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THE SUDAN-SAHELIAN GROVE:
A multi-scale ecological alternative to climatic change.

Valet S.[1], M. Motélica-Heino[2], Ph. Le Coustumer [3] & P.S. Sarr[4]

[1]Consultant. PASSERELLES, 9, rue du Bât d'Argent, 69001, Lyon France ; valet.serge2@wanadoo.fr ; [2] Université de BordeauxI, av. France.; [3] Unité : UMR6113 Institut des Sciences de la Terre d'Orléans (ISTO), France ; mikael.motelica@univ-orleans.fr.; [4] ISRA (Institut Sénégalais de la Recherche Agronomique) BP199, Kaoloack, Sénégal ; papsar2000@yahoo.fr.

Abstract

The problems of the 21st century in the sudano-sahelian zone, besides the food self-sufficiency constantly postponed to the next decade, are ecological and greatly magnified by the climatic change. Because of the double failure of the struggle against the degradation of ecosystems and of the green revolution, promoted by agronomists, new modes of patrimonial management of the environment are required. Though several studies have shown the fundamental role on the agricultural zones on the hydrological balance (runoff, water reserves) and on the carbon stocks of the soil, cultivated area are poorly represented in global models. The "sustainability" of the interactions between the production and the environment assumes the integration of the variability of the specific productivity of media and of the spatial distribution of resources to adapt to environmental fluctuations. To reduce the dependence of traditional food crops on environmental constrains, the management of media must rely on a large scale of innovative and traditional biophysical techniques. These techniques are based on the runoff control and the runon agroforested management and valorization . The runon is a part of the runoff and is defined as "*a natural, complementary and simultaneous irrigation to the rainfall that has generated it in according to natural (topographical, morphological, permeability) anthropogenic (soil work) conditions*". Where the runon infiltrates, organic carbon and nutriments that enrich the soil deposit. Organic fertilisation practices will complete the fertilisation acquired by the soil, such as BRF, mulching, animal feces, and compost Recommended techniques have been used separately with some result but their joint and rational use has been poorly studied. These techniques such as quickhedges (trees and bushes), herbeous strips, "*zai*", half-moons, earth ridges perpendicular to the slope can be implemented along the slope in combination that will be function of the morphopedological conditions.

The results of these implementations on the conservation of the medium and on the soil productivity, at the field and the hillslope scale, could be used to complete and calibrate predictive models for crop yield (ORCHIDEE-SARRAH-BIPODE).

Key-words : Runon, runoff, AET, nutriment sequestration, traditional biophysical and innovative techniques.

LE « *BOCAGE SOUDANO SAHELIEN* » :
Une alternative écologique multi échelle au changement climatique.

Résumé

Les problèmes du XXIème siècle dans la zone tropicale, outre l'autosuffisance alimentaire, sont d'ordre écologique. La double faillite de la lutte contre la dégradation des écosystèmes et de la révolution verte, prônée par les agronomes est patente. Aussi, l'élaboration de nouveaux modes de gestion patrimoniale de l'environnement est devenue une des priorités majeures des politiques publiques. Elle doit s'appuyer sur un large éventail de technologies traditionnelles et innovantes. Le ruissellement, entraînant une accélération de la dégradation des sols, a été constaté à toutes les échelles de perception, du m² au bassin versant. Ce ruissellement peut être piégé naturellement ou anthropiquement. Cette part du ruissellement ou report hydrique se définit comme une «*irrigation naturelle, complémentaire et simultanée à la pluie qui l'a générée en fonction des états évolutifs de surface et profond avec transfert de fertilité* ». Là où s'infiltre le report hydrique se déposent du CO et des nutriments qui enrichissent le sol. Il est impératif pour assurer un développement durable de combiner l'implantation de techniques traditionnelles et innovantes biophysiques avec des pratiques de fertilisation organique. L'éco-développement raisonné proposé associera un aménagement bocager filtrant du milieu avec utilisation des BRF et le maintien ou le retour des cultures associées traditionnelles semi intensives.

Les résultats de ces techniques sur la conservation du sol et de la fertilité à différentes échelles pourraient être utilisés par des modèles prédictifs (ORCHIDEE-SARRAH-BIPODE).

Mots-clés :

Report hydrique, ruissellement, techniques traditionnelles et innovantes biophysiques, zone soudano sahélienne.

I. OBJECT

The problems of the 21^{th} century in the sahelian to tropical zone, besides food sovereignty, are ecological and socio-ecological. The food security in Africa is particularly dependant on the conservation state of ecosystems and environmental processes that control them. Climatic change that worsens the bio-physical impacts on the ecological systems affects the economical values of potential or used resources. The fall of the hydrological offer by the diminution of rain and by the increase of runoff is dramatic. Consequently the choice of practices well adapted and decisions for an optimal use of hydrological resources and minimisation of drought risks are crucial for the summer monsoon agriculture (Sivakumar and al., 2000). This requires a good knowledge of agro-systems and the variability of hydro-bio-physical processes. The degradation of the environment generates a continuous adaptation of practices by the actors and uses of the environment. The elaboration of new modes of sahelian to tropical environmental management has become a major priority of public policies. They must rely on a large scale of traditional and innovative technologies that will be applied for a good management. It is important to prepare right from now the after-petroleum. However the relations of societies to their environment do not obey to command, thus the different landscapes that result at a given moment from the interaction of bio-geophysical conditions and exploitation systems of resources by mankind must be taken into account. The Kyoto protocol recommends the promotion of sustainable conditions for agriculture to face climatic change. It has been shown that mineral fertilisation is not sustainable without organic amendment which leads to the re-evaluation of its role in vegetal production (Woomer and al., 1994). Thus those who rely on the use of organic matter of little cost and on agroforestry must be seek among ecological anti-erosive traditional techniques in order to counterbalance the soil organic carbon loss. (Roose et de Noni, 2004 ; Valet et al., 2007).

These ecological bio techniques that have been largely used by peasants of all continents, Africa, the Mediterranean basin, South America and Asia could be reinforced by innovative techniques to face the major transformations related to climatic change, demographic pressure and economical conditions imposed by globalisation (Roose and al., 2000; Valet, 2000).

The runoff involved in the erosion, with the loss in water, N, organic carbon and nutrients, is an important component of the hydrological and biochemical balance (Koro and al., 1995; Valet and al., 2002). But it is not the only one and the hydrological report appears as the discriminating criteria of hydrological stocks and hydrological, organic and mineral balance of food crops. This runon is defined as « *a natural irrigation, complementary and simultaneous to the rain that as generated it as a function of the evolutive states of surface and depth , with a transfer and sequestration of nutrients*” (Valet, 1985 ; Valet and al., 2002).

Thus a multi-scale strategy of runoff control and management and valorisation of the runon must be developed.

The goal of this study is to investigate the traditional and innovative biophysical techniques that are adequate to the problems of the Sudan-Sahelian zone:

1) techniques of total or partial control of the runoff (Ridges, mulch, RCW);

2) techniques of sustain of a controlled non-erosive runoff (Quickhedge, Strings of filtrating stones;

3) techniques of a total trapping of the runoff (1/2 moon, *Zaï*).

2. LOCALISATION

This study is made of results realised in the south of the Sahara in the Sahelian to tropical zones.

3. RESULTS AND DISCUSSION

3.1. Techniques of partial or total control of the formation of runoff

3.1.1. Earth ridges and runon

In Mali (at Kassela), at the top of the hillslope with a slope of 5%, for a same size of earth ridges measured during harvest, the millet yield is negatively correlated to the size of earth ridges parallel to the slope and positively correlated to those perpendiculars (Fig. 1).

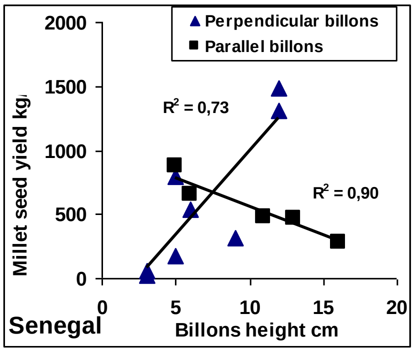


Figure 1– Residual height of perpendicular and parallel billons vs millet yield at Kassela-Mali.

(Relation entre le rendement du mil et les billons parallèles et perpendiculaires à la pente à la récolte à Kassela (Mali).

These results in a deepening of the parallel earth ridges by the runoff and in the trapping of a fraction of the runoff by the perpendicular ones. The most abraded earth ridges located at the top of the slope where less thicker stock less water and generate a strong hydrological report downwards.

In Senegal (at Thyssé), at the bottom of the slope with slope between 0,45 and 1,2%, a study has demonstrated that in the parcels with earth ridges perpendicular to the slope after ploughing and chiselling the yield of mil is negatively correlated with the residual height of earth ridges.

Runon of one splot by strip.			
D- 0mm	A- 126mm	C- 0mm	B_{R1}- 126mm
			
ox chiselling		*ox ploughing*	
Stock cumulé:137mm	300	143	343
Stock final: 17mm	67	18	56
Drainage: 0mm	36	0	80
Runoff: 44mm	38	18	0
AET **188**mm	**226**	**197**	**289**
Yield : 140 kgha^{-1}	**1100**	**170**	**1300**

Pictures 1- Billon erosion in chiselled (A) and ploughed (B-R1) stripes with the best millet yield due to runon at Thyssé- Note the leaves and twigs in A and Br1 stripes with runon and different millet water budget and yield. *(Aspect des billons dans les parcelles sans et avec report hydrique et les ETR et le rendement du mil).*

The earth ridges of parcels protected from the runoff (Pictures 2D and 2C) are better conserved than those not protected (Pictures 2A and 2B). This results in the abrasive effect of the runoff which a fraction, 126mm, constitutes a hydrological report that infiltrates during the mil cycle (Valet and Sarr, 1999).

It is not the dominant *splash* effect, a hypothesis developed by Planchon and al. (1999), that explains this erosion but the runon and the runoff.

Boukong (2000), in Cameroun on Oxisol of the western high plateau, from 1991 to 1994, has demonstrated the effect of earth ridges perpendicular to the slope on the runoff (3.6% against 6 8% for a slope of 9 % and 5 to 10 1% a slope of 20 %), the loss in earth (12 against 235 Tha^{-1} and 15 against 471% respectively for a slope and 9 and 20%) and the increase of yields. Kalifa and al. (2005) in Mali, and Rockström and Valentin (1997), in Niger, have demonstrated that on the slope the runoff decreased strongly from the top to the bottom of the slope; this runoff could be significatively reduced by the implementation of earth ridges perpendicular to the slope (Fig. 2). However the increase of sorghum yield over four years varied from 1.7 (23kgha^{-1}) to 57% (305kgha^{-1}) for the millet and from 33 (404kgha^{-1}) to 37% (500kgha^{-1}) only for the sorghum.

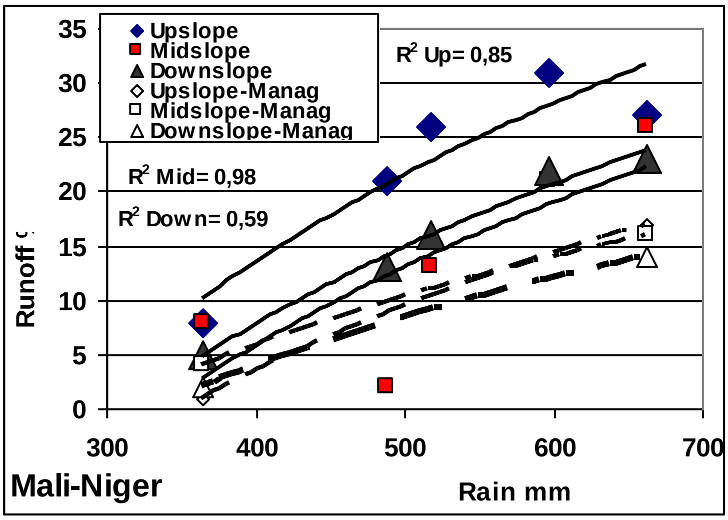


Figure 2- Runoff vs rain (mm) on different position on hillslope with or without billon management. *(Effet de la pluie sur le ruissellement en parcelles aménagées ou non le long d'un versant).*

These results show that large earth ridges reduce dramatically the runoff but not totally. The effect on the yield is not proportional to the good management of the runoff. However if the earth ridges are smaller they are submitted to a runoff that transforms itself into a runon then the augmentation of yields is more elevated and globally superior.

3.1.2. Mulching

Physical and biological mulch is recognised for its amelioration and its multiple ecological effects.

It action operates on :

- the nutrient «*turnover*»
- the decrease of the risk of erosion ;
- the limitation of the soil evaporation in dry season compared to a soil with a crust of 120cm deep in Senegal (Thyssé), during the dry season 1984, after an annual rain of 400mm, with a mulch of millet, of about 2.2t ha^{-1} (Fig. 3).

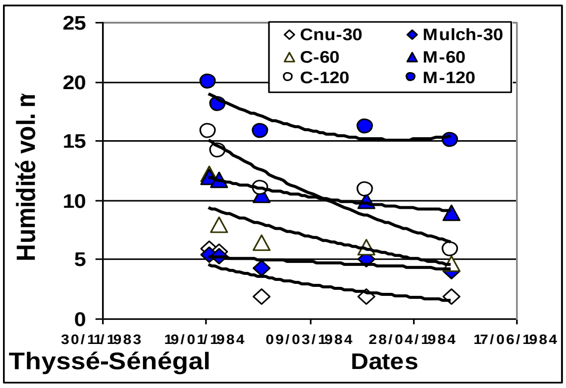


Figure 3- Soil water content mulched parcel (M) vs crusted bared parcel (C) at three depths (-30, -60 and -120cm) during dry season in Sudano-Sahelian region (Senegal).

(Effet des pailles de mil sur la variation de l'humidité du sol à 3 profondeurs pendant la saison sèche).

On a depth of -120cm the soil with a crust looses very rapidly 60% of its water reserve than it decreases again with depth. On the contrary with mulch the loss is only 15% and then diminishes very slowly with depth under -70cm. The mulch realises an economy of water of 56mm on the 16th of May on a depth of 130cm.

- the decrease of the soil temperature ;
- the reinforcement of the structural resistance of the soil aggregates whatever its nature, graminaceous, bushy and growing leguminous, banana leaves (Leonard and Rajot, 1998) ;
- the development of a roughness that diminishes the runoff by 50% on a strong slope (>9.5%) and the channelling only on a low slope (<3.5%) in Nevada (Sidle and al., 1993);
- the yield however in the West-Cameroon, in the tropical zone, the mulch is positive only in the dry season with grains of 150 % for soybean, 172% for beans and 44% for green beans (Valet, 1999);
- a loss of yield of 19 % and 7 % respectively with and without mineral amendment in the rain season;
- the limitation of earth loss and losses in N and organic carbon, in Ghana and Burundi (Quansah and al., 1999) ;
- the augmentation of infiltration in Niger, from 12 to 52 % under mulch and from 11 to 21% under the erosion crust (Leonard and Rajot, 1998) (Fig.4) ;

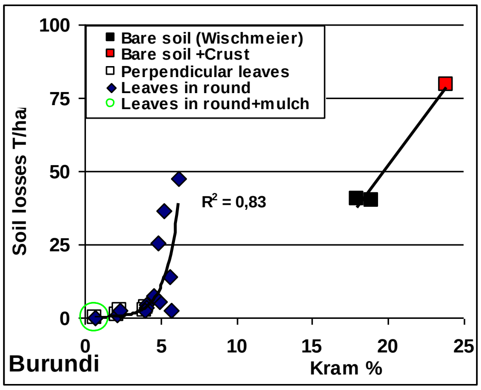


Figure 4– Runoff ratio vs soil losses with banana mulch around and perpendicular to slope from 2 to 5m spacing

(Relation entre le taux de ruissellement maximum et la perte en terre en sol nu, parcelle de Wischmeier et sous un mulch disposé différemment).

3.1.3. Ramial Chipped Wood (RCW)

It is an original technique developed by Canadian forestry based on the use of chipped branches of a diameter lower than 7cm considered as wastes and usually not exploited (Dodelin, 2007). They represent a source of energy with a slow degradation of the lignin (Stevanovic and al., 2007). They are rich in nutrients, sugars, proteins, cellulose and lignin that play a specific role in the soils aggradation after biotransformation and not decomposition (Lemieux, 2007). This process generates an accumulation in the soil of organic matter and humus more durable than the input of manure, compost, green manures that are immediately

destroyed by plants. This aggradation generates a structural and biological reorganisation of the soil. This technique favours a better use of soil water (Godron, 2007). This phenomena is observed under extreme pedoclimatic conditions (Soumaré and al., 2006 ; Gomez, 2003).
The effects of RCW play on:

- the yield :

The augmentation is of 400% for sweet tomato, 300% for bitter tomato (*Solanum aethiopicum),* 400% for aubergine with a diminution of the attacks by nematodes and control of sclérotes, from 40 to 50% for maize and 38% to 43% for potato, rye, oat and strawberries (Furlan and Lemieux, 1996 ; Chervonyl, 1999 ; Gomez, 2003 ; Lemieux, 1994 ; Seck and Lö, 2007). The effects last 3 to 5 years (Table 1).

Table 1– Ramial Chipped Wood effect on rye *(Secale cereale)* fongus, yield, and humus, nutriments soil at Kiev (Chervonyl, 1999).

Species of RCW	% d'attaque de *fongus* *	Grain	Straw	Roots	Soil			
		Yield qx ha^{-1}		Ms %	Humus %	N Mg/kg	P Mg/kg	K Mg/kg
Test	78	12	27,8	91,4	1,91	72	102	80
Quercus r.	75	17,2	80,8	93,4	2,25	64	116	108
Betula v.	63	14,9	30,4	92,6	2,75	73	106	85
Populus t.	63	15,8	31	91,8	2,76	63	104	89
Salix a.	88	14,5	30,6	92,2	2,92	73	104	74

** Varieties : Fusarium sp., a. et g.; Altermana a. ; Mycelia st. ; Nigrospora o. ; Macor h. et Acromoniella a.*

- adventices :

Decrease the loss of the adventices of the Alfalfa with an increased yield of 72% in the year that follows the application of RCW in Begium (Noël, 2006).

- biological activity :

600m3/ha de RCW stimules biological activity and soil aggradation (Lalande and *al.,* 1998);

- Different attacks :

Decrease the strockes of sclérotes, nématodes, fongus et plant-louse (Chervonyl, 1999; Gomez, 2003) (Table 1).

This important augmentation of the organic matter content limits the washing of nutrients and biocides limiting the pollution of groundwaters (Noël, 2007). This technique that implies forestry and agriculture relies on agroforetsry that can generate a stable carbon (Lemieux and al., 1999). A great amount of organic carbon is subtracted from the atmosphere, thus limiting the greenhouse effect.

3.2. Techniques of management of a non-erosive runoff;

3.2.1. Traditional filtrating grove : hedges

Complex traditional hedges such as the ones of Western Cameroon (Pictures 2A & 2B) or modern ones (König, 1992 ; Ndayzigiye, 1993 ; Valet, 1999 ; Köning, 2004) constitute a real grove structurating the agricultural space. They are implemented on slopes cultivated from 12 to 40%. They provide many biophysical advantages.

Photos 2- A) Quickset hedge at Bafu and B) traditional fence at Dschang with mixed-crops during dry season- West-Cameroon (1/01/2000).

A: (Haie à Bafou et B:Cloture à Dschang avec des associations culturales traditionnelles –Janvier 2000).

The results show that :
- the sole plantation of forest is not sufficient to limit the erosion though a net diminution is seen;
- the implementation of hedges of *Leucaena*, *Calliandra* and *Setaria* reduce considerably the erosion and this from the second year;
- the choice of species is important : *Leucaena* has a effect inferior to the one of *Calliandra* and *Setaria*;
- the confirmation that the associated cultures reduce the erosion significantly the erosion compared to monoculture;
- direct sowing ameliorates the effects of the hedges;
- alley cropping reduce considerably the erosion under associated cultures more significantly than earth ridges;
- sustain of a non-erosive runoff that maintains a runon about 3% on a watershed of 1,5ha (Valet and Sarr, 1999c) (Table 2);

Tableau 2- Quickset hedges effect on erosion and runoff at field scale (2.5ha). *(Effet d'une haie sur le ruissellement et l'érosion (basin versant de 2,5ha)*

Years	**1984**	**1985**	**1986**	**1987**	**1988**	**Mean**	**1989**	**1990**	**1991**	**1992**	**Mean**
Management date					------	**before**					**after**
Runoff Kr%	2,8	5,3	5	2,4	4	***3,9***	0,5	5,2	5	1	***2,9***
Soil losses $tha^{-1}an^{-1}$	1	-	1,8	11,5	1	***3,8***	0,4	0,1	0,10	0,10	***0,4***

- stop the transfer of eroded sediments up to 95% of the solid load that deposit upwards the hedges modifying the long term declivity (uneven of 1m) (Table 2);
- amelioration of fertility and yield by uptake of nutrients and produced biomass, 124kg ha^{-1} $year^{-1}$ of N, 6 to 9kgha^{-1} $year^{-1}$ of P_2O_5 and 18kgha^{-1} $year^{-1}$ of K ; preservation of organic matter and nutrients compared to the test experiment with cassava monoculture (Köning, 2004) (Table 3);

Tableau 3- OM and nutrients losses (kg$ha^{-1}year^{-1}$) according to treatments (13 seasons mean). (Köning, 2004). *(Pertes en matière organique et en éléments nutritifs (kg$ha^{-1}an^{-1}$) en fonction des traitements (moyenne de 13 saisons de cultures).*

Treatements . kg $ha^{-1}an^{-1}$	**Barred fallow**	**Monoculture Cassava**	**Ecologic agriculture**	**Relatif préservation %**
Organic matter	8700	6400	50-200	+12700-+3100
N	247	176	2-6	+8700-+2800
P	4	4	0,1-0,2	+3900-+1900
K	10	8	0,2-0,6	+3900-+1233

- ameliorate the hydrological satisfaction by the runon and increases its yield as a function of the rain (Valet and Sarr**,** 1999c) (Table 4).

Tableau 4- Runon effect on the millet median grain yield in managed or not fields (Senegal).
(Effet du report hydrique naturel ou aménagé sur le rendement médian du mil pour des pluies extrêmes).

Rainfall	**Exces**	**Mean**		**Deficit**	
Quick hedge effect				Chiselling Below Site	Ploughing Below Site
chiselling before site	800	**1150**	900		
below site	**1120**	850	600		
Natural effect with runoff				300	-
of runon: without runoff				750	**1150**
Test				***145***	***155***

The combined use of mulch and double mixte hedge reduces the runoff from 25 to 90% and a soil loss of 45 to 97%. This loss decrease assumes a yield significantly superior. This attenuates from 30% the slope initially of 28% (Duchaufour and al., 1996) (Fig. 5). Moreover it brings wood for heating and fodder.

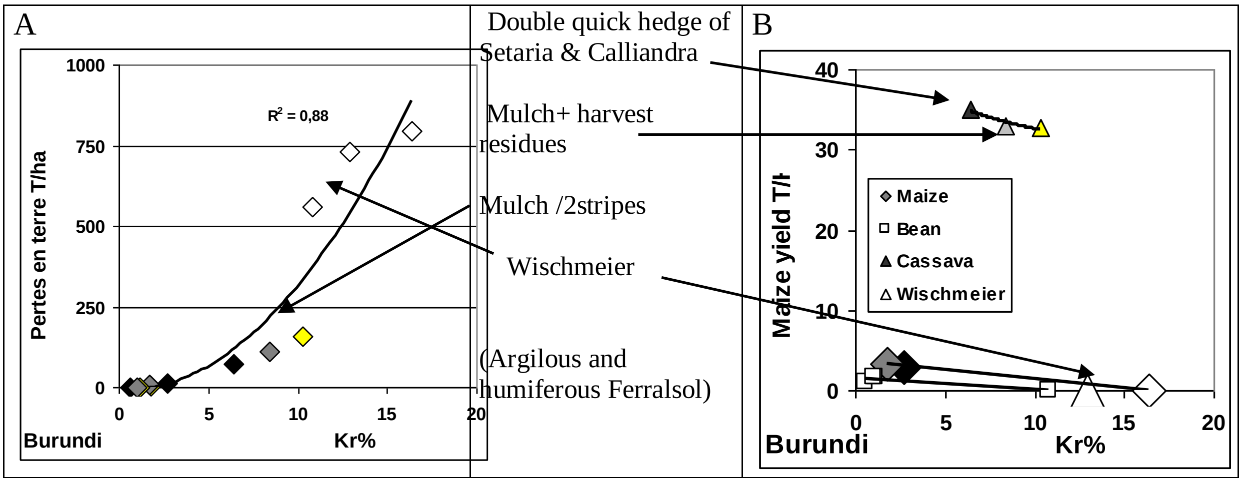


Figure 5- Soil losses vs runoff per cent and crop yield vs runoff per cent of different treatments in Burundi. (Duchaufour and al., 1996).
(Relation a) entre le coefficient de ruissellement et la perte en terre et b) entre le rendement pour différents traitements sur butte (cassava) par rapport à la parcelle Wischmeier au Burundi.

The ecological agroforestry represents an efficient strategy for the soil conservation.

However, they can be competitive for water and light (Bizimana and Duchaufour, 1995; Duchaufour and al., 1996).

3.2.2. Strings of filtrating stones

In Burkina Faso, strings of filtrating stones increase the yields from 48 to 1000% depending of the rain in periods of pluviometric stress (Wright and Bonkoungou, 1986). These results corroborate that the ecological techniques which increase the OC sequestration with improving soil aggradation struggle efficacy against erosion (Barthès et Roose, 2002 ; Roose, 2004). The runoff balance on silted soil fallow is again dangerous; Then, on argilous soil, it reduce the risk of soil flooding and soil slide. So, it should research an adequate technique which strengthen the efficacy of fallow and zero or minimum tillage.

3.3. Techniques of total trapping of the runoff

3.3.1. « *zaï* » (Burkina), « *tassa* » (Mali) or « *towalen* » (Niger)

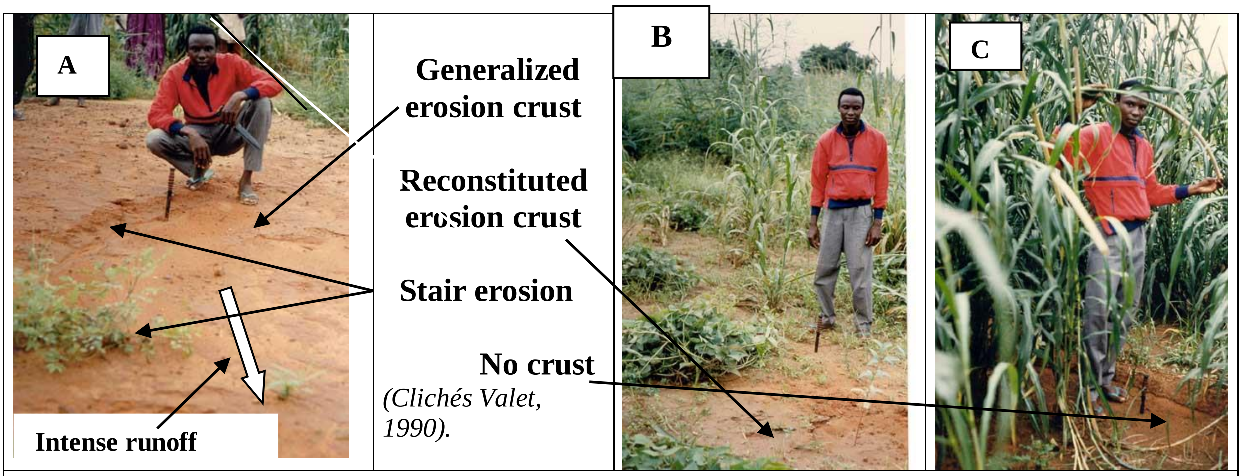
In Burkina *zaï* is a traditional technique of water collection and conservation used to remediate the « *zipele »e* (Bare, compact, and infertile soils). The *zaï* is made of circular or square holes displayed in quinconce, of 0.3m diameter, every 0.7 to 1.2m and 0.08 to 0.20m deep. The excavated earth is displaced downwards to block the runoff. Twigs and straw is placed in each hole to attract termites that generate a soil porosity that favours the infiltration of rains and runoff (Somé and al., 2000).

This technique can generate

- a signicative and stable production of sorghum (IRAT 204 of 90 days) from 0 to 2.8, 3.7qx ha^{-1} respectively for the test, on the *zaï* alone (*9.5 Tha^{-1} of ox manure)*, with twigs and straws and with BP (*natural phosphate of Burkina)* (Zougmoré and al., 1999).
- a significative increase of Ca^{++}, of P_2O_5, and organic carbon explains the involving significantly more elevated of the sorghum yield with a compost amendment of $10Tha^{-1}$ or $5Tha^{-1}$ with mineral amendment, 1070 $kgha^{-1}$ against 206 without compost (Zougmoré and al., 1999 ; Sawadogo and al., 2007) ;
- involving of the infiltration thanks to the effect of termites in Niger according to Léonard and Rajot (1998).

3.3.2. Half-moon

In Niger, at Kouré on sandy soils with a weak slope, the half-moon traps fully the runon (Pictures 3A, B & C). The initial state with strong crusts (Picture 3A) reconstitutes rapidly with traditional chiselling submitted to runoff (Picture 3B). But the half-moon infiltrates totally the runon and assumes a better hydrological satisfaction and limits the development of crusts (Picture 3C).



Pictures 3- Half-moon effect on whole transfer of water and nutrients sequestration with crusting limitation and biomass increasing. (Kouré, Niger) *(Clichés S. Valet-1999). (Effet de demi lune sur le développement du mil grâce au piégeage du report hydrique et des nutriments avec destruction des croûtes).*

- high increase of the biomass plus addition of eolian deposits trapped by the half-moon (Ramsperger and al., 1998). On the same soil of Burkina yields of half moon overtake those of « *zaï* » only with significative amendment of organic matter, compost and especially manure (Zougmoré and al., 1999).

4) CONCLUSION

The results of this study show that traditional and innovative biophysical anti-erosive techniques of total or partial control of the runoff and management and agroforestry valorization of runon play a key-role in the sequestration of carbon and nutrients. The reduction of erosion, the increase of the water offer and the amelioration of biomass production under varied pedoclimatic conditions could be a major strategy against the climatic change. Their rational use could reverse the continuous decline in organic matter content and the soil fertility due to their erosion and exhaustion. This sequestration of organic carbon, of short duration, must be associated to agroforestry and breeding for certain durability. Even outside tropical zones, large spaces can compensate the weakness of soil and plants storage capacity.

On the hillslope and on the field, the joint use of different biophysical techniques combined to varied organic matter amendments would increase their efficiency (Valet et al., 2007). They are ecologically reliable, economically viable, agriculturally reasonable and technically reproducible. The results of these techniques on the conservation and rehabilitation of soil and fertility at different scales could be used by predictive models (ORCHIDEE-SARRAH-BIPODE).

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