987) Conservation practices: Relation to the management of plant nutrients for crop production. In: Soil Fertility and Organic Matter as Critical Components of Production Systems. Special Publication 19. Madison, WI: Soil Science Society of America

Gachene CK (1989) Nutrient losses in eroded soil material from some Kenyan soils. In: Thomas DB, Biamah EK, Kilewe AM, Lundgren L and Mochoge BO (eds) Soil and Water Conservation in Kenya, pp 34–37. University of Nairobi and SIDA

Gichangi EM, Jones RK, Njarui DM, Simpson JR, Mututho JMN and Kitheka SK (1990) Pitting practice for rehabilitating eroded grazing land in the semi-arid tropics. In: Hurni H and Tato K (eds) Erosion, Soil Conservation and Small Scale Farming, pp 313–327. Bern: Geographica Bernensia

Greenland DT and Nye PH (1959) Increases in the carbon and nitrogen contents of tropical soils under natural fallow. Journal of Soil Science 10: 284–299

Gregorich EG, Greer KJ, Anderson DW and Liang BC (1998) Carbon distribution and losses: erosion and deposition effects. Soil and Tillage Research 47: 291–302

Harmand JM (1998) Rôle des espèces ligneuses à croissance rapide dans le fonctionnement biogéochimique de la jachère. Effets sur la restauration de la fertilité des sols ferrugineux tropicaux (Bassin Bénoué, Nord Cameroun). Montpellier, France: CIRAD-Forêts

Hudson NW (1973) Soil conservation. London: Batsford

Juo ASR and Lal R (1977) The effect of fallow and continuous cultivation on the chemical and physical properties of an Alfisol in Western Nigeria. Plant and Soil 47: 567–584

Jurion F and Henry J (1967) De l'agriculture itinérante à l'agriculture intensifiée au Congo belge. Bruxelles: INEAC

Kabore V (1994) Amélioration de la production végétale des sols dégradés (zipelle) du Burkina Faso par la technique du Zaï. Thèse Doctorat Ecole Polytechnique Fédérale Lausanne

Kaihura F, Kullaya I, Kilasara M, Aune J, Singh B and Lal R (1998) Impact of soil erosion on soil productivity and crop yield in Tanzania. Advances in GeoEcology 31: 375–381

Kang BT, Grimme H and Lawson T (1985) Alley cropping sequentially cropped maize and cowpea with Leucaena on a sandy soil in Southern Nigeria. Plant and Soil 85: 267–276

Kang B and Wilson G (1987) The development of alley cropping as a promising agroforestry technology. In: Steplerand H and Nair P (eds) Agroforestry, a Decade of Development, pp 227–243. Nairobi: ICRAF

Kiepe P and Young A (1990) Soil conservation through agroforestry: four years of experience at Machakos, Kenya. In: Hurni H and Tato K (eds) Erosion, Conservation and Small-Scale Farming, pp 303−312. Bern: Geographica Bernensia

Klein HD (1994) Introduction de légumineuses dans un système coton-céréales au Nord Cameroun. Bulletin Réseau Erosion 14: 393−398. Montpellier, France: ORSTOM

Lal R (1975) Role of mulching techniques in tropical soil and water management. Technical Bulletin 1. Ibadan: IITA

Lal R (1976) Soil erosion problems on an Alfisol in Western Nigeria and their control. Monograph 1. Ibadan: IITA

Lal R (1985) Soil erosion and its relation to productivity in tropical soils. In: Soil Erosion and Conservation, pp 237−247. Ankeny, IO: Soil Conservation Society of America

Lavelle P, Blanchart E, Martin A, Spain A and Martin S (1992) Impact of soil fauna on the properties of soils in the humid tropics. In: Myths and Science of Soils in the Tropics, pp 157−185. Special Publication 29. Madison, WI: Soil Science Society of America

Levang P (1984) Shifting cultivation for Transmigration projects? How primitive techniques could help to solve development problems in Central-Kalimantan Transmigration areas. Llmu. Pert. (Agric. Sci.) 3 (6): 275−283

Levang P, Michon G and De Foresta H (1997) Agriculture forestière ou agroforesterie? Bois et Forêts des Tropiques 251 (1): 29−42

Minae S, Bunderson WT, Kanyama-Phiri G and Izac AM (1998) Integrating agroforestry technologies as a natural resource management tool for smallholder farmers in Malawi. Advances in GeoEcology 31: 1073−1082

Moreau R (1993) Influence de la mise en culture et de la jachère forestière sur l'évolution des sols forestiers tropicaux. In: Floret C and Serpantié G (eds) La Jachère en Afrique de l'Ouest, pp 245−256. Paris: ORSTOM

Moreau R, Nzila JDD and Nyeté B (1998) La pratique de l'écobuage " Maala " et ses conséquences sur l'état du sol au Congo. Proc. 16th Congress of International Soil Science Society, Montpellier, France

Moyo A (1998) The effect of soil erosion on soil productivity as influenced by tillage with special reference to clay and organic matter losses. Advances in GeoEcology 31: 363−368

Mustin M (1987) Le compost. Gestion de la matière organique. Paris: Dubusc

Ndayizigiye F (1993) La gestion conservatoire de l'eau et de la fertilité des sols au Rwanda. Analyse des techniques antiérosives et de leurs effets sur la productivité des terres. Thèse Doctorat Université Strasbourg, France

Pieri C (1989) Fertilité des terres de savanes. Bilan de 30 ans de recherche au sud du Sahara. Paris: Ministère Coopération and CIRAD

Rasmussen PE and Albrecht SL (1998) Soil C and N changes under tillage and cropping systems in semi-arid Pacific Northwest agriculture. Soil and Tillage Research 47 (3−4): 197−205.

Rishirumuhirwa T (1997) Rôle du bananier dans le fonctionnement des exploitations agricoles sur les hauts plateaux de l'Afrique orientale. Application à la région du Kirimiro au Burundi. Thèse Ecole Polytechnique Fédérale Lausanne

Rishirumuhirwa T and Roose E (1998a) Effets des matières organiques et minérales sur la réhabilitation des sols acides de montagne du Burundi. Proc. 16th Congress of International Soil Science Society, Montpellier, France

Rishirumuhirwa T and Roose E (1998b) The contribution of banana farming systems to sustainable land use in Burundi. Advances in GeoEcology 31: 1197−1204

Roose E (1976) Contribution à l'étude de l'influence de la mésofaune sur la pédogenèse actuelle en milieu tropical. Adiopodoumé, Côte-d'Ivoire: ORSTOM

Roose E (1977) Erosion et ruissellement en Afrique de l'Ouest. Vingt années de mesures en petites parcelles expérimentales. Travaux et Documents 78. Paris: ORSTOM

Roose E (1978) Pédogenèse actuelle d'un sol ferrugineux tropical sous une savane arborescente du plateau Mossi (Gonsé: campagnes 1968−74, Burkina Faso). Cahiers ORSTOM série Pédologie 16 (2): 193−223

Roose E (1980) Dynamique actuelle de sols ferrallitiques et ferrugineux tropicaux. Etude des transferts hydrologiques et biologiques de matières sous végétations naturelles ou cultivées. Travaux et Documents 130. Paris: ORSTOM

Roose E (1996) Land husbandry - components and strategy. FAO Soil Bulletin 70. Rome: FAO

Roose E, Kabore V and Guenat C (1993) Le Zaï: fonctionnement, limites et amélioration d'une pratique traditionnelle africaine de réhabilitation de la végétation et de restauration de la productivité des terres dégradées de la région soudano-sahélienne. Cahiers ORSTOM série Pédologie 28 (2): 159−174

Roose E, Kabore V and Guenat C (1999) Zaï practice: a West African traditional rehabilitation system for semiarid degraded lands, a case study in Burkina Faso. Arid Soil Research and Rehabilitation 13 (4): 343−355

Roose E and Ndayizigiye V (1996) Agroforestry, water and soil fertility management to fight erosion in tropical mountains of Rwanda. Soil Technology 11 (1): 109−119

Sanchez P (1998) Soil fertility replenishment in Africa: an investment in natural resource capital. Proc. 16th Congress of International Soil Science Society, Montpellier, France

Schrempp B (1990) Non-conflicting multi-purpose tree integration: a case study in the Harerge Highlands, eastern Ethiopia. In: Tato K and H Hurni (eds) Soil Conservation for Survival, pp 109−117. Ankeny, IO: Soil and Water Conservation Society

Shaxson F (1999) New concepts and approaches to land management in the tropics with emphasis on steeplands. FAO Soils Bulletin 75. Rome: FAO

Stocking M and Peake L (1987) Erosion induced loss in soil productivity: trends in research and international cooperation. In: Pla Sentis I (ed) Soil Conservation and Productivity, pp 392−438. Proc. 4th Conference of International Soil Conservation Organization, Maracay, Venezuela

Thézé M (1998) La gestion des terroirs au Nord Cameroun. Coton et Développement 25: 31−35. Montpellier, France: CIRAD

Wischmeier WH, Jonhson CB and Cross BV (1971) A soil erodibility nomograph for farmland and construction sites. Journal of Soil and Water Conservation 26 (5): 189−192

Wischmeier WH and Smith DD (1960) A universal soil loss estimating equation to guide conservation farm planning. Proc. 7th Congress of International Soil Science Society, Madison, WI

Young A (1989) Agroforestry for soil conservation. Oxon, UK: CAB and ICRAF

Zougmore R, Zida Z and Kambou F (2000) Réhabilitation des sols dégradés: rôle des éléments nutritifs des plantes dans le succès des techniques de demi-lunes et de Zaï au Sahel. Bulletin Réseau Erosion 19: 453−462. Montpellier, France: ORSTOM

Table 1. Carbon deposits by rainfalls, carbon losses by erosion, runoff and leaching, and carbon stock in the topsoil (30 cm) under natural and cropped field conditions, in runoff plots at Adiopodoumé, Korhogo (Ivory Coast) and Saria (Burkina Faso). Data from Roose (1980).

Station	C deposits by rainfall ($kg\ ha^{-1}\ yr^{-1}$)	C losses ($kg\ ha^{-1}\ yr^{-1}$)				C stock at 0-30 cm depth ($kg\ ha^{-1}$)
		Erosion	Runoff	Leaching	Total	
Adiopodoumé (2100-mm rainfall)						
Sub-equatorial forest	155.6	13.0	1.2	73.9	88.1	45 670
Cereals	27.3	1801.0	64.8	7.0	1872.8	34 180
Korogho (1300-mm rainfall)						
Sudanian savanna	46.1	5.5	2.1	12.6	20.2	22 570
Maize, with fertilizers	14.9	64.1	17.6	2.5	84.2	20 583
Saria (800-mm rainfall)						
Sudano-sahelian savanna	22.4	8.5	1.1	1.5	11.1	14 545
Cereals	11.2	149.7	5.4	0.3	115.4	13 205

Figure 1. Influence of living hedges (*Calliandra calothyrsus* and *Leucaena leucocephala*) on annual runoff rate (1a), soil erosion (1b) and yields of a maize-bean association (1c), in runoff plots of Rubona Station in Rwanda. Plots were manured at the annual rate of 10 t ha^{-1} (20 t ha^{-1} in 1991), they were also fertilized (60N, 54P, 25K) and limed (2.5 t ha^{-1} of dolomite) in 1992. Traditional system was a maize-bean and sorghum rotation, with hand-plowing (after Roose and Ndayizigiye, 1996).

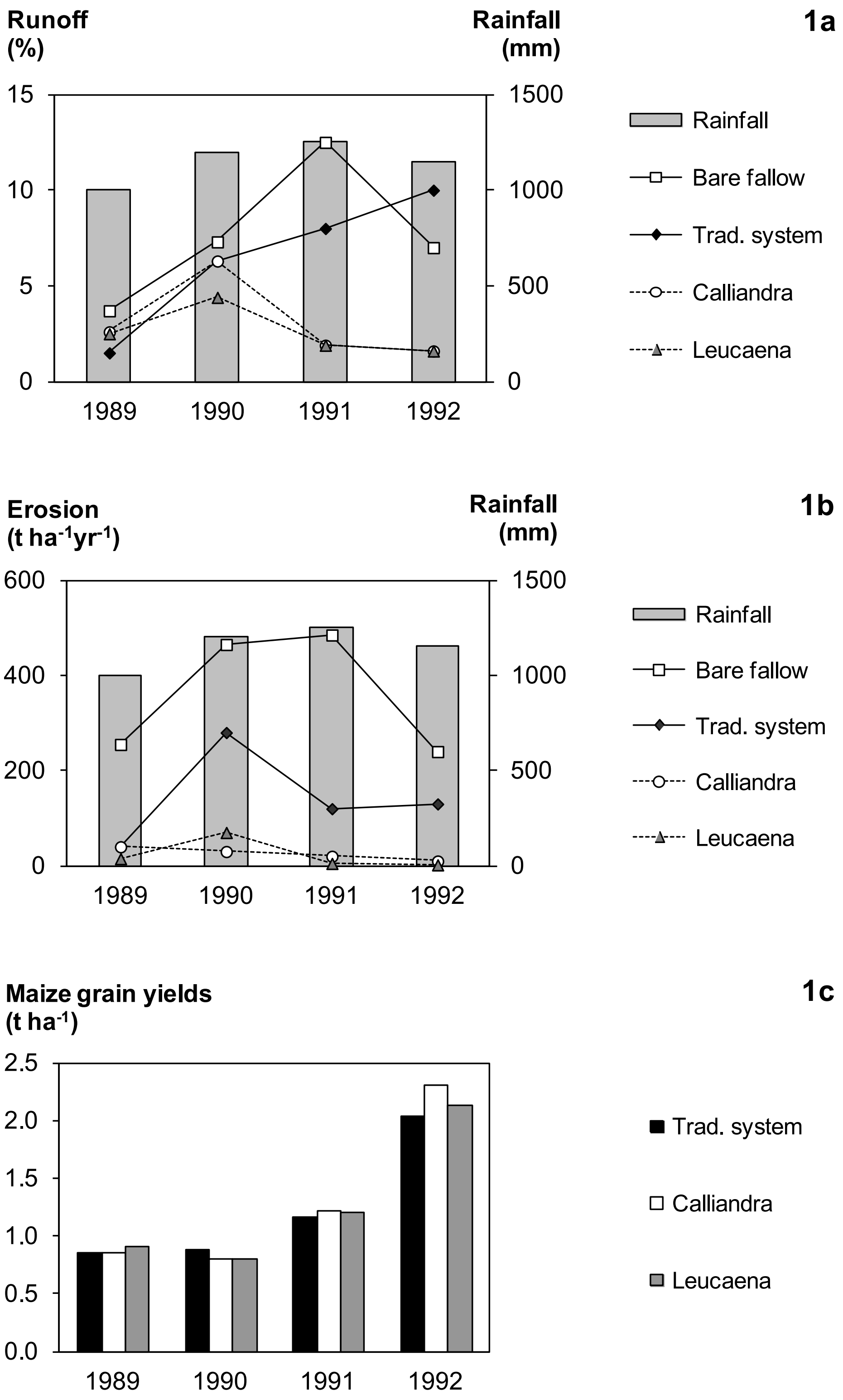
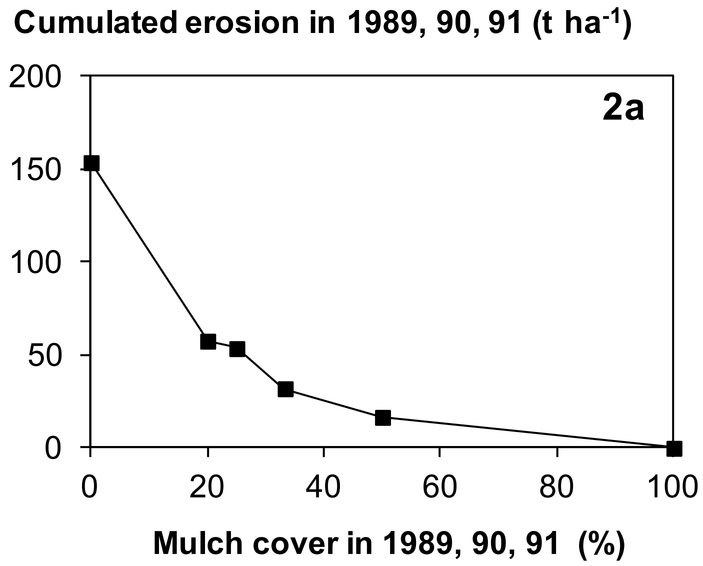


Figure 2. Influence of mulch cover (linked to banana plantation density) on erosion (2a), and effect of this previous erosion on grain yield of the next maize crop (2b), in runoff plots (8% slope) of Mashitsi Station (Burundi). During maize crop, manure input was 20 t ha^{-1}, fertilizers level was 60N, 40P, 60K, and dolomite, 500 kg ha^{-1} (after Rishirumuhirwa and Roose, 1998a).



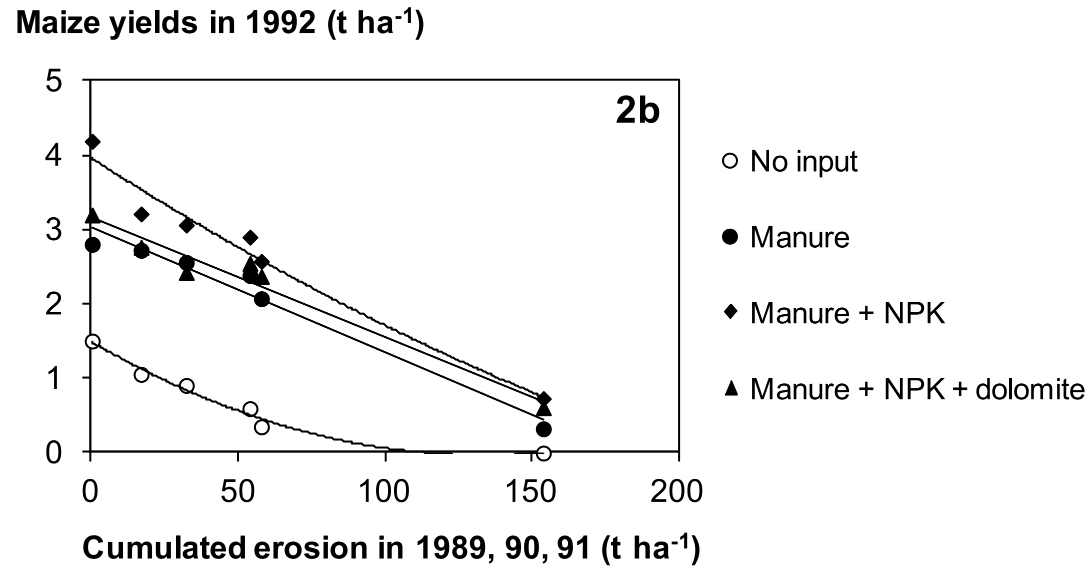


Figure 3. Evolution of carbon content in the 0-10 cm horizon, as affected by time and treatment, in runoff plots of Mbissiri Station in North Cameroon (after Boli and Roose, 1998).

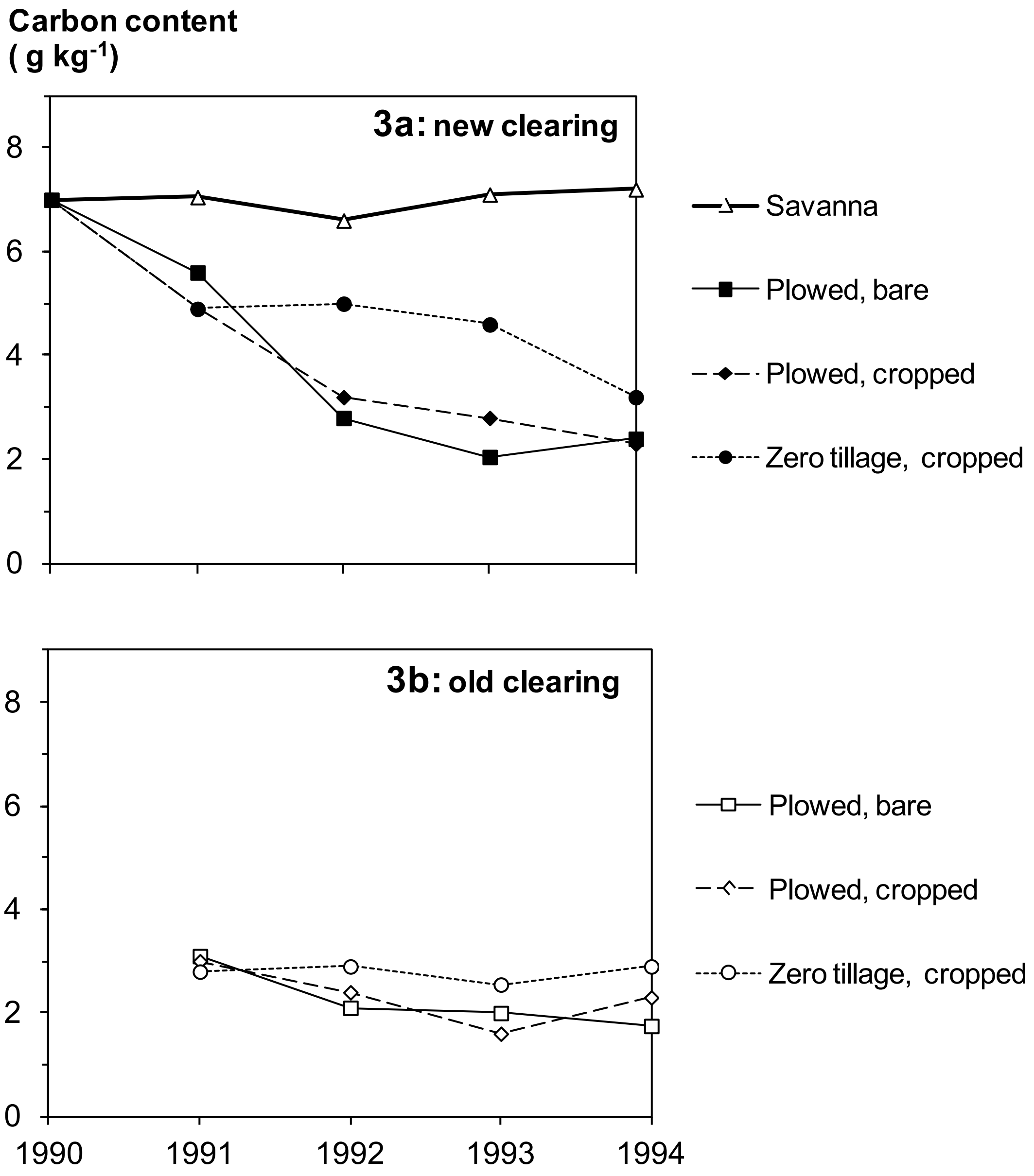


Figure 4. Effect of depth of soil mechanical de-surfacing on maize grain yield, at Mbissiri Station in North Cameroon (after Boli and Roose, 1998).

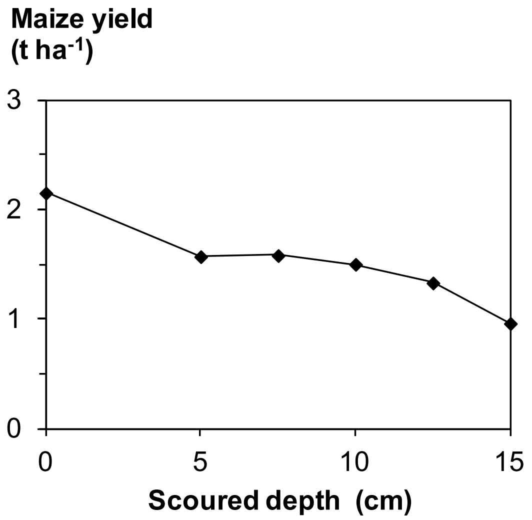


Figure 5. Effect of tillage and organic matter management on 4-year cumulated sheet erosion, and on the next maize grain yield, at Mbissiri Station, North Cameroon (after Boli et al., 1998).