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STRATEGY OF MORPHOPEDOLOGIC UNITIES INNOVANT USE FACE TO CLIMATIC CHANGE IN SUDAN SAHELIAN ZONE.

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Abstract

In Sudan Sahelian zone, the yield and quality of cultures are essential to the human well-being and the stability of societies. Climatic change, rain losses and the accentuation of its spatio-temporal variability generate an increase of the hydrological stress on traditional food crops. At the hillslope and the field scale, the accumulation of water by the crops is modified by the Runoff. A part of this runoff, even during a year of high hydrological deficit, forms the runon of the same importance on the field than on the hillslope. This runon is defined as *"a natural, complementary and simultaneous irrigation to the rainfall that has generated it according to natural (topographical, morphological, permeability) anthropogenic (soil tillage) conditions*". It can explain the yield variability that does not correspond to the potential fertility of the different morphopedological units.

Cultivated areas are only partially represented in global models. Now the elaboration of new patrimonial management modes of the Sudano-Sahelian zone must rely on the analysis of the spatio-temporal dimension of the climatic factors. They regulate the land and environmental dynamics and this suggest that their co-evolution must be integrated in an evolutionary and flexible scheme of such as the cultivators use empirically.

The study investigated the hydrological balance of the mil for 90 days duration, cultivated traditionally, including the impact of climatic change (three contrasted rain years, one normal, one year showing a deficit and one very rainy) and the variability of the morphopedological units on the slope. The Runon was taken as a complementary irrigation. On the slope, the actual evapo-transpiration (AET) expected varies from 125 to 245mm during a year showing a rain deficit, from 296 to 361mm during a normal year and too during a very rainy year. To these commotions in real water simulated correspond to extreme yields of 0 to 1273kg.ha^{-1}, of 911 to 1886kg.ha^{-1} and from 1071 to 1957kg.ha^{-1} for the three years respectively.

Results demonstrate that face to the climatic change, the integration of the multi-scale variability of the productivity of the media and of the spatial distribution of hydrological resources to adapt to environmental fluctuations allows to foreseen this change and attenuate its violence. The mastery and control of the hydrological fluxes on the slope and on the field to eradicate the erosion could be realised through grove planning.

Key-words

Runon, simulated hydrological budget, millet simulated yield, morphopedologic unities management, Sudan-Sahelian zone.

STRATEGIE D'UTILISATION INNOVANTE DES UNITES MORPHOPEDOLOGIQUES FACE AU CHANGEMENT CLIMATIQUE EN ZONE SOUDANO SAHELIENNE.

Résumé

En zone soudano sahélienne, le rendement et la qualité des cultures constituent le point capital du bien être et de la stabilité des sociétés. Le changement climatique, baisse de la pluviosité et accentuation de sa variabilité spatio temporelle, provoque une augmentation du stress hydrique des cultures vivrières. Aux échelles du versant et du champ, l'alimentation en eau des cultures est encore modifiée par le ruissellement. Une partie de ce ruissellement, même en année à très fort déficit hydrique, constitue le report hydrique de même importance sur le champ que sur le versant. Ce report hydrique se définit comme «*une irrigation naturelle, complémentaire et simultanée à la pluie qui l'a générée en fonction des conditions naturelles (topographiques, morphologiques, perméabilité et d'un horizon profond durci) et anthropiques (travail du sol)***»**. Il explique la variabilité des rendements qui ne correspondent pas à la fertilité potentielle des différentes unités morphopédologiques.

Les zones cultivées sont représentées à l'heure actuelle de manière incomplète dans les modèles globaux. Or l'élaboration de nouveaux modes de gestion patrimoniale de l'environnement soudano sahélien doit s'appuyer sur l'analyse de cette dimension spatio-temporelle des facteurs édapho-climatiques. Ils régulent les dynamiques foncières et environnementales et ceci suggère d'en intégrer la co-évolution dans un schéma « évolutif et souple » de gouvernance tel que les agriculteurs le font de façon empirique.

L'étude a porté sur l'analyse du bilan hydrique du mil de 90 jours, cultivé traditionnellement, en incluant l'impact du changement climatique (trois années pluviométriques contrastées, année normale, très déficitaire et très pluvieuse) et la variabilité des unités morphopédologiques sur le versant. Le report hydrique a été pris comme une irrigation complémentaire. Sur le versant, l'ETR espérée varie de 125 à 245mm en année à fort déficit pluviométrique de 296 à 361mm, en année normale comme en en année à pluviométrie excédentaire. A ces consommations en eau réelle simulées correspondent des rendements extrêmes de 0 à 1273$kg.ha^{-1}$, de 911 à 1886$kg.ha^{-1}$ de 1071 à 1957$kg.ha^{-1}$respectivement pour les trois pluviométries retenues.

Les résultats de cette étude démontrent que face au changement climatique, l'intégration de la variabilité multi échelle de la productivité des milieux et de celle des distributions spatiales des ressources hydriques dans une adaptabilité aux fluctuations environnementales, permettrait d'en prévoir et d'en atténuer sa violence. La maîtrise et le contrôle des flux hydriques sur le versant et à la parcelle pour éradiquer l'érosion pourraient être réalisés par des aménagements de type bocage.
Mots Clés

Report hydrique, bilan hydrique simulé, rendement simulé, mil, unités morphopédologiques aménagées, zone soudano sahélienne.

1. OBJECTIF

In the sudan-sahelian zone, the yield and quality of cultures are the capital pointg of well being and stability of societies. Food systems result from dynamic interactions between and within biogeophysical and human factors, and encompass food availability. Climatic change, the loss of rain and the accentuation of its spatio-temporal variability affect all ecosystems in the sudano-sahelian zone. It generates an increase of hydrological stress of crops. However the variability of yields at the scale of the slope and of the field, suggest that crops can respond non-linearly to changes in their growing conditions, exhibiting threshold responses and they are subject to combinations of stress factors that affect their growth, development and yield. The climate change is among the most frequently cited drivers of food insecurity. For the sustainability of an agricultural production facing impacts on ecosystems (bio-physical), affecting the economical values of resources (used or potential) and the environment itself due to this change, new management modes of the sudan-sahelian management must be elaborated. From a conceptual point of view, the spatio-temporal dimension of the productivity dynamics must be analysed.

At the scale of the slope and of the field, the alimentation in water of cultures is still modified by the runoff for slopes higher than 0.45% depending of the type of soils (Valet, 1992). A fraction of this Runoff, even during a year with a severe hydrological loss, is the hydrological report of the same importance on the slope than on the fields, also called "*runon*" (Kachanoski et al., 1985; Valet 1985a & c). This runon is defined as "*a natural, complementary and simultaneous irrigation to the rainfall that has generated it according to natural (topographical, morphological, permeability) anthropogenic (soil work) conditions*". (Valet, 1992). It explains the variability of yields that do not correspond to the potential fertility of the different morpho-pedological unities.

Cultivated areas are incompletely represented in global models. However the elaboration of new modes of management of the sudan-sahelian environement must rely on the analysis of the spatio-temporal dimension of edapho-climatic factors. They regulate the land and environmental dynamics and this suggest that the co-evolution must be integrated in an evolutive governance scheme such as peasants empirically practice.

The analysis of landscapes allows the evaluation of their degradation and to propose biophysical techniques adequate to cancel or reduce significatively their erosion. Those who have been selected in this study allow a total and limited control that will be taken into account in the calculations of the hydrological satisfaction and the yield of mil corresponding expected in peasant conditions.

The goal of this study is to:

1) simulate the millet evapotranspiration under different *scenarii* at different scales;

2) calculate the expected millet yields as a function of simulated hydrological consumptions;
3) propose a strategy of eco(agro)systems use taking into account the climatic change.

2. MATERIAL AND METHODS

2.1 Localisation

The study was carried out on the Sine Saloum at Thyssé-Kaymor located at 70km south-east of Nioro du Rip (Fig 1). Selected parcels are located on a transect located on a slope including the watershed S2 de 59ha and inside two fields (Terrace and footslope) of 1.35 and 1.5ha (Fig. 2 and 3A& 3B).

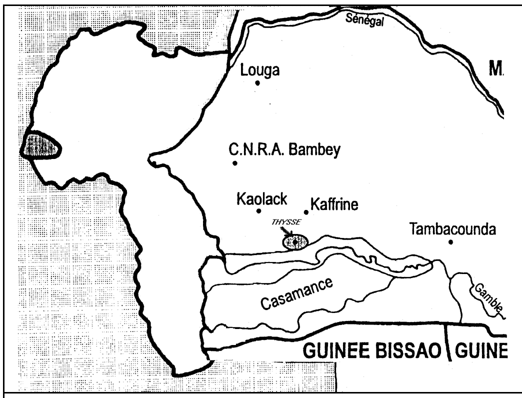


Figure 1- Trial location in Senegal

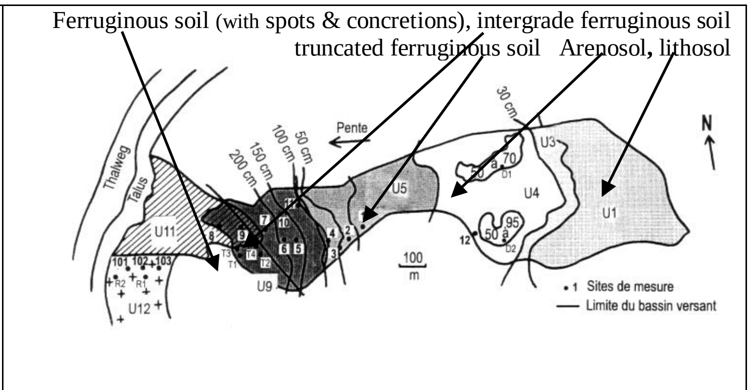
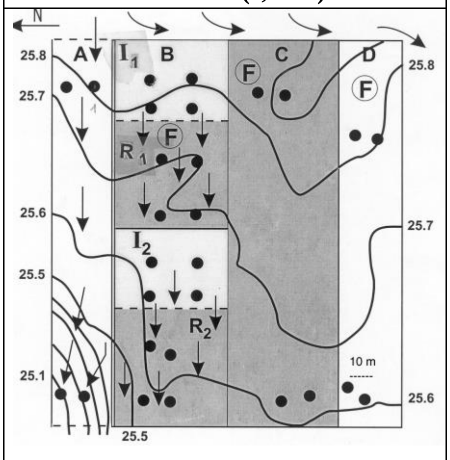


Figure 2– Geomorphologic unities and soils in S2 watershed (59ha).

In the two fields the treatments include four bands of 120m long dispatched in the direction of the slope and of 25 to 35m large (Fig. 3A & B). On the scale of statistical analyses the measurements of the 16 to 24 plots inside the field and of the 14 plots of the slopes can be considered as reproducible.

Terrace
Terrasse **(1,35ha)**



Nord ----- Sud

(Jachère) **Fallow**

(Grattage) **Chiselling**

(Labour) **Ploughing**

I 1-2 : impluvium
R 1-2: réceptacle (compluvium)
F : fertilisation
Runoff
36 (Placettes) **Plots**
25.8= altitude in meter.

Footslope
Glacis **(1,50ha)**

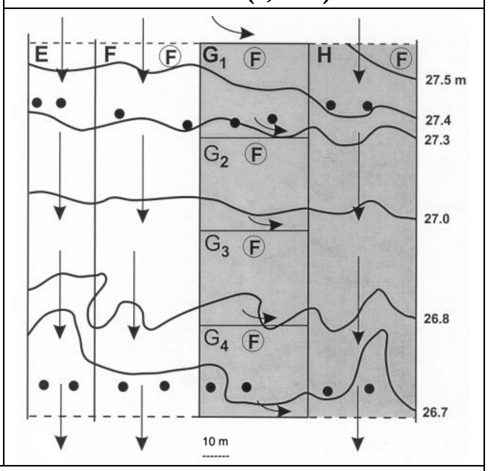


Figure 3- Trial location in A terrace and B footslope with treatment stripes and plots. *(Schéma des essais à Thyssé et courbes altimétriques).*

2.2. Climate

Since 1968, the drought characterised by a loss of 30% of rain with an increase of its aleatory repartition has changed the sudanian climate into north sahelian. This loss has little influence the date if sowing optima but has manifested itself by a reduction of the amount of rain, mostly in July and August as observed for the total area of the sudano-sahelian zone (Valet, 1983 ; Morel, 1990). If the first rains appear at the same dates, the last ones come earlier. Four pluviometric years with probalistic characteristic levels have been selected: deficit = 387mm (1984); median = 491mm (1991); meadow = 780mm (1989); excess = 946mm (1988).

2.3. The soils

At the Sine Saloum, lithosol, arenosol, ferruginous soil, intergrade ferruginous, ferruginous with spots and concretions are developped on a homogeneous substrate made of argillaceous greys of the Continental Terminal (Bertrand, 1972). In all cases they have a superficial horizon poor in clays and organic carbon.

The infiltration capacity of these soils are of the order of 3 to 6cm.h^{-1} independently of the formation of permeable superficial crusts and is lower than the high intensity rains that occur annually (Valet, 1985a).

The hydrological properties for the studied units are very close as shown by the maximum of minimal humidity for several pedological horizons (Table 2). This indicates a similar texture and thus a hydrological storage capacity of the field comparable. At the Sine Saloum, the hydrological state of the different soils on the principal geomorphological units has been investigated every week from the first to the last rain.

2.4. Culture and treatments

The mineral fertilization (150kgha^{-1} of 6N-20P_2O_5-12K and 100kg ha^{-1} of urea) was spread on the terrace and footslope fields (B_{1-2}, C, D, F, G and H), no fertilization on the hillslope. Hillslope plots, A, D, E and F stripes were chiselled, B_{1-2}, C, G and H stripes were ploughed and I_{1-2} were no tilled. The I_{1-2}, C, D and G stripes were protected from runoff by a mound.

The hydrological profiles were followed up every week with a hand hunger every 10cm on one meter depth and then every 20cm up to 2m for the plots at each corner of each band and under-band. The radical yield of mil was then measured on the same plots.

Mil (*Pennisetum glaucum)*, variety Souna III, 90 days duration, currently cultivated by peasants is the plant used for this simulation.

The maximum rooting has been measured on all parcels of the two fields. For those of the hillslope, the speeds or depths have been taken from the literature (Chopart, 1980) or have been deducted from the depth of the wetting front. This maximum rooting depth is defined as the level above which the totality of the rooting takes place. The radical useful water reserve represents the quantity of water available for the culture on the maximum rooting depth (RAWCmm=EU*Z_{root} cm).

2.5. AET simulation.

The hydrological balance has been calculated with a capacity-based functional model (Albergel, al., 1991). The soil is characterised by two reservoirs, a fixed reservoir characterised by the reserve of useful soil water and by the maximum rooting depth and a variable reservoir evolving with the rooting speed. The hydrological report is considered as a complementary irrigation simultaneous to the rain that has generated it. The millet maximum evapotranspiration value is (MET) (MET=Kc*PET where Kc is the millet cultural coefficient and PET the Potential EvapoTranspiration which varies from year to year depending of the date of sowing (Table 1).

Table 1– The values of PET, MET and annual and available rain (mm) during 90 days.

Rain mm	**PET**	**MET**	**Available rain**	**Annual rain**
Maxi (1988)	486	386	598	946
Mean (1989)	512	391	527	780
Median (1991)	489	376	355	491
Deficit (1984)	498	387	255	387

The cultural coefficients of mil are given in the literature (Dancette, 1983).

2.6. Runoff management

Three scenarii, based on innovative and traditional biophysical techniques of struggle against erosion, have been used:

1) Stop whole runoff;
2) Runoff control and runon management and valorization;
3) Bad control of runoff.

2.7. Millet yield prediction equations

Taking into account the runon, the equations of production of the Souna millet in peasant cultures are given in Table 2. The response is lower on the slope where less fertile soils receive traditionally less organic fertilisation. In the fields cultivated with more a difference of production of 9 % by mm of consumed water in the favour of chiselling can be seen.

Table 2- Millet grain yield equations

Morphological unities	**Soil tillage**	**Slope**	**Intercept**	**R²**
	Chiselling	10,38	-1800	0,96
Terrace	Ploughing	11	-1996	0,96
Footslope	Ploughing- Chiselling	8,93	-1222	0,91
Hillslope	Chiselling	7,26	-1012	0,85

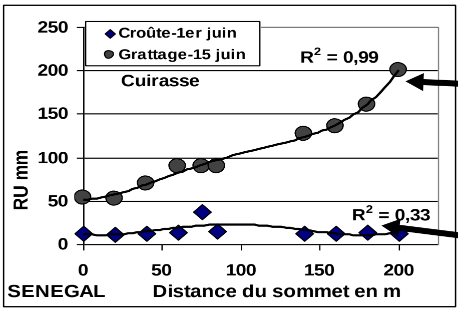
The intercept is lower for the footslope than for the terrace suggesting that the soil has a specific fertility quality.

3. RESULTS AND DISCUSSION

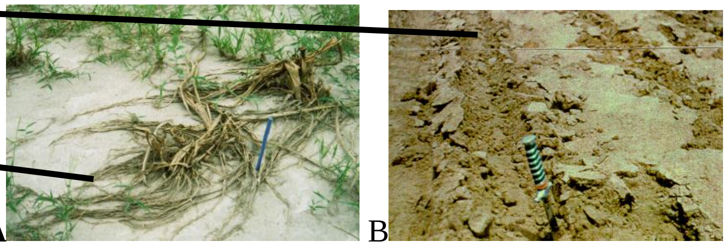
3.1. Estimation of the hydric soil functioning

3.1.1. At the hillslope scale

The cuirass occupies half of the oriental slope. Shallow soils with a low reservoir of useful water (RAWCmm), on 150m distance, go from a thickness of 30cm up to 300cm with a good water reservoir. For a rain of same height and intensity (35mm on the 5th and 17th of June) the hydrological stock is the same on the whole of the slope because of the soil crust (Photo 1A and Fig. 4). It increases along the slope after chiselling (11th of June) that destroys this crust (Photo 1B and Fig. 4). This stock of footslope is significantly higher than the rain. The polynomial function highlights the effects of several factors taking place in the repartition of Runoff and infiltration. All soils have a surface horizon poor in clays and organic carbon, with a weak aggregating power, prone to the formation of crusts, with a sever risk of erosion (Bresson and Boiffin, 1990). The destructuration and the formation of crusts increase towards the hill of the slopes (Valentin, 1990). These crusts and their variability of formation modify differently the infiltration of ecosystems (Hoogmoed and Stroosnijder, 1984 ; Valet et al., 2007).



A



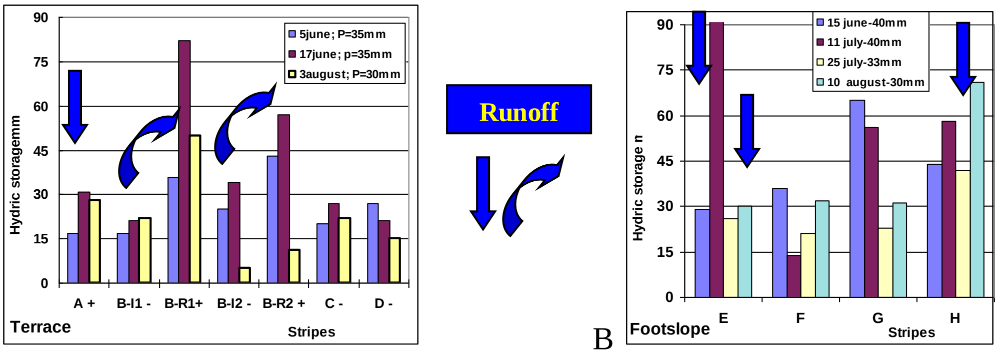
B

Figure 4- Evolution of soil root AWC along the hillslope before and after the	**Photos 1- A : Generalized crust and B : Crusts breaking by chiselling on the hillslope (dried year)** ***(Clichés S. Valet, 1983).***

crusts breaking by chiselling.	

3.1.2. At field scale

After the rain hydrological stocks of bands non protected from the Runoff on the footslope and the terrace display an important spatio-temporal variability. For the other protected bands the hydrological stocks are lower than rain except for two plots of band G on the. This suggests the variable temporal antagonist effect of the Runoff and hydrological report.

A  B

Figures 5 – Hydric storages after some rains in A: footslope and B: terrace.

For these crusts, sensibly of the same nature, the variability of the Runoff and hydrological report depends on the specific effect of other discriminating factors such as the slope, the concave-convex micro-modelling, the soil work, the position of the billons and the occurrence of lines of herbs or bushes (Valet and al., 1993; Valet and al., 2007). Each morphopedological unit constitutes an ecological system whose hydrological and nutrition dynamic depends on their proper characteristics, of the modes of use and of the climatic change.

At every scale, this different "*runon*" constitutes *"a natural, complementary and simultaneous irrigation to the rainfall that has generated it according to natural (topographical, morphological, permeability) anthropogenic (soil tillage) conditions*" (Valet, 1992).

3.2. Simulated millet AET

3.2.1. At the hillslope scale

<u>- Management which stops the whole Runoff</u>

In the absence of runoff, optimum expected AET are close (AET=360mm) for excess and average rains, decrease to 300mm for the median rains and for the low rains (260mm).

<u>- Management which Runoff control & runon valorization and management</u>

In the case of a Runoff control that maintains a non-erosive runon, for the maximal and average rains the satisfaction is close to the optimal one (in the order of 340mm) only for the ecosystems with a good RAWC (Fig. 6 A). Then the loss is strong (315mm to 280mm) for the median rain and very strong (180 to 245mm) for the low rain. For all pluviometric situations soils at the top of the slope with a low RAWC the loss of satisfaction is constant (280, 240 then ca.140mm).

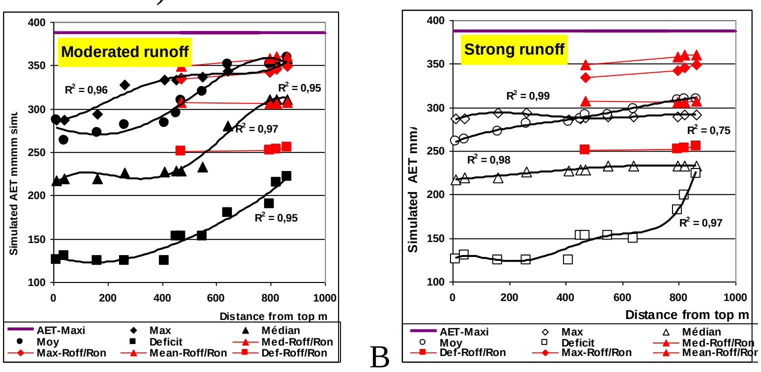
A  B

Figure 6- Millet AET mm along the hillslope A: with moderated runoff and B: with strong runoff at Thysse.

<u>- Without management</u>

In this case, the curves of hydrological satisfaction are considerably flat (260 to 310mm for maximum and minimum rain; 220 to 240 for median rain) with the exception of the deficitary rain (130 to 250mm) (Fig. 6B).

3.2.2. At the field scale

<u>- Management which stop whole runoff</u>

The satisfactions potentials obtained under the maximum and median rains are of the order of 340mm and identical under labour and chiselling on the footslope and terrace (Fig. 7A & B).

- Management which runoff control & Runon valorisation and management

The loss of AET begins to be significative but weak for the median rain and very strong for the weak rain mostly on the footslope. On the terrace the runon is more important and compensates the hydrological deficit in TO, BR_{1-2}. C and D not receiving any runon have the lowest AET.

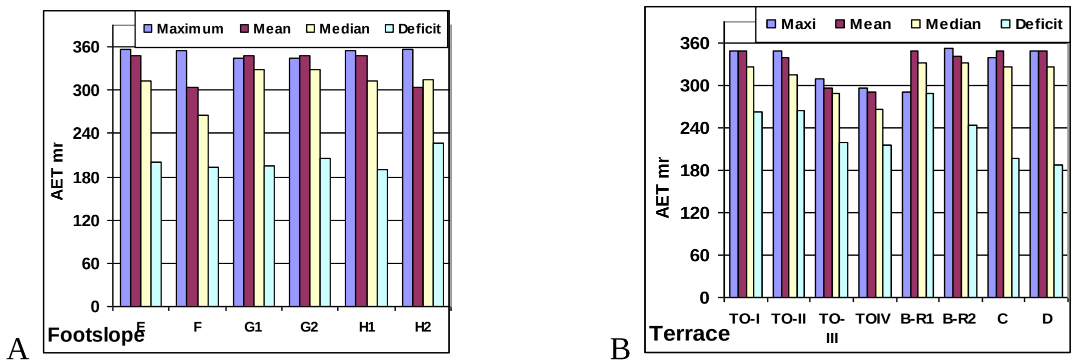


Figure 7- Millet AET (mm) for different plots inside A: footslope and B: terrace.

Such a variability of the expected AET confirms those calculated at different scales in Niger (Pilbeam and al., 1995; Gaze and al.,1997). The results of the AET non complementary to the different scales invalidate the hypothesis of Lal (1991) and Klaij and Vachaud (1992); according to them the water balance assumes that the surface overland flow is equal zero, because the systems are open.

3.3. Prediction of the millet yield

3.3.1. At hillslope scale

<u>- Management which stops of whole runoff</u>

In the absence of runoff, optimum expected yields are close (Yield=1600kgha^{-1}) for average and excess rains, decreasing to 1250kgha^{-1} for the median rains then to 800kgha^{-1} for the deficitary rains.

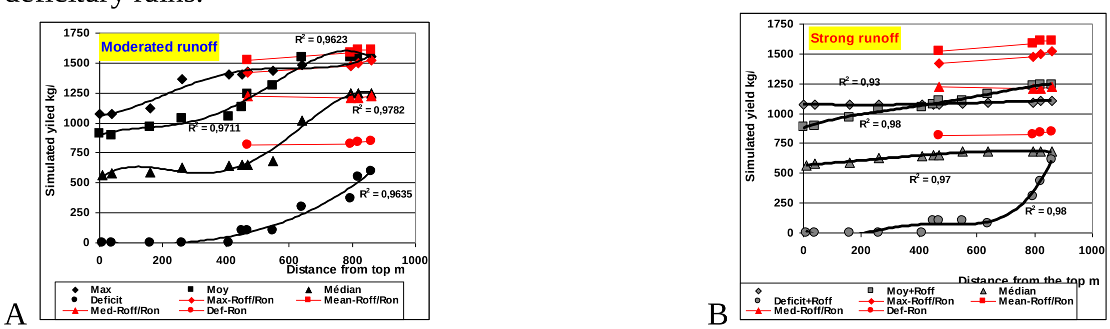


Figure 8- Millet yield kgha-1 vs the hillslope in A: with management and B: without management.

- <u>Management which runoff control & runon valorization and management</u>

With the techniques that maintain a non-erosive runoff and a runon for all rains a net effect of the rains can be noticed together with a net effect of the AWC (Fig. 8A). For the maximum and median rains expected yields decrease from 1600kg ha^{-1} to more or less 1000kgha^{-1}. In case of a deficitary rain the yield falls from 620 to 0kg ha^{-1} from a RAWC of 70mm. The median rain gives yields closer to the average rain (1260 to 600kg ha^{-1}) (Fig. 8B).

- <u>Without management</u>

In the case of non-control of the runoff, yields fall more for good rains than for the deficitary ones (Fig. 8B). Yields have a maximum of 1100-1260kg ha^{-1} with a good AWC and they are little modified for low AWC.

These expected yields are very close to those measured on different hillslopes that vary form 366 to 800kg ha^{-1} without manure on several slopes with no cuirass for rains of 488 to 596mm in Niger (Manu and al.,1994; Rockströem and Al., 1999).

3.3.2. At the field scale

- <u>Management which stops the whole runoff</u>

For pseudo dolines the absence of runon penalises greatly the average and low rains (Fig. 9A). For both fields they are significantly lower to those receiving a runon. For all rain and in the absence of runon yields are better on the footslope than on the terrace, for instance stripes G1-2 have a higher yield than C and D (Fig. 9B & C). The AWC plays a key-role.

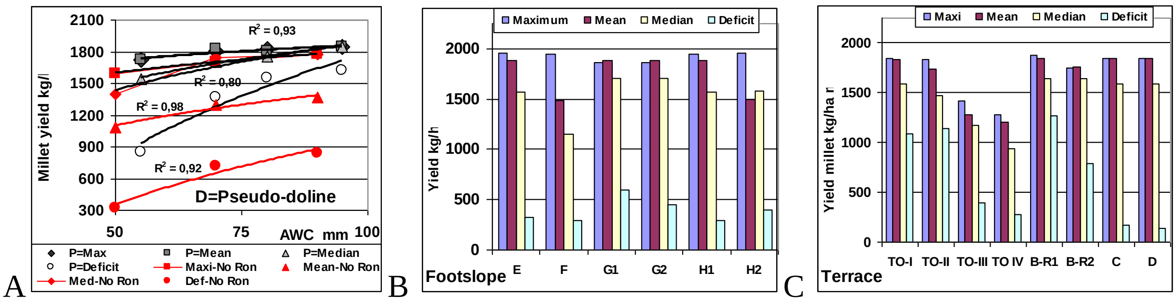


Figure 9- Millet yield kgha^{-1} A: in pseudo doline, B: in footslope and C: in terrace.

- Runoff control & runon valorization and management

For the footslope and the terrace the runon does not compensate the pluviometric deficit and yields decrease significantly for the medium rains (Fig. 9B & C). During the deficitary rain, the loss is brutal on the footslope and less on the terrace where the runon is bigger (Fig. 9B-C : stripes TO and BR_{1-2}).

These expected yields are very similar to the ones measured on different fields at the base of the hillslope that vary from 223 to 1430kg ha^{-1} without manure for rains of 488 to 596mm and near the 250-800kg ha^{-1} without fertilisation and the 500-1200kg ha^{-1} with fertilisation measured by Laoualy and Rockström (1993) in Niger and Diouf (1990) in Senegal. The optimum expected yield obtained for this study is enough equal to the maximum yield of 1800kg ha^{-1} obtained elsewhere (Hebel 1995).

5. CONCLUSION

The main results of the study include climate-change impacts, different ecosystems at two scales (field and hillslope) on the prevalence of environmental constraints to crop agriculture; changes in potential agricultural land; and changes in crop production patterns. The analysis assesses trends in food production, trade, and consumption, and the impact on income levels and risk of hunger of alternative development pathways and varying levels of climate change. The hierarchical analysis integrating the hydrological functioning and runoff/on management biophysical techniques, leads to the definition of heterogeneous functional spaces correlated as a function of the development and of the control of surface hydrological fluxes. These fluxes explain the variability of the millet yields that attain the optimum the years of excess rain whatever the AWC and during average years for good RAWC. During average and bad years the role of RAWC and runon is crucial to get a satisfactory yield.

These results show that the adaptation of agriculture to climate change which appears to be central to an integrated strategy to reduce risks and impacts of climate change may indicate that the Sudan Sahelian population can be fed only if this population involves itself in ecosystem management.

A new approach of the dynamics of ecosystems for their sustainable use must take into account the spatial physical variables of the medium that generates the hydrological fluxes responsible for the variability of agricultural production.

5. REFERENCES

Albergel J., M. Diatta, E. Juncker, P. Pérez, P. Ruelle, M. Sène, 1990. Méthode pour améliorer l'infiltration et réduire le ruissellement. Présentation du cas du Sine Saloun (Sénégal). Réseau Erosion, Bull. 10, ORSTOM, BP 5045, Montpellier, 34042, France, pp :68-85.

Angé A. 1984. Stratification des paysages agraires pour l'identification des contraintes à la production agricole. La mise au point de solutions techniques. Actes de l "atelier la Recherche agronomique pour le milieu paysan. Nanning, 5-11 mai 1985- Sénégal. : 40-50.

Bertrand R. 1972. Morphopédologie et orientations culturales des régions soudaniennes du Sine Saloum (Sénégal). 1 carte au 1/100 000. Agron. Trop. 11: 1113-1190.

Bresson L.M. and J. Boiffin, 1990. Morphological characterisation of soil crust development stage on an experimental field. *Geoderma 47, 301-325.*

Chopart J.L. 1980. Etude au champ des systèmes racinaires des principales cultures pluviales au Sénégal (Arachide, mil, Sorgho, riz pluvial). Doctoral thesis. Inst. Nation. Polytechn. Toulouse. France. 160p.

Dancette C. 1976. Carte d'adaptation à la saison des pluies des mils à cycle court dans la moitié nord du Sénégal. In Comité consultatif AIEA, Bambey, Sénégal. FAO-AIEA. : 19-47.

Diouf M., 1990. Diagnostic agronomique en parcelles paysannes : une méthode d'amélioration des systèmes de culture. Rencontres Internationales : « Savanes d'Afrique, terres fertiles ? » Comment produire plus et de façon durable en zone de savanes au sud du sahara. Montpellier 10-14 décembre. 30p.

Gaze S.R.,L.P. Simmonds, J. Brouwer, and Bouma , 1997. Measurement of surface redistribution of rainfall and modelling its affect on water balance calculation of a millet field on sandy soil in Niger. J. Hydrol.188-189:267-284.)

Hebel, A., 1995: Einfluß der organischen Substanz auf die räumliche und zeitliche Variabilität des Perlhirse-Wachstums auf Luvic Arenosolen des Sahel (Sadoré/Niger). Hohenheimer Bodenk. Hefte 24. Hohenheim University. 170p.

Hoogmoed W.B., and L. Stroosnijder. 1984. Crust formation on sandy soils in the Sahel I: rainfall and infiltration. Soil and Tillage Research. 4 : 5-23.

IRAT-SOPRA. 1989. BIPODE : Bilan hydrique à la parcelle pour la prévision et l'optimisation des doses en eau. Version 2.0-01/89. SOPRA Clamart, France. 41p.

Kachanoski R.G., E. De Jong, and D.E. Rolston. 1985. Spatial and spectral relationships of soil properties and microtopography : I Density of thickness A horizon II : Density of B horizon . Soil Sci. Soc. Am. J., 49: 804-820.

Klaij, M.C., and G. Vachaud, 1992. Seasonal water balance of a sandy soil in Niger cropped wit pearl millet , based on profile moisturenmeasurements. Agri. Water Management. 21:313-330.

Klaij, M.C., Renard, C., and Reddy, K.C., 1994: Low input technology options for millet based cropping systems in the Sahel. Expl. Agric. 30: 77-82.

Lal R., 1991. Current research on crop water balance and implications for the future. p 31-44, *In* M.V.K. Sivakumar (ed). Soil water balance in the Sudan-Sahelian zone (Proc.Int. Workshop; Niamey, Niger, February ,1991). IAHS Press. Institute of Hydrology Wallingford UK.

Laouali, A. and Rockström, J., 1993: Diagnostique sur les systèmes agraire du "Zarmaganda Central" (Niger). Mémoire de fin d'études. INA.-PG. Paris, Grignon. France. 83p.

Manu, A., Thurow, T.L., Juo, A.S.R., Sanguina, I., Gandah, M., Mahamane, I., 1994: Sustainable Land Management in the Sahel: a case study of an agricultural watershed at Hamdallaye, Niger. TropSoils/TAMU Bulletin No. 94-01. Texas A&M University, USA. 44p.

Pilbeam C.J., C.C. Dameen, and L.P. Simmonds, 1995. Analys of water budgets in semi arid lands from soil water records. Exp. Agri, 31:131-149.

Morel M., 1990. Atlas agrométéorologique.

Valentin C., 1990. Les états de surface des bassins versants de Thysse-Kaymor (Sénégal). ORSTOM Dakar, Sénégal. 10p.

Valet S., 1983. Evolution de la pluviométrie sur 30 ans et conséquence sur le déficit d'alimentation hydrique du mil pénicillaire en zone sahélienne (cas du Niger). Séminaire sur l'impact des "Relations sol-Eau-Plante sur l'intensification de l'agriculture pluviale en zone de savane. CPAC- Brasilia. 1-7 déc. 1983.20p.

Valet S., 1985- Action-test d'aménagement de la parcelle pour l'amélioration du bilan hydrique et de la lutte contre l'érosion (Essais en milieu paysan). ISRA-CIRAD-IRAT. 114p.

Valet S., 1992. Place du report hydrique (Runon) dans le cycle de l'eau à la parcelle et sur le versant en zone soudano-sahélienne. IRAT/CIRAD. Montpellier, France. Février 1992. 2p.

Valet S., M. Sene., P. Pérez et P.S. Sarr, 1993. Gestion agricole des reports d'eau sur le versant et à la parcelle à l'aide de barrages filtrants en zone soudano-sahélienne (Sénégal). Bull. 13, Réseau Erosion; ORSTOM, Montpellier, France. 143-157.

Valet S. et P.S. Sarr, 1999. Concept du report hydrique superficiel (Runon) : Conséquences physiques, hydriques et agronomiques à l'échelle de la parcelle en zone soudano-sahélienne. 24ème Journées Scientifiques du GFHN, novembre 1999, Strasbourg. 3 p.

Valet S., Ph. Le Coustumer, M. Motelica-Heino & P.S. Sarr, 2007. Rôle de l'encroûtement superficiel des sols sur leur fonctionnement hydrique : Conséquences hydrologiques & hydro-pédologiques. 32èmes Journées scientifiques (21 et 22 novembre 2007) Nantes. *« De la particule au milieux poreux : formation, évolution et transferts ».* Le Groupe Francophone d'Humidimétrie et TraNsferts en Milieux Poreux.

Wallace J.S., J. Brouwer, J. Allen, S.J. Banthorp, D. Blyth, E. Bromley, M. Blyth, k., A.C. Buerkt, and al. , 1994. Haplex Sahel southern super site report: on overview of the site and the experimental programme during the intensive observation period of 1992. Wallingford UK Institute of Hydrology P55.