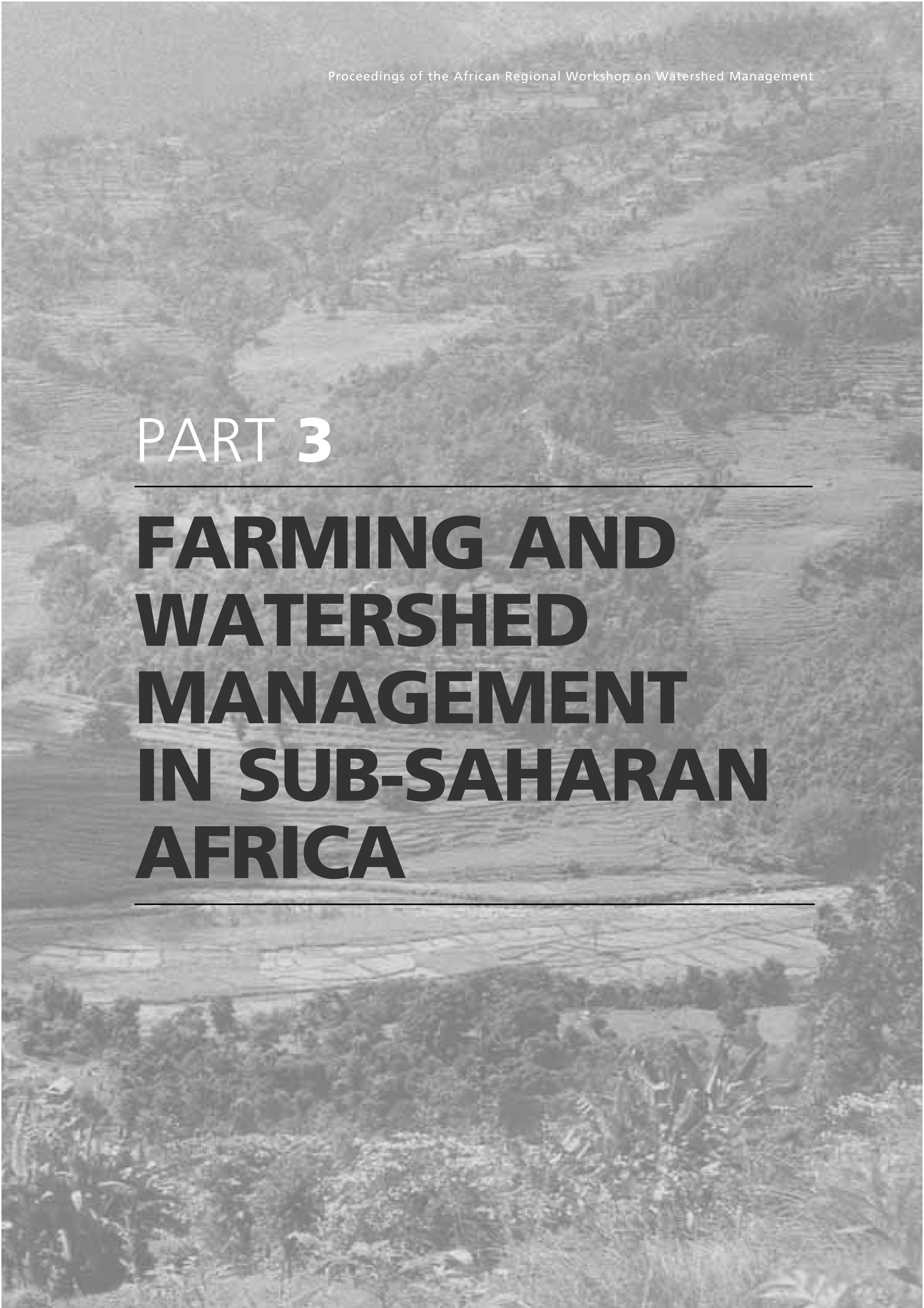


# PART 3

# FARMING AND WATERSHED MANAGEMENT IN SUB-SAHARAN AFRICA

# CHAPTER 5
# RUNOFF AND EROSION CONTROL UNDER IMPROVED FALLOWS IN WESTERN KENYA

**Anja Boye**, World Agroforestry Centre, Kisumu, Kenya

**Alain Albrecht**, World Agroforestry Centre, Nairobi, Kenya

## ACRONYMS

| | |
|---|---|
| **BD** | bulk density |
| **C losses** | soil carbon losses (g C $m^{-2}$) |
| **CT** | conventional tillage |
| **CC** | continuous crop |
| **IF** | improved fallow |
| **IF-Tc** | improved fallow sp. *Tephrosia candida* |
| **IF-Ss** | improved fallow sp. *Sesbania sesban* |
| **NT** | no-tillage |
| **PCA** | principal component analysis |
| **RP** | soil resistance to penetration (kg $cm^{-2}$) |
| **RS** | soil resistance to shear (kg $cm^{-2}$) |
| **SC** | sediment concentration (g $l^{-1}$) |
| **SL** | soil loss (g $m^{-2}$) |
| **SOC** | soil organic carbon |
| **WSA** | water-stable aggregates |

Food security and flooding have become issues of much concern in western Kenya in recent years. Changes in land use have greatly altered the vegetative cover and thereby the natural protection of the soil provided by plants and crops during heavy rainstorms. Accelerated soil erosion is the major land degradation process in Africa (Cooper *et al.*, 1996), and many small-scale farmers are experiencing low soil fertility and decreasing yields. At the onset of the rainy season, when the soil surface is bare, detachment of soil particles by raindrops and transport by runoff carry away the more fertile topsoil, depositing it further down slope or in water bodies. Thus, there is a need to find alternative land management systems that replenish soil fertility, provide an early plant cover and enhance the infiltration of rainwater.

The World Agroforestry Centre (ICRAF) has for several years been undertaking research in planted nitrogen-fixing shrubs (improved fallows) to replenish soil fertility. Many authors (Ingram, 1990; Niang *et al.* 1998; ICRAF, 2000; Mutuo, 2004) have shown that cropping improved fallows in the short rainy season greatly enhances soil fertility, and thereby crop production. Furthermore, these practices produce large amount of biomass, which can be left on the soil and provides a cover during the onset of the rainy season. These improved systems have been tested for various soil types in regions of Africa, Asia and Central America.

However, less is known of the role that improved fallows play in enhancing and improving infiltration and soil health, and thereby in reducing and controlling runoff and soil erosion.

Soil health is a term often used in literature to describe the status of the soil. Soil organic carbon (SOC) is acknowledged as one of the most important soil parameters to maintain good soil health (Doran, Sarrantonio and Liebig, 1996). However, a considerable challenge exists to maintain adequate SOC levels for cultivated soils, especially in the tropics, where carbon losses through cultivation, decomposition and erosion often exceed carbon inputs. The main sources of SOC input in the tropics are returned biomass (above- and below-ground biomass) and manures, which are often less than required to maintain adequate SOC levels (Nandwa, 2001). Agroforestry has shown to be a good management option to produce sufficient biomass to maintain or increase SOC (ICRAF, 2000; Mutuo, 2004).

Another land management practice that has received much attention elsewhere in the tropics is no-tillage (NT). No-tillage has been shown to build up SOC and thereby stimulate soil aggregation (Arshad, Franzluebbers and Azooz, 1999; Franzluebbers, 2002). Soil aggregation has been directly linked to soil erodibility by many authors, and is accepted as the most important physical property of soil when discussing soil erodibility and erosion (Le Bissonnais, 1996; Barthès *et al.*, 2000; Barthès and Roose, 2002). The potential improvement in soil properties is dependent on soil texture. The larger potential for improving soil properties on fine textured soils can be attributed to the chemical connections formed between clay particles and organic matter. However, Franzluebbers (2002) found runoff to reduce under NT for both sandy and clayey soils.

Thus, the objectives of this study were: 1) to examine runoff and soil and carbon losses for various improved fallow species for a sandy loam and a clay soil; and 2) to assess the impact of NT in these systems.

## METHODS

### Site description

The results presented in this paper were collected between June and August 2002 on two farms in western Kenya: Sophia farm and Nyabeda farm. Sophia farm is located in Busia district with sandy loamy soils and an annual rainfall of 1 500 mm, whereas Nyabeda farm is located in Siaya district with clay soils and an annual rainfall of 1 800 mm. Soil texture, initial soil carbon content and annual rainfall are listed in Table 1.

TABLE 1

**Soil texture, carbon content (0 to 20 cm) and rainfall for the study sites**

| Site | Soil texture | | | Soil carbon content | RainfalL |
|---|---|---|---|---|---|
| | Sand (%) | Silt (%) | Clay (%) | $g/kg^{-1}$ | $mm/year^{-1}$ |
| Sophia | 76 | 6 | 17 | 6.9 | 1 500 |
| Nyabeda | 34 | 28 | 38 | 25.0 | 1 800 |

### Experimental design and management

The experiment was established in September 2000 when improved fallows (IF) were planted. The design was a completely randomized block design with three replicates. The following improved fallow species were tested: *Tephrosia candida* and *Sesbania sesban,* with continuous maize (*Zea mays*, hybrid 513) intercropped with beans (*Phaseolus vulgaris,* roscocco glp2) as the control. The fallows were harvested 18 months after planting, in February 2002. The beans were harvested in June 2002 and the maize in July/August 2002. During the maize season, no striga was seen for the IF plots, whereas the control plots experienced striga. However, the striga was not assessed in this study.

### Rainfall simulations and soil sampling

Rainfall simulations were carried out at harvest of the first maize after fallowing (July/August 2002), and all treatments were tested. The rainfall simulation campaign consisted of three events with the objectives of pre-wetting the soil and simulating on a wet and a very wet soil with medium and high rainfall intensities. Two distinct rainfall intensities were chosen, which represent a medium and a high-intensity rainstorm in the two respective areas. The medium intensity was 50 mm $hr^{-1}$, and the high intensity was 90 mm $hr^{-1}$. The duration was 45 minutes for the pre-wetting phase, and 30 minutes for the wet and very wet runs.

Rainfall was simulated with the Orstom rainfall simulator over a 4-$m^2$ plot. (See Asseline and Valentine, 1978, for a detailed description of the Orstom rainfall simulator.) Runoff was collected from a marked 1-$m^2$ plot. In this study, runoff was collected every minute, and a sample was kept every second minute to determine sediment concentration and soil loss. Soil resistance to penetration and shear stress were measured adjacent to the frame before each rainfall simulation using a penetrometer CL 700A (kg $cm^{-2}$) and a torvane CL 600 (kg $cm^{-2}$) produced by Gravquick, Esbjerg, Denmark. Each measurement was replicated six times.

Soil samples were collected for bulk density, soil aggregate analysis and soil carbon content. Soil was sampled in June 2002 (before the harvest of beans) at 0 to 5 and 5 to 10 cm using 98-$cm^3$ cores with three replicates for each plot. The three replicates were then bulked to one sample per replicate. Water-stable aggregates (WSA) were determined by wet sieving after shaking. (See Boye and Albrecht, forthcoming, for a detailed description of this method.) Total carbon content of soil and sediment samples was determined by the CNS Carlo Erba micro-analyser method. In the absence of carbonates, all carbon was considered organic.

### Data analysis

The data were statistically analysed using ANOVA for a completely randomized block design. Statistical significance was determined at the 95 percent confidence level. A contrast analysis was run to test the effect of tillage practice in association with improved fallows on soil properties, runoff and soil and carbon losses. The control was continuous maize under conventional tillage (CC CT), and the improved system was improved fallow under no-tillage and conventional tillage (IF NT and IF CT).

A principal component analysis (PCA) was carried out with the ADE4 statistical package (Thioulouse *et al.*, 1997), in order to identify the dominant factors explaining soil carbon losses for the three land-use systems and two tillage practices. The variables were soil carbon content, percentage water-stable aggregates, soil bulk density and soil resistance to penetration and shear stress.

## RESULTS AND DISCUSSION

### Improvement in soil properties after fallowing

In this study, changes in soil properties after fallowing were highly affected by soil texture ($p \leq 0.001$) and treatment (see Table 2a). Generally, soil properties (SOC and WSA) improved under IF at the Nyabeda site (clay soil), whereas little or no improvement was seen at the Sophia site (sandy loam). On the clay soil, cropping improved fallows, increased soil organic carbon by 16 to 38 percent and reduced bulk density by 8 to 11 percent (only significant for IF-Tc, $p \leq 0.074$ and $p \leq 0.040$, respectively). WSA increased by 11 to 14 percent under IF for the clay soil (only significant for IF-Ss, $p \leq 0.10$). For the sandy loam, IF-Tc increased SOC by 38 percent, whereas no improvements were seen for IF-Ss plots and for bulk density (BD) and WSA. These results are in line with the hypothesis that stipulated larger improvements in soil properties for the clay soil. When farmland is rested from cultivation there is a build-up of SOC and soil aggregation (Ingram, 1990; Niang *et al.*, 1998; ICRAF, 2000; Mutuo, 2004); however, time is a crucial factor when examining the processes of restoring degraded land. The results from this study show that SOC and soil aggregation increased after fallowing for the clay soil, but did not change significantly for the sandy loam. However, the trends indicate that with time larger improvements are likely on these soils.

Soil bulk density decreased for IF-Tc for the clay soil, which confirms the results of Zeleke *et al.* (2004). They found incorporation of biomass to decrease bulk density (BD) for a clay and a sandy soil. In this study, changes in BD were not significant for the clay soil. Soil resistance to penetration (RP) and shear stress (RS) were not clearly influenced by soil texture and treatment in this study, which is contrary to the results of Boye and Albrecht (forthcoming) and Zeleke *et al.* (2004). Boye and Albrecht found IF to reduce RP and RS for a sandy loam and IF to increase RP and RS for a clay soil compared with the continuous maize plots. Similar results were found by Zeleke *et al.*

Table 2b lists the effects of no-tillage in association with improved fallows in improving soil properties. For the clay soil, SOC significantly improved and BD decreased under IF-Tc NT and CT compared with the control (CC CT). However, NT in association with IF-Ss did not significantly enhance SOC and WSA. IF-Ss CT increased WSA and decreased BD for this site. For the sandy loam (Sophia), IF in association with NT did not influence soil properties, but IF-Tc CT increased SOC. Similar studies in western Kenya have reported SOC and WSA to increase under NT for a clayey soil, but found no improvement in soil properties for a sandy loam (Boye and Albrecht, forthcoming), which corroborate these findings. NT has in many instances resulted in improved soil structure. This has been attributed to the stabilization of the surface by increased SOC contents and the accumulation of crop residues at the surface (Ingram and Fernandes, 2001; Van den Bygaart *et al.*, 2002) and by the lack of mechanical disturbance and its consequences on biological activity (Beare, Hendrix and Coleman, 1994).

TABLE 2a
**Changes in soil properties after improved fallowing**

| Site | Treatment | Soil carbon | Bulk density | Water-stable aggregates | Resistance to precipitation | Resistance to shear stress |
|---|---|---|---|---|---|---|
| | | $g/kg^{-1}$ 0–5 cm | $g/cm^{-3}$ 0–5 cm | $g/kg^{-1}$ 0–5 cm | $kg/cm^{-2}$ 0–10 cm | $kg/cm^{-2}$ 0–2 cm |
| Sophia | CC CT | 6.9 | 1.33 | 245.2 | 0.76 | 1.18 |
| | CC NT | 8.0 | 1.33 | 217.2 | 0.70 | 1.01 |
| | Tc CT | 10.6 | 1.29 | 235.9 | 0.81 | 1.46 |
| | Tc NT | 9.9 | 1.27 | 233.3 | 0.60 | 1.11 |
| | Ss CT | 8.3 | 1.25 | 341.3 | 0.54 | 1.32 |
| | Ss NT | 7.9 | 1.33 | 229.7 | 0.59 | 1.11 |
| Nyabeda | CC CT | 25.7 | 1.10 | 193.6 | 0.76 | 1.09 |
| | CC NT | 24.8 | 1.00 | 196.1 | 0.73 | 0.78 |
| | Tc CT | 35.1 | 0.92 | 214.6 | 0.81 | 1.05 |
| | Tc NT | 34.8 | 0.94 | 216.0 | 0.84 | 1.11 |
| | Ss CT | 28.3 | 0.95 | 228.8 | 0.64 | 0.96 |
| | Ss NT | 30.3 | 1.00 | 214.2 | 0.65 | 1.07 |
| Sophia | LSD (0.05) | 1.8* | 0.09 | 26.3 | 0.32 | 0.48 |
| Nyabeda | LSD (0.05) | 4.1** | 0.09* | 26.5 | 0.15 | 0.32 |

* = significant at 0.05.
** = significant at 0.01.

However, time is a crucial factor. Rhoton, Shipitalo and Lindbo (2002) found improvement in soil physical properties of 17 percent after four years, and a 70 percent increase in SOC and WSA after 14 years. In this study, the recent time since conversion (18 months) can explain the relatively slow improvement in soil properties, but the degraded status of these two soils also influences the effect of NT practices. The trends in this study and in those of Boye and Albrecht (forthcoming) indicate that, with time, these systems can improve soil properties.

### Effect of improved fallows on infiltration, and soil and carbon losses

The effect of improved fallows on infiltration was influenced by soil texture ($p \leq 0.001$) and treatment. Larger improvement in infiltration was found for the clay soil (Nyabeda), where IF increased infiltration by 35 to 38 percent. For the sandy loam, IF increased infiltration by 21 to 54 percent (only significant for IF-Ss). The improvement in infiltration can partly be attributed to improvement in soil structure during the fallow phase. In this study, there was a trend to larger SOC and WSA and reduced soil bulk density. However, for the sandy loam, the improvements were not significant. Several studies have found a close relationship between runoff and improved soil structure, e.g. soil organic carbon, soil aggregation and bulk density

TABLE 2b

**Significance levels of contrast analyses to test the effect of tillage practice in association with improved fallows in enhancing soil properties**

| Site | Contrast | Soil carbon | Bulk density | Water-stable aggregates | Resistance to precipitation | Resistance to shear stress |
|---|---|---|---|---|---|---|
| | | $g/kg^{-1}$ 0-5 cm | $g/cm^{-3}$ 0-5 cm | $g/kg^{-1}$ 0-5 cm | $kg/cm^{-2}$ 0-10 cm | $kg/cm^{-2}$ 0-2 cm |
| Sophia | CC CT vs. Tc NT | NS | NS | NS | NS | NS |
| | CC CT vs. Tc CT | 0.025 | NS | NS | NS | NS |
| | CC CT vs. Ss NT | NS | NS | NS | NS | NS |
| | CC CT vs. Ss CT | NS | NS | NS | NS | NS |
| Nyabeda | CC CT vs. Tc NT | 0.003 | 0.021 | NS | NS | NS |
| | CC CT vs. Tc CT | 0.002 | 0.012 | NS | NS | NS |
| | CC CT vs. Ss NT | NS | NS | NS | NS | NS |
| | CC CT vs. Ss CT | NS | 0.028 | 0.039 | NS | NS |

(Le Bissonnais, 1996; Barthès *et al.*, 2000; Barthès and Roose, 2002). Increased infiltration can also be attributed to reduced crusting on the IF plots. Crusting processes increase runoff through sealing of the soil surface (Bryan and De Ploey, 1983; Le Bissonnais, 1996; Le Bissonnais *et al.*, 1998; Rao *et al.*, 1998), and are often prevailing on degraded sandy soils. In this study, the soil surface of the sandy loam crusted quickly (within 5 to 10 minutes), increasing runoff rate and depth. Zeleke *et al.* (2004) also found incorporation of biomass to reduce soil strength, which Boye and Albrecht (forthcoming) also report for two soils in western Kenya.

The enhanced infiltration and soil structure under IF reduced soil loss. Soil loss (SL) was smaller for the clay soil (Nyabeda) compared with the sandy loam (Sophia) under IF (100 percent), whereas SL was similar under CC. The smaller SL for the clay soil was largely caused by smaller runoff rate because sediment concentration (SC) generally did not vary across sites. For the clay soil, SC was significantly reduced by IF (55 percent), whereas SC was not influenced by treatment for the sandy loam. A similar trend was seen for SL. IF reduced SL by 80 percent for the clay soil and by 70 percent for the sandy loam (only significant for IF-Ss). The soil loss values found in this study are in the same range as those reported elsewhere for simulated rainfall conditions (Merzouk and Blake, 1991; Meyers and Wagger, 1996; Boye and Albrecht, forthcoming).

NT in association with IF-Ss significantly reduced infiltration for the clay soil, whereas sediment concentration and soil loss were significantly reduced for both IF species (Table 3b). For the sandy loam, sediment concentration and soil loss were significantly reduced by IF-Ss CT, whereas no-tillage and IF-Tc did not influence SC and SL for this soil type. These results confirm those of Meyers and Wagger (1996) and Rhoton, Shipitalo and Lindbo (2002), who found long-term, no-tillage practices to reduce runoff.

TABLE 3a

**Effect of improved fallows on infiltration, sediment concentration, and soil and carbon losses**

| Site | Treatment | Infiltration | Sediment concentration | Soil loss | Carbon losses |
|---|---|---|---|---|---|
| | | % | g/l-1 | g/m-2 | g/m-2 |
| Sophia | CC CT | 44 | 1.8 | 43 | 1.97 |
| | CC NT | 51 | 1.7 | 31 | 1.40 |
| | Tc CT | 47 | 1.5 | 32 | 1.14 |
| | Tc NT | 68 | 2.4 | 30 | 1.15 |
| | Ss CT | 73 | 1.0 | 5 | 0.19 |
| | Ss NT | 74 | 2.1 | 18 | 0.65 |
| Nyabeda | CC CT | 65 | 3.2 | 66 | 2.29 |
| | CC NT | 61 | 2.8 | 34 | 1.01 |
| | Tc CT | 88 | 0.9 | 3 | 0.11 |
| | Tc NT | 86 | 1.4 | 6 | 0.27 |
| | Ss CT | 83 | 1.4 | 7 | 0.28 |
| | Ss NT | 87 | 1.3 | 5 | 0.20 |
| Sophia | LSD (0.05) | 24 | 0.6 | 25 | 0.93* |
| Nyabeda | LSD (0.05) | 18* | 0.9** | 22** | 0.79** |
| Site | LSD (0.05) | 19*** | 0.7*** | 21** | 0.79*** |

* = significant at 0.05
** = significant at 0.01
*** = significant at 0.001

In recent years, much focus has been given to soil carbon losses on the plot, slope and landscape levels. Several studies have found selective detachment and transport of SOC and fine particles, resulting in depletion of SOC for *in situ* soil and enhanced SOC for depositional areas (Watung, Sutherland and El-Swaify, 1996; Wan and El-Swaify, 1997; Jacinthe, Lal and Kimble, 2002; Owens *et al.,* 2002; Lal, 2003). On the slope scale, the most important way to reduce C losses is to reduce and control runoff and soil loss. This study has shown the potential for IF to increase infiltration and reduce soil loss for a clay soil and a sandy loam. Associated soil carbon losses were significantly reduced by IF-Ss for both sites and by IF-Tc for the clay soil (Table 3b). NT significantly reduced soil carbon losses for IF-Ss and for IF-Tc (only for the clay soil). Tillage practice did not influence soil carbon losses within treatment for the two sites.

TABLE 3b

**Significance levels for contrast analyses to test the effect of tillage practice in association with improved fallows in reducing infiltration, sediment concentration, and soil and carbon losses**

| Site | Contrast | Infiltration | Sediment concentration | Soil loss | Carbon losses |
|---|---|---|---|---|---|
| | | % | $g/l^{-1}$ | $g/m^{-2}$ | $g/m^{-2}$ |
| Sophia | CC CT vs. Tc NT | NS | NS | NS | NS |
| | CC CT vs. Tc CT | NS | NS | NS | NS |
| | CC CT vs. Ss NT | NS | NS | NS | 0.034 |
| | CC CT vs. Ss CT | NS | 0.020 | 0.025 | 0.008 |
| Nyabeda | CC CT vs. Tc NT | NS | 0.009 | 0.002 | 0.002 |
| | CC CT vs. Tc CT | 0.046 | 0.002 | 0.001 | 0.001 |
| | CC CT vs. Ss NT | 0.054 | 0.006 | 0.001 | 0.002 |
| | CC CT vs. Ss CT | NS | 0.010 | 0.002 | 0.002 |

A principal component analysis (PCA) of soil carbon losses shows C losses to be predominantly controlled by soil texture and treatment. The eigen values show that the first factor (F1) explains 40 percent of the variance and is opposed by soil carbon content, BD and water-stable aggregates (Figure 1a). The second factor (F2) explains 28 percent of the variance and is explained mainly by soil resistance to penetration (RP) and shear stress (RS).

The points on the factorial map of treatments are clustered mainly into two groups, one group placed to the right of the diagram, representing the clay soil (Nyabeda), and one group placed to the left of the diagram, representing the sandy loam (Sophia) (Figure 1b). For both sites, the points for CC are placed towards the upper part of the diagram (larger C losses), whereas the points for IF are placed towards the lower part of the diagram (smaller C losses). Cropping IF prior to maize reduced C losses by 79 to 83 percent (0.19 to 0.24 vs. 1.15 g C $m^{-2}$) for the clay soil and by 32 to 75 percent for the sandy loam (0.42 to 1.15 vs. 1.69 g C $m^{-2}$, only significant for IF-Ss). Similar C losses have been reported by Boye and Albrecht (forthcoming) for western Kenya, however, they found no effect of treatment on C losses for a sandy soil. Similar C losses have been reported by Jacinthe, Lal and Kimble (2002) for long-term experiments.

FIGURE 1a

**Correlation circle of variables**

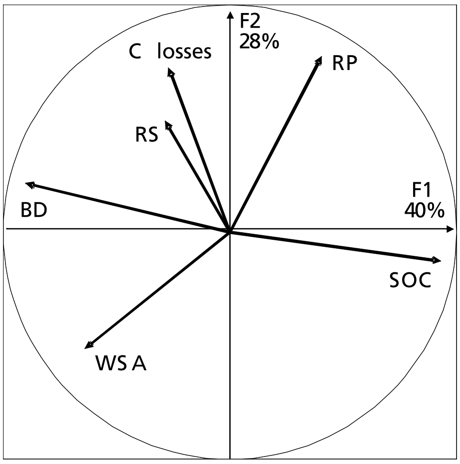
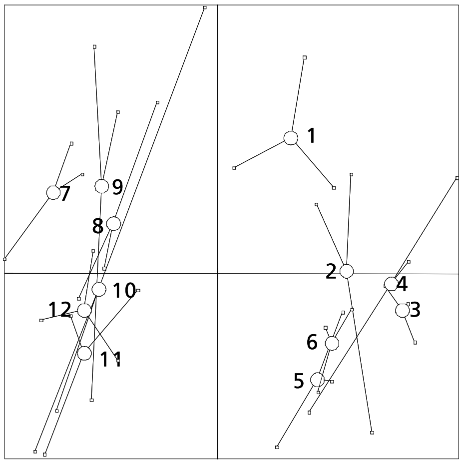



FIGURE 1b

**Factorial map of treatments**




Nyabeda: 1. CC-T, 2. CC-NT, 3. IF-Tc T, 4. IF-Tc NT, 5. IF-Ss T, 6. IF-Tc NT.
Sophia: 7. CC-T, 8. CC-NT, 9. IF-Tc T, 10. IF-Tc NT, 11. IF-Ss T, 12. IF-Tc NT.

## CONCLUSION

The results from this study show that improved fallows have the potential to improve soil properties and thereby reduce runoff, and soil and carbon losses. The improvement in soil properties was larger for the clay soil compared with the sandy loam, hence larger infiltration and lesser soil and carbon losses for the clay soil. The larger control found for the clay soil can be attributed to the significant improvement in soil properties, e.g. SOC, WSA and BD, which was found here. Despite the slow improvement in soil properties for the sandy loam, infiltration increased for the IF plots, and soil and carbon losses reduced, however only significantly for IF-Ss. Improved fallows reduced crusting for the sandy loam, which can explain the larger infiltration found for the IF plots on this soil type. No-tillage in association with improved fallows enhanced soil properties and infiltration, and reduced soil and carbon losses for the clay soil. The effect of no-tillage on the sandy loam was less clear, however, there was at trend for improved soil structure on this soil type, but long-term experiments are needed to address the impact of improved fallows and no-tillage in relation to runoff, soil and carbon losses.

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# CHAPTER 6
# RESULTS FROM TEN YEARS OF WATERSHED AND WATER RESOURCES RESEARCH IN SEMI-ARID SOUTHERN ZIMBABWE

**F. T. Mugabe**
Department of Land and Water Resources Management, Midlands State University, Gweru, Zimbabwe

## ACRONYMS

| | |
|---|---|
| **AREX** | Agricultural Research and Extension Services |
| **CEH** | Centre for Ecology and Hydrology |
| **DFID** | Department for International Development, United Kingdom |
| **HOF** | Hortonian overland flow |
| **IES** | Institute of Environmental Studies |
| **SOF** | saturated overland flow |
| **START** | System for Analysis Research and Training |

The semi-arid areas of Zimbabwe located in natural regions IV and V receive low and erratic rainfall, such that dryland crop production is not reliable. The rains are unevenly distributed in both time (Figure 1) and space, resulting in frequent crop failures that occur in three out of every five years. This makes life difficult for communities living and farming in such areas, forcing them to rely on water stored underground or in surface storage during wet seasons.

Watershed and water resources research commenced in the early 1990s in semi-arid southern Zimbabwe. The objectives of the studies were to determine the effect of land management on groundwater recharge (Bromley *et al.*, 1999; Butterworth *et al.*, 1995; Lovell *et al.*, 1998) and surface water resources (Mugabe and Hodnett, unpublished). It also determined runoff generation and groundwater recharge mechanisms (Bromley *et al.*, 1999; Butterworth *et al.*, 1995; Lovell *et al.*, 1998; Mugabe and Hodnett, unpublished). Similarly the studies determined the extent to which water use can be stretched without depleting surface water resources (Mugabe and Hodnett, unpublished; 2003).

## STUDY SITES

The research on watershed and water resources concentrated on two headwater micro-catchments (~ 5 $km^2$) of the Runde catchment (Figure 2), which were fully instrumented to enable measurements of all components of the hydrology, including rainfall, runoff, soil moisture and groundwater recharge.

FIGURE 1

**Annual rainfall recorded at Chiwi, as deviation from long-term mean and cumulative deviation from mean annual rainfall**

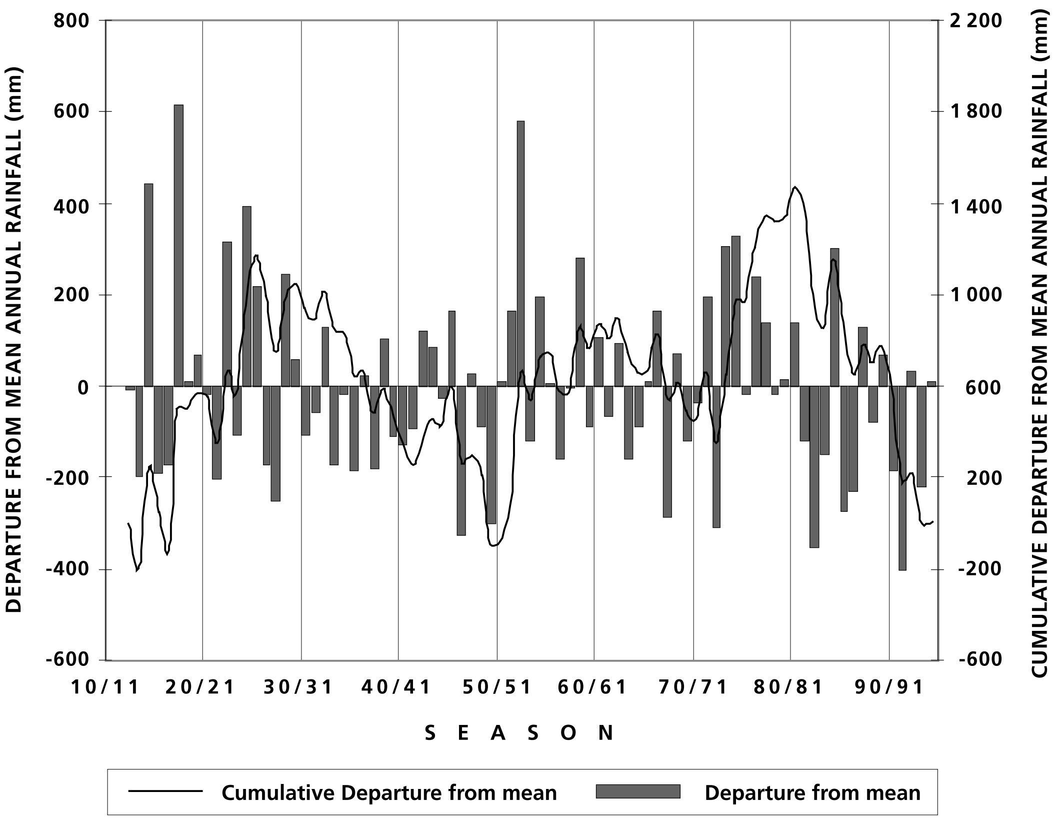
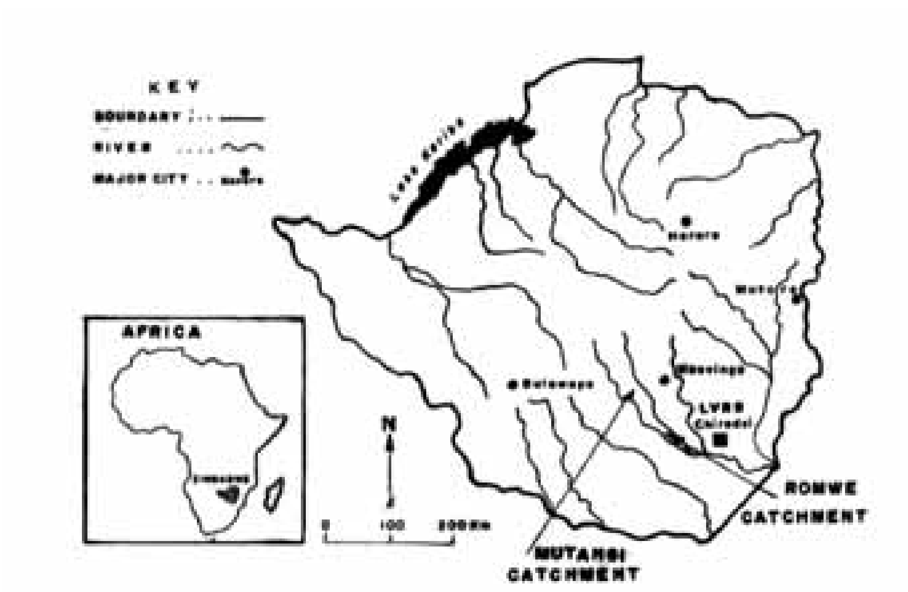



FIGURE 2

**Location of Romwe and Mutangi communal areas.**



## RESULTS FROM THE CATCHMENT AND WATER RESOURCES RESEARCH

### Runoff

At the catchment scale, runoff from the semi-arid areas is generally a small part of the water balance, and is highly variable – even within small catchments. The grey soils at Romwe catchment (4.6 km$^2$) generated more runoff than the red soils (Table 1).

TABLE 1

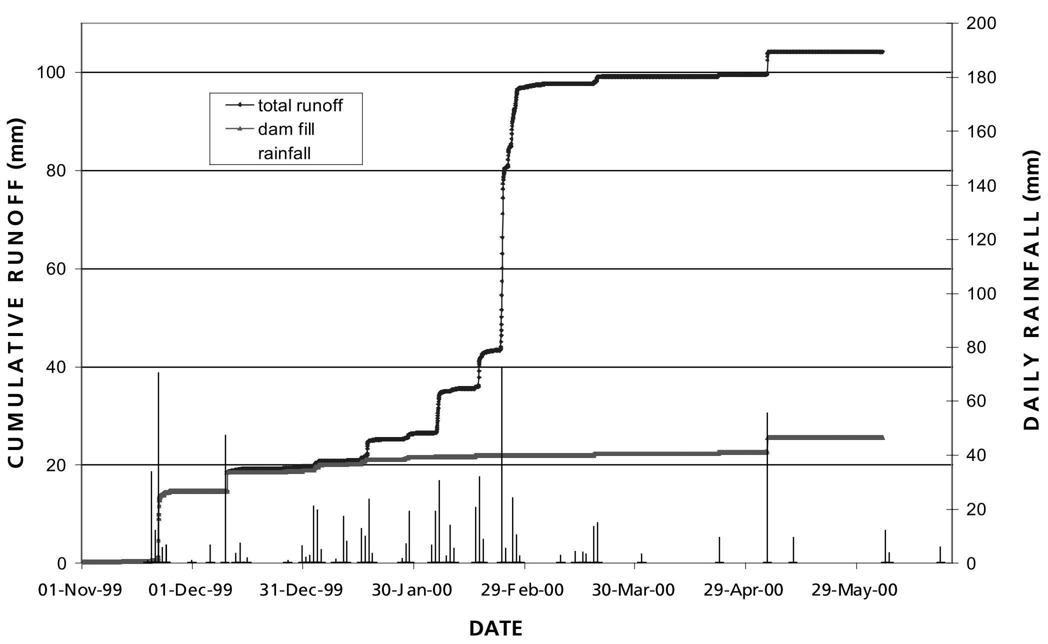
**Rainfall and runoff from the red and grey subcatchments in the Romwe micro-catchment (4.6 km$^2$)**

| SEASON | RAINFALL (mm) | RED SOILS | | GREY SOILS | |
|---|---|---|---|---|---|
| | | Runoff (mm) | Runoff conversion efficiency (%) | Runoff (mm) | Runoff conversion efficiency (%) |
| 1994/5 | 738 | 9 | 1.2 | 48 | 6.5 |
| 1995/6 | 990 | 46 | 4.6 | 203 | 20.5 |
| 1996/7 | 1 140 | 64 | 5.6 | 335 | 29.4 |
| 1997/8 | 798 | 67 | 8.3 | 206 | 25.8 |
| 1998/9 | 1 084 | 22 | 2.0 | 151 | 13.9 |

Of the runoff studied in Romwe, between 20 and 30 percent is captured by the small dams that are found in these semi-arid areas (Figure 3), while the remainder leaves the catchment (Mugabe and Hodnett, 2003; unpublished).

FIGURE 3

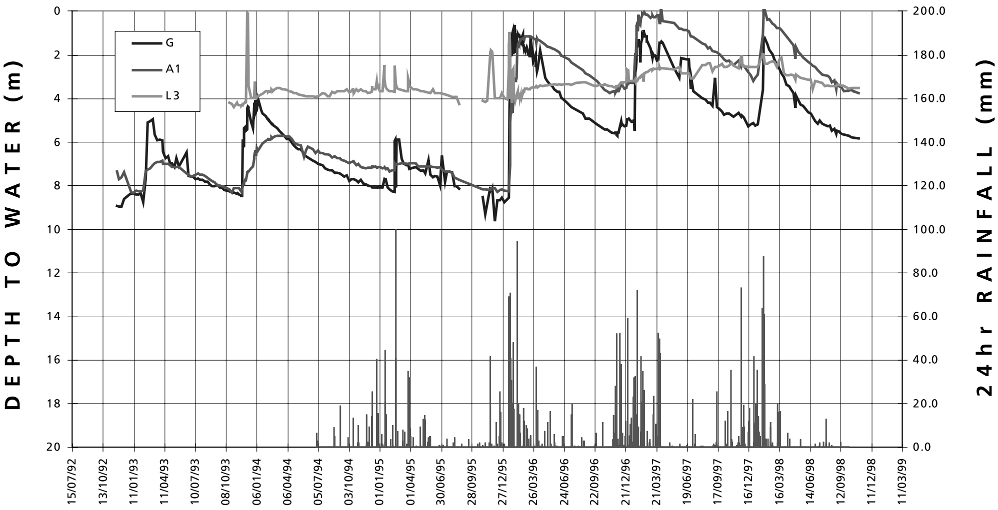
**Cumulative total runoff and dam fill, and daily rainfall during the 1999/2000 season**



### Effect of rainfall on groundwater levels

Long-term trends in groundwater levels reflect the effect of cycles in rainfall. Figure 4 shows there is more fluctuation of the water table in the red soils than the grey soils. Piezometer G is located on a grey soil (G), while A1 and L3 are located on a red soil.

FIGURE 4
**Long-term water table hydrographs for three Piezometers**




### Groundwater recharge and runoff generation mechanisms

Research in the Romwe catchment area shows that groundwater recharge is not uniform throughout the catchment, but is erratic and episodic (Lovell *et al.,* 1998; Butterworth *et al.,* 1999a, b and c). Drainage from the unsaturated zone during the 1994/1995 seasons on both red clay and grey duplex soil types was associated with a single rainstorm. Drainage through the soil profile in 1994/1995 was highly spatially variable on both the red clay and the grey duplex soils. In the red clay soils, subcatchment drainage was observed at nine out of 16 sites, and in the grey duplex clay, subcatchment drainage occurred at only four out of 20 sites. Locations of high drainage were in areas where surface water was concentrated through redistribution during rainstorms (Butterworth *et al.,* 1999b). In particular, high drainage was observed above contour bunds, along lines of surface water drainage and along storm drains (where infiltration of water was enhanced by the construction of infiltration pits by farmers). If surface redistribution of rainfall had not occurred during this year, there would have been no deep drainage to groundwater through the soil matrix below fields with either soil type (Butterworth, 1997).

Research at Mutangi catchment shows that some runoff appears to be generated by Hortonian overland flow (HOF), mainly in the early wet season before ploughing creates a rougher soil surface (Mugabe and Hodnett, unpublished). The dominant process of runoff in this catchment was saturated overland flow (SOF), which occurs when the soils become saturated from below (Mugabe, no date) along the catena. The sodic soils along the stream channels appear to generate most of the runoff because of their small capacity to store water before saturation. The ridge soils are coarse sands, with a large capacity to store rainfall. The transitional (slope) soils have an intermediate capacity to store water. If there is a sequence of daily events that completely fills the storage available for both the sodic and the transitional soils, and begins to saturate the ridge soils, subsequent events can produce very large amounts of runoff (> 50 percent of the daily rainfall). The occurrence of such runoff events depends very heavily on the distribution of rainfall. Dry spells between rain events create storage, thereby reducing the risk of runoff from the next events (Mugabe, no date).

**Can current water use be increased without drying the dam?**

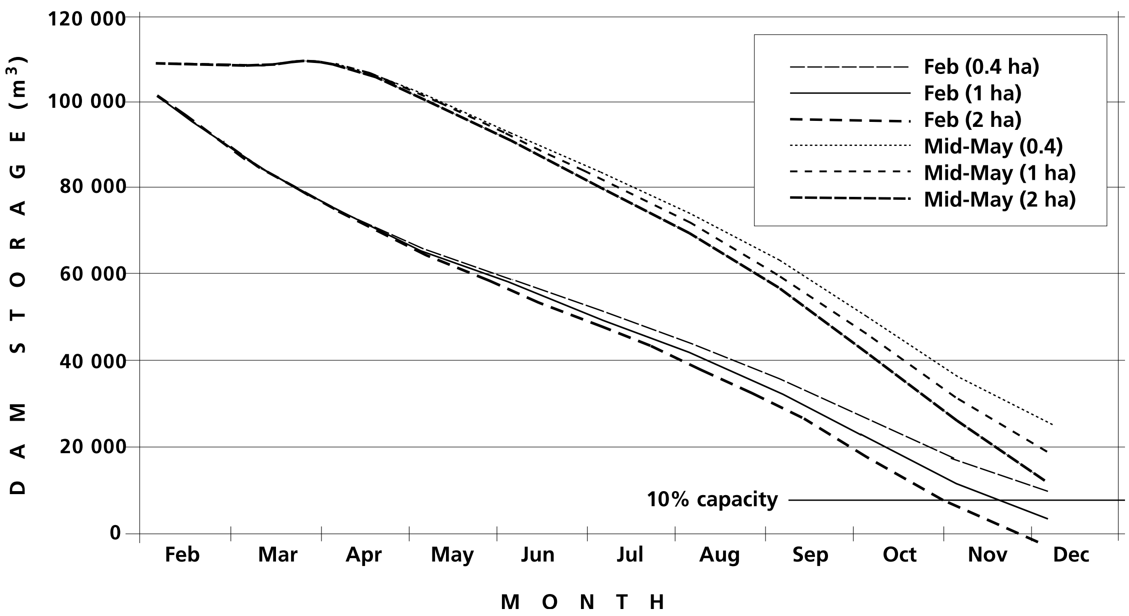
The amount of water available for irrigation depends on the amount of water stored in a dam at the beginning of the irrigation season, and the evaporation and seepage losses. Six scenarios were run to determine the effect of increased abstraction on dam water level if the dam last filled in February or in mid-May (Figure 5).

The scenarios illustrated in Figure 5 show that garden size (water use) can be increased by up to five times without the danger of drying up a dam if the dam was last filled up in May. When the dam was last filled in February, water use can only be increased 2.5 times. This highlights the importance of knowing when the dam was last filled up, and the amount of water in the dam at any given time, in determining the amount of water (garden size) to use in a season. Most dam users do not have this information, and often do not know how much water their dams hold at full capacity.

Modelling results using historical rainfall data show that water use from small dams can be safely increased by up to ten times without drying up the dam in 78 percent of cases (Mugabe, no date).

FIGURE 5

**Reservoir storage when last full in February and in mid-May for three garden sizes**



## CONCLUSION

The following conclusions and recommendations can be made from the research:

- At the catchment scale, runoff from the semi-arid areas is generally a small part of the water balance.
- Long-term trends in groundwater levels reflect the effect of cycles in rainfall.
- Runoff generating processes can be SOF or HOF, depending on the quantity, distribution and intensity of the rainfall.
- Of dam water balance in the semi-arid areas, only 3 percent is used for productive purposes, and the remainder is lost as evaporation.
- Water use from small dams can safely be increased by up to ten times without drying up the dam in 78 percent of cases.
- The amount of water available for productive purposes depends on when the small dams were last filled – the later in the season this is, the more water is available for gardening.

## ACKNOWLEDGEMENT

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# CHAPTER 7
# CONSERVATION FARMING – A STRATEGY FOR IMPROVED AGRICULTURAL AND WATER PRODUCTIVITY AMONG SMALLHOLDER FARMERS IN DROUGHT-PRONE ENVIRONMENTS

**Johan Rockström**
Stockholm Environment Institute, Stockholm, Sweden

**Kurt Steiner**
German Agency for Technical Development (GTZ), Germany

## ACRONYMS

| | |
|---|---|
| **C** | control |
| **CF** | conservation farming |
| **Fert** | fertilizer |
| **HIV/AIDS** | human immunodeficiency virus/acquired immune deficiency syndrome |
| **Ripp** | Magoye ripper |
| **SIWI** | Stockholm International Water Institute |
| **SSA** | sub-Saharan Africa (SSA) |
| **TFSC** | Tanzania Farm Service Centre |

The frequent crop failures and yield reductions due to drought observed in the last years in many parts of Africa are not just a consequence of climatic variability but, to a large extent, a consequence of land degradation due to inappropriate agricultural practices. Land degradation, reducing rainfall infiltration, crop water availability and crop water uptake capacity, lead to agricultural droughts where the crop suffers from water scarcity despite adequate amounts of rainfall. Unlike meteorological droughts, agricultural droughts can often be managed through integrated soil and water management practices that focus on maximizing crop water access and uptake. Conservation tillage systems that have in common non-inversion of soil with the purpose of harvesting water and building soil quality can, together with improved soil nutrient management, result in substantially improved yields by mitigating droughts and dry spells.

One of the most important natural resources is soil, especially agricultural soil. However, the soil resource can fulfil its functions only in the presence of another precious resource – water, in particular rainwater. There are close interactions between these resources, as only a healthy soil can take up and store sufficient amounts of rainwater and make it available to plants over a prolonged period. These interactions among soil, water and plants (crops) are influenced by human activities, and are in many cases disturbed. Soil quality (soil structure, soil organic matter, soil life) is lowered in most cases by tillage operations; soils degrade and the ability to take up and store rainwater suffers. A great percentage (> 50) of rainwater is lost by runoff and evaporation, and crops suffer from water stress after only a few days without rain.

Food security and poverty reduction, the main objectives of all development efforts, can only be achieved if sustainable land and soil management practices are applied on a large scale. This calls for a drastic change, first of all of tillage practices. Tropical soils should be disturbed as little as possible, and protected by a cover of mulch or crops (wherever possible by cover crops) the greatest part of the year. Ploughing and intensive hoeing should be replaced by ripping, direct planting or pitting. These conservation farming techniques, complemented by the breaking of hardpans, contribute to a better water infiltration and reduce losses of precious rainwater as runoff. Conservation farming is therefore integrated soil and water management. It is an *in-situ* water harvesting strategy.

Semi-arid and dry subhumid regions constitute some 40 percent of the arable lands in sub-Saharan Africa, and host some 40 percent of the population. Rainfall is highly erratic, with large spatial and temporal variability resulting in frequent periods of particularly dry spells. The correct ecological term for these regions is savannah.

Water is the major limiting factor in savannahs, even on soils with a poor nutrient status, which means that the increase of rainwater productivity needs to gain priority before the application of mineral fertilizers. However, it is more often the poor distribution of rainfall over time that causes water scarcity than low overall rainfall. This is not always well understood, and in the normal jargon these regions are generally denoted “drylands”. However, they are not all that dry (generally receiving at least 600 mm of rainfall). There is generally enough water, but it is there at the wrong time and such a large proportion is lost to the crop as evaporation and runoff. This indicates a window of opportunity to improve yield levels through improved water management.

The objective of this paper is to give evidence that conservation farming in sub-Saharan Africa is an important water harvesting strategy with beneficial impact on yields in water scarcity-prone semi-arid and dry subhumid areas.

## RAINWATER PRODUCTIVITY

### Dry spell mitigation

Rainfed farming in savannah agro-ecosystems is a highly risky business owing to the extreme temporal and spatial variability of the rainfall. Rain is generally concentrated in one or two short rainy seasons, followed by distinct dry seasons exceeding six months of the year. The high rainfall variability results in a high risk of occurrence of meteorological droughts – here defined as a cumulative rainfall below the minimum water requirement to produce a crop (i.e. resulting in complete crop failure – in general when seasonal rainfall is < 250 mm). Statistically, meteorological droughts occur in between one and two seasons in a decade. They are difficult if not impossible to manage (there is simply no freshwater resource to manage) and form a natural part of the savannah reality. Most important therefore is to focus on meteorological dry spells – short periods of two to four weeks of no rainfall, resulting in crop growth reduction.

If occurring during stress-sensitive growth stages, such as flowering, a severe dry spell can result in complete crop failure. Meteorological dry spells are very common in savannah farming systems, occurring almost every rainy season. These dry spells are manageable, but generally require management practices such as storage water harvesting systems for supplemental irrigation (SIWI, 2001).

However, crop water stress may increase dramatically as a result of poor land management. Water stress causing dry spells and agricultural droughts is caused primarily not by low rainfall but by poor rainfall partitioning, resulting in large losses of water (from the perspective of the cultivated crop) in the water balance (as evaporation, runoff and drainage).

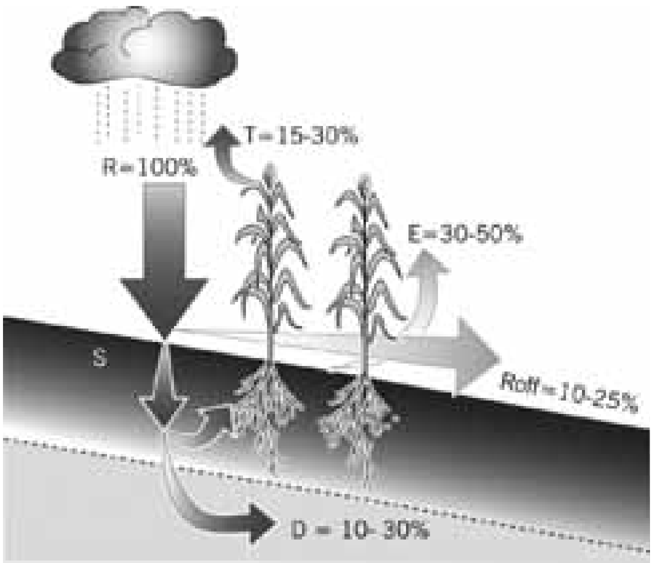
Water balance analyses from rainfed farming systems in savannah environments of sub-Saharan Africa indicate that only some 15 to 30 percent of rainfall on average is used for productive crop growth (Rockström, 1999). On smallholder farms subject to land degradation – both in terms of structural degradation impeding rainfall infiltration, water holding capacity and plant water uptake potential and in terms of soil fertility decline – less than 10 percent of the rainfall takes the productive flow path as crop transpiration (Rockström, Jonsson and Barron, 1998). Yield levels in such degraded farming systems, which are systematically subject to management-induced dry spells, oscillate around 0.5 to 1 tonne of grain per hectare. This is the common yield level generally observed among smallholder farming in eastern and southern Africa. It suggests that: 1) there is a large management-induced crop water scarcity; and 2) there is a large potential for upgrading rainfed savannah farming through improved soil and water management.

#### Conservation farming – a water harvesting strategy

Conservation farming aims at reversing a trend that is persistent in many production systems – i.e. the reduced infiltration capacity of soils due to compaction and crust formation, and reduced water holding capacity due to oxidation of organic materials (due to excessive turning of the soil). From this perspective, conservation farming is a form of water harvesting, where runoff is impeded and soil water is stored in the root zone of the crop. This means that conservation farming constitutes a very interesting approach to achieve improvements in water productivity, and "crop per drop" increases, in line with the newly launched global dialogue on water for food and environmental security (Anonymous, 2001).

We know that for large parts of the developing world subject to rapid population growth, yield levels of staple foods need to at least double over the next generation in order to keep pace with population growth. We also know that a majority of these countries are in savannah environments. Generally, it is assumed that water requirements increase linearly with increased food production, i.e. that a doubling of yields would result in a doubling of crop water use. Empirical research shows that water requirements range in the order of 1 000 to 3 000 $m^3$/tonne of grain (Falkenmark and Rockström, 1993), which explains why agriculture is the world's largest direct water using sector. However, there is strong evidence showing that water productivity can be improved (i.e. improvement in the amount of crop produced per drop of water) through management (Rockström, Barron and Fox, 2003).

FIGURE 1
**Rainfall partitioning in the semi-arid tropics in sub-Saharan Africa**




Two key factors need to be improved in order to increase water productivity in agriculture. These are:

- increased crop water availability (through improved rainfall infiltration and water holding capacity, and reduced soil evaporation losses through minimum or no-tillage and soil cover);
- increased crop water uptake capacity (improved root depth and canopy development in order to maximize productive transpiration flow).

An aim of conservation farming is to improve both of these key water productivity-enhancing factors. One major goal is to change the partitioning of rainfall in favour of infiltration, soil moisture storage and plant water uptake. Rockström and Falkenmark (2000) have in a recent study shown that a doubling, and in many cases even a quadrupling, of crop yields in African savannahs is feasible from a hydrological perspective if such measures are accomplished.

Rainwater productivity can be increased further by timely farm operations such as timely planting and weeding. Planting is often delayed by up to several weeks owing to tillage operations. Adoption of reduced or no-tillage systems permits farmers to plant directly after the onset of the rains, thus exploiting the entire rainy season. Timely weeding is as important, as weeds compete for water. A permanent ground cover by crop residues and cover crops suppresses weed growth and reduces the labour requirements for weeding.

## FARMER EXPERIENCES WITH CONSERVATION FARMING IN THE UNITED REPUBLIC OF TANZANIA

### Approach and methodology

Farmer-designed conservation farming trials have been carried out since 1998 in semi-arid and dry subhumid (rainfall depth averaging 700 to 1 000 mm $yr^{-1}$) parts of Arusha and Arumeru districts, in northwestern Tanzania. The trials involved eight to ten farmers each year in three villages; Sakila (subhumid), Ngorobob and Mkonoo (semi-arid). The basic tillage implements involved are ox- and tractor-drawn subsoiler, ox-drawn Magoye ripper, and hand hoe.

The trials included four principal production systems: 1) ripper/subsoiler; 2) a ripped broad-bed system; 3) a manual pitting system; and 4) the conventional ploughing system. These four systems were then combined and site-adapted regarding: 1) intercropping (lab-lab or cowpea depending on location); 2) fertilization (manure, Mijingu rock phosphate and Urea); 3) traction (oxen or tractor); 4) crop rotation; and 5) crop varieties. The main crop in all experiments is maize (*Zea mays*). Common to all sites was the use of a standard plant density of 80 x 30 cm, and fertilization (for all treatments expect the non-fertilized control). The experiment was a randomized block design with two repetitions per farm site (i.e. two blocks with six treatments each). Each production system was repeated 16 to 20 times each rainy season (the variation depends on the varying number of farmers involved in the trials).

Subsoiling was carried out with either tractor or ox-drawn subsoiler. Subsoiling was carried out during the dry season to a depth of 40 to 50 cm for tractor subsoiling and 25 to 35 cm for ox-drawn subsoiling. The subsoiling was followed by ripping, which was done to establish permanent planting lines, along the contour at 75-cm spacing.

The pitting system was very similar to the zai-pitting found in the Sahel. A hand hoe was used to dig planting holes with dimensions of roughly 20 x 20 x 20 cm. Most important was that the depth exceeded the conventional ploughing depth (which in this region is 12 to 13 cm).

The conventional system (control) was similar in all locations, based on post-onset ploughing with mouldboard plough. All conservation farming treatments were dry-planted, and crop residue was left on the fields as mulch (except for maize leaves, which were taken for fodder). Weeding control was done manually, following the normal practices in the area. However, one additional weeding operation was carried out after harvest in order to reduce weed infestation from weed seeding.

The trials started effectively with the long rains (March to June/July) of 1999. Despite a bimodal rainfall pattern, the short rains (generally from mid-October to January) are so poorly distributed with low cumulative rainfall that most farmers do not even attempt to cultivate rainfed crops. The trials have been ongoing for four years, and in this paper, yield data from the long rains of 1999 to 2002 are presented.

### Yield results

Table 1 shows the average yield results from the long rains of 1999 to 2002 for the eight to ten participating farmers for each year. The average conventional ploughed maize yield is

1.3 tonnes/ha$^{-1}$, which is a factor three times lower than the ripper treatments (yielding on average 3.8 to 4.0 tonnes/ha$^{-1}$).

Conservation farming systems yielded on average 2.2 to 2.4 times higher yields than the present conventional practice based on mouldboard ploughing. This large and persistent difference can be attributed to the combined effect of improved water (through conservation tillage) and soil fertility management (through spot application of fertilizer and manure). The water effect of conservation farming can be assessed by comparing the ripped system with the control receiving fertilizer, which resulted in a significant yield increase of an average 40 percent. The soil fertility effect alone is indicated by the 70 percent yield increase between the controls with and without fertilizer application. It is interesting to note that addressing water alone – i.e. by adopting conservation farming without soil fertility management (represented by Ripp-fert) results in roughly the same yield level as if the farmer addresses soil fertility alone (represented by conventional + fert). This suggests two important issues. First, that water is not necessarily the only, and often not even the major, limiting factor for crop growth, even in this semi-arid savannah environment. Second, it clearly shows that it is only when combining water and soil fertility management that a synergy effect is achieved, which is manifested in large yield increases.

Similar results have been achieved in semi-arid Babati district, Tanzania, where tractor subsoiling of maize resulted in an immediate (first-season) 2.8-fold increase in maize yields during the favourable rains of 1995/1996 (from 1.7 to 4.8 tonnes/ha$^{-1}$ for fertilized maize and

TABLE 1

**Maize grain yield of farmer trials in Tanzania for long rains 1999 to 2002**

| TREATMENT | N | AVERAGE YIELD (kg/ha) | SD (kg/ha) | TREATMENT EFFECT | | MULTIPLIER | |
|---|---|---|---|---|---|---|---|
| | | | | Control | C+fert | Control | C+fert |
| Ripp | 39 | 3 874 | 1 781 | 0.0000*** | 0.0023*** | 2.4 | 1.4 |
| Ripp+CC | 39 | 3 633 | 1 809 | 0.0000*** | 0.0000*** | 2.2 | 1.3 |
| Ripp-fert | 27 | 2 539 | 1 513 | 0.0024** | 0.4727 | 1.6 | 0.9 |
| Pitting | 39 | 3 523 | 1 515 | 0.0000*** | 0.0198* | 2.2 | 1.3 |
| C+fert | 39 | 2 783 | 1 217 | 0.0000*** | 0.0000*** | 1.7 | 1.0 |
| C | 41 | 1 621 | 885 | | | | |

Notes: Treatment effects are shown compared with C (control; conventional mouldboard ploughing without fertilizer application = farmer's current practice) and with C+Fert (conventional mouldboard ploughing including fertilizer application equal to the fertilization of the CT treatments). Ripp = Magoye ripper, Ripp + CC = Magoye ripper plus lab-lab cover crop, Ripp-fert = Magoye ripper without fertilizer application. Pitting = manual hand hoeing of planting pits, plus fertilization.

from 1.3 to 3.7 tonnes/$ha^{-1}$ for non-fertilized maize), and a 25 percent increase in yields during a drought season (short rains 1996/1997) (Rockström and Jonsson, 1999).

The results of on-farm trials with subsoiling, cover crops and minimum-tillage conducted in the neighbouring Hanang and Karatu districts confirm these findings. Yields of maize and wheat could be more than doubled during three consecutive years (1999 to 2001). The highest increment was observed in the dry year 1999, where the annual rainfall was only 233 mm and 451 mm compared with an average of 800 mm, and crops failed completely on conventionally tilled fields in Karatu district (TFSC, 2000; 2001; 2002).

## YIELD AND WATER PRODUCTIVITY

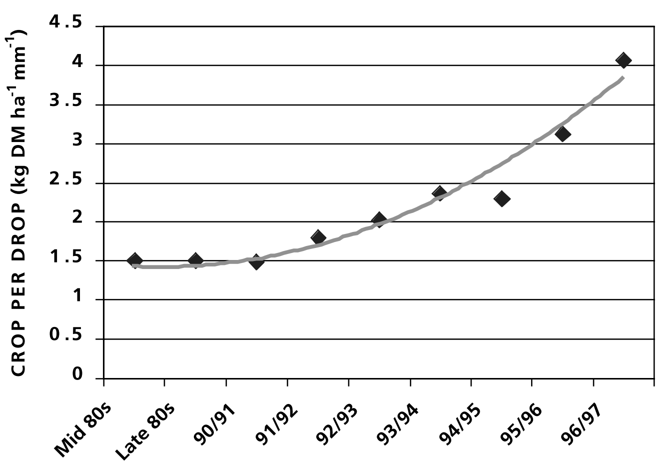
### Rainwater productivity

The animal-drawn ripper-based conservation farming system resulted in increased rainwater productivity (an average $WP_R$ of 2 400 $m^3$/tonne compared with 3 800 $m^3$/tonne for the conventional [non-fertilized] farmers' practice). According to the farmers participating in the trials, conservation farming resulted in practically zero surface runoff. This suggests that the reduction in water consumption per unit crop under CT is a result of a reduction in soil evaporation and/or deep percolation. Rainwater productivity was increased by fertilizer application in both systems (conventional = 1 750 $m^3$/tonne; ripping = 1 400 $m^3$/tonne). Using cover crops instead of fertilizer in ripped fields gave similar results to conventional farming with fertilizer (1 600 $m^3$/tonne versus 1 750 $m^3$/tonne). Data suggest a synergistic effect of rainwater harvesting and fertilizer application, indicating that fertilizer use efficiency is increased by conservation farming (i.e. improved soil moisture status).

The subsoiling trials discussed above in Babati district in western Tanzania using tractor-drawn subsoiling and ripping resulted in similar water productivity improvements (Figure 2). Over a

FIGURE 2

**Development of rainwater use efficiency (kg DM grain $mm^{-1}$ $ha^{-1}$) of maize in Babati district, Tanzania before introduction of conservation tillage (mid-1980s to 1990/1991) compared with after introduction of conservation tillage (1991/1992 onwards)**




*Source:* adapted from Rockström and Jonsson, 1999.

period of seven years, a progressive improvement of $WP_R$ could be observed from an average of 1.5 kg grain per millimetre of rainfall (6 600 $m^3$/tonne) in the 1980s (based on conventional disc ploughing by tractor) to approximately 4.5 kg grain per millimetre of rainfall (2 500 $m^3$/tonne) in the mid- to late 1990s after adoption of deep tillage and non-inversion technologies (adapted from Rockström and Jonsson, 1999). It is assumed that this is primarily owing to a reduction in surface runoff, improved water infiltration and storage and a more profound root system.

## FARMER EXPERIENCES WITH CONSERVATION FARMING IN MADAGASCAR

In Madagascar, the French research organization CIRAD has been working since 1994 on the development of direct planting practices for smallholder farmers. The objectives are to maintain soil fertility, prevent soil erosion and increase yields of food crops, as well as producing forage for livestock (cattle). A key issue is the maintenance of a permanent soil cover by crop residues and relay cropping of forage plants (oats, etc.) or associations with permanent species such as *Desmodium uncinatum* or *Trifolium semipilosum*, Kikuyu grass or *Pennisetum clandestinum*. Crop yields, labour productivity and household incomes could be increased significantly with a steady upward trend.

Figure 3 shows data of on-farm trials of six successive years. Data are derived from three different regions in the semi-arid parts of the Madagascar highlands; three on-farm plots (= repetitions) were installed at two different sites in each region, in total 18 on-farm plots. Soils are sandy alfisols (*sols ferrugineux tropicaux*) with 70 percent sand and 15 percent clay. Annual rainfall varied between 480 and 850 mm. By stopping ploughing and direct planting, bean yields could be raised from 200 to 400 kg/ha to 800 to 1 700 kg/ha in unfertilized plots and from 400 to 600 kg/ha to 1 800 to 2 000 kg/ha in fertilized plots. Rainwater productivity was simultaneously raised from 0.1 to 0.2 kg of grain per $m^3$ of water to 0.38 kg maize grains and 0.58 kg of maize and cowpea grains (intercropping).

## DEVELOPING RAINWATER HARVESTING TECHNIQUES IN THE KORDOFAN PROVINCE OF THE SUDAN

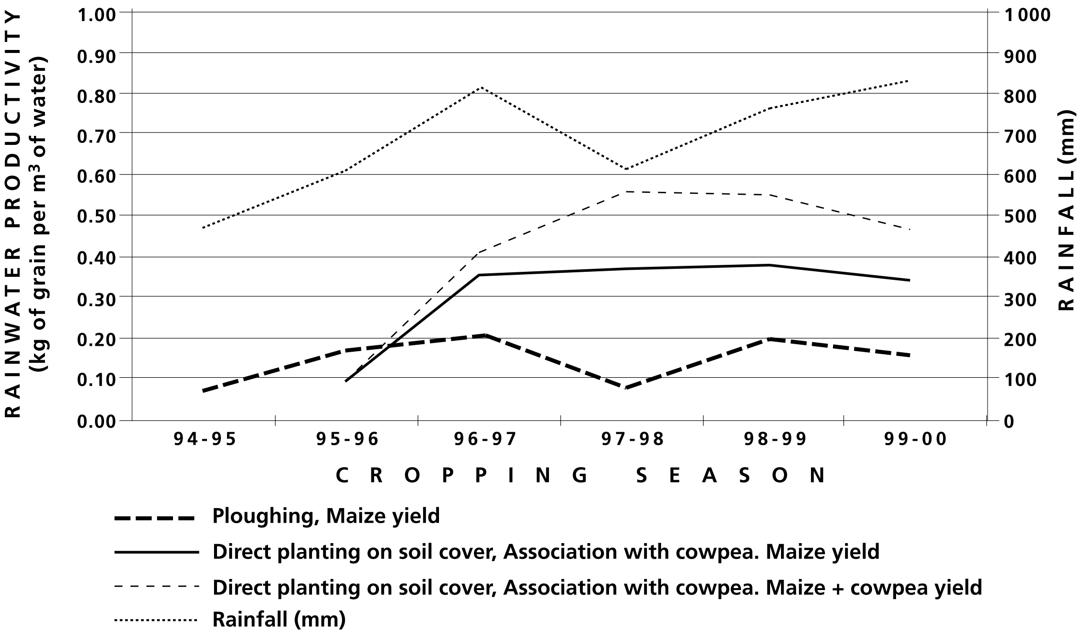
In the Sudan, food security in dryland agriculture is threatened by low average rainfall and frequent droughts. Owing to population growth, more and more traditional pastureland is used for cropping. Since 1998, the National Agricultural Research Institute has been conducting on-farm trials with rainwater harvesting methods in the Kordofan province, with the objective of increasing yields and reducing the risk of crop failure due to drought. The land is almost flat, with gradients of 1 percent only. Soils are sandy to sandy clay loams. Rainfalls are erratic, with annual means varying between 140 and 624 mm (1998 to 2002). Prolonged dry spells during the cropping season are frequent.

Traditionally farmers till or scratch the land only superficially with hand tools. The main crops are sorghum, millet, watermelon and groundnut. With the first rains, the soil surface gets crusted, resulting in runoff and high losses of precious rainwater.

The rainwater harvesting techniques tested consist of parallel earth bunds, about 40 cm high, built at 10 m distances. The upper half of the strip between bunds serves as a runoff area, the lower half is planted with sorghum. The sorghum is planted in ripped (by chisel or tine) rows, outlets for excess water are placed to ensure even water distribution, while cowpea or groundnuts and Roselle are planted on the inner side of the earth bunds (as soil protection and an additional source of food and income). With this simple technique, sorghum yields can be tripled or quadrupled in normal years, and total crop failure can be prevented in dry years (Figure 4). The rainwater productivity is a rough estimate, based on total rainfall in the growing season, and crop yields.

FIGURE 3

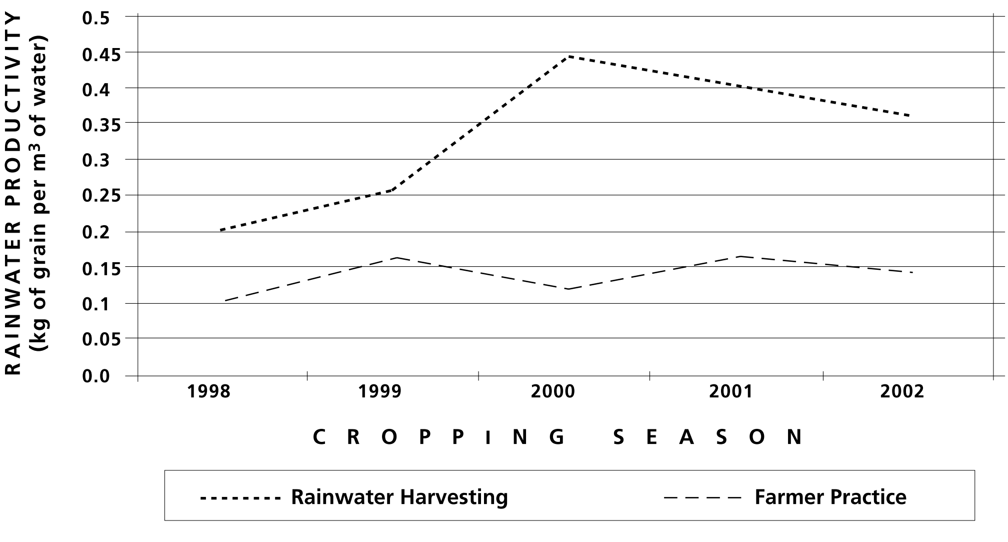
**Development of rainwater productivity under direct planting through soil cover in Tulear, highlands of Madagascar**




*Source:* O. Husson, personal communication

FIGURE 4

**Impact of rainwater harvesting on sorghum yields in Obeid, Kordofan province, the Sudan**




Notes: Data from researcher-managed on-farm trials 1998 to 2002. "Farmer practice" refers only to tillage and not to other management aspects, which equal those of "Rainwater harvesting". Data on farmer practice 1998 and 2002 interpolated. Complete crop failure due to drought in 2002

*Source:* O. Alfadni, personal communication.

## CONCLUSION AND DISCUSSION

Conservation farming systems are not new and have, during the last decades, been adopted at a large scale in several countries in Latin America, in parts of Asia and in North America. Common to this wide adoption is that most success has been experienced in relatively wetter hydroclimatic zones, with limited success in drier, savannah agro-ecosystems. This paper addresses the water harvesting advantages of conservation farming systems, which form an entry point to conservation farming development in relatively drier savannah environments. It is interesting that commercial farmers in semi-arid and dry subhumid regions of, for example, Tanzania and Zimbabwe have adopted conservation farming practices, resulting not only in higher and more stable yields but also in significantly reduced labour and fuel needs (Oldreive, 1993). Only very limited adoption has been experienced among smallholder farmers in savannah agro-ecosystems.

On-farm trials in savannah agro-ecosystems among smallholder farmers in Tanzania show that yield levels of maize can effectively be more than doubled over consecutive years, with varying rainfall levels, through the adoption of conservation farming practices. A cornerstone in these practices is the *in situ* water harvesting effect of ripping and subsoiling, which instead of turning the soil at shallow depth (as done by ploughing) opens a deep planting furrow, which effectively collects rainwater.

Mouldboard ploughing is still perceived among farmers, extension agents, development officers and most researchers as a *sine qua non* in every crop producing system. The very notion of abandoning the plough in favour of various techniques of reduced tillage was initially not easy to convey. However, the obvious benefits of reduced tillage, especially in years with extended dry spells, rapidly turned disbelief into a strong local ownership of the adaptive process of designing site-specific conservation farming systems. This highlights again that farmers are open-minded and prepared to make fundamental changes to their land-use practice if they can see the benefits in doing so.

Rainwater productivity is increased by a soil cover of crop residues and cover crops. However, this is difficult to achieve in dry savannahs, where rainy seasons are followed by long dry seasons, biomass growth is overall low and livestock and humans compete for the use of post-harvest biomass remaining in the fields. A challenge in savannah regions is, therefore, to develop integrated crop–livestock production systems. This requires further research and development activities together with farming communities.

Conservation farming systems provide farmers with an effective tool to maximize rainfall infiltration into the soil and to build up water holding capacity and crop water access. They do not provide farmers with a solution to mitigate dry spells, even though the length of dry spells and their effects can be reduced somewhat thanks to an increase in soil moisture availability. An interesting, unexplored avenue is to integrate conservation farming practices as a form of *in-situ* water harvesting with external water harvesting systems where runoff water upstream from cropland is harvested and stored for supplemental irrigation. Together, such practices could enable farmers to increase and stabilize food production, and thus improve rural livelihoods in the long term.

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# CHAPTER 8
# ABOVE-GROUND TRANSFORMATIONS IN AGROFORESTRY SYSTEMS IN WATERSHEDS: CASE OF COCOA AGROFORESTS OF CENTRAL CAMEROON

**P. Mbile**
World Agroforestry Centre, Messa, Yaounde, Cameroon

**N. Besingi**
University of Dschang, Cameroon

**M. Tonka**
University of Dschang, Cameroon

**Z. Tchoundjeu**
World Agroforestry Centre, Messa, Yaounde, Cameroon

**A. Atangana**
World Agroforestry Centre, Messa, Yaounde, Cameroon

## ACRONYMS

| | |
|---|---|
| **CFA** | Communauté financière africaine |
| **MT** | median tree |
| **NMT** | non-median tree |

Local knowledge passed down from ancestors to descendants indicates that a considerable proportion of the forest margins of central Cameroon was previously covered by forest savannah. These forest savannahs have since been occupied by pioneer settlers who have developed traditional agroforestry systems. These agroforests are simultaneous land management systems, in which tree components occupy the same area as crops and, sometimes, animals. Similar to home or forest gardens, the agroforests possibly constituted the first transformation of original vegetation into a consciously managed agroforestry system. To date, their value is based on their flexibility, both economically (i.e. flexible demand on labour) and ecologically (i.e. diversity of species and different harvest periods for products) and in terms of the adaptation of products to local and national markets as well as household needs (Minchon, Mary and Bompard, 1989).

Many of these traditional agroforestry systems experienced their second transformation approximately 30 to 50 years ago with the onset of cocoa plantations (Tonka, 2003). There was a move towards transforming forest savannah to cocoa agroforests. Indigenous trees in these cocoa systems continued to serve as medicine, fruit and food sources, with the vast majority set aside as shade trees for the cocoa crops. In this second transformation, the health and productivity of the cocoa crop was the main concern and driving force behind the management of these agroforestry systems.

The decline of the cocoa sector, which began in 1989, came to a head in 1995 with the quasi-liberalization of the production chain for cocoa. The devaluation of the Communauté financière africaine (CFA) franc in 1994 led to the doubling of Cameroon's external debt, therefore the Government of Cameroon was forced to reorganize the sector by withdrawing subsidies to farmers. The combined crises of a failing international market, rigorous national policies, social pressures, low inputs and low yields at the farm level meant that farmers could no longer fully observe technical guidelines (Bernard, 2000), maintain the cocoa plantations and depend almost entirely on the cocoa crop for their livelihood. This period saw a gradual disenchantment by farmers with cocoa as a dominant livelihood strategy. In addition, cocoa is not directly used in indigenous culinary and health strategies.

These circumstances led to the third transformation, characterized by both the increasing diversification of the use of cocoa systems by integrating and managing greater numbers of indigenous fruit and medicinal trees, and the development of smallholder plantations. Both strategies were geared towards more profitable land use and greater food and health security. This third and latest transformation of agroforestry systems was accompanied by the spread of smallholder plantations and mixed systems, the latter being characterized by variations in three important above-ground factors:

- tree species diversity;
- spatial and horizontal disposition of trees;
- spatial and vertical stratification of the systems.

While the smallholder plantations tend to follow the lines of intensification (using less complex methods of monocultures, high-yielding varieties, regular spacing and single strata), the cocoa agroforests are characterized by a more complex and dynamic arrangement in which economic, ecological and management questions are less predictable. Two transformation processes are currently evident, smallholder monocultures and annual crop agroforests; the latter are by far the more complex, and therefore are analysed in this paper. Numerous factors are undergoing change in this current process of transformation of agroforestry systems. Even for annual tree crop-based agroforests such as the cocoa systems, tendencies are towards simplification of system structure, regularization of inter-tree distances, integration of more uniform and high-yielding trees, and greater domestication of the agricultural landscapes, largely for socio-economic reasons.

It is likely that other processes such as the environmental consequences of these transformations will tend to be less obvious, hence these tendencies and trends will form the basis for this research. The work was carried out in order to capture these latest transformations in agroforestry systems as they unfold, and to raise some pertinent research questions regarding the potential links that may exist between the visible above-ground transformations and the less visible systems, watershed properties, as part of a potential future research agenda for the region.

The study focused on the characterization of spatial, quantitative and qualitative aspects of indigenous trees within cocoa agroforests in the study sites. The following three specific hypotheses guided this above-ground characterization study:

1. The degree of variation in the horizontal inter-tree distances of indigenous trees is a measure of irregularities in their horizontal spatial distribution, and a cause of sparseness and/or clustering in different parts of the system.

2. The height distribution of the indigenous trees largely determines the vertical stratification of the agroforest system.
3. The knowledge of the species and the extent of their use by local communities is a strong determinant of management requirements and therefore of what practices are likely to be retained, eliminated, substituted or replaced.

The legitimacy of these hypotheses can be found in observable characteristics in the cocoa systems and in current scholarly knowledge on the potential effects of trees and tree systems on components of the hydrological cycle (interception, percolation, transmission, retention, discharge, evapotranspiration), as well as the ways in which these influence the water budget of a farming system on a watershed. Trees on farms can have these effects in their influence on water-related properties of the soil (Stevenson and Cole, 1999; van Noordwijk *et al.*, 1999) such as organic matter content or their hydraulic conductivity (Angers and Caron, 1998).

According to the hypothesis, the greater the variations in inter-tree distances, the more irregularly the soil surface of the farming system is likely to be covered, resulting in sparsely covered or exposed areas and densely covered or choked up sections. This creates a patchwork of tree cover as a result of both farmer intervention and natural processes that stem from the need to provide shade to cocoa crops.

In tree-based systems with minimal undergrowth, the more developed the stratification or height class distribution (light and heavy crown) of the trees, the more developed the system's mosaic or overlapping characteristics. An increase in raindrop interception (achieved mostly by trees in the highest stratum) results in a reduction in impact velocity. This leads to less surface crusting of the soil, greater percolation and infiltration to the soil, and reduced runoff resulting in a potential increase in groundwater.

Farmers are able to influence the properties of soil in the cocoa systems in the choice of trees to introduce. Deciduous, broad-leaved and fruit producing trees create larger amounts of biomass that is added to the soil. Similarly, the even distribution of these trees over the farm surface will result in fewer disparities in such factors as organic matter accumulation, soil surface exposure and wetting and drying cycles of the soil. These factors affect the hydraulic conductivity of soils (Angers and Caron, 1998), however; the overall water retention and discharge within a cocoa system can be indirectly managed. This is achieved through factors affecting reception and infiltration, soil retention, evapotranspiration and discharge to groundwater, resulting in reduced variation across agroforests in important watersheds throughout the African humid tropics.

## RESEARCH METHODS

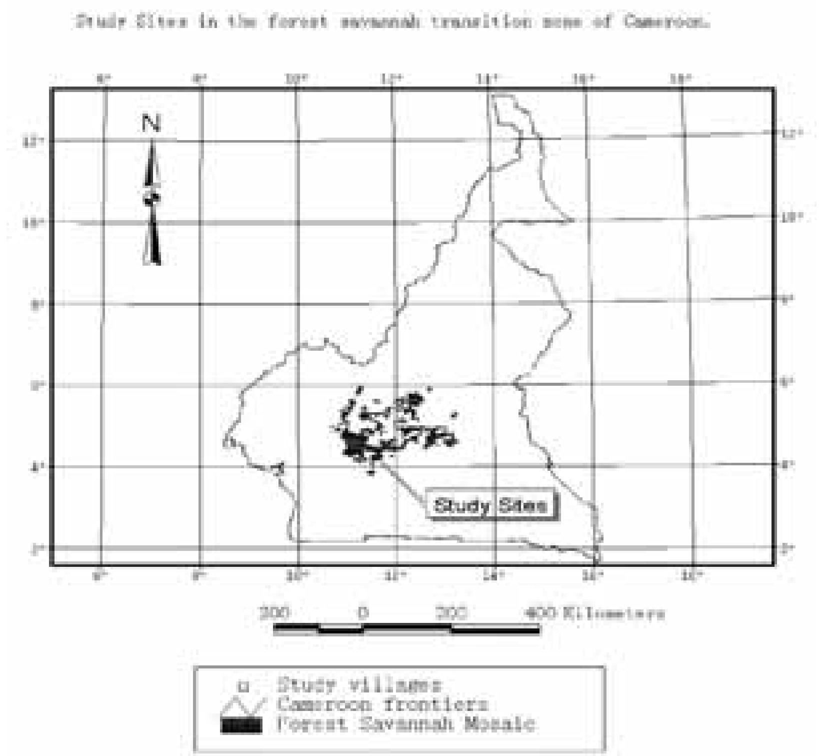
### Research site and sampling design

Thirty cocoa farms were selected systematically within the forest savannah study site (Figure 1). The general characteristics of the forest savannah showed little or no variation in dominant tree or herbaceous species; therefore, no vegetation-based stratification was deemed necessary. Instead, stratification was carried out at the community level where three villages, each between 2 and 3 km apart, were selected for the study. The basic rule was that no two farms were to constitute a contiguous block. Ten farms were selected per village by randomly selecting numbers from a list of all cocoa producers within that village.

Within each cocoa farm, a median was estimated with the help of the farmer, and all trees within 8 to 10 m on either side of the median were characterized. This study transect (20 m wide), cutting across all 30 farms, covered a total distance of more that 1 000 m, thus constituting a total study surface area of more than 20 000 m² or 2 ha.

FIGURE 1

**Forest savannah zone where study was carried out.**



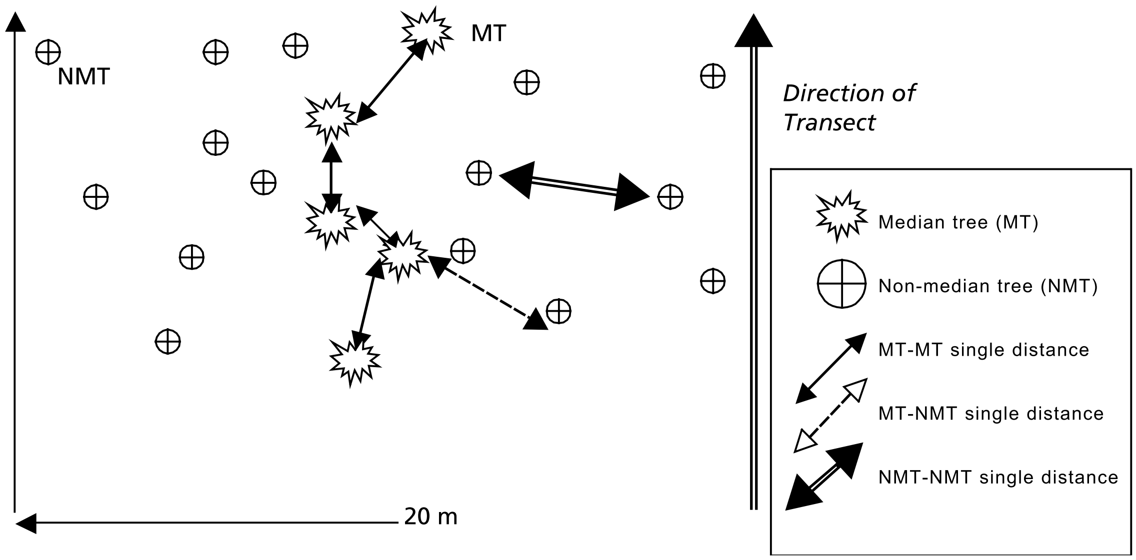

## Data collection

A research team consisting of three people (including the farm owner) carried out the data collection. In order to maintain the median of the cocoa farms or subplots, a series of median trees were identified throughout the length of the farm (Figure 2). Non-cocoa indigenous trees within this median were referred to as median trees (MTs). All other trees on the left and right of the MTs were referred to as non-median trees (NMTs). The following measurements were then taken within these transects:

- Tree heights were estimated using an improvised "thumb method". A stake 1.8 m tall was placed against the tree and used as a yardstick for measurement. Two or three people independently estimated the height of the tree by mentally counting the number of yardsticks that would correspond to the height of the tree. This number could not differ by more than 2. The two or three readings were then averaged and multiplied by 1.8 m to get the estimated tree height.

- Single horizontal distances between MTs of heights greater than 3 m were measured using a measuring tape.
- Single horizontal distances between NMTs of heights greater than 3 m were also measured using a measuring tape.
- All trees that were measured were also identified by their local name. Those not known by the farmer were recorded as “unknown”.

FIGURE 2
**Cocoa farm transect characteristics**




### Data analyses

An analysis of variance in inter-tree distances was carried out using GENSTAT (Edition 6). Tree height classes were sorted using Microsoft™ Excel, and a diagrammatic representation of a compressed “unit” cocoa agroforest was generated. Additional quantitative analysis was carried out using Excel. The main results are presented in the following.

## RESULTS AND DISCUSSIONS

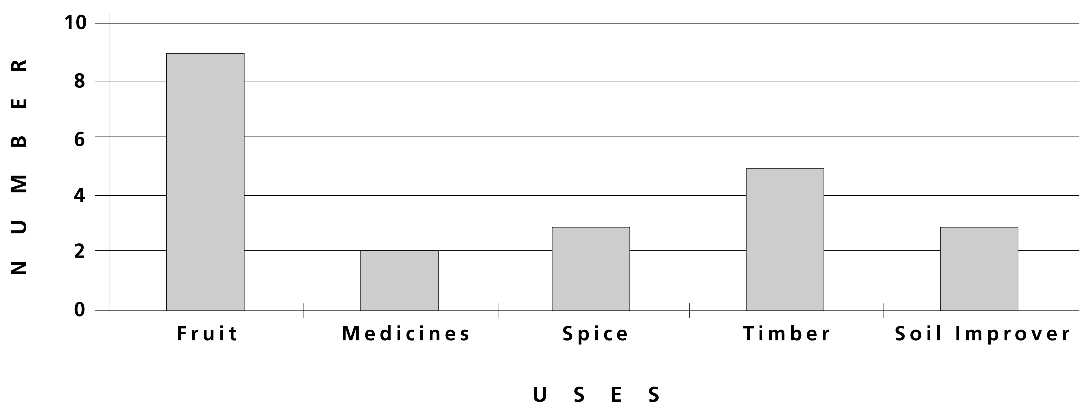
Table 1 shows that a relatively wide range of indigenous trees were encountered on the study site farms; however, farmers generally use only trees that they know, while others remain to provide shade for the cocoa crop.

TABLE 1
**Trees species that are unknown, known and used by farmers**

| ITEM STUDIED | RESULT |
|---|---|
| Total number of different species of trees encountered | 162 (100%) |
| Number of species unknown to the farmers | 96 (59%) |
| Number of species known but not used | 44 (27%) |
| Number of species most used by the farmers | 22 (14%) |

With the present transformations in the cocoa system, more than half of the indigenous trees are unknown to the farmer and remain in the agroforest only to provide shade for the cocoa crop. Indications are that as the value of the cocoa crop continues to be uncertain, trees within this category are most likely to be replaced. Of the 22 most used species the vast majority were indigenous and exotic fruit species (Figure 3). Farmers claimed that "duplicates" for these trees occurred in the woodlands nearby. Their performance in terms of form, height and productivity was generally poor. Trees were too tall and impossible to climb. Fruits were generally small for the species, and management was non-existent. Indications are that these fruit trees were not fully valued by the farmers as they generally performed badly in the cocoa systems. Therefore, with the introduction of even a mildly more profitable alternative land use, farmers may not hesitate to transform the system further at the expense of these trees.

FIGURE 3
**Uses of most-used species**



Therefore, unless new steps are sustained in the diversification and intensification of the cultivation of high-value trees, the cocoa systems and the trees in them are likely to see increasing instability in the years to come.

In terms of the spatial arrangement of the trees, the irregularity was very marked (underlined by variations in inter-tree distances). As Table 2 indicates, the distances between all the categories of MTs and NMTs varied considerably ($p < 0.001$). This is a strong indication of the potential for clustering in some parts of the farm and/or sparse distribution in others, which was supported by direct observations on the farms. Generally, the horizontal spatial distribution is irregular for all the trees, irrespective of species.

TABLE 2

**Extent of variations in inter-tree distances in cocoa agroforest**

| Parameters | Results for inter-tree distances between MTs (MT-MT) | Results for inter-tree distances between NMTs (NMT-NMT) | Results for inter-tree distances between MTs and NMTs (MT-NMT) |
|---|---|---|---|
| Values (n) | 234 | 506 | 351 |
| Mean | 7.466 | 7.008 | 8.387 |
| Probability | (< 0.001) | (< 0.001) | (0.001) |
| Standard error | 3.702 | 3.448 | 4.180 |
| Coefficient of variation | 49.6 | 49.2 | 49.8 |

In light of the current transformations in new plantations within the zone of study and elsewhere, there is a tendency towards conscious regularization of inter-tree distances in order better to manage space, tree growth and maintenance activities. This is very marked, particularly in new oil-palm-based plantations.

In terms of vertical stratification, a clear and consistent structure could not be discerned in the agroforests. One precondition for optimum use of vertical space is the three-tier model proposed for the "ideal" agroforest (Minchon and De Foresta, 1997). These cocoa agroforests show a great dominance within the 10 to 20 m height class.

The 10 to 20 m class shown in Table 3 is so large that in order to analyse it correctly, it required further division into subclasses. When related to the three-tiered model, two classes (5 to 10 m and 20 to 25 m) appear dispensable. According to the farmer, these two intermediate classes often constituted points of increased disease spread from tree to tree and from stratum to stratum. It is possible that the greater efficiency achieved by the ongoing transformations of improved space management and pest management may require these intermediate strata to be thinned out.

TABLE 3
**Tree height class distribution in the cocoa systems**

| Stratum according to Figure 2 | Tree height class | Number of indigenous trees | Proportion of system |
|---|---|---|---|
| Stratum A | 5 m | 30 | 3% |
| T1* | > 5 m < 10 m | 99 | 11% |
| Stratum B | > 10 m < 15 m | 198 | 25% |
| Stratum B | > 15 m < 20 m | 240 | 29% |
| T2* | > 20 m < 25 m | 187 | 21% |
| Stratum C | > 25 m | 89 | 11% |
| **Totals** | **6 classes** | **843 trees** | **100%** |

Notes: * T1 is intermediate between strata A and B; T2 is intermediate between strata B and C.

Figure 4 is a cross-section representing all the cocoa agroforests that were studied and showing the "smallest denomination" of these trees. Clearly, T1 and T2 are strata requiring elimination if the ideal three-tier structure is to be attained. Stratum B has also been found to be too dense, and may need to be thinned out. On the other hand, stratum C may be too thin.

## CONCLUSIONS

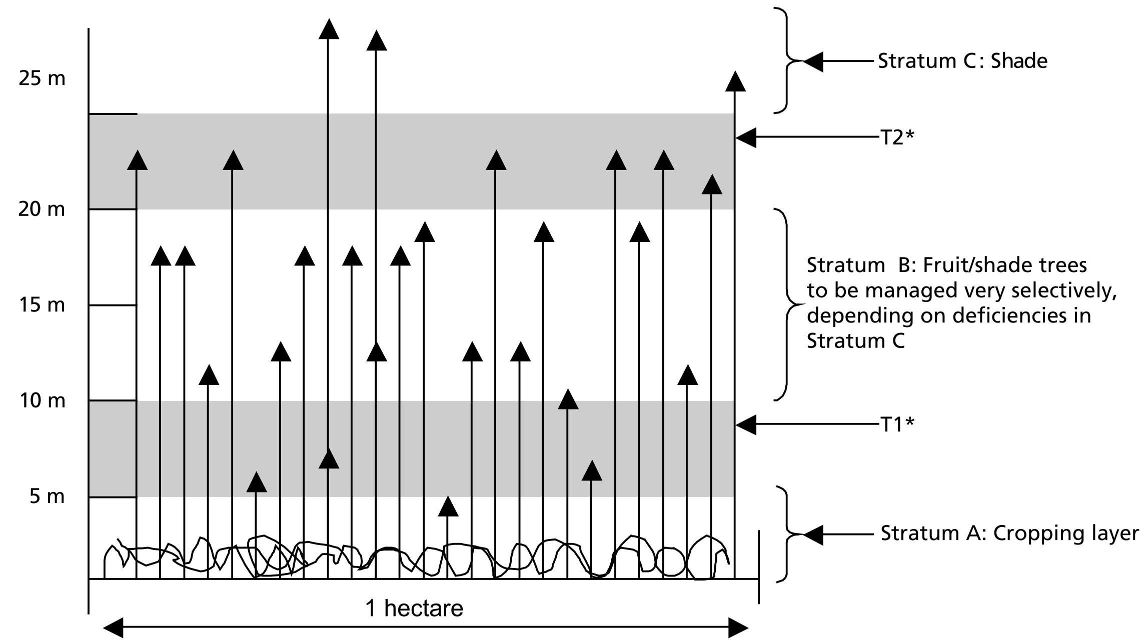
The results of this research raise a number of important management questions that can be directed towards two main areas. The first is in terms of the hypotheses given at the beginning of the research, and the second in terms of the potential effects of these transformations on the watershed functions of these agroforests.

When reviewing the original hypotheses, the results show conclusively that there are highly significant variations in inter-tree distances within all height classes in traditional cocoa agroforest systems. This variation leads to considerable irregularity in the spatial arrangements of the more dominant components in these agroforests. The questions that are therefore raised are:

- How will such variations relate to vital watershed functions of these increasingly rampant and ubiquitous agroforests?
- How should they be managed in the coming years?

Second, the results show quite conclusively that vertical stratification in these agroforests is a function of the height class distribution within the system. Furthermore, although the maturity and productive form of some indigenous trees are known, heights of trees in systems such as those studied are equally influenced by competition (due to environmental factors) with other trees. Therefore, to develop and maintain a model structure with potential benefits for space

FIGURE 4
**Compressed unit cocoa agroforest**




* T1 is intermediate between strata A and B; T2 is intermediate between strata B and C.

management would require intensive management of the agroforest. However, the management of such a system creates potentially contentious and critical issues. The farmer should be responsible for making decisions regarding thinning, eliminating, substituting or replacing trees within the agroforest system. The potential costs and benefits involved and the trade-offs necessary need to be evaluated to enable the farmer to take calculated decisions with balanced or more acceptable outcomes. This appears to be a classic case of the application of optimum pessimism: success results in moderate benefits and failure in moderate losses. Current possibilities would suggest a non-specific (generic) decision providing a range of options to farmers, with associated possible outcomes and different levels of risks. In a society where the level of production of cocoa for individual farmers may mean the difference between destitution and survival, care needs to be taken to unite better the environmental and livelihood objectives. Similarly, the level of management given to the cocoa may rely directly on the value given to the product by individual farmers. The value of a tree is directly related to accumulated knowledge relating to that tree by the farmer, thus playing a large role in the management decision-making process. Therefore, gaining additional knowledge relating to the indigenous trees within an agroforest system is beneficial in the management process.

In order for the potential effects of these transformations on the watershed functions of agroforest systems to be assessed, substantial medium- to long-term research must be carried out in order fully to support such theories. Important factors will need to be addressed relating to watershed functions that are relevant to the main components of the hydrological cycle. These factors can significantly influence the water budget of any agroforest system.

Additional and relevant research, modelling and management (at the local level) may be necessary to reach equilibrium in balancing both the costs and benefits accruing from agroforest systems. These can provide optimum benefits both for the environment and for the livelihoods of farmers. Current knowledge regarding the effects of trees and tree systems on components of the hydrological cycle (i.e. interception, retention, discharge, evapotranspiration, soil moisture storage, water deficit) that apply to existing situations is needed to support and justify future efforts.

The results of this study clearly indicate that transformations in agroforestry systems within the region are increasingly characterized by trends in spatial distribution of trees in agroforests from irregular to regular distribution. This was shown by a decrease in the variations between inter-tree distances and changes from complex to simpler vertical stratification (i.e. multi- to fewer strata). However, the issues relating to trends in tree diversity, an expanded knowledge base and indirect values of trees on farms are more varied and less conclusive. What is certain is that as transformations continue in agroforests, driven by economic considerations, transformations also occur in the biophysical processes within the system. Greater understanding of these processes is still required. Furthermore, these economically driven transformations tend to simplify the system from complex and dynamic to ordered, less complex and more predictable or "domesticated" systems. Tree domestication activities carried out by the World Agroforestry Centre tend to support a more ordered and predictable system, closely resembling traditional agroforests in both diversity and stratification. Questions remain to be answered relating to the optimum balance between sustainable livelihoods for farmers and an equitable environmental balance.

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