CONTOURED RIDGE-TILLAGE INCREASES CEREAL YIELDS AND CARBON SEQUESTRATION

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Abstract
In southern Mali, under a semi-arid climate, contour-ridged tillage can reduce soil erosion and substantially increase the infiltration of rain water resulting in increased growth of the crops and the trees associated with the crops in the traditional farmed landscapes. Permanent contour ridges, covered with perennial grasses, are maintained in the fields, thus giving the main frame for drawing the contour lines. The farmers follow those permanent ridges when dressing the annual contour ridges for their crops. Contoured ridges increased infiltration of rain water by up to 10% of the total annual rainfall (800 mm), even in fields with a gentle slope between 1 to 2%. Crop growth was improved. Cereal yields (millet, sorghum and maize) were increased on average by 30%, and over 50% during the dry years. The increased infiltration replenished water stocks in the subsoil and increased the growth of existing trees (*Vitellaria paradoxa* and other valued species) in the traditional cultivated tree parks. This cropping technique facilitated the germination of seeds from those trees and the establishment of seedlings. The ligneous bio-mass was increased, contributing to carbon sequestration. Therefore, contour-ridge-tillage, increasing cereal yields and carbon stocks in the soil, promotes a more sustainable small scale farming in semi-arid Western Africa.

Additional Keywords: soil, water, conservation, infiltration, small-scale farming, semi-arid tropics

Introduction
Contour cultivation is a well-known method for reducing water run-off and for controlling soil erosion. However, in Western African semi-arid countries, public agencies had mitigated results when building terraces on large scales in watersheds and in large village lands because little attention was paid to individual farmers fields (Marshall, 1986; Delisle and Jacob, 1995). The research programme shared by the Institut d'Economie Rurale in Mali and Cirad in Central and Southern Regions of Mali has promoted a renewed approach of this well-known technique with the participation of small scale farmers, adapted to the management of individual fields and to agriculture with animal draught. In Southern Mali, in most farmers fields water run-off is high, often reaching 20% and even 40% of the total annual rainfall, in spite of gentle slopes (1 to 3%). This important run-off reduces the availability of water for the crops, which are sensible to drought, and crop yields are affected. The proposed method of cultivation with contour- ridges was applied with the participation of farmers in order to reduce run-off and to improve the availability of rain water for crops. The impact of this technique on water stocks in soils, on cereal yields and on the behaviour of trees associated with the crops were monitored.

Materials and Methods
Field sites
In Southern Mali, farmers use animal draught for cropping cotton and cereals (Maize, Sorghum, Millet) within various crop rotations. Typical small scale farms, managing 10 to 30 ha, are divided into fields by 1 to 3 ha. A strip of grass, by 1 m wide, is usually left between two neighbouring fields. Valuable trees (Vitellaria paradoxa and other species) are associated with crops in all fields. On the old sandstones, deep luvisols present a good porosity all over the soil profile; however crusts occur according to soil management practices. Water run-off is important, even on soils under grassy fallow (Diallo, 2000). On cropped fields, up to 20 or 40% of total rainfall is often lost through run-off, in spite of the low slopes of the landscape (1 to 3%). Soils in the upper part of the slopes are affected by soil erosion. Annual rainfall stands between 800 mm and 1000 mm and all rains fall between May or June and September or October.

Drawing contour lines in the field
Water run-off from the slopes above the field may be a problem limiting the output from contour cultivation. Thanks to a visual survey along the upper boundaries of the field, places where the run-off have not created problems are identified; in those places, the grass strip bordering the field has faced water circulation. Places where run-off has removed the soil are located as well. On those locations, a ditch, with a gentle slope (0.3 to 0.5 %) is dug out in order to collect run-off waters and to drive it into a permanent natural waterway (Figure 1). Even under

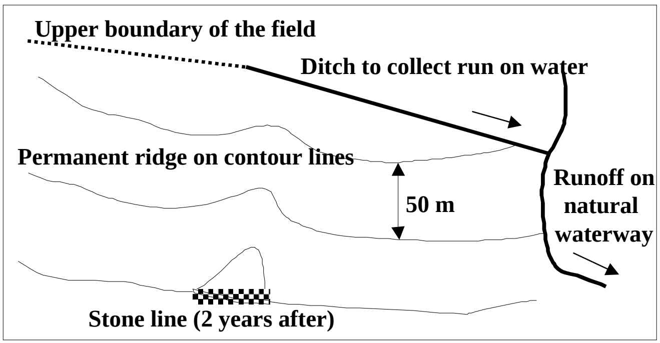

Figure 1. Drawing contour lines in an individual field. (Gigou *et al*., 1997).

Figure 2. Building the ridge on the contour line.

semi arid climatic conditions, during the rainy season water may fall in excess and have a negative impact on crop growth during a few weeks. Thus, permanent waterways are important for draining this water in excess. For such drainage, it is possible to use the existing natural waterways bordering the fields. A permanent strip of grass on both sides of such waterway is sufficient for preventing soil erosion, because the slope is very low. Contour lines are marked up in the field. Then farmers follow the marks with their oxen plough in order to build a ridge, through the combination of one or two tilled bands on each side of the contour line (Figure 2). The resulting large ridge is covered permanently by planted or natural grass. The run-off water generated between two permanent ridges is maintained in the field by the lower ridge on the slope. Water in excess may slowly be evacuated along the contour line towards the edges of this line which is protected with a strip of grass.

Contour cultivation in the context of animal draught

Farmers are tilling their land in parallel with the permanent large contour ridges, and the lines of sown crops will follow this pattern. Two different methods are in use:

- Ploughing the land and closing the removed soil bands one on another; sowing the crop with a sowing machine in parallel to the large contour ridge; ridging the crop lines one month after the emergence of the seedlings;
- Ridging up the land with the plough and raising the removed soil bands one against another, then sowing manually the crop on the ridge. This second method is quicker than the first one at the beginning of the rainy season

Measurement of the soil water content in soil profiles

The water content of the soil was measured on samples by weight difference between the wet soil on field and the soil dried out into an oven at 105 °C. Soil samples were collected with an helicoid auger, down to a depth of 200 cm in humid soils, or to a dry layer. 3 samples were collected as replicates within a ring of a radius of 2 m; the mean value of measurements was considered.

For every sampling date, samples were taken from a field with contour ridges and from a neighbouring field in which the same farmer has made traditional ridges following the main slope. This pair of fields was homogeneously managed, as far as sowing dates, cropped species and other cropping techniques are concerned.

Figure 3. A field with contour ridges.

Three sampling dates have been considered: (i) July – the early rains occur; the upper layer of the soil profile contains rainwater, but deeper soil layers are dry; (ii) End of August – the monthly rainfall is maximal; (iii) End of September – the main rains are over. When the annual rainfall has been important, the humidity of the soil profile reached the field capacity over a depth of 2 m at the end of September. On dry years, the upper part of the soil profile only was wet; then, the difference of water regime between the plot with contour- ridges and the plot with ridges along the main slopes was very important.

Runoff measurement

Run-off was measured on an area of 70 m², corresponding to the surface between two neighbouring ridges (distant by 0.7 m) and a length of 100 m on the ridge. 1/10 of the running water was collected into a 200 l can and measured after each rain.

Estimates of crop yields
In case of drought spells, the difference in crop growth between the two plots compared in each pair of plots is clear. However, comparing the crop yields on those two plots has not been an easy task. Farmers having identified the effect of contour-ridges on their crops have frequently supplied more fertilisers on the contour ridged area than on the plot traditionally managed and use as a witness plot. The improved availability of water through contour-ridging has encouraged them to aim at higher yields through increased fertiliser use. This participatory experimentation did not allow a control of such attitude of farmers. Thus, in order to cope with the emergence of such management of the experiments, it has been necessary to control the degree of fertiliser supply through an experimental set up. A set of agronomic trials has been developed over several years, with many replications of the couples of plots (with and without contour ridging) in order to elaborate some significant estimates of the effect of the proposed technique on crop yields. The ANOVA (StatITCF) allowed a checking of the significance of yield differences every year.

Observing the regeneration of trees through contour cultivation
One researcher participating to the experiment (Traoré, 2003) checked in 2002 the density of the trees in cropped fields on three locations, namely at the top, in the middle and at the bottom of a soil sequence close to the village of Konobougou, which lays between Bamako and Ségou. All trees higher than 2 m were accounted. On the middle site, as far as the field had been opened a few years before 1956 and has been maintained under cultivation since, the changes in the tree cover could be checked out. This field had hosted the experiment since 1994. The number of young trees in this field was identified in 2002. Those data were compared to the number of trees visible on pictures from aerial surveys on the same sites in 1956, 1978 and 1991.

Carbon sequestration by trees
The trees in the farmers field contain a large quantity of carbon. The growth of those trees participates to carbon sequestration. Cutting those trees for cropping the land would release carbon dioxide to the atmosphere. The potential for carbon sequestration in the fields of the studied area by the tree parks maintained by the farmers was estimated from the estimated stock of carbon in the aerial parts of those trees and in their roots. The study was developed in the lower section of the soil sequence analysed by Traoré, where the density of mature trees is high. The density of the trees there was by 24 ha^{-1}; 98% of the trees were *Vitellaria paradoxa*. The girth of every tree was measured at the height of 1.3 m. Thanks to the model proposed by Louppe *et al.* (1994), the corresponding volume of wood of every tree was calculated (Total volume = -0.0735 + 0.7499 C^2 where C means girth at 1.3 m). The density of wood for *V. paradoxa* is close to 0.85 kg dm^{-3}. The weight of wood of each tree could be estimated. The total weight of leaves per tree was measured on 10 selected trees through the collection of those leaves up to the end of the dry season. The carbon content of dried wood and leaves was estimated at 50%. The estimation of carbon in the roots is obtained as a percent of the carbon in the aerial parts. Breman and Kessler (1995) have given values for this percentage for many tree species in semi- arid tropics. According to their findings, the percent of carbon from roots in *V. paradoxa* was estimated at 50% of the carbon in aerial parts of this species.

Results and Discussion

Contour ridging modifies the water content of the soil during the cropping season, reduces run-off, improves crop yields and the growth of the trees associated with crops in farmers fields. Those aspects have been monitored and the main data are listed below.

Increased humidity of the soil by contour cultivation
Contour ridges retain running water on the slopes. Accordingly, water infiltration is increased and the quantity of water stored in the soil is higher, which favours the development of the crop. After the early rains, farmers noticed that they can plough during one or two more days in areas with contour ridges than in areas without, which increases their potentials for correctly preparing their land. In case of a drought spell, the crops planted on land with contour-ridges wither up latter than those planted in traditional fields. At the end of the rainy season, the

stored water in soil is higher, and the depth of soil to which this water is stored is higher with contour- ridges than without. On a dry year, with contour –ridges, the upper part of the soil is keeping some water, while without those ridges the soil is dried out. Then, the effect of contour ridging on the soil water regime is particularly obvious (Figure 4). This contrast has a direct impact on the water supply to the crops at flowering and grain filling stages.

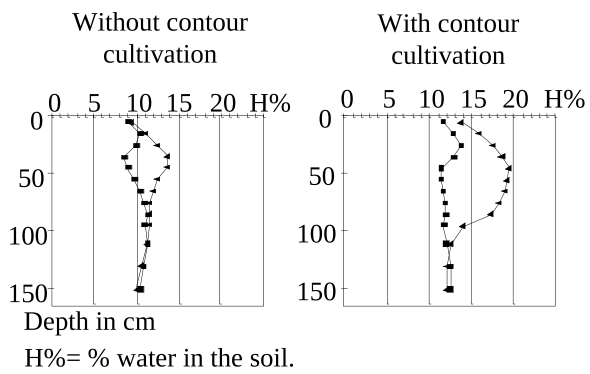

Figure 4. Soil humidity at the beginning (28/7/98) and at end (29/8/98) of the rains. (Konobougou, total rainfall in 1998 = 678 mm).

Under contour- ridges, the crops have a better access to water in the upper layer of the soil and thus are less affected by the drying up of water reserves at maturing stages. On years with high rains, the soil was damped down to two meters deep or more, with and without contour- ridges. No difference was checked out in water supply to the crops caused by contour- ridging. But, the improved deep infiltration of rainwater caused by contour ridges in those rainy years supply water in the deep layers of the soils for the trees for the long dry season. An indirect estimate of this water supply to the deep soil layers as developed through water supply models by Gigou *et al*., 1999). It suggests that contour ridging supplies more significant water in rainy years to the deep soil layers than traditional land management.

Reducing run-off water

Contour ridges hold the falling rain water through an increased unevenness of the soil surface and a number of small local dam- like structures; they increase water infiltration in soils. Thus contour ridges is heavily decreasing water run-off. Table 1 shows the percentage of annual rainfall left through run-off for three years with similar annual rainfall, but differentiated rainfall regime, according to the position of the field in the landscape and to the method for controlling water movement on the surface.

Table 1: Reduction of water runoff by contour cultivation. Slope = 1-2%. Konobougou.

year	**1995**		**1996**		**2002**	
contour cultivation	with	without	with	without	with	without
annual rainfall	630 mm		633 mm		663 mm	
upper slope	21%	31%	40%	55%	17%	27%
lower slope	14%	25%	40%	47%	19%	26%

Run-off has been extremely high in 1996, which relates to an important development of crusts on the soil surface caused by several intense and important rains at the beginning of the rainy season. Run-off increases when the share of large and intense rains increases in the annual rainfall (Traoré, 2003). Without contour cultivation, run-off varied from 25% to 55%, which means that an important amount of water is lost for the crops in cropping conditions in which water is scarce. Contour ridges reduced run-off by approximately 10% of the annual rainfall. So, for each year, contour ridges held in average 60 mm of rainfall in addition to the rainwater that traditionally cropped fields could hold. Such water can maintain crop growth for at least two weeks.

Increasing cereal yields

Table 2 shows the improvement of cereal yields as caused by contour ridges. Maize yields were increased by 35 – 38% during the 3 years of the trials. This crop is sensible to water shortage, and an improved water supply through contour ridging causes better yields. The effects of contour-ridges on millet yields have been variable. They are related to the availability of water at the end of the rainy season. Traditional photo periodic varieties were used. Those varieties are flowering and filling their grains at the end of the rainy season, and the ripening stage takes place in dry conditions, ensuring a fair quality of grains. Therefore, when the last rains are small, this crop depends on the water held in the soil stocks for developing and filling the grains. This situation occurred in 2000, and the increased water storage in soils through contour ridging had a huge effect on grain yields.

Table 2. Yield increases by contour cultivation (grain as kg ha^{-1})

	maize			millet		
year	1998	1999	2000	1998	1999	2000
Number of tests	2	10	6	3	5	7
Without contoured ridges	2603	2082 a	1550 a	892	1430	630 a
With contoured ridges	3599	2836 b	2088 b	1128	1453	1008 b
% increase in yield	38%	36%	35%	27%	2%	60%

a, **b**: values in the same column accompanied by the different letters are significantly different at P = 0.05.

The management of trees associated to the crops by the farmers and the effects of contour-ridges

Farmers are keeping in their fields some wild trees for their use. Most of those trees are saved while clearing the bush land. The density of those trees is different according to the position of the field on the slopes (Table 3). On the upper part of the slope, there are less trees than in the lower part of the slope. This fact may relate to a better availability of water stored in the deep soil on the lower part of the slope in the dry season. Water lost through run-off and drainage on the upper part of the slope is mostly stored in the lower parts of the slope in this landscape, and the dense network of small local waterways may play an important role for such infiltration of run-off water on the long, regular and gentle slopes (Traoré, 2003).

Table 3. Variation of tree density in the catena. Vitellaria paradoxa is the species preferred by the farmers. Konobougou. (Traoré, 2003)

Position	Number of trees ha^{-1}	Young trees ha^{-1}	% V. paradoxa
Upper location	8.5	1.0	18%
Middle location	12.3	6.8	24%
Bottom location	24.0	0	98%

Young trees were found in the upper part and middle part of the slope. This indicates that farmers wish to increase the density of trees in those sections of the landscape. Farmers explained that the absence of young trees on the lower parts of the slopes was due to the clearing of the seedlings, as far as they feel that the density of trees is satisfactory. Those data may suggest that farmers would target a density of trees in their fields by 20 – 25 trees ha^{-1}, which means a soil cover by the canopies in the range of 5 to 8%.

The species of trees maintained by farmers in their fields depends on the position of their fields on the slope. On the lower parts of the slope, most trees are of the *Vitellaria paradoxa* species, which is preferred by farmers. In the upper and central sections of the slopes, this species is less important than in the lower sections. In the central section of the slopes, farmers have kept three species: *V. paradoxa*, *Adansonia digitata* and *Faidherbia albida*. The young trees kept by farmers are *A. digitata* and *F. albida* in this section. In the upper sections of the slope, many tree species have been maintained.

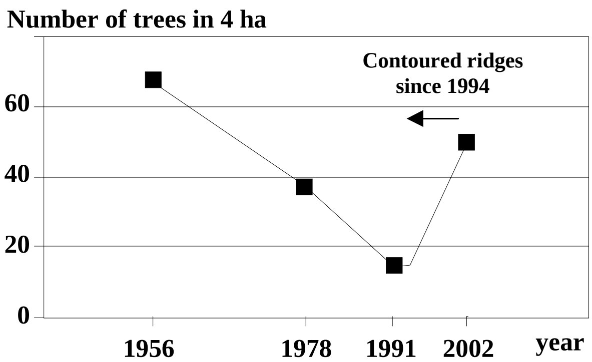

Figure 5. Increased number of trees with contour cultivation (Traoré, 2003).

In the middle section of the slopes, the evolution of the density of trees for half a century could be scrutinised on one site through the analysis of aerial slides. The land was cleared from the bush a few years before the earliest available slide has been made (1956). From this initial density of trees, rather high, the number of trees on the field sharply fell down up to 1991. In 2002, a great number of young trees was observed, and the number of significant trees on the field is over the corresponding number in 1978 (Figure 5). This field was put under contour-ridge cultivation in 1994 and maintained under this cultivation system since. Thus, contour ridging increasing the amount of water hold in soil stocks has helped existing trees which survive and has created favourable conditions for seedlings

Potential of carbon sequestration by trees associated to crops in southern Mali
On the lower parts of the slope, the density of trees seems to meet farmers' goals; most trees are mature. The actual quantity of carbon contained in the trees, including their roots, is an estimate of the potential carbon sequestration that may take place if this density and development of trees could be generated on the central sections of the slopes through the adoption of the proposed contour ridging techniques. These estimated stocks in trees are higher than the actual stocks of carbon within the upper layer of the soils (0 – 40 cm), ie. 14 t ha^{-1}.

Table 4. Stock of carbon in the trees and their roots at a site of good mature tree density: 24 trees ha^{-1} (Traoré, 2003).

Variables		Volume (m^3)	weight (t ha^{-1})	Carbon (t ha^{-1})
Estimation from observed girth	wood	35	30	15
	leaves	-	1	1
Estimation as % of aerial biomass	roots			8
Total				24

Conclusions

Cropping on contour-ridges can be implemented through oxen- draught farming systems and through traditional cropping practices of farmers in Southern Mali. This technique is increasing crop yields, because it increases the infiltration of rain water, a key factor of crop yields in semi- arid tropics. It also increases the growth of the trees associated to the crops, which contributes to carbon sequestration. Contour- ridging efficiently reduces soil erosion in the fields that are under the risk of soil erosion in this landscape. However, farmers have not the perception of soil erosion on their crop yields, while the effect of water conservation through contour ridging are fairly understood because this conservation increases crop yields.

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References

Breman H. and Kessler J. J. (1995). Role of woody plants in agro-ecosystems of semi-arid regions, with an emphasis on the sahelian countries. *Springer-Verlag, Berlin, Advanced series in agricultural sciences*: 340 p.
Delisle Y. and Jacob J.P. (1995). Opération de développement et droits fonciers en Afrique. La lutte anti-érosive au centre–ouest du Burkina Faso. *Sécheresse* 6, 295-302.
Diallo D. (2000). Erosion des sols en zone soudanienne du Mali, transfert des matériaux érodés dans le bassin versant de Djitiko (Haut Niger). *Thèse, Université de Grenoble*. Montpellier, France, IRD: 202 p.
Gigou J., Coulibaly L., Wenninck B., Traore K.B. (1997). Aménagements des champs pour la culture en courbes de niveau au sud du Mali. *Agriculture et Développement* 14, 47-57.
Gigou J., Traore K., Coulibaly H., Vaksmann M., Kouressy M. (1999) Aménagement en courbes de niveau et rendements des cultures en région Mali-sud. In: *L'influence de l'homme sur l'érosion. Volume 1: à l'échelle du versant*. Montpellier, France, IRD, *Bulletin Réseau Erosion ORSTOM* 19, 391-404. Colloque International « L'homme et l'érosion », 1999/12/09-19, Yaoundé, Cameroun.
Louppe D., M'bla K. and Coulibaly A. (1994). Relations dendrométriques préliminaires pour six essences secondaires de la forêt de Badénou (Nord Côte d'Ivoire). *Côte d'Ivoire, Cirad-Forêt*: 35 p.
Marchal J.Y. (1986). Vingt ans de lutte anti–érosive au Nord du Burkina Faso. *Cahiers ORSTOM, Ser. Pédologie* 22, 173-180.
Traoré K.B. (2003) Le parc à Karité: sa contribution à la durabilité de l'agrosystème. Cas d'une toposéquence à Konobougou (Mali-Sud). *Thèse, Ecole Nationale Supérieure Agronomique de Montpellier*, 174p.