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Agroforestry, water and soil fertility management to fight erosion in tropical mountains of Rwanda

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Abstract

African tropical mountains are often overcrowded because the climate is healthy and favorable to intensive agriculture. Consequently the density of population in the mountains of Rwanda and Burundi has reached an exceptional level (150 to 800 inhabitants/km^2) that leads to delicate problems of soil protection against runoff and various types of erosion on steep cultivated hillslopes. Previous measurements on runoff plots have shown that sheet and rill erosion risks have reached 300 to 700 t/ha/year on 20 to 60% slopes with regional rainfall erosivity ($R_{usa} = 250$ to 700), very resistant ferrallitic soils ($K = 0.01$ to 0.20) and traditional farming systems ($C = 0.8$ to 0.3). Curiously, the runoff rate (10 to 30%) is relatively moderate so that it is possible to restrict erosion with a natural or leguminous fallow, a pine plantation (litter effect) or by mulching coffee, banana or cassava plantations. The problem is now to produce enough biomass to mulch the whole surface with the help of agroforestry. A new strategy (GCES = land husbandry) was suggested to meet the major farmer problems: what should be done to increase the soil productivity rapidly and protect the rural environment? A part of the answer is to be found in the efficient management of water, organic matter and soil fertility restoration (Roose et al., 1988). This strategy was first tested in 9 runoff plots (5 × 20 m) on a 23% slope of a very acid ferrallitic soil (pH = 4). Three types of living hedges (leucaena, calliandra, calliandra + setaria) twice replicated, were compared with the international bare standard plot and with the regional farming system (maize + beans during the first season, and sorghum during the second season). After 2 years, living hedges reduced runoff to less than 2% and erosion to 2 t/ha/year: they produced fire wood and high quality leguminous forage (3 to 8 kg/m) and return to the soil as much as 80 to 120 kg/ha/year of nitrogen, 3 kg/ha/year of phosphorus, 30 to 60 kg/ha/year of calcium and potassium, 10 to 20 kg/ha/year of magnesium. Thanks to agroforestry it was possible to reduce erosion hazard but not to restore the soil productivity. Without 2.5 t/ha/3 years of lime to

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increase the pH up to 5 and reduce the aluminium toxicity, without 10 t/ha/2 years of farm manure and mineral fertilizers to nourish the crops, the yield remains very low (800 kg/ha/season of cereals). Thanks to agroforestry and a mineral fertilizer complementation, erosion hazard was controlled and the productivity of soil and labour intensified more than 3 times.

Keywords: Rwanda; Land husbandry; Agroforestry; Living hedges; Leguminous bushes; Soil fertility restoration; Tropical mountains; Ferrallitic soil (ultisols); Biomass management

1. Introduction

Although many African plains are thinly populated (5 to 40 people/km), tropical mountains are often overcrowded because rainfall and the climate is more healthy, the production more diversified, the volcanic soils are more productive and the topographic conditions provide some protection against various pressures. With the improvement of the medical aid, the population density between 1000 to 2500 m of altitude has reached exceptional levels in Rwanda and Burundi, which leads to dramatic problems of soil degradation, runoff and erosion on steep cultivated slopes (up to 80%) (Hurni and Messerli, 1990).

As long as the population was scattered in the mountains, problems of soil degradation and soil erosion were solved by long fallowing or migration and new land clearing. After 1930, however, the population in Rwanda gathered on a few hillslopes and got starvation and erosion problems. The colonial administration imposed perennial crops (cassava and tea or coffee) and antierosive structures (infiltration ditches protected by grasslines, mulching for coffee plantation and step terraces for tea plantation). The 'colonial imposed strategy' was poorly accepted by the farmers as it requires a lot of labour for installation (100 to 350 labour days) and maintenance (20 to 50 days/year) without increasing the crop yield. After independence (1962) these structures were abandoned for that reason and soil degradation and erosion increased seriously.

Just before 1992, the problems got worse: the population doubles each 20 years and exceeded 150 to 800 inhabitants/km^2. Two thirds of cultivated grounds are acid, exhausted but continuously cultivated because no ground remains for fallowing. The average land available for a cultivating family was less than 0.8 ha in 1992.

It is too late to preserve the land. The productivity of the soil is already very low (400 to 800 kg/ha of beans, corn or sorghum, 1 to 3 t/ha of sweet potatoes or cassava): why should one spend so much labour to protect the soil without significant increase of production? The new objective must be clear: management of water, biomass and soil fertility to double the production every 20 years (like the population), to improve the farmers life level without damaging the rural environment. But in Rwanda, farmers are so poor that mineral fertilizers are lacking, tillage is made by hoe and pesticides are rarely available on time.

The new strategy (GCES; Roose et al., 1988) was first tested for 4 years on the acid ferrallitic soil (ultisol) of a 23% hillslope to evaluate runoff and erosion risks and the possibility to stop erosion losses by living hedges of 3 species of leguminous bushes and to intensify the production by mulching the biomass produced by cuttings.

2. Existing data on sheet and rill erosion on hillslopes of Rwanda and Burundi

Table 1 gives a summary of the main results of 250 plot · year data of erosion measured on runoff plots of Rwanda and Burundi on ultisols of very steep slopes (23 to 55%) (Ndayizigiye, 1992; König, 1992; Duchaufour and Bizimana, 1992; Rishirumuhirwa, 1992).

From these data, it is important to remember that:

- the rainfall amount varies between 1000 to 2000 mm from the eastern savanna to the crest Zaire–Nile;
- the rainfall erosivity index (Wischmeier and Smith, 1960) is high: R varies from 250 to 700 in Rwanda (Ryumugabe and Berding, 1992) and reach 950 in Burundi (Duchaufour and Bizimana, 1992);
- the risk of runoff (up to 40% of major storms) and erosion is very high on bare plots (300 to 700 t/ha/year);
- runoff and erosion risks are not increasing regularly with the slope steepness because there are more stones and less sealing crusts on the steepest slopes;
- traditional associated cropping systems reduce erosion quite a lot ($E = 20$ to 150 t/ha/year) but not enough if tolerance is 1 to 12 t/ha/year according to soil depth;
- 200 trees (*Grevillea robusta*) planted in between the crops are not enough efficient for soil conservation;

Table 1
Erosion (t/ha/year) and runoff (% of the annual rainfall) on some runoff plots of Rwanda and Burundi

Vegetal cover and management	Erosion (t/ha/year)	Runoff K_{ram} of annual rainfall (%)
Bare soil, cultivated along the slope	300–700	10–40
Traditional crops		
Cassava and sweet potatoes	20-150 (300)	10–37
Maize + beans or peas and sorghum		
Agroforestry		
Trad. crops + 200 trees/ha	30–50 (111)	5–7
Id. + trees + living hedges each 10 m:		
first year	7–16	10–15
4th year (3 to 8 kg/m/year)	1–3	1–3
Id. + trees + l.h. + covered ridges each 5 m.	1–4	0.1–2
Permanent crops		
Banana:		
open, residues exported (10 t/ha/year)	20–60	5–10 (45)
dense, mulch spread or on lines	1–5	1–2
Coffee plantation (or cassava) + mulch (20 t/h/year)	0.1–1	0.1–10
Pine forest (5 to 10 t/ha/year of litter) or old fallow, grassland not degraded	0,1–1	1–10

A synthesis after data of Roose et al., 1992; Ndayizigiye, 1992; Ndayizigiye, 1993; König, 1992; Rishirumuhirwa, 1992, 1993; Duchaufour and Bizimana, 1992)
( ) Maximal value observed.

- a first solution to restrict erosion is to plant living hedges of grass (Setaria) and leguminous bushes (*Leucaena leucocephala* or *L. diversifolia* and *Calliandra callothirsus*, better on acid soils) every 10 m and to dig a big ridge covered with permanent sweet potatoes or leguminous forage crops every 5 m to stop the runoff energy;
- mulching with crop residues (mainly with banana leaves, sorghum stalks and various tree leaves) is the best solution under banana, tea, coffee and cassava plantations;
- leguminous cover crops are also useful under permanent plantations.

Finally, reforestation with *Pinus kessia* (very good litter) and other forest species growing above a dense soil cover will reduce runoff and erosion risks under acceptable level after 2 to 5 years.

Fig. 1 (Duchaufour and Bizimana, 1992) and Fig. 2 (König, 1992) show that many biologic antierosive systems are efficient to reduce erosion risks sufficiently even on fragile sandy ferrallitic topsoil of the mountains: they associate a source of biomass

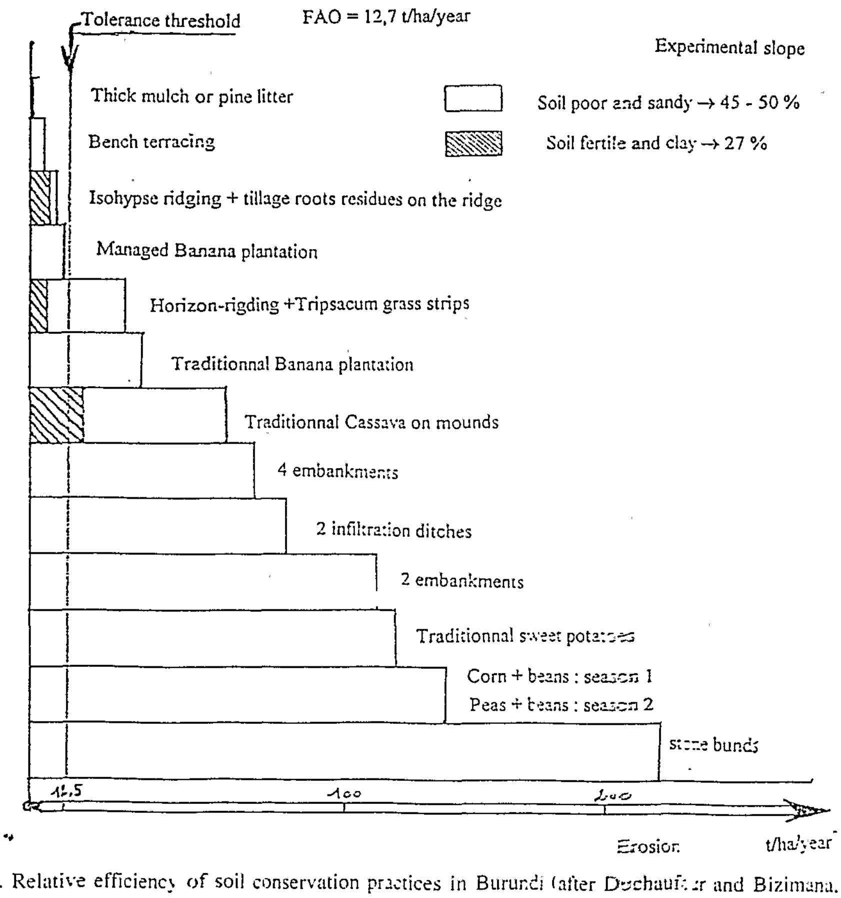

Fig. 1. Relative efficiency of soil conservation practices in Burundi (after Duchaufour and Bizimana, 1992).

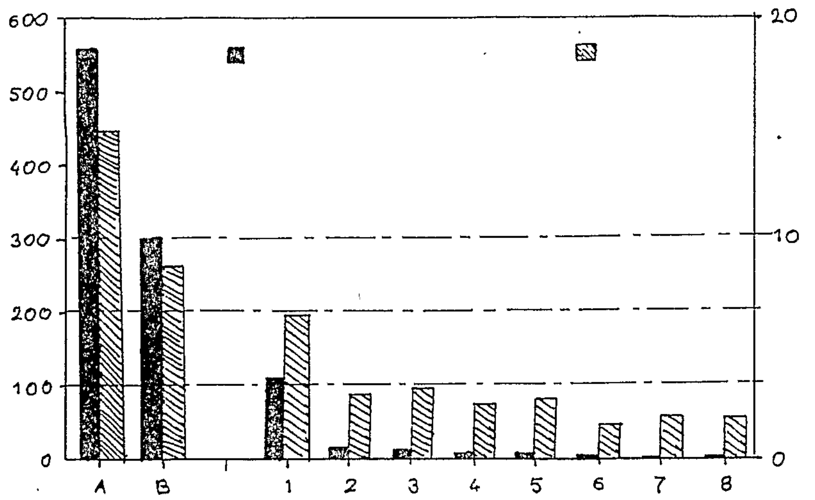

Fig. 2. Erosion (t/ha/year) and runoff (%) on runoff plots of Butare PASI project (Rwanda): average 1987–1990 König, 1992. (A) International reference: bare fallow cultivated. (B) Local reference: Cassava on mounds. (1) Grevillea 200 trees/ha. (2), (3), (4) and (7): Grevillea + calliandra hedge. (5) ad (8) Grevillea + leucaena hedge. (6) GR + setaria hedge.

(banana, pinus, grevillea, eucalyptus or other trees) with a management system of litter and weeds on the soil surface.

Bench terracing is also very efficient, but this traditional system requires 800 to 1200 labour days/ha and expensive soil fertility restoration (10 t/ha/2 year of manure, 3 t/ha/2 year of lime and 300 kg/ha/year of NPK 17:17:17) before the crop yield increases.

Infiltration ditches, graded channels and permeable stone bunds are less efficient and require 200 to 350 labour days/ha for their construction and 20 to 50 labour days for their maintenance. Permeable stone bunds, which are so useful on Western African glacis, do not seem to be efficient on steep slopes of Central Africa: the runoff flow seems to be concentrated below the permeable stone bunds and to create rills and gullies.

The most sustainable farming system is a combination of a small piece of ground cultivated on the contour between embankments protected by grasses and living hedges alternating with a broad ridge permanently covered. Living hedges, banana plantations and *Grevillea robusta* trees produce a lot of biomass available for breeding or mulching. This system is sustainable and profitable if associated with breeding of cattle in sheds producing manure to be composted with crop residues, ashes and family residues (up to 5 m^3 per family).

From these data it appears that integrating agroforestry in the farming system will be more efficient than antierosive mechanical structures in order to reduce erosion hazard.

Living hedges are still to be tested to determine their ability to produce the maximum of biomass, to return nutrients to the soil and, finally, to increase crop production significantly.

3. Situation and method

In 1989, Ndayizigiye built 9 standard runoff plots (5 × 20 m), on a 23% hillslope of the research station of the "Institut de Recherche en Sciences Agronomiques du Rwanda" (ISAR) of Rubona, 25 km northeast of Butare, southwest from Kigali, the Rwanda capital. One is the standard bare cultivated fallow of the USLE model (Wischmeier and Smith, 1960), two plots represented the regional farming system (beans and maize mixed during the first rainfall season and sorghum for the following season). Duplicated three runoff plots were cropped with the same farming system between living hedges of Leucaena, Calliandra or Calliandra plus 2 lines of Setaria.

Rainfall amount and intensity were measured with 0.1 mm accuracy with an automatic bucket raingauge for each storm. Runoff volume, fine and coarse sediment were measured daily, yield of crops seasonly. The cuttings were weighed and laid on the soil surface 3 times a year. Soil, eroded sediment, runoff water, grain and cuttings yield were analysed yearly.

4. Results and discussion

Variations between duplicate treatments are so little that we present here only the average value for each treatment.

Rainfall amount (Fig. 3). It varied from 1000 to 1250 mm/year on this hillside with a maximum erosion in 1992, the third year of the experiments: the effects of this maximum erosion seems clearly on runoff and erosion measured on the bare fallow.

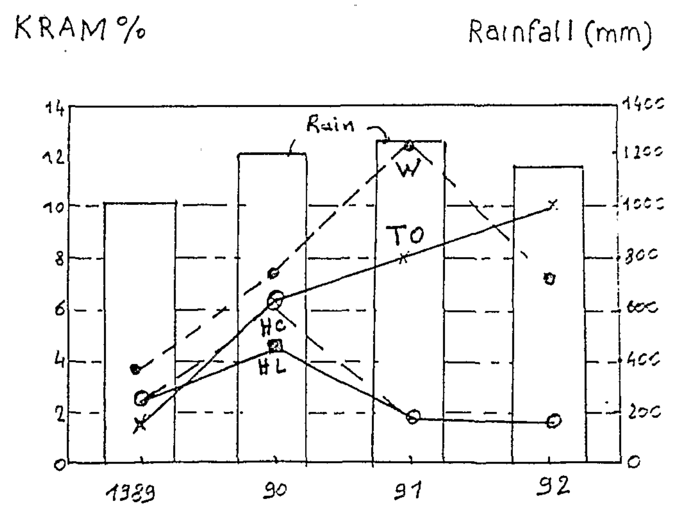

Fig. 3. Influence of living hedges of *Leucaena leucocephala* and *Calliandra calothyrsus* (spacing 7 m) on average annual runoff (K_{ram} %) at ISAR station of Rubona on a 23% slope of an acid ferrallitic soil (ultisol) Ndayizigiye, 1993.

Runoff (Fig. 3). Except during the first month after plantation, the soil surface was quite well covered with traditional crops and there were many cultivation practices (2 manual hoeings and 2 weedings for each season) improving the roughness and the infiltration capacity of the topsoil. Consequently, 2 years after plantation, the annual mean runoff (K_{ram}%) is relatively low: 12% for bare fallow, 8% for traditional cropping and less than 3% for the same cropping system but with living hedges every 7 m. Runoff appears mainly during the second rainy season when abundant rains fall on wet soils badly covered with sorghum. The maximum runoff rate (K_{rmax}) decreases from 68% under bare fallow to 35% on hedged cropped fields: the risks of gully on hillslopes and peak floods in the valleys are reduced by living hedges and by the mulch they have produced.

Erosion (Fig. 4). According to rainfall erosivity and soil degradation, sheet and rill erosion decreased from 450 to 250 t/ha/year on the bare fallow, 250 to 120 t/ha/year on the regional cropping system and from 27 to < 2 t/ha/year on the cropped and hedged plots 2 years after hedge plantation. It is important to remember that cropped plots received 10 t/ha of manure each year and even 20 t/ha before the third year: even this much manure was not efficient to reduce erosion under the tolerance level. Although runoff, erosion and soil degradation increased on bare fallow and cropped fields, it is encouraging to note that erosion risks decreased on hedged plots to an acceptable low level (less than 2 t/ha/year). This reduction in soil losses, however, is not sufficient to improve crop production.

Crop yields (Fig. 5). Experimental field production capacity has been homogenous because yields and erosion were not significantly different during the first year before hedges became efficient. The second year, in spite of 10 t/ha manure, yields decreased by 10 to 30% depending on erosion importance. The third year, with 20 t/ha f manure,

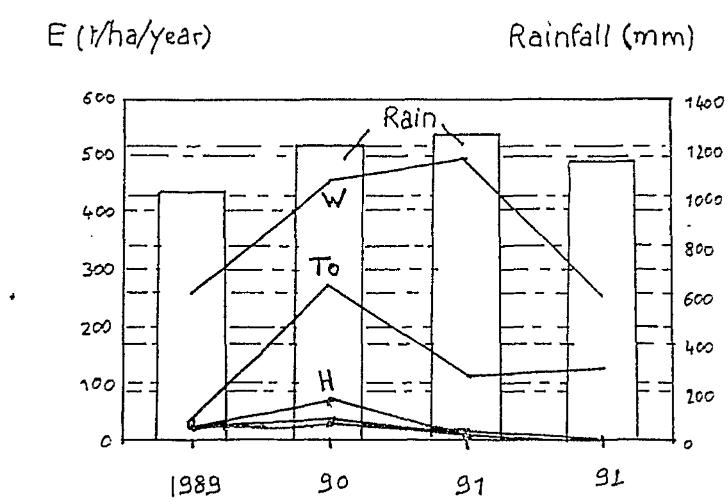

Fig. 4. Influence of living hedges of *Leucaena leucocephala* and *Calliandra calothyrsus* (spacing 7m) on soil erosion (E t ha^{-1} year^{-1}) at ISAR station of Rubona on a 23% slope of an acid ferrallitic soil (ultisol) Ndayizigiye, 1993.

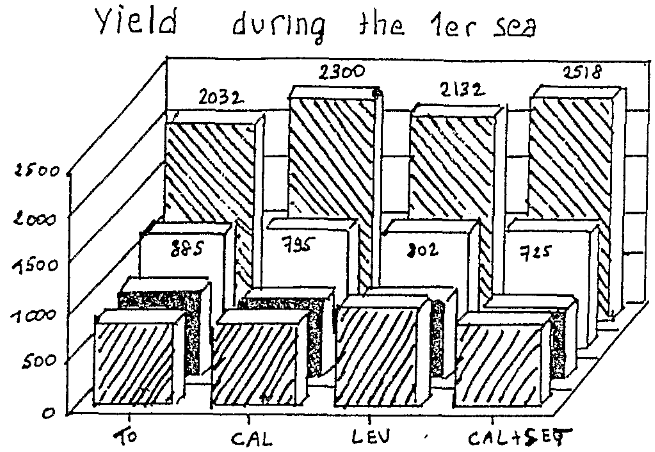

Fig. 5. Impact of living hedges on yields of maize during the first agricultural seasons. W = bare fallow standard of Wischmeier and Smith (1960). T_0 = cultivation standard. CAL = hedge of calliandra. LEU = hedge of leucaena. CAL + SET = hedges of calliandra + setaria.

yields increased from 32% on the local standard to 53–68% in hedged fields. In the 4th year, after 2.5 t/ha of lime, 10 t/ha of manure and N_{51} + P_{51} + K_{51}, yields increased up to 2032 kg/ha grains of maize and beans for the standard and 2318 kg/ha for hedged fields, in spite of the space occupied by the hedges (15%).

In each second season, (Fig. 6) yields of sorghum remained very low (640 to 420 kg/ha) except after pH correction and NPK fertilization, where it produced double on the standard and almost 3 × on the hedged plots. It seems that when erosion increased, yields decreased probably because organic and mineral fertilizers were taken off by the

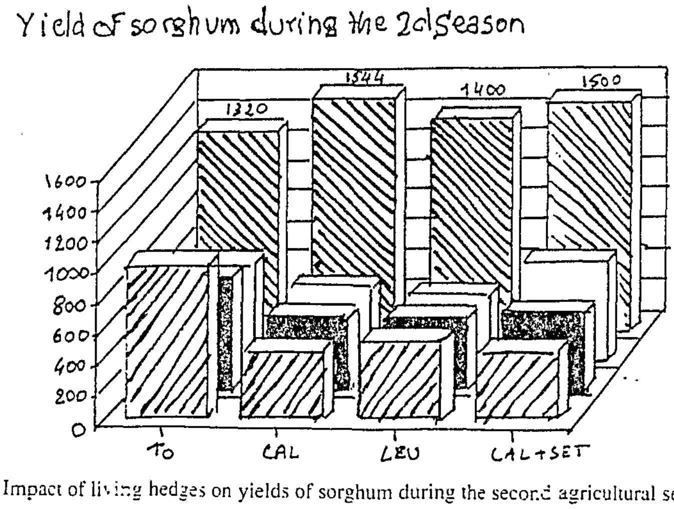

Fig. 6. Impact of living hedges on yields of sorghum during the second agricultural seasons.

erosion. Ten tons of manure and 6 tons of leguminous mulch have not increased the production of grains significantly and the yield effect of 20 t/ha of manure was no more significant on the second crop (sorghum). The effect of the manure is limited to one season.

On these acid and very poor ferrallitic soils (ultisols) it was not possible to increase soil productivity significantly in spite of the efficient water and soil conservation management and a dressing of ten tons/ha of cattle manure and 6 t/ha of leguminous mulch. Organic fertilization of that phosphorus, nitrogen and calcium deficient soil cannot be efficient because soils, plants, animals and manure are deficient in phosphorus. With complementary mineral fertilization the manure composition is slightly improved as well as the pH of the soil (up to pH = 5 to avoid aluminium toxicity) and the assimilable N and P content of the topsoil. Thus it was possible to multiply the crop yield by 2 to 3 and valorize the supplementary labour required to maintain the soil conservation structures (hedges and grassed embankments). It is important to note further that fertilization is better valorised on managed plots than on the local reference plots, probably because runoff and erosion are restricted: but soil and water management were not efficient to increase grain production. So far, farmers have been more interested in hedges as a source of forage during the dry season and as a field limit than as a soil conservation practice.

Biomass production (Fig. 7). In four years, living hedges gave 17.37 to 31.92 kg m^{-1} of green cuttings. *Calliandra calothirsus* produced twice as much biomass as *Leucaena leucocephala* (3 to 6 t/ha/year of dry organic matter if planted at 7 m spacing). Mixing Setaria (grass) with Calliandra (bush) is the best during the two first years, but Setaria disappears after 2 to 3 years on these poor soils. The production of

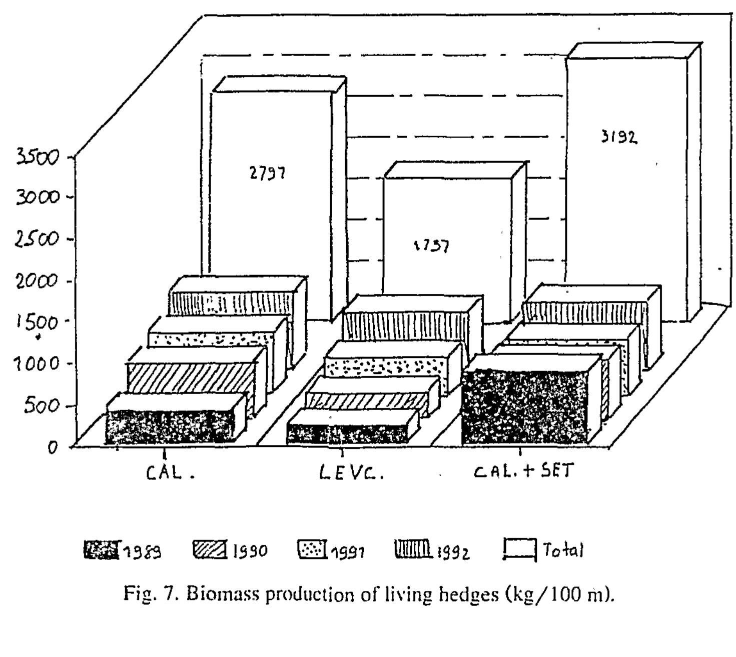

Fig. 7. Biomass production of living hedges (kg/100 m).

biomass, cut three times a year, increased each year and the lifetime of these living structures is not well known, depending on termite resistance and cutting technology. The cuttings were spread on the seedbed as a light mulch covering 80% of the soil surface for Calliandra plots and only 40% for Leucaena plots. Nevertheless, two weeks later, there were only twigs left: little leaves were blown by the wind or digested by the soil fauna and the impact of bush types was not significant on runoff and erosion. In others experiments in Rwanda, hedges of *Calliandra calothyrsus*, *Leucaena leucocephala* or *diversifolia*, or *Cassia spectabilis* produced 3 to 9 t/ha/year of leaves (excellent forage) and 2 to 7 t/ha/year of twigs for the fire if they are planted at 5 to 10 m apart (König, 1992; Balasubramanian and Sekayange, 1992; Duchaufour and Bizimana, 1992). Two hundred trees like *Grevillea robusta*, *Cedrella serrata*, *Poliscias fulva*, planted around or in the field can produce enough firewood for the family fuel needs and also 1 to 4 t/ha/year of leaves and twigs appreciated for mulching.

The nutrients return. Ndayizigiye (1993) got a litter production on the Rubona station of 4.8 to 6.4 t/ha/year of dry organic matter representing a dressing of 80 to 120 kg/ha/year of nitrogen, 2 to 3 kg of P., 30 to 60 kg of K and Ca and 10 to 20 kg of Mg. König (1992) on a very acid ferrallitic soil near Butare, showed that a well adapted Calliandra hedge has brought 105 kg/ha/year of N., 10.3 kg of P. and 21.8 kg of K for 9.7 t/ha/year of leaves (at 25% of H_2O). Balasubramanian and Sekayange (1992) have measured in semi-arid savannah of Rwanda a return of 3 to 4 t/ha/year of dry organic matter to the soil, 72 to 119 kg/ha of nitrogen, 1.4 to 3.2 kg of phosphorus, 30 to 60 kg of potassium, 47 to 94 kg of calcium and 8 to 18 kg/ha/year of magnesium after 4 years of plantation without decrease of biomass. This annual nutrients contribution is equivalent to the amount brought by 10 tons of local farm manure.

5. Conclusions

The living hedges, what ever their type, were able to restrict runoff and erosion risks efficiently on this 23% hillslope of a very acid ferrallitic soil (ultisol). It was not the cover, nor the stumps which have trapped runoff water and sediments, but a litter between the hedges stumps made by weeds, crops residues, stones found in the topsoil and leguminous plants sown in front of the hedges and creeping on the embankment. Earthworms are fond of this wet organic matter and dig galleries improving the infiltration capacity of the soil.

Living hedges produce 4 to 6 t/ha/year of valuable biomass, quite as much as a forest, returning to the topsoil about $N_{100} + P_4 + K_{40} + Ca_{40} + Mg_{20}$. Even with an additional 10 t/ha of manure these organic fertilizers were not sufficient to increase crop yields because of phosphorus deficiency and the strong acidity of the soil. The organic matter impact on crop yield was limited to the first season.

Once soil erosion was restricted and soil fertility was restored with organic matter, it remained to insure nutrition of the cultivated plants according to their needs (local setting in fractioned doses) in relation with the level of production (N 40 to 160 kg/ha + P 30 to 100 kg/ha and K 20 to 100 kg/ha, and micronutrients: Rutunga, 1992), and the risks of leaching. Rutunga (1992) observed on poor soils that liming (3 t/ha) must be renewed every 3 years and manure (10 t/ha) every 2 years. On moderately rich soils, liming is not effective and on rich volcanic soils even light mineral fertilization has not been proved to increase the yield significantly.

Soil conservation is not sufficient to increase soil productivity. For this it is necessary to develop a strategy where water, organic matter and nutrients are correctly managed as a whole.

Agroforestry can efficiently preserve the soil, but not increase the productivity significantly. It is essential to correct the soil acidity, the aluminium toxicity and the phosphorus deficiency. Then we can multiply the soil productivity by 2 or 3 and interest farmers in efforts for rural environment protection.

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