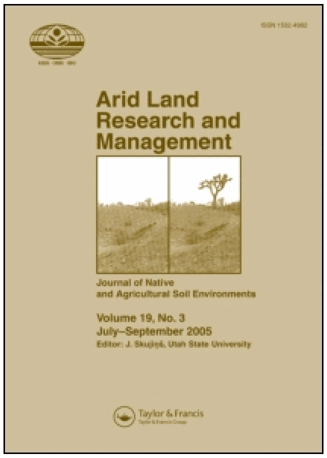

Arid Land Research and Management

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926000

"Aménagement en courbes de niveau," Increasing Rainfall Capture, Storage, and Drainage in Soils of Mali

Richard Kablan [a]; Russell S. Yost [a]; Kevin Brannan [b]; Mamadou D. Doumbia [c]; Kalifa Traoré [c]; Abdramane Yoroté [c]; Youssouf Toloba [c]; Salif Sissoko [c]; Oumar Samaké [c]; Michel Vaksman [c]; Lasana Dioni [c]; Mankan Sissoko [c]
[a] University of Hawaii at Manoa, Honolulu, Hawaii
[b] Virginia Polytechnic and State University, Blacksburg, Virginia, USA
[c] L'institut d'Economie Rurale (IER), Mali

To cite this Article: Kablan, Richard, Yost, Russell S., Brannan, Kevin, Doumbia, Mamadou D., Traoré, Kalifa, Yoroté, Abdramane, Toloba, Youssouf, Sissoko, Salif, Samaké, Oumar, Vaksman, Michel, Dioni, Lasana and Sissoko, Mankan (2008) '"Aménagement en courbes de niveau," Increasing Rainfall Capture, Storage, and Drainage in Soils of Mali', Arid Land Research and Management, 22:1, 62 - 80
To link to this article: DOI: 10.1080/15324980701784191
URL: http://dx.doi.org/10.1080/15324980701784191

Arid Land Research and Management, 22:62–80, 2008
Copyright © Taylor & Francis Group, LLC
ISSN: 1532-4982 print/1532-4990 online
DOI: 10.1080/15324980701784191

Taylor & Francis
Taylor & Francis Group

"Aménagement en courbes de niveau," Increasing Rainfall Capture, Storage, and Drainage in Soils of Mali

Richard Kablan[1], Russell S. Yost[1], Kevin Brannan[2], Mamadou D. Doumbia[3], Kalifa Traoré[3], Abdramane Yoroté[3], Youssouf Toloba[3], Salif Sissoko[3], Oumar Samaké[3], Michel Vaksman[3], Lasana Dioni[3], and Mankan Sissoko[3]

[1]University of Hawaii at Manoa, Honolulu, Hawaii
[2]Virginia Polytechnic and State University, Blacksburg, Virginia, USA
[3]L'institut d'Economie Rurale (IER), Mali

Food security is a concern in many parts of the tropics, but it is an acute problem in a band of countries bordering the Sahara desert on the south-Sub-Saharan Africa. Crop productivity and production, stability, and resilience to adverse events seem to be diminishing with time. Low productivity is related to both adverse soil conditions and insufficient rainfall amounts and distribution. Portions of the region receive substantial amounts of rainfall, yet much is lost during intense storms. A rainfall capturing technology "Aménagement en courbes de niveau" (ACN), a variant of closely spaced, narrow-base terraces, has been developed in Mali and has proven beneficial in several West African countries. A field where ACN had been installed was instrumented to quantify the effects of ACN on soil/water availability. Capacitance probes were installed to 160 cm so that soil moisture measurements could easily be taken two to three times a week during 2 years—2003 and 2004. Soil moisture profiles indicated that substantially more water was retained in soils where the ACN technology was installed than where it was not present. The ACN technology led to increased soil moisture during the first month of rains. However, the differences in soil moisture were greatest at the end of the rainy season when soil moisture of the subsoil was much greater where the ACN technology had been implemented. Moisture contents were greater in the soil profile 80–160 cm with values ranging 0.18–.21 $cm^3\ cm^{-3}$ *compared to 0.15 in the No-ACN plots.*

Keywords Aménagement en courbes de niveau (ACN), deep drainage, ground water storage, landscape management, ridge tillage, soil moisture, watershed

Introduction

Africa has changed from an exporter of food in the 1960's to one of imports and frequent food shortages and famine. Food imports, accounting for 17% of food needs in the region are projected to double by 2010 (Nana-Sinkam, 1995). The decline in

Received 28 August 2006; accepted 12 September 2007.

Address correspondence to Richard Kablan, 3190 Maile Way, St. John 102, University of Hawaii, Honolulu, HI 96822. E-mail: rak@hawaii.edu

food production has mainly been attributed to soil fertility decline and adverse changes in climate. The recent famine in Niger is a grim reminder of these changing conditions.

Climate

Climate effects on food security are multiple, but the ones we will describe and consider in this article are those associated with rainfall—its amount, distribution, and intensity. Regions in West Africa can be grouped based on annual rainfall (Gore and Steeds, 1987):

- Sahel – 200–400 mm
- Sahelo–Sudanian – 400–600 mm
- Sudanian – 600–800 mm
- Sudano–Guinean – 800–1200 mm

The site selected for this study falls in both the Sahelo-Sudanian and Sudanian zones of average annual rainfall. Rainfall intensity is an important aspect of rainfall because of its interaction with soil properties, especially the rate of infiltration. The intensity of the rain is much higher than that observed in many regions of the world, especially with similar amounts of rainfall. Hoogmoed and Stroosnijder (1981) report studies of two sites where high rainfall intensities are evident:

- Niono, Mali (3-year average of 368 mm annual rainfall): six locations were measured in 1977, 1978, and 1979 and provided peak intensities of 190 mm hr^{-1} in 1977, 230 mm hr^{-1} in 1978, and 300 mm hr^{-1} in 1979.
- Niamey, Niger (3-year average of 392 mm): Hoogmoed and Stroosnijder (1981) also measured very high intensities in an earlier study in 1970 of 231 mm hr^{-1}, 1971 of 150 mm hr^{-1}, and 1972 intensities of 253 mm hr^{-1}.

These intensities were among the highest measured in tropical conditions by Hoogmoed and Stroosnijder (1981).

Soils

Soils of the region are classified mostly as Alfisols according to Soil Taxonomy (Soil Survey Staff, 1999), with many Paleustalfs and frequent Plinthustalfs. The Ustalf classification indicates that the soils are, indeed, highly weathered and highly leached. The classification of Plinthustalfs is of special concern because it indicates that the soils contain a plinthite layer of soft Fe and Al oxides that will harden irreversibly into lateritic stone if exposed. Landscapes of the region have many surfaces resulting from exposed plinthite that have hardened into stone. Such occurrences emphasize the critical need to control and prevent erosion exposure of such surfaces—else additional land will be irreversibly lost.

The Alfisol soil order indicates that the soils are constrained by both small amounts of nutrients and a low capacity to retain nutrients due to the chemical constituents. Crop productivity is further diminished due to the low quantities of organic carbon and the exhausted state of the soil fertility. While there are debates as to what are the most limiting factors—nutrients or water—(Bremen and de Wit, 1983), it is usually necessary to ensure that both nutrients and water are supplied to obtain maximum crop productivity. Pieri (1995) has described the pervasive nutrient deficiency of the region. The extensive nutrient mining that has been occurring in the region is discussed in Pol and Traoré (1993). It also seems clear that not only have nutrients been mined but also stocks of soil organic carbon have and are still being mined, which obviously plays a key role in such low clay, low silt soils (Pieri, 1995).

Other soil factors that limit productivity are the soil physical properties. The soils are characterized by a low water-holding capacity due to the small amounts of silt and clay (Pieri, 1995). In addition, the soils tend to crust very easily and in ways that drastically reduce infiltration of the scarce rainfall (Hoogmoed and Stroosnijder, 1984). Hoogmoed and Stroosnijder (1984), for example, describe the crusting, its influence on infiltration, and management options. They point out that soil crusts and its impact on infiltration are nearly impossible to measure directly—hence their emphasis on the use of rainfall simulators. Based on their results, infiltration rates of no more than 0 to 2 mm/hr are often measured. In other studies, Casenave and Valentin (1989) have obtained similarly low infiltration rates but went on to identify as many as seven to nine types of soil crust depending on the generating process.

Water Balance

Water balance analyses from rainfed farming systems in the Sahelian environments of sub-Saharan Africa indicate that only 15–30% of the rainfall on average is used for productive crop growth (Rockström et al., 1998). The major loss of rainwater appears to be due to high runoff and low infiltration rates during the high intensity rainfall. On smallholder farms subject to land degradation, less than 10% of the rainfall is used by crops for transpiration (Rockstrom et al., 1998). This condition leads to frequent agricultural drought and yields of cereals around 0.5 to 1 tonne ha^{-1} (Doumbia, 2007, personal communication), even when rainfall of as much as 1000 mm may occur.

Water and Soil Conservation Technologies

With recurring droughts and decreased agricultural productivity during the last two decades in West Africa (Sivakumar, 1992), there have been many attempts to better utilize the available rainfall with technologies such as the stone lines, "zai" technology, and more recently with "Aménagement en courbes de niveau" (ACN), a variant of closely spaced, narrow-base terraces. A recent summary of technologies available in the Sahel is given in Bertelsen and Brewster (2003).

Kaboré and Reij (2004) report that the zai technology has been effective on heavier textured soils of Burkina Faso. Techniques suitable for the broad expanses of sandy soils of the Sahel, however, continue to be a challenge. One of the innovations that holds promise on sandy soils is a holistic landscape level method of managing surface water on farmers' fields referred to as "Aménagement en courbes de niveau". One of the unique aspects of the ACN technology is to retain or capture rainfall on the field near the crop roots, along with retaining the rainfall through contoured ridge that leads to increased infiltration.

Long-term studies initiated by Gigou et al. (1997, 1999, 2006) and have shown that soil erosion is essentially halted if farmers' fields are managed using the ACN technology. The ACN technology can result in increased infiltration of rainfall, which can increase water availability for crop growth and reduce erosive runoff.

Field studies of the ACN technology have shown that during drier years, crop yield can be increased as much as 50% for millet, sorghum, and maize (Gigou, 1996; Gigou et al., 2006).

The goal of this study was to quantify rainfall capture and soil moisture storage within the field resulting from ACN management.

Materials and Methods

Site Characteristics and Conditions

The experiment site, Siguidolo, Mali is located in the Sahelian zone, near the Niger River floodplain, with lateritic uplands alternating with gentle slopes and lowlands, in which rainfall ranges from 600–800 mm. The topography of the region is dominated by flat surfaces with an average altitude of about 300 meters and hills that seldom exceed 400 meters in altitude.

Crops produced in the Siguidolo include millet, cotton, sorghum, maize, peanuts, watermelon, cowpeas, and tomatoes. The growing season varies from 90 to 150 days, and is determined by the highly seasonal rainfall. Cotton (*Gossypium hirsutum*, L.) is produced in the region with the assistance of Compagnie Malienne de Developpement des Textiles (CMDT). The population of the village is organized into 46 agricultural production units (UPA). Typically, the CMDT provides fertilizers, cotton seed, and credit to farmers of the villages and collects the cotton crop at a set price after harvest. Farmers often rotate sorghum and millet or occasionally maize with the cotton to take advantage of the residual fertilizer effects.

ACN Construction and Field Layout

Aménagement en courbes de niveau is a holistic landscape approach to manage water and capture rainfall on a watershed scale (Gigou et al., 2006). The permanent ridges, about 100 cm wide, are constructed prior to the planting of crops. The annual small ridges can be constructed along the major ridges depending on cropping systems. Waterways to evacuate excess water off the fields may also be constructed as part of the ACN system. Using the ASABE classification of terraces, the ACN is very similar to the "narrow-base terrace" (ASABE, 2006). The ACN terraces, a technology developed locally by the Institut d'Economie Rurale (IER) and CIRAD (Gigou et al., 2006), are much closer spaced, likely due to the low infiltration rate of the soil and the high rainfall intensity described earlier.

Placing a field under ACN management involves three steps: 1) A survey of the land and a diagnosis of water flow problems of the particular field, jointly carried out by the soil and water conservation technician and the farmer for the purpose of developing a general plan of water management ("Diagnostique"); 2) Staking of the locations of the permanent ridges on the contour (Ados) by the field technician using a level ("Piquetage"); 3) Construction of the Ados (permanent ridges) by the farmer using a ox-drawn plow, or hoes if plows are not available. Usually five or six passes by the plow are sufficient for the initial ridges, but careful maintenance is required by the farmer, especially during the first season and if there are large storms. Usually, the Ados stabilize after the first year with minimal but critical maintenance needed subsequently. A typical distance between the permanent ridges (Ados) ranges from 20 to 50 meters with distance between Ados decreasing with

Table 1. Selected properties of the soil at the experimental site, Siguidolo Village, Konobougou, Mali

	Plinthic Paleustalfs						
Soil classification	Water pH	Bulk density	Org. C	Org. N	Sand	Silt	Clay
Soil depth, cm			- -%- -				
0–20 (n = 24)	5.89	1.58	0.24	0nd	79	16	4.9
20–40 (n = 24)	5.36	1.52	0.22	0	66**	20*	13.5**

nd = none detected; *significant at $P \leq 0.05$; **significant at $P \leq 0.01$.

increasing slope. If the slope is very flat, the maximum distance between the Ados will be 50 m. If the slope is steep, the Ados will be placed such that change in elevation between the Ados never exceeds 80 cm.

At Siguidolo, crops are planted on the annually drawn ridges that are formed just after the first rains loosen the soil and prior to planting and according to the contours indicated by the permanent ridges (Ados). The heights of the Ados were about 50 cm and have been in place since 1994. Annually drawn ridges between adjacent Ados were about 20–30 cm in height. Dates of planting and harvesting of the cotton are given in Table 2.

Measurements of Soil Water Status

Soil moisture was measured using a soil moisture measuring instrument, the Diviner 2000® (Sentek Sensor Technologies, Stepney, Australia). The instrument consists of a handheld, portable data logger display unit, connected by cable to a depth-scaled probe rod with a sensor attached. The probe is nonradioactive and detects water based on capacitance differences (Starr and Paltineau, 2002). The accuracy of the probe was better than 1% volumetric soil moisture. Soil moisture measurements from one of the 160-cm access tubes could be taken and electronically recorded in 10–15 seconds. Readings were taken almost daily over the growing season and weekly thereafter in Siguidolo.

Calibration

Soil moisture sensor readings of a particular site were converted into values that represent volumetric soil moisture using a specific calibration for the site. The calibration of the sensor was carried out by comparing the scaled frequency

Table 2. Planting and harvest dates for crops in Siguidolo Village, Konobougou, Mali, 2003 and 2004

	Konobougou	
Year	2003	2004
Crop	Cotton	Cotton
Planting date	June 4	June 11
Harvest date	September 16	September 22

readings from an access tube installed in the field with values of volumetric soil moisture determined gravimetrically from soil adjacent to the tube. Soil bulk density was measured at each 10 cm depth increments.

Calibration Equation

The relationship between scaled frequencies (SF) and independently determined volumetric soil moisture values provided the calibration curve. This was obtained by plotting the scaled frequency data on the X-axis and plotting volumetric soil moisture on the Y-axis in Sigmaplot (Systat Software, Inc., San Jose, California), a graphic software program, and by performing a regression analysis on the data. The equation obtained was as follows:

$$\theta_{\mathrm{v}} = \mathrm{A}\ (\mathrm{SF})\ \mathrm{B}, \tag{1}$$

where θ_{v} is the volumetric soil moisture and SF is the "scaled frequency" produced by the sensor equipment. The equation was then used to fit the measured data in the field to determine the volumetric soil moisture (θ_{v}) of each profile.

Field Measurements

Two treatments were instrumented at the Siguidolo experimental site in 2003, where the ACN and no-ACN comparison had been in place for 9 years. Two replications were established in a randomized complete block experimental design as shown in Figure. 1. Twelve PVC access tubes were installed in each of the two replications (Figure 1). In each treatment, four access tubes were installed at random distances from the Ados. The tubes were located across the slope but at equal distances along the slope (between two Ados). Two additional tubes were installed above and below the two selected Ados. Each PVC access tube (5.1 cm ID and 5.6 cm OD) was installed to a depth of 160 cm. When the access tubes were installed, steps were taken to ensure the least disturbance to the surrounding soil profile, and to ensure firm contact between the access tube and the soil to avoid air pockets along the length of the access tube. Both of these concerns could compromise the readings of soil capacitance (Starr and Paltineau, 2002). The access tubes must, in fact, be installed with a specially designed tool that ensures good contact between the soil and the tube surface.

Data Handling and Analysis Methods

Calculation of Soil Water Storage

To quantify the water stored in each soil profile, soil volumetric soil moisture was converted into soil equivalent depth of water (ED). Equivalent depth is the depth of water that would result from extracting all of the water from the soil. Soil water equivalent depth (ED, mm) was obtained by multiplying the volumetric soil moisture ($\mathrm{cm}^3\,\mathrm{cm}^{-3}$) by the thickness of the depth increment along the access tube. For the 16 horizons (10 cm increments for a total depth of 160 cm) of a given soil profile, ED was obtained as follows:

$$\begin{aligned} &\int_i^Z \theta_{vi}(Z_i) = \textit{General form} \\ &\sum_i (\theta_i Z_i) = \textit{Equivalent depth of the soil profile} \end{aligned} \tag{2}$$

where: θ_{v} = volumetric soil moisture, ($\mathrm{cm}^3\,\mathrm{cm}^{-3}$) $\mathrm{Z_i}$ = depth increment, cm.

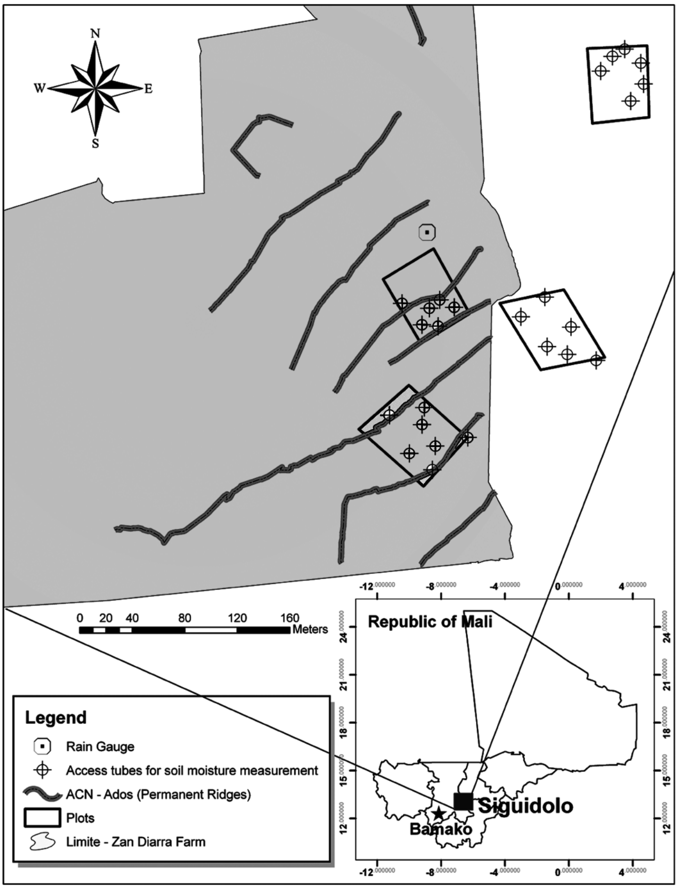

Figure 1. Layout of the experimental site at Siguidolo, Zan Diarra field (lines are Ados; dots are the location of the Diviner 2000® PVC access tubes for soil moisture measurement).

In this way, the soil moisture of each 160 cm soil profile was totaled. Equivalent depth (ED) was then compared for soil profiles in ACN and in No ACN plots for each of the two replications. Equivalent depth values were also used to calculate changes in soil moisture percentage (ΔED %) between ACN and No ACN treatments for a given soil horizon or soil profile and growing season as follows:

$$\Delta\mathrm{ED}\ (\%) = [(\mathrm{ED}_{\mathrm{ACN}} - \mathrm{ED}_{\mathrm{no\ ACN}})/(\mathrm{ED}_{\mathrm{no\ ACN}})] \times 100\%, \tag{3}$$

where $\mathrm{ED}_{\mathrm{ACN}}$ = the soil water equivalent depth in the ACN plots and $\mathrm{ED}_{\mathrm{no\ ACN}}$ = the soil water equivalent depth in the No ACN plot.

The difference in soil moisture storage between ACN and No ACN treatments was calculated as follows:

$$\Delta\mathrm{ED}\ (\mathrm{mm}) = \mathrm{ED}_{\mathrm{ACN}} - \mathrm{ED}_{\mathrm{no\ ACN}}. \tag{4}$$

Representative Soil Moisture Profiles

In order to characterize soil moisture during the season, two tubes located in the center of each experimental plot were selected to represent the soil water status during the cropping season. The selected tubes were distant from the boundaries of the plots and included all of the measurement tubes. The interior position of these tubes was chosen such that border effects would be minimized. ACN and No ACN treatments are represented by soil moisture from tubes from these locations for the months of July and September in 2003. Values for August were similar to those of September and thus were not shown. Values for 2004 were similar to those of 2003 and were also not shown. Equivalent depth values for 2004, however, are included for comparison with those of 2003.

Data Processing

Profile Soil Moisture

A large number of data points were recorded as a result of six tubes for each of the four plots, with 16 measurement depths and multiple readings during the growing season. Consequently, over 10,000 data points were recorded for each year. A systematic search for outliers was carried out using MATLAB® software (The Mathworks, Inc., Natick, Massachusetts). Minimum and maximum values for soil moisture were set at $0.005\,\mathrm{cm}^3\,\mathrm{cm}^{-3}$ and $0.30\,\mathrm{cm}^3\,\mathrm{cm}^{-3}$, respectively. Values outside this range were examined and usually replaced by the average value of the moisture content in the depth increments directly above and below the outlier.

Data Analyses

Mean comparisons and analyses of variance considering ACN and No ACN as treatments in a two-way analysis of variance were carried out using the SAS GLM and MIXED procedures (SAS PC, Version 9.13, SAS Institute Inc., Cary, North Carolina).

Measurements of Infiltration Rate

Infiltration rates were determined for both ACN and the non-ACN treatment areas (Figure 1). Three replications of infiltration measurements were made for each treatment (ACN and no-ACN) using double-ring infiltrometers with an inner diameter of 12 cm and an outer diameter of 24 cm, and otherwise as described by Reynolds et al. (2002). Infiltration rate measurement continued for more than 24 hours, usually with an initial wetting on one day and detailed measurement on the following day. Measurements were made for 2004, 2005, and 2006 and combined for the analysis here. Data were analyzed by regression for the steady-state conditions after at least 12 hours or prewetting. Specifically, we fit a regression equation to the rate of infiltration versus time. The coefficients of this regression were then analyzed by standard analysis of variance techniques (Little et al., 2002). The infiltration rates reported were obtained from the regression coefficients obtained as previously described.

Statistical Analysis

The experiment was designed as a "superimposed" experiment, wherein the treatments were already in place and in progress for 4 years previously. There are several important limitations to such studies; firstly is the lack of true randomization in the application of treatments to the experimental material (Cochran and Cox, 1957).

The first type of limitation, the lack of true randomization and replications, was considered but no satisfactory answer was found. The usual methods of treating this issue were not possible in this experiment. Typically, this limitation is addressed by laying out plots, taking initial measurements, randomly applying treatments, and following treatment effects with subsequent data collection.

The second limitation is that of assuring that all practices except the ACN were similar in the ACN and no ACN plots. Effort was applied to ensure that the tillage, cropping, fertilization, and other practices remained the same on the control farm. A subsidy was provided for the control farmer in view of the considerable evidence that crop yields were greater where ACN was implemented (Gigou et al., 2006).

A third type of limitation in watershed experiments is that with small plots of the type typically used in fertilizer experiments, the effects of neighboring plots are minimized and excluded from the analysis. With water conservation experiments of the type described here, effects of adjacent plots are extremely important as are effects of any specific plot on the other plots adjacent to it. These effects could not be quantified or controlled in the current experiment, but previous experience by the technology originator were that ACN tends to be more effective if several fields are implemented together rather than one isolated field (Gigou, 2004, personal communication).

These experimental considerations indicate a need for better statistical methods for multiple field and watershed scale experiments.

Results

Rainfall

The annual rainfall data shows that year 2003 was much wetter than the year 2004, 840 mm versus 521 mm, respectively (Table 3). According to data from Hoogmoed (1981), these amounts are well within the expected range of rainfall of the region.

Profile Moisture Comparisons: Volumetric Soil Moisture

Soil moisture storage patterns of the soil profiles of three selected zones that appear dissimilar were compared as follows:

1. Zone 20–40 cm, where the soil moisture was at field capacity (0.24 $cm^3 cm^{-3}$) and even exceeded the estimated field capacity at 30 cm depth in the ACN plots (Figure 2, ACN July and Figure 3, ACN September).

Table 3. Annual rainfall during the cropping seasons of 2003–2004, Siguidolo Village, Konobougou, Mali

Rainfall distribution at Konobougou						
	Monthly (mm)					
Rainfall period	May	June	July	August	September	Annual (mm)
2003	5.8	153.2	198.8	218.8	264	840.6
2004	4.8	80.80	196.2	142.4	97.0	521.20

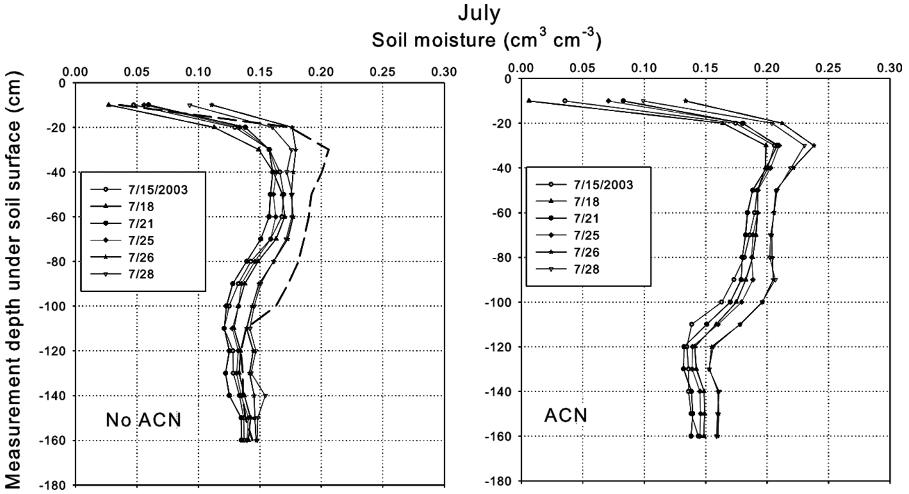

Figure 2. Soil moisture profiles over time at Siguidolo in the ACN and No ACN plots (July 2003).

2. Zone 40–80 cm, zone where soil moisture remained nearly uniform in July and September in the No ACN plots but below field capacity (Figure 2, No ACN July and Figure 3, No ACN September).
3. Zone 80–160 cm, zone where soil moisture decreased steadily with depth and never exceeded soil water values recorded in July (Figure 2, No ACN July and Figure 3, No ACN September).

However, soil water storage in the ACN plots for July in the 20–40 cm zone, increased in the ACN plots with time from 0.16 $cm^3 cm^{-3}$ to about 0.24 $cm^3 cm^{-3}$. In the 40–80 cm zone horizon soil moisture decreased and ranged from 0.22 $cm^3 cm^{-3}$ to

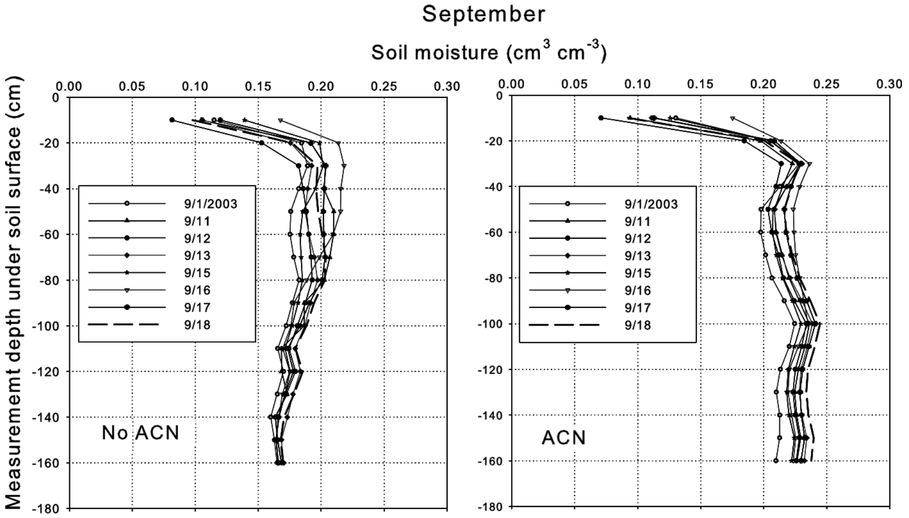

Figure 3. Soil moisture profiles over time at Siguidolo in the ACN and No ACN plots (September 2003).

0.18 $cm^3\,cm^{-3}$. For the zone 80–160 cm, soil moisture decreased and ranged from 0.21 to 0.13 $cm^3\,cm^{-3}$. For the No ACN plots, in the 20–40 cm zone, soil water increased with time. This increase ranged from 0.11 cm to 0.18 $cm^3\,cm^{-3}$, while in the 80–160 cm zone soil moisture remained below 0.15 $cm^3\,cm^{-3}$.

In September, soil moisture in the ACN plots for the 20–40 cm zone remained similar to the one in July, while the zone 40–80 cm and 80–160 cm became nearly uniform with soil moisture values approaching field capacity. In the No ACN plots, however, soil moisture decreased with depth ranging from 0.20 down to 0.16 $cm^3\,cm^{-3}$ in the 40–80 cm depth and from 0.20 to 0.16 $cm^3\,cm^{-3}$ in the 80–160 cm zone. There was no indication that water had moved downward from the zone above (0–80 cm) into the lower depths (80–160 cm) and it probably remained well below field capacity (estimated at 0.2 to 0.25 $cm^3\,cm^{-3}$).

Profile Soil Moisture Comparisons: Equivalent Depth of Water

The soil water ED was calculated to allow comparison of the soil water dynamics between ACN and No ACN plots during the cropping and after the cropping season, for each one of the selected zones, 20–40 cm, 0–80 cm, and 80–160 cm. The ED calculation permits a quantitative estimate of the cumulative soil moisture in all the tubes associated with the ACN and no ACN. This calculation indicates that, indeed, the amount of water in the 20–40 cm zone was significantly greater in the ACN plots and about 29% greater where ACN was present (Table 4). By September, after essentially all rains had been received, this percentage increased to about 37.6% (Table 4).

When the soil profiles were divided into two—0–80 and 80–160 cm zones—the results indicated substantially more water was retained in the profile where ACN was present (Table 5). In 2003, the increase in water where ACN was present was 12.7% of ED, in the 0–80 cm and 21.7% in the 80–160 cm zones. In the lower rainfall year of 2004, the percentages were 5.7 in the 0–80 cm zone and 9.2% in the deeper 80–160 cm zone. Higher ED values in the deeper zones indicate the possibility of deep soil water percolation.

Table 4. Comparison of soil moisture, equivalent depth (ED) of water, for the soil horizon 20–40 cm between ACN and No ACN, Siguidolo Village, Konobougou, Mali (2003)

	[1]ED for horizon 20–40 cm depth (mm)			
	Treatment[2]			
Crop growing period (month)	ACN	No ACN	% increase due to ACN	Significance level-ACN vs. No ACN probability
July (n = 36)	59.87a	46.38b	29.1	.0001
September (n = 48)	64.81a	47.11b	37.6	.0001
June, July, September (n = 102)	63.27a	55.09b	14.8	.0001

[1] ED (equivalent depth – mm of water per specified depth).

[2] Treatments with the same letter are not statistically different at $P = 0.05$.

Table 5. Summary comparison of the soil water dynamics between ACN and No ACN during the cropping season at Siguidolo Village, Konobougou, Mali, 2003 and 2004

		Cropping period (July–September)				
		Treatment[1]				
		ACN		No ACN		
Soil horizon (cm)	Growing year	[2]ED_{ACN} (mm)	% of horizon 0–160	$ED_{no\ ACN}$ (mm)	% of horizon 0–160	ΔED (%) moisture increase due to ACN
0–80 (n = 544)	2003	156.1a	50	138.5b	52	12.7
80–160 (n = 544)		156.2a	50	128.4b	48	21.7
0–160 (n = 1088)		312.3a	[3]NA	266.9b	NA	17.0
0–80 (n = 244)	2004	122.5a	48	115.9a	49	5.7
80–160 (n = 244)		131.9a	52	120.8b	51	9.2
0–160 (n = 488)		254.4a	NA	236.8b	NA	7.4

[1] Treatments with the same letter are not statistically different at $P = 0.05$.
[2] ED (equivalent depth-mm of water per specified depth).
[3] NA (not applicable).

Profile Soil Moisture Comparison: Equivalent Depth of Water During the Rainy Season

Using the equivalent depth values, an average moisture gain due to ACN was calculated for the whole growing season and is presented in Table 5 and Figure 4. Over the growing season, the ACN soil profile stored 17% more water on the average than No ACN in 2003. But when the soil profile was divided into two horizons (0–80 and 80–160 cm), the soil moisture gained due to ACN was 21.7% in the lower horizon (80–160 cm) versus 12.7% in the top 80 cm. This increased amount of water in the 80–160 cm zone, the zone of deep-rooted shrubs and trees such as the shea butter (*Vitellaria paradoxa*) is likely to lead to greater shrub and tree growth and productivity. These results may be a reason for farmer reports of longer availability of groundwater in the dry season since ACN was implemented in his watershed (Yaya Diassa, personal communication, 2007).

Profile Soil Moisture Comparison: Equivalent Depth of Water After the Rainy Season

Soil moisture monitoring after the rainy season (Figure 5) indicates that the soil profile continues to store a greater amount of soil water where ACN has been implemented. The lower soil horizons appear to have benefited to a greater extent from the rainy season where ACN management was in place (Table 6). The change in soil water storage between ACN and No ACN was less in the top horizons (0–80 cm), which may be due to increased plant water consumption associated with increased yields and biomass as well as surface water evaporative loss.

Infiltration Rate

The infiltration rates for 3 years (2004–2006) of all the sites tested is shown in Table 7. The ACN sites had significantly higher infiltration rates than those of the

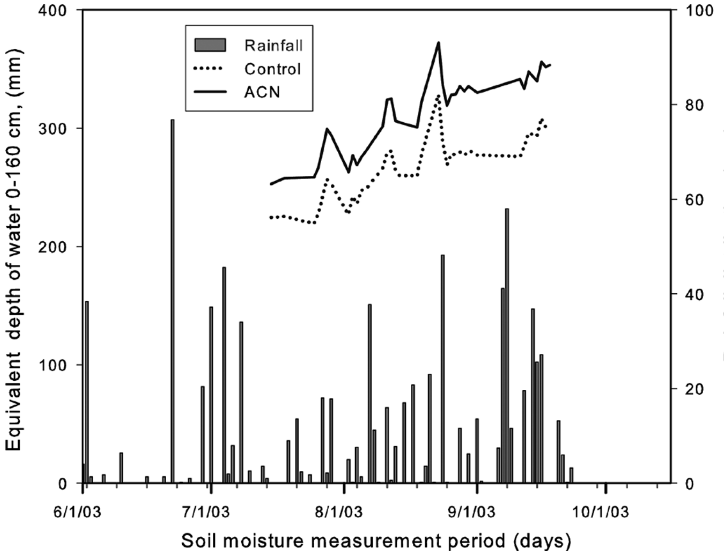

Figure 4. Daily evolution of soil water storage between ACN and No ACN during the growing season (horizon 0–160 cm) of 2003.

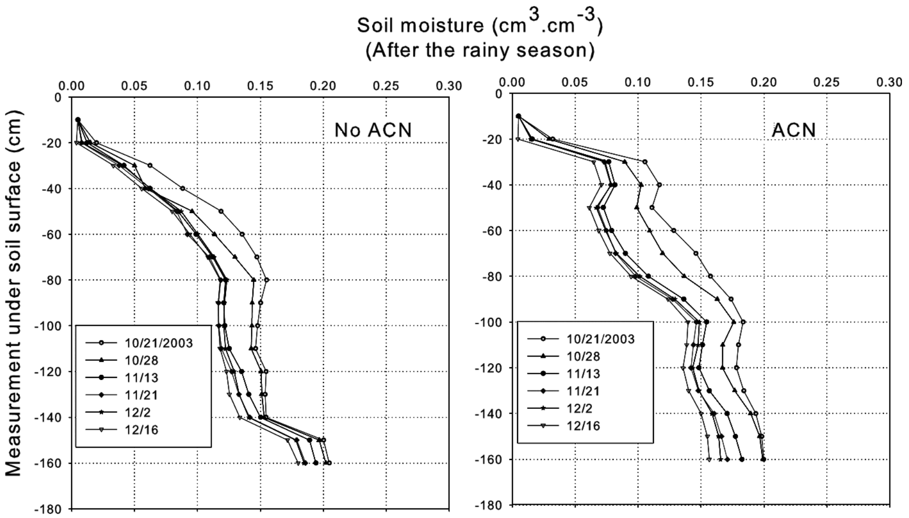

Figure 5. Soil moisture differences between ACN and No ACN over time after completion of the rains in 2003.

No ACN sites. The mean surface infiltration rates for the 3 year period were 7.48 cm/hr and 4.49 cm/hr in the ACN and the No ACN plots, respectively. There also appears to be a trend towards more difference in infiltration rate with time.

Discussion

Equivalent Depth of Water During the Rainy Season

The data of this study indicates that the ACN soil profile stored 17% more water than No ACN in 2003. This increase occurred more in the deeper soil depth (80–160 cm) where the equivalent depth of water increased to 21.7% as compared to a 12.7% increase in the top 80 cm. This increased amount of water in the deeper zone, the zone of deep-rooted shrubs and trees such as the shea butter (*Vitellaria paradoxa*), is likely to lead to greater shrub and tree growth and productivity. These results also support the hypothesis of deep water infiltration and the reports of increased groundwater recharge and dry season irrigation (personal communication, Siguidolo villagers, 2006).

Growing Season 2003 Versus 2004

In general, the soil water dynamics for the year 2004 were similar to those of 2003. In the No ACN plots, the soil moisture versus depth showed that a maximum soil moisture of 0.24 $cm^3\,cm^{-3}$ as measured in the ACN plot was never reached. During the whole growing season, the lower soil horizons (80–160 cm) contained less than 0.15 $cm^3\,cm^{-3}$, while in the top horizons (0–80 cm) soil moisture remained close to 0.20 $cm^3\,cm^{-3}$ (Table 6). The equivalent depth comparisons followed the same trend observed in 2003. Over the growing season, the ACN soil profile stored 7.5% more water than No ACN in 2004. But, when the soil profile was divided into two

Table 6. Summary comparison of the soil water status between ACN and No ACN after the rainy season (during the dry season) at Siguidolo Village, Konobougou, 2003

	Dry season of year 2003 (October to December)					
	Treatment[1]					
	ACN		No ACN			
Soil horizon (cm)	Moisture stored (mm)	% of horizon 0–160	Moisture stored (mm)	% of horizon 0–160	% moisture increase due to ACN	Significance level-ACN vs. No ACN probability
0–80 (n = 368)	58.24a	31	58.13a	30	0.19	0.05
80–160 (n = 368)	129.89a	69	119.39b	67	8.79	0.05

[1] Treatments with the same letter are not statistically different at $P = 0.05$.

Table 7. Summary comparison of the infiltration rates in ACN and No ACN plots at Siguidolo Village, Konobougou, Mali, 2004–2006

	Infiltration rate (cm h^{-1})			
	Treatment[1]			
Year	ACN	No ACN	Percent increase due to ACN (%)	Significance level-ACN vs. No ACN probability
2004 (n = 26)	8.30a	4.11b	102	0.0001
2005 (n = 30)	7.17a	5.71b	25.57	0.0001
2006 (n = 80)	6.96a	3.59b	93.87	0.0001
2004, 2005, 2006 (n = 136)	7.48a	4.49b	66.59	0.0001

[1] Treatments with the same letter are not statistically different at P = 0.05.

horizons (0–80 and 80–160 cm), the soil moisture gain due to ACN was 9.18% in the lower horizon (80–160 cm) versus 5.67% in the top 80 cm (Table 5), indicating that in years with lower rainfall, the ACN system still captures and retains more soil moisture. This result seems, at first, contrary to the frequent observation that ACN makes more difference in dry years than in wet ones (Gigou, 2002, personal communication). It may be, however, that in times of drought the smaller increase in stored water in the ACN treatments can make more difference if droughty conditions occur.

These attributes of the ACN technologies are important factors in the Sahel where rainfall often limits yield. Successful water and soil conservation practice may be a key to reversing the productivity decline if soil capacity to retain both nutrients and water can be increased.

Equivalent Depth of Water After the Rainy Season

Soil moisture monitoring after the rainy season (Figure 5) indicates that the soil profile continues to store a greater amount of soil water where ACN has been implemented. The lower soil horizons appear to have benefitted to a greater extent from the rainy season where ACN management was in place (Table 6). The change in soil water storage between ACN and No ACN was less in the top horizon 0–80 cm, which may be due to increased plant water consumption associated with increased yields and biomass as well as surface water evaporative loss. This result also suggests that deep-rooted crops or green manures or shrubs and trees should benefit from the increased soil moisture in the 80–160 cm zone.

Infiltration Rate

The statistical analysis showed that there was a significant difference ($\alpha < 0.01$) between ACN and No ACN infiltration rates. The mean infiltration rate indicates a net increase of 66.59% in infiltration associated with the ACN treatments of this study. Soils of the Sahel form a variety of crusts, hence reducing infiltration (Casenave and Valentin, 1989). As a result, a technology such as ACN appears to better capture rainfall and promotes infiltration to increase the soil moisture of the soil profile and possibly increase deep percolation of the water, which may lead to groundwater recharge. The increase in infiltration rate over time appears to be due to the control losing infiltration capacity yet further. Other studies (Doumbia, 2004, personal communication) indicated that soil organic matter increases where soils have been placed under ACN technology. Increased soil organic matter could lead to an increase in infiltration rate.

Conclusions

From the results of soil moisture data obtained at Siguidolo, it can be concluded that soil conservation practices affect many aspects of the water cycle. As well as reducing soil erosion, proper soil management such as "Aménagement en courbes de niveau" (ACN) can increase soil moisture reserves by capturing rainfall and transporting it into deeper soil depths where it can be stored or further moved through the soil profile to recharge groundwater. It has become evident that the 20–40 cm section of the profiles was probably near field capacity and even exceeded field capacity at 30 cm depth in the ACN plots early in the cropping season. In contrast, the No ACN treatment did not exhibit the increased moisture in the 20–40 cm horizon observed in the ACN treatment. Compared with the remainder of the soil profile, the 20–40 cm horizon held most of the soil moisture in July during the early stage of the rainy season. This higher clay containing horizon notably retained more water throughout the season and even into the post season. In Siguidolo, many crops are planted most years in the early part of June. Farmers prefer to plant as soon as possible after the beginning of the rainy season. Farmers report that with ACN management, earlier planting is possible (Roncoli, 2002, personal communication). The local cultivars of sorghum and millet are photo period-sensitive, which means that the plants grow and accumulate photosynthate until the day length is sufficiently short as to trigger reproductive growth. Consequently, with photo period-sensitive cultivars, early planting directly translates into increased biomass and thus the greater yields with ACN are to be expected.

ACN practices clearly increased water storage in the soil profile. One of the reasons for the increased soil water storage may be due to increased infiltration resulting from the retention of rainfall on the soil surface for a longer period of time, which may overcome the condition of low infiltration rates. The increased rates of infiltration where ACN was present suggest that the ACN led to longer term soil changes that increased the infiltration rate. Therefore, a reduction in runoff from the surface of the field is expected and may be associated with more rainfall capture and deep percolation into the soil. Reduced runoff and greater infiltration may have several implications: 1) soil surface erosion is reduced; 2) downstream flooding from runoff may be reduced; 3) deep-rooted crops such as tree species (shea butter trees) and shrubs may be able to take advantage of the extra reserve of deep moisture; 4) farmers and village residents report that drinking water supplies and water for irrigation in the off-season becomes greater than earlier (Siguidolo villagers, 2006, personal communication). It is likely that the higher yields recorded from production systems that have been improved with the ACN system can be attributed to the additional rainwater captured and the subsequent increase in available soil water stored during the growing season. The frequently observed greater yield, however, could be due simply to the earlier growing of a photo period-sensitive crop, made possible by more efficient capture and harvest of the earliest rains. These results point out the need to evaluate the larger scale effects of ACN when several farms or villages together place their land under ACN. Such effects may explain the anecdotal effects offered by farmers of increased groundwater supplies, reduced flood frequency, and reduced flood damage, which occur at the watershed scale.

References

American Society of Agricultural and Biological Engineers (ASABE). 2006. *Design, layout, construction and maintenance of terrace systems*. American Society of Agricultural and Biological Engineeers, St. Joseph, MI.

Bertelsen, M. and C. Brewster. 2003. *A new model for international collaborative research and technology transfer: The NRM interCRSP project in West Africa*, Michael Bertelsen and Charlen Brewster eds., Office of International Research Education and Development, Virginia Tech. Blacksburg, VA.

Bremen, H. and C. T. de Wit. 1983. Rangeland productivity and exploitation in the Sahel. *Science* 221:1341–1347.

Casenave, A. and C. Valentin. 1989. *Les états de surface de la zone Sahelienne influence sur l'infiltration*. ORSTOM Cahiers. Edition de l'orstrom. Institut Francais de Recherche. Scientifique pour le Developpment en Cooperation. Paris.

Cochran, W. G. and G. M. Cox. 1957. *Experimental designs*. John Wiley & Sons, New York.

Gigou, J., L. Coulibaly, B. Wenninck, and K. B. Traoré. 1997. Aménagements des champs pour la culture en courbes de niveau au sud du Mali. *Agricultural Development* 14:47–57.

Gigou, J. 1996. Méthode d'aménagement en courbes de niveau à l'échelle du champ, pp. 249–262, in A. Ratnadass, J. Chantereau, and J. Gigou, eds., *Amélioration du sorgho et de sa culture en Afrique de l'Ouest et du Centre. Actes de l'atelier de restitution du programme conjoint 4 sur le sorgho Icrisat-Cirad.* 1997/3/17–20. Bamako, Mali. Collection colloques, Montpellier, Cirad-ca.

Gigou, J., K. Traoré, F. Giraudy, H. Coulibaly, B. Sogoba, and M. Doumbia. 2006. Aménagement paysan des terres et réduction du ruissellement dans les savanes africaines. In: Agricultures (2006) vol. 15: no. 1, p. 116–122.

Gigou, J., K. Traoré, F. Giraudy, H. Coulibaly, B. Sogoba, and M. Doumbia. 2006. Aménagement paysan des terres et réduction du ruissellement dans les savanes africaines. *Cahiers Agricultures* 15(1).

Gore, J. E. and D. Steeds. 1987. Desertification in the Sahelian and Sudanian zones of West Africa, *World Bank Technical Paper* No. 61. Washington, DC.

Hoogmoed, W. B. 1981. Analysis of rainfall in some locations of West Africa and India. Appendix 5, in W. B. H. E. Rawitz and Y. Morin, eds., *Development of criteria and methods for improving the efficiency of soil management and tillage operations, with special reference to arid and semi-arid regions*. Agricultural University, Wageningen, The Netherlands.

Hoogmoed, W. B. and L. Stroosnijder. 1984. Crust formation in sandy soils of the Sahel. I. Rainfall and infiltration. *Soil Tillage Research* 4:5–23.

Kaboré, D. and C. Reij. 2004. *The emergence and spreading of an improved traditional soil and water conservation practice in Burkina Faso*. Environment and Production Technology Division Paper No. 114, Washington, D.C., International Food Policy Research Institute, U.S. http://www.ifpri.org/divs/eptd/dp/eptdp114.htm

Little, R. C., W. W. Stroup, and R. J. Freund. 2002. *SAS(r) for linear models*. SAS Institute, Inc., Cary, NC.

Nana-Sinkam, S. C. 1995. *Land and environmental degradation and desertification in Africa*. Joint UNECA/FAO publication, Addis Ababa, Ethiopia, February.

Pieri, C. 1995. Long-term soil management experiments in Semiarid Francophone Africa, pp. 225–266, in R. Lal and B.A. Stewart, eds., *Soil management experimental basis for sustainability and enviromental quality.* Adv. Soil Sci. CRC Lewis Publishers, Boca Raton, FL, USA.

Reynolds, W. D., D. E. Elrick, and E. G. Young. 2002. Single-ring and double or consecutive ring infiltrometers, in J. H. Dane and G. C. Topp, eds., *Methods of soil analysis. Part 4–Physical methods*, Vol. 4. American Society of Agronomy, Madison, WI.

Rockström, J., P. E. Jonsson, and J. Barron. 1998. Seasonal rainfall partitioning under runon and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modeling. *Journal of Hydrology* 210:68–92.

Sivakumar, M. 1992. Empirical analysis of dry spells for agricultural applications in West Africa. *Journal of Climate* 5:532–539.

Soil Survey Staff. 1999. *Soil taxonomy. A basic system of soil classification for making and interpreting soil surveys*. U.S. Department of Agriculture, 2nd ed. U.S. Government Printing Office, Washington, D.C.

Starr, J. and I. C. Paltineau. 2002. Capacitance Devices, in R. H. G. S. Campbell, W. A. Jury, D. R. Nielsen, H. Van Es, P. J. Wierenga, J. H. Dane, and G. C. Topp, eds., *Methods of soil analysis, Part 4. Physical methods*. Soil Science Society of America, Inc., Madison, WI.

Van der Pol, F. B. and B. Traoré. 1993. Soil nutrient depletion by agricultural production in Southern Mali. *Fertilizer Research* 36:79–90.