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Research article

Sequestration of organic carbon in West African soils by *Aménagement en Courbes de Niveau*

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Abstract – A recent Intergovernmental Panel on Climate Change (IPPC) report concludes that global warming, while already a global crisis, is likely to become even more devastating. The scientific consensus is that global warming is caused by increases in greenhouse gases including carbon dioxide. The Sahel of West Africa seems to be more adversely affected by such climate changes, leading to reduced and more sporadic rainfall. In addition, food security in the region is tenuous and fragile, due to adverse climate change, but also due to the historical mining of nutrients and carbon. With the adoption of the Kyoto accords, at least by some countries, sequestered carbon (C) has become a tradable commodity. This provides a double incentive to increase soil organic carbon in the C-depleted and degraded soils of West Africa – return C to improve soil quality and assist in removing CO_2 from the atmosphere to assist in mitigating climate change. A challenge, however, remains to determine which agricultural systems can actually sequester C. The technology called *Aménagement en courbes de niveau* (ACN), which can be roughly translated as 'Ridge-tillage', has given crop yield increases of 30 to 50%. To date, there has only been anecdotal evidence suggesting that *Aménagement en courbes de niveau* leads to increased soil organic C. The objectives of the study reported here were to determine whether the technology has the potential to sequester C in West African soils, and, if so, how much. In this study, soil organic C was measured by combustion methods in soils sampled at 0–20 and 20–40 cm depths in a series of experiments in Mali, Senegal and The Gambia. Soil organic C was measured in three very different types of experiments, all including *Aménagement en courbes de niveau* technology, resulting in three methods of measuring C sequestration. Our results indicate that the *Aménagement en courbes de niveau* technology significantly increased maize yields by 24% by weight in the Gambia experiment while soil organic C was increased by 26% in The Gambia, by 12% in Siguidolo, Mali, and by 14% in peanut systems of Nioro, Senegal. These increases in soil organic C are likely due to three factors: (1) reduced erosion and movement of soil, (2) increased crop growth resulting from the greater capture of rainfall, and (3) increased growth and density of shrubs and trees resulting from the increased subsoil water, resulting in turn from the increased capture of rainfall, and reduced runoff. Measuring soil C on fields that were successively placed under *Aménagement en courbes de niveau* management and the use of replicated experimental plots appear to be the best methods to quantify the C sequestration potential of the practice. These results indicate that this soil and water conservation technology not only harvests water and increases food production, but also increases soil organic carbon. This technology thus is a successful technique to sequester C in soils and if carried out in a large region may both offset CO_2 emissions and help mitigate climate change.

ACN / *Aménagement en courbes de niveau* / ridge-tillage / Mali / Senegal / The Gambia / soil organic carbon / reductions in carbon dioxide / carbon sequestration / climate change

1. INTRODUCTION

Atmospheric carbon (C) levels have risen from 315 ppmv in 1959 to 377 ppmv in 2004, as indicated by atmospheric records from Mauna Loa, Hawaii (Keeling and Wharf, 2008). Soils play a major role in the global C budget because they contain more carbon than the atmosphere and plant biomass combined (Brady and Weil, 2002). The soil carbon content in the top 1 m of soil contains 3/4 of the earth's terrestrial

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C. Nonetheless, soils have the potential to sequester far more C if properly managed to do so. Some estimates are that 15% of the fossil fuel emissions of CO_2 could be offset by soil C sequestration alone (Roberts, 2007). The recent availability of carbon (C) trading markets resulting from the Kyoto accords raises the possibility that growers and producers in the developing world might participate and raise capital through increased sequestration of C as soil organic C (Antle and Uehara, 2002). This is a potential win-win situation, whereby detrimental atmospheric CO_2 could be turned into a valuable improvement in soil quality.

Food security in the Sahel of West Africa is adversely affected not only by climate change-related decreases in rainfall (Traoré, 2000) but also nutrient and carbon mining (Pieri, 1992; Antle and Uehara, 2002). The sequestration of C in soils of West Africa could have multiple benefits – to mitigate global climate change, the trading of C could be a rare source of revenue, and the role of soil organic C in increasing productivity and in achieving food security in soils of Africa has been noted (Pieri, 1992). Lal (2008) points out that soil and crop management now and in the future needs to consider the critical role of organic C for sustainable agriculture. He suggests the need to "farm carbon" to meet these new challenges.

For C trading to occur, however, a quantification and verification of soil C levels is needed in diverse production systems. In addition, given the importance of soil C in improving productivity and stability of production (Gigou et al., 2006), the quantification of soil organic C is, itself, a useful endeavor, as it could be used with other criteria to evaluate cropping systems. It is also important to identify production systems that lose C and quantify the amounts they lose as a negative factor.

1.1. Soil resources

The region to which these studies refer is Sub-Saharan Africa in the rainfall belt of 500 mm annual rainfall to about 1100 mm. Soil organic C levels in this region are, in general, very low (1 to 8 $\mathrm{g\,kg^{-1}}$) in the low clay, sandy soils (Bationo and Buerkert, 2001). In addition, these soils are known for their crusting behavior, which leads to accelerated runoff (Casenave and Valentin, 1989; Hoogmoed, 1984). Bationo and Buerkert (2001) estimate that only 10–15% of the rainfall is used by the vegetation. Increasing soil organic C is of critical importance to improve the soil resources because of the increases it provides in; nutrients for plants, cation exchange capacity, water-holding capacity, and greater soil aggregate size and stability (Pieri, 1992; Bationo and Buerkert, 2001). The loss of organic C below a critical threshold results in rapid degradation of soil physical properties and decreased permeability results in nearly irreversible degradation (Pieri, 1992). Small increases in organic C may, therefore, improve chemical and physical properties in these soils with such low levels of clay and organic C (Pieri, 1992). Attempts to increase soil organic C have been widespread and extensive as a result of early research pointing out the importance of this soil constituent in the extremely coarse-textured soils of West Africa (Pieri, 1992). A review of alternative cropping systems and practices that have been proposed to increase soil organic C has been presented by Bationo and Buerkert (2001). These authors point out that few food production systems maintain soil organic C and fewer yet result in soil organic C increases.

1.2. "Aménagement en courbes de niveau" (ACN) technology

ACN, as it is referred to in Gigou and Traoré (1997); Gigou et al. (2006), has been approximately translated as 'Ridge-Tillage', and is a multiple field or landscape level method of harvesting rainfall and managing surface water in West African crop production systems. The technology consists of controlling water that could run onto the field as well as water that accumulates on the field in excessive quantities and must be disposed of through the use of waterways or similar structures. While the technology considers landscape water flow through consideration of run-on and waterways draining multiple fields, it can be implemented for a specific field, permitting a field-by-field introduction of the technology into a specific farm. Indeed, Gigou and Traoré (1997) have recommended a field-by-field implementation because the method requires that the growers become more cognizant of water management on their land. Farmers report that it often takes them a year or two to learn how to manage ACN systems (Roncoli et al., personal communication, 2002).

Traoré et al. (2002) summarize the expected benefits of the ACN on soil carbon as including the following factors: (1) reduced erosion losses of soil and residue C, (2) increased growth of trees, especially those that annually shed their leaves, (3) increased crop yields due to increased soil moisture, and (4) forage and building material from grasses that stabilize permanent ridges and waterways.

The technology includes the following phases:

1. Diagnosis ("Diagnostic") of the water management constraints and opportunities in the farmer's field. This is a joint activity carried out with the grower and a water and soil conservation technician. The purpose of the activity is to identify specific run-on and excessive run-off conditions, the need for waterways, and special water management structures required for the specific field.

2. Staking the permanent ridges ("Piquetage"). This activity usually requires the expertise of the water and soil conservation technician to plan and locate the number and distance between the permanent ridges (*Ados*). Guidelines have been proposed by Gigou and Traoré (1997) for the location of these structures.

- The maximum spacing of the permanent ridges is 50 m, with closer spacing if the slope is high.
- The maximum elevation change between permanent ridges is 1 m. If the slope is higher then the permanent ridges will be placed closer together

The permanent ridges (*Ados*) are positioned perpendicular to the slope and capture the small rains but divert the most intense, potentially damaging, rainfall to grassed waterways off the field (Brannan, 2007, personal communication). Once these structures are marked on the field, the actual drawing of the ridges, usually with an oxen-drawn moldboard plow, can proceed. Usually these ridges are drawn shortly after the first rains – the only time when these soils become workable. The *Ados* or permanent ridges are formed by multiple passes with the moldboard or disk plow turning the soil to the ridge on both passes along the ridge. There usually is no preferred up size or down side of the permanent ridge. Annual ridges, however, should begin at the permanent ridge and proceed upslope to achieve maximum efficiency in water capture and retention in the plant root zone.

3. Annual ridging is carried out according to the local practice and advice of the water and soil conservation technician. Ridges or crop rows, whichever are done first for each rainy season, begin at the *Ados* or permanent ridges and proceed upslope to maximize the capture and retention of rainfall. In Mali, crops are planted on annually drawn ridges and this was the method used at the Siguidolo site. In Sougoumba, Mali; Nioro, Senegal and in The Gambia seeding is done on flat seedbeds (small furrows, if needed, are drawn after the plants are established). Furrows are drawn for all crops elsewhere in Mali, except for groundnut (*Arachis hypogaea,* L.) and cowpea (*Vigna unguiculata,* L.). The original ACN design was modified for flat planting of peanut by one of the authors (M. Sene, ISRA, Senegal).

4. Maintenance operations are usually needed if very heavy rains occur, breeching the *Ados* or permanent ridges. Often annual maintenance of the *Ados* or permanent ridges is needed. During the first year the *Ados* need to be reinforced and specific problem areas of the field repaired. The ridges become solid and stable after the first year, which can be enhanced with the planting of grasses such as *Andropogon gayanus,* L. that provide forage and building material.

The ACN Technology, developed initially in Mali by Gigou and associates of the Institut d'Economie Rurale (IER), Mali, has been applied in rainfall regimes of 600 mm annual rainfall in central Mali to 1200 mm rainfall regimes in southern Mali, and The Gambia. Terrain slopes have ranged from near 1% to as high as 20%, with adjustments of closer-spaced permanent ridges (ADOs) at higher slopes. The technology appears to be most successful to combat the low infiltration rates of West African soils (Casenave and Valentin, 1989; Hoogmoed and Stroosnijder, 1984; Kablan et al., 2008), by retaining rainfall for a longer period of time, enhancing infiltration and capture. The technology has been most successful on the very sandy soils that crust and have low rates of infiltration. Other technologies such as the "zai" technology seem to work well on the high clay content soils (Reij et al., 1996). These soil and water conservation technologies have also reported anecdotal reports of higher water tables and increased availability of drinking water (M. McGahuey, 2006, personal communication).

Additional research is needed to optimize the spacing between the permanent ridges (*Ados*), and the height and width of the *Ados* in relation to rainfall, soil slope, texture and infiltration rate.

1.3. Tied ridges and "Aménagement en courbes de niveau"

Recent studies by Chivenge et al. (2007) indicate that among soil conservation technologies on heavy clay soils the "tied ridges" have been found to lead to soil C increases, while on sandy soils, tied ridges did not lead to soil C increases. The authors suggest that on sandy soils, similar to those in West Africa, efforts should be focused on increasing organic carbon inputs into the system rather than on changing tillage management such as reduced tillage or "no till", for example. This conclusion derived from their observation that residue management such as mulching increased the organic C in the coarse-sized sand fraction of soils. These authors noted that one of the technologies that might seem similar to ACN, "tied ridges", did not increase soil organic C in sandy soils. This technology differs fundamentally from the ACN technology in that the "tied ridges" technology does not include the permanent ridges, *Ados*, of the ACN technology that capture the first rains no matter when they fall.

1.4. Effects on crop yields

The ACN technology has been tested on cotton, groundnut, millet, maize and sorghum, usually producing yield increases of 30–50% (Gigou and Traoré, 1997; Gigou et al., 2006). The studies presented here were conducted to examine the potential of the ACN technology to increase soil organic C.

While the ACN was introduced and adaptation began in 1994 (Gigou and Traoré, 1997), to date there has not been a field assessment of the potential of the technology to increase soil organic C. One of the objectives of the Carbon from Communities project, initiated in 2002, was to assess and quantify how much soil organic C could be sequestered by the practice. The assessment of soil C was complicated by several factors:

1. As of the date of the Carbon from Communities Project, there were no replicated field studies in which the soil organic C status of the technology could be assessed.
2. Replicated comparisons of the ACN effect are difficult because the technology needs to include the landscape considerations such as control of run-on; often, special structures such as grassed waterways are needed to harmlessly drain water from the extremely intense tropical storms.
3. The initial objectives of the ACN practice were to examine the effect of better water capture on crop productivity and on reducing soil erosion losses (Gigou et al., 2006). Interest in C sequestration has, until the present, always been a secondary research objective.

The specific objectives of the research were to: (1) assess the potential of the ACN technology to increase soil organic C in food-producing systems in West Africa, and (2) suggest methods to quantify soil organic C increase associated with water and soil management practices that have watershed-level effects.

2. MATERIALS AND METHODS

With these constraints in mind, three methods were proposed to quantify the effects of the ACN practice on soil organic C:

1. *Measuring soil C on adjacent fields.* An attempt was made to identify adjacent control fields that were as similar as possible to the ACN fields, with respect to soil type, crop rotation history and topography, but without the ACN practice. This comparison was implemented in Siguidolo, Mali. An incentive was provided to compensate the control farmer for the expected yield benefit due to ACN.
2. *Sampling over years of multiple fields.* Because the ACN practice was implemented over several years, with successive fields or sections of fields being brought under the practice, we measured soil organic C on the respective fields and plotted those data versus the number of years under the technology. This method was also applied in Siguidolo, Mali.
3. *Replicated experiments.* In The Gambia and Senegal the conventional field experimental designs were adapted as follows:
   - Allocating a pair of plots, one ACN and one non-ACN per farmer/producer. Thus, each farmer effectively became a replication of the soil and water conservation treatment.
   - Adding berms above the treatments to prevent run-on from affecting the ACN treatments because they might benefit from additional water capture and retention if they were downstream from a non-ACN treatment.
   - Hydrologically isolating the ACN and non-ACN plots with a naturally-occurring ravine between the plots.

2.1. Site description

2.1.1. Mali

The Mali farms in Sougoumba and Siguidolo were selected in consultation with the Compagnie Malienne de Dévéloppement des Textiles, (CMDT), a parastatal company that manages the production and export of cotton from Mali. A farm representative of the cotton-growing area was selected to test the ACN technology. This site was suggested by the CMDT because it was representative of a growing number of unproductive and degraded cotton lands that were operated under contract to the CMDT. This site represented a dry extreme of cotton production (Siguidolo at 800 mm per year) while much cotton is also grown in regions with 1000 mm per year, (M. Vaksman, personal communication, 2004). Method 1, that of sampling adjacent fields, one with ACN and one without, and Method 2, sampling over years of multiple fields, were implemented in Siguidolo, Mali.

The farm near Siguidolo (Fig. 1) (6^o 47’ W, 12^o 55’ N) was populated with tree and shrub vegetation during the dry season, including shea butter trees (*Vitellaria paradoxa,* Gaertn.) and baobab (*Adansonia digitata*, L.). Soils at this site were

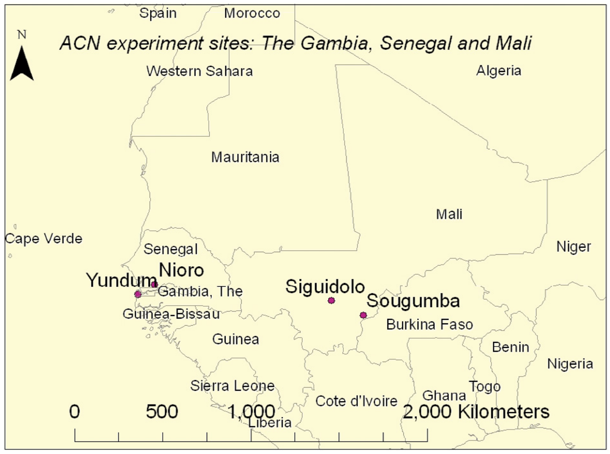

Figure 1. The *Amenagement en courbes de niveau* (ACN) experimental sites: Yundum, The Gambia; Nioro, Senegal, Siguidolo and Sougoumba, Mali.

classified as Plinthic Paleustalfs in the Soil Taxonomy (Soil Survey Staff, 1975). The two fields, one with ACN and one without, were identified by local collaborators as on the same erosion surface, with similar slope position, and with similar management except for the ACN.

2.1.2. The Gambia

Method 3, the use of replicated plots adapted to “landscape” processes were installed to assess the effect of ACN on soil C at the National Agricultural Research Institute site, Yundum, The Gambia, located at 13° 14’ 16” N and 16° 38’ 34” W (Fig. 1). This site tends to have higher rainfall than the other sites at approximately 1100 mm per year (A. Jarju personal communication, 2004). The soils are also sandy and are cultivated during a rainy season of approximately June through October. These soils were also classified as Paleustalfs by Soil Taxonomy (Soil Survey Staff, 1975). Both this site and the site in Nioro, Senegal, were well populated with spontaneous shrubs such as *Icacina senegalensis*, Juss. and occasional legumes such as *Cassia tora* L., which grew well during the dry season and the biomass was incorporated before rainy season planting.

The perennial shrubs were cut and tilled in each year prior to the planting of annual crops. In addition, the shrubs needed to be cut back to reduce competition with the newly planted annual crop. We chose to incorporate the perennial shrub biomass rather than to remove it because of the potential impact on the soil C status. Some farmers cut and remove the shrubs while others incorporate the shrub biomass, as in this experiment.

In The Gambia the “landscape” treatment pair of ACN and non-ACN formed the whole plots in a split-plot design, which was replicated three times and was established in 2002 as a randomized complete block arrangement of the whole plots (40 m × 60 m), which were the ACN and non-ACN treatments. Levels of added fertility were subplots (10 m × 60 m in size).

The berms were constructed to channel excessive run-off from treatments to be delivered to a nearby waterway and away from the experiment and thus avoid run-on from adjacent plots.

Levels of fertilizer were the control, ½, 1 and 2 times the National Agricultural Research Institute (NARI) recommendation for the zone. The NARI recommendation was 200 kg ha^{-1} each of elemental N, P and K, which was applied as the fertilizers 8–24–24, with urea applied to bring the total application to 200 kg N/ha in 2003, but as 15-15-15 plus supplemental urea for 2004. Maize (*Zea mays*, L., cv. *"Jeka"*) was planted at a population of 53 000 plants ha^{-1} (Jarju personal communication, 2003).

2.1.3. Senegal

The study area in Senegal was comprised of several villages in the peanut basin in the Department of Nioro, Senegal. Intensive agriculture with no mineral fertilizer or organic matter input is practiced in the area. Peanut (*Arachis hypogaea* L.), millet (*Pennisetum glaucum* L.) and sorghum (*Sorghum bicolor* L.) are the principal crops grown in the Department of Nioro. These crops are grown in a rotation of peanut-millet and peanut-sorghum. Farmers' fields are mainly left barren after the cropping season because crop residues, especially peanut hay, are removed and sold on the market as animal feed. This practice exposes the land to wind and water erosion.

Replicated "landscape" experiments somewhat similar to those in the Gambia were installed in Senegal in 2003 on peanut fields of 7 farmers. The "landscape" aspect of the experiment in Senegal was implemented by placing either ACN or non-ACN on either side of a naturally occurring ravine occurring in each farmer's fields. Peanut (*Arachis hypogaea* L.) was planted annually after installation of the conservation treatments.

2.2. Soil sampling

2.2.1. Soil sampling for method 1 (adjacent fields)

Soil samples for this method were obtained from the matched pair of fields that were in a top slope position of the regional geomorphic surfaces near Siguidolo. Because the geomorphic surfaces in Mali are so large, the entire field was in a top slope position. A berm was established just above the ACN and non-ACN fields to prevent run-on in both cases. Soil samples of approximately 500 g were collected from the 0–20 cm depth for analysis and combined to make up a single composite sample. Samples were collected from February to March 2002.

2.2.2. Soil sampling for method 2 (sampling over years of multiple fields)

Soil samples were collected in fields that had been brought under ACN management at various years from 1994 to 2004. Five fields were selected with soils of similar color, texture and topography and reportedly cropped in a similar rotation of crops but with five different dates of implementing the ACN technology. A composite sample was obtained by combining three 500 g subsamples collected from the 0–20 cm depth and at four locations in the specified field. Samples were taken away from the tree canopy as we learned from the initial sampling and Traoré (2003) that samples taken near a tree are usually much higher in soil C than those taken outside of the tree canopy. Soil samples were collected from February to March, 2004.

2.2.3. Soil sampling for method 3 (replicated experiment)

Gambia. Sampling of the replicated experiment was carried out by collecting a composite soil sample from each experimental plot. Each composite sample was prepared by combining three or more 500 g subsamples at four or more locations throughout the plot (0–20 cm depth). Since the annually drawn ridges were still evident, soil samples were taken on the ridges. We expected that this might result in higher soil C levels than if samples were taken from the furrows, but considered soil collected on the ridges should best represent the crop rooting environment. Soil samples were collected February to March, 2004 in The Gambia.

Senegal. Soil samples were collected in 7 farmers' fields located in 3 villages; Djiguimar, Prokhane and Paoskoto. Soil samples were collected during the 2004 and 2006 cropping seasons in a grid pattern. Approximately 60 samples were taken per field at two depths, 0–20 and 20–40 cm, using an auger, and mixed to form a composite sample. GPS coordinates were recorded for each sample point. The samples were air-dried, screened through a 2 mm stainless steel sieve, packaged in airtight labeled plastic bags and shipped to the Agricultural Diagnostics Service Center (ADSC) at the University of Hawaii for soil carbon determination.

In all fields, care was exercised to ensure samples were at least 6m from the nearest tree, in order to avoid tree influence (Traoré, 2003). Samples were collected in February to March of the respective year.

2.3. Laboratory methods

Prior to analysis all soils were dried, sieved to the less than 2 mm fraction and stored air-dry until analysis. Soil organic C was analyzed by combustion (LECO C Analyzer, at the University of Hawaii in Manoa).

2.4. Statistical analyses

2.4.1. Method 1 (adjacent fields)

In Siguidolo, eight soil samples were collected from similar topographic positions within each of two fields, which were adjacent to each other. The 16 samples were then analyzed by

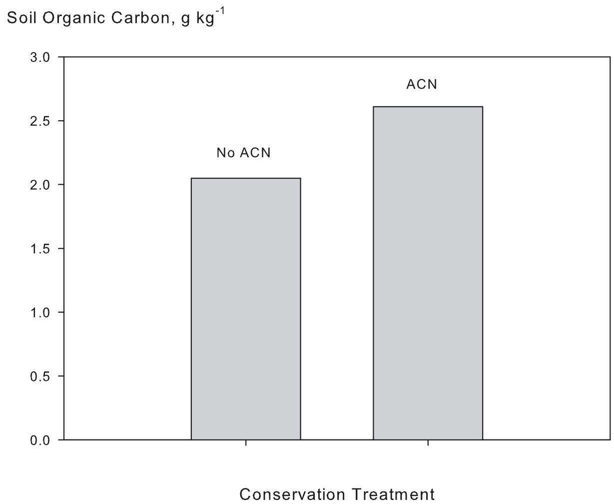

Figure 2. A comparison of soil organic C on adjacent matched farms, one without *Amenagement en courbes de niveau* (ACN) and one with ACN, Siguidolo, Mali. Soil C was significantly higher with the ACN technology. Treatments differed at the $P = 0.076$ level.

ANOVA methods using SAS PROC GLM (Littell, 2002). The eight positions were considered as replications in a paired test of ACN vs. non-ACN (Fig. 2).

2.4.2. *Method 2 (sampling over years of multiple fields)*

In Siguidolo soil C data of five fields were regressed on years under ACN using SAS PROC REG. The regression coefficients provided an estimate of the rate of C sequestration associated with the ACN practice (kg C $ha^{-1}y^{-1}$).

2.4.3. *Method 3 (replicated experiments)*

In the Gambia, the replicated experiment was a split-plot experiment with whole plots as ACN management and levels of added fertilizer as subplots. The experiment was analyzed by ANOVA using PROC GLM (Littell, 2002). In Senegal, each of the seven farmers was considered one replication of the treatment of ACN versus non-ACN and analyzed as a randomized complete block using PROC GLM.

3. RESULTS AND DISCUSSION

3.1. Comparison of soil organic C levels among sites

Soil organic C levels included some low values but also some relatively high values for sites in Mali – values ranged from 1 g kg^{-1} to 10.0 g kg^{-1} (Tab. I, Fig. 2). While the soils were taxonomically the same, soil organic C was higher at sites with higher rainfall – approximately 2.0 g kg^{-1} in Siguidolo (800 mm annual rainfall) compared with 5.0 to 8.0 in The Gambia. Values of clay content varied widely, generally in the 2.0 to 6.0 g kg^{-1} range, and soil pH in a 1:1 soil to water ratio varied between 5.0 and 6.0. The Mali sites, with values of 2.0 to 4.0 g kg^{-1}, contained typically low levels of soil organic C.

Table I. Results of Method 3, replicated experiments, on testing the effects of *Aménagement en courbes de niveau* (ACN) and no ACN and fertilization on soil organic C and maize yields in Western Gambia, 2004.

	Conservation treatment			
	ACN	No ACN	ACN	No ACN
Fertilizer	Soil organic C (g kg^{-1})		Yields, kg ha^{-1}	
Control (no fert.)	6.1	5.6	620	570
½ Recommended rate/2	10.6	7.6	2690	2120
Recommended rate	9.2	8.2	2210	1690
2 times rec. recommended rate	9.0	7.9	2120	1830
	Analysis of variance		Analysis of variance	
Source	F-value	*P*-value	F-value	*P*-value
Conservation system (T)	43.52	0.022	31.29	0.030
Fertilizer (F)	54.49	< 0.001	280.8	< 0.001
T×F	7.47	0.004	6.588	0.007

Levels of soil organic carbon were, as expected, quite low (Doumbia et al., 1998; Pieri, 1992). The variation in soil organic C was particularly large at the Siguidolo site (1.0 to 4.0 g kg^{-1}). A subsequent inspection revealed that the samples with 4 g kg^{-1} were close to shea butter trees (*Vitellaria paradoxa*). Traoré (2003) have shown that these trees contribute substantially to the soil organic C in their vicinity. This effect might be related to the deciduous character of the trees – a complete loss of leaves each year. The major increases in subsoil water associated with ACN may provide for greater tree and shrub growth during the dry season (Kablan et al., 2008).

3.2. Tests of the hypothesis that soil organic carbon was increased with ACN

3.2.1. *Method 1, Adjacent fields*

The results of this method indicated that while there were large differences in soil organic C between the two treatments (2.05 vs. 2.60), the differences were barely significant ($P = 0.076$) (Fig. 2). This method of testing appears to be the least statistically powerful of the three methods. Even if there were large differences, such an effect could be confounded with farmer management, which may include different crops, varieties, tillage and fertilization. Such factors were controlled in this comparison through a direct subsidy to the farmer.

3.2.2. *Method 2, sampling over years of multiple fields*

The second method, that of comparing estimates of soil C over time, also suggested a strong effect of ACN in increasing soil organic C (Fig. 3). Caution is needed in interpreting

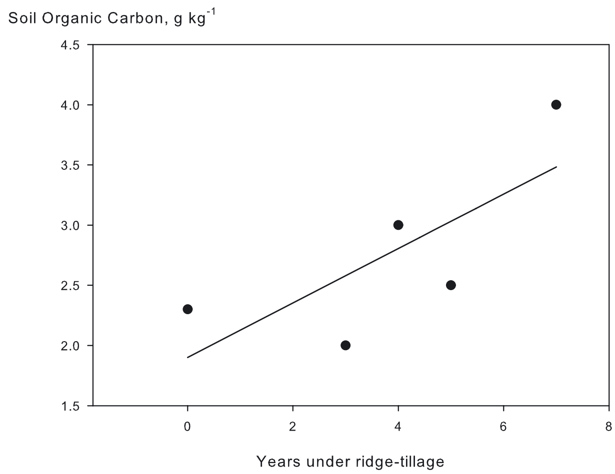

Figure 3. The change in soil organic C with time under *Aménagement en courbes de niveau*, (*ACN*) Siguidolo, Mali. Prediction equation: Soil organic C, g kg^{-1} = 1.987 × 0.226 × Years, Adj R^2 = 0.41. The regression was significant at P = 0.035. The results indicate a continual increase of soil organic C with longer time under the ACN soil and water conservation practice.

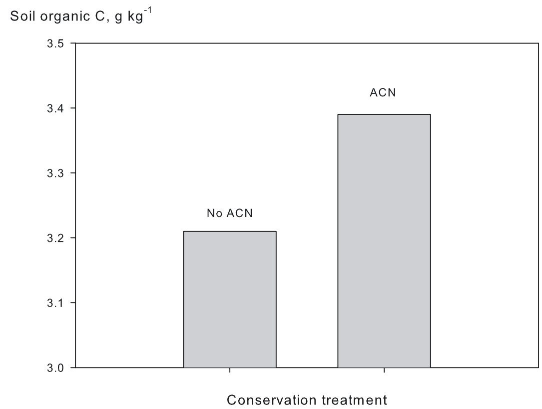

Figure 4. The change in soil organic C, Senegal Peanut Basin, 2004–2006. Mean of 7 farm experiments. Soil organic C in the *Amenagement en courbes de niveau* (ACN) plots was higher than in plots without ACN (no-ACN) at Prob. (<0.01). The ACN technology was adapted for planting on the flat rather than on ridges as in Mali and soil organic C increased as well.

these data, however. One assumption is that the fields initially placed under ACN management were identical to the most recent ACN fields. In subsequent discussions with the farmer, it was clarified that the farmer actually selected some of the most degraded fields for the initial ACN installation. Also assumed is that the tree density and proximity to sample sites was the same for the first fields placed under ACN management and the most recent. Given these considerations, the regression estimates indicate that over a seven-year period soil organic C increased by an average of 12% per year; in other words, soil organic C increased from 1.90 g kg^{-1} C to 4.0 g kg^{-1} over this period of time (Fig. 3).

Soil organic carbon was again significantly higher where fields had been under the ACN technology for a longer period of time.

3.2.3. Method 3, replicated experiments

The third method, that of testing the ACN management in a replicated experiment, was carried out at the Yundum site in The Gambia. During the first two years of the experiment, considered establishment years, there were no significant effects of the ACN treatments on soil C or yields. The results of the third year, 2004, are presented in this report. The results from year four, 2005, repeat those of 2004. The shrub *I. senegalensis* and the legume *C. tora* grew especially well in the ACN treatment plots. The *I. senegalensis* was incorporated prior to the planting of the rainy season crop. The results (Tab. I) indicate a significant increase of 26% in soil organic C where the ACN technology was implemented. Maize yields also increased significantly, 24%, as a result of the ACN management (Tab. I). As expected, fertilization significantly increased yields but only to the first rate of application ($^1/_2$ of the recommended rate of fertilization). As expected, fertilization increased yields more on the ACN treatment than on the non-ACN treatment as indicated by the significantly positive interaction (Tab. I). The results of the positive interaction indicated that when the fertilizer is applied where ACN had been installed it produces 33% more grain, thus significantly increasing fertilizer efficiency.

This initial rate of fertilization is approximately that recommended in Mali for similar soils (M. Doumbia, personal communication 2002). Gigou and Traoré (1997, pp.18–19) also obtained a positive interaction of fertilizer and the ACN, indicating that fertilizer applications were more effective when applied where ACN had already been implemented.

We speculate that the growth of the local shrub *Icacina senegalensis* and the legume *Cassia tora* contributed to the ACN effect since they remained green and grew during the dry season, probably due to the greater capture of rainfall and storage in subsoil due to the ACN (Kablan et al., 2008). Traoré et al. (2002) observed greater growth of the tree *Vitellaria paradoxa* where ACN had been implemented in Mali. Another possible explanation for the increased soil organic C, however, is the reduction in soil C loss as a result of reduced erosion (McCarty 2005, personal communication). Gigou et al. (1999) and Traoré (2003) have pointed out that ACN should reduce C losses through reduced soil erosion. Traoré et al. (2002, p. 8) estimate that reducing the loss of C due to erosion may be greater than the increases in C resulting from tree or crop biomass. Likely the size of these effects on soil organic C change with location, but certainly need to be better quantified.

Senegal The results of two years of implementation of the ACN modified for peanut cropping also indicated a significant increase in soil organic C on the 7 farm experiments (Fig. 4). The average increase in soil C per 40 cm depth (the sampled depth) was 270 kg C ha^{-1} yr^{-1} over the 7 farms.

These results show that the ACN technique can be modified depending on the cropping system, yet continues to provide soil organic C increases. Evaluation of watershed level impacts such as effects on groundwater availability during the usual dry season await expansion to implementation on many fields and at village levels, as has occurred in Mali.

3.3. Crop choice as affected by "Aménagement en courbes de niveau"

The sites compared in this analysis also differ in the crops that are grown, with maize being grown where rainfall is higher. Farmers report that with the adoption of ACN their cropping options can change from millet and sorghum to higher value crops such as cotton and maize (Roncoli et al., personal communication, 2002). The drier site (Siguidolo, Mali) was planted to millet and sorghum, but with ACN cotton and sorghum are more frequent. At the site in The Gambia, highly productive and high market value maize was successfully grown.

3.4. Increased biodiversity

As indicated in The Gambia, the shrubs such as *Icacina senegalensis* and the legume *Cassia tora* continued to grow during the dry season in Senegal (November to May) and were cut and incorporated into the soil at the beginning of the rainy season before the planting of crops. The shrubs are typically cut and burned in Mali, but this may be changing with the recent increased awareness of the value of biomass for soil C. Shrub biomass was significantly greater in ACN treatments (data not shown). Species such as *Annona senegalensis*, L. and *Terminalia macroptera*, Guill et Perr., both of which have recognized medicinal value, were found in the ACN treatments in The Gambia but not in the control (Diedhiou, 2006, personal communication). The shrub species may have contributed to the effect of ACN in increasing soil organic C (Djediou, 2006, personal communication).

4. CONCLUSION

4.1. Methods of assessing soil carbon change

In summary, all three methods (Method 1, paired fields; Method 2, multiple fields; and Method 3, matched, replicated plots) appear capable of testing the hypothesis that ACN management affects soil organic C in these experiments. Method 2 permitted a quantitative estimate of C accretion by regression, and Method 3 permitted an experimentally rigorous testing of the ACN technology in a controlled field experiment. All methods indicated a strong effect of ACN management on increasing soil organic C. Method 1 has an experimental flaw in that an observed C gain could have been caused by different management of the different farmers.

4.2. Scaling up from field to regional measurements of soil C

Because the unit of C trading is quite large (100 000 Mg) and trading will likely take place on a region-wide basis including many fields, possibly including regions of 10 000 to 20 000 ha, a regional soil C inventory will likely be scaled up from fields, and thus field-level measurements of soil C tonnages are necessary as input to the region-wide C accounting system (Doraiswamy et al., 2007). It is also clear that community organizations such as "Les Associations Villageoises" and possibly commune-level natural resource organizations as well as the parastatal organizations such as the *Compagnie Malienne de Développement des Textiles* (CMDT) must be involved in the organization of such large amounts of land. Some of these issues have been discussed in (Roncoli et al., personal communication 2003). As has been pointed out by Antle and Uehara (2002), it may be that simply maintaining the practice of ACN would be one way to ensure that the sequestered C remains stored in the soil and does not re-enter the atmosphere through mismanagement or accidents. Nonetheless, there are many social, cultural and political organizational issues that need to be addressed before C trading can be associated with this conservation practice. Kelly (2000) describes some of these issues with regard to other soil and water conservation practices. In our view, social and cultural issues rather than the biophysical factors and chemical measurements described in this paper will be the greatest challenges to the use of water and soil conservation techniques to increase soil organic C to offset CO_2 emissions. The organizing of farmers into groups sufficiently large to meet the minimum unit of trading and maintaining a particular practice seem to be the key challenges to effectively scaling up this technology for carbon trading. Other components of the Carbon from Communities project have addressed some social and cultural issues (Roncoli et al., personal communication 2003) and, to some extent, scaling up (Doraiswamy et al., 2007). Lastly, while this paper discussed one water and soil conservation technology, it is clear that there are many other such technologies (Kelly, 2000). Some of the methods and issues discussed in this paper relative to ACN may be helpful in evaluating soil organic C sequestration by other technologies.

5. BENEFITS FOR THE LOCAL SOCIETY

All results indicate that the ACN ('Ridge-tillage') water and soil conservation management technology increased soil organic C. The increase in soil organic C was 12% per year in Siguidolo over seven years and 26% as measured at the Yundum site, The Gambia and 14% in new fields in the peanut basin of Senegal. The increase in soil organic C appears to be related to at least three factors: (a) increased crop growth and yields, (b) increased growth of trees and shrubs and their input of litter and soil C, and (c) the reduction in soil erosion losses of soil C. These components of the yield increase remain to be quantified as studies continue. Data from the current experiments are also being analyzed by geospatial methods, which are expected to provide quantification of some of the effects proposed herein as well as recommendations for optimal sampling distance, frequency of sampling and estimates of uncertainty related to the C tonnage calculations (Querido, 2008). Further studies on how the technology might be scaled up and how to measure its impact on a watershed or commune scale are clearly needed in order to adequately assess the impact of this and other water conserving technologies.

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