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Water Conservation in Arid and Semi-Arid Agriculture: A Case Study Analysis for West Africa

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ABSTRACT

Water conservation is a necessary component in efforts to raise the productivity of traditional rainfed farms in West Africa. Soil-water balance relationships and a whole-farm modeling approach are utilized to estimate benefits of conservation on a typical farm in Mali. Increased rainfall infiltration could increase income from 2 to 4 times and food grain production from 60 to 90 percent in combination with small amounts of fertilizer.

INTRODUCTION

The seven West African countries of the Sahel (Senegal, Gambia, Mauritania, Mali, Burkina Faso, Niger, Chad) are among the poorest of the world: per capita income averages $235; average food intake is below minimum requirements falling as low as 1500 calories per day in some locations (FAO, 1982); and, average life expectency is about 42 years. Despite an extremely harsh natural environment, agriculture is the dominant economic sector in the region supporting 75 to 90 percent of the population (World Bank, 1985). Yet, less than 4 percent of the region is classified as arable (FAO, 1984). Dryland production accounts for 99 percent of all cultivation in the region today.

Population growth rates are high. The average in the past decade has been between 2 and 3 percent annually. For the region as a whole it is projected at 2.8 percent per year (World Bank, 1985). Since the late 1960's per capita food production has declined steadily by about 1.7 per cent per annum (OTA, 1986). This alarming trend is expected to continue. By the year 2000, for example, the population of the Sahel will approximate 54 million and exceed carrying capacity under traditional rainfed production systems by about 30 million people (World Bank, 1985).

Given the limited role of irrrigation in the Sahel, the dryland sector must become more productive if significant changes are to occur. Major issues are what new technologies are appropriate for the natural environment of the Sahel, and what are the farm level economic and productivity benefits of technology transfer. Appropriate soil and water management practices can lead to sustained agricultural productivity in dryland environments. In this paper water conservation through increased rainfall infiltration is evaluated in a case study analysis of a typical dryland farm in Mali, West Africa.

GENERAL BACKGROUND: DRYLAND FARMING IN MALI

The situation in Mali is typical of Sahelian countries in general. Eighty-five percent of all cultivated land is in food grains--largely sorghum, millet, rice and maize. From 1966-83 per capita food production of major cereals declined an average of 3 percent annually (Shapouri, et al., 1986). The current population growth rate is 3 percent.

Ninety percent of Mali's arable land is farmed under strictly rainfed conditions. Sixty percent of the country receives less than 400 mm of rain per year (TAMS, 1983). Throughout the area, rainfall is highly variable in terms of date of onset, length of the rainy season, and in the total amount and timing through the year.

Exacerbating the rainfall situation is the poor quality of soil resources. In many areas the combination of soil crusting and intense storms cause low infiltration. Soil water holding capacity generally is low. The natural fertility of the soil is not high; organic matter is lacking and soils are deficient in nitrogen, phosphorous, sulfur and organic matter (TAMS, 1983).

Crop varieties are largely local landraces tolerant to low moisture, low nutrient levels and pests, but also low in productivity especially under good conditions and higher input levels. Much of the tillage operations are done manually.

Farms are small and labor is usually limiting at some time during the cropping season. Farm prices tend to be very low relative to production costs. Producing for home consumption is a primary objective and farmers are reluctant to risk scarce capital and needed food supplies on new and costly practices with uncertain returns.

It is in this context that one must appraise the technical and economic feasibility of improved water management options.

TECHNOLOGICAL OPTIONS FOR DRYLAND FARMING

A number of technologies and related farm management practices are suitable for conditions found in the Sahel. These practices include: use of fertilizers; soil water conservation measures such as tied-ridges, bunds, micro-catchment basins, mulching, small scale soil

erosion and runoff retention devices (diguettes); various tillage and cultivation schemes with and without animal traction; better crop selection and more flexible scheduling of crop calendars.

Both tied-ridges and fertilizer can economicallly increase yields and net income; moreover, in combination with each other there is an interactive effect such that the increase in return is more than additive (Roth and Sanders, 1984). If insufficient soil moisture exists fertilizer may not be profitable. Animal traction for tillage in combination with tied-ridges and fertilization can also be economically beneficial, i.e., gains of 50 to 70 percent in both farm income and food production have been reported.

Crop breeding programs currently underway emphasize short cycle varieties. These varieties can increase farm income by allowing farmers more flexibility in planting, re-planting, intercropping and relay-cropping rotations. Stewart (1987) has shown that the amount of rain and the duration of the rainy season can be strongly correlated with date of onset. Important cropping decisions should thus be made in response to the onset and pattern of rain as it evolves shortly thereafter.

Much of the economic research on technological innovations for the Sahel has addressed the issue of rainfall variability only from the point of view of inter-seasonal variability of total rainfall. Yet in rainfed farming the intra-seasonal variation is also important. It is the intra-seasonal pattern of rainfall (timing and amount) together with soil water infiltration rates and soil water holding capacities that determine the amount of moisture actually available to crops at different stages of their growth cycle. Plant water requirements, in turn, differ in time depending on planting date and variety. For example, if infiltration rates are 40 percent of rainfall, and 20 percent of infiltration is lost to deep percolation, then no more than 40 percent of rainfall is likely to be available for plant use. Adjusting plant dates and/or variety can bring water requirements more into line with water availability. These interactions must be taken into account when evaluating soil, water, and crop management practice.

The principal conclusions from this review of literature are, (1) it is a combination of soil, water, and crop management practices that offer the best chance of improving productivity and income in the Sahel and (2) evaluation of the economic feasibility of such measures requires the use of data and analytical methodologies that reflect soil characteristics and weather related variability within a crop growing season.

THE ANALYSIS

The objective of this analysis is to estimate the impacts of improved water conservation on a traditional Sahelian farm. Estimates of (a) the potential economic benefits of increased infiltration and (b) the

production and resource use decisions that are complimentary to increased soil water availability are generated. In the following sections the methodology followed and the input data utilized in the analysis are described.

Methodology

Whole-farm modeling is widely recommended as a useful methodology for farm level technology appraisal (Ghodake and Hardaker, 1981). Such models can reflect the basic production processes involved in agriculture as well as many of the resource characteristics and constraints with which farmers must work. For this analysis a representative farm linear-programming model and a soil-water balance LOTUS spreadsheet routine, both calibrated to reflect within-season crop water availability and requirements, were developed to serve as basic analytical methodologies.

The Representative Mali Farming Situation

Farm Characteristics

Drawing upon farm level surveys conducted in nine villages and 55 farms in the Kita region during 1978 and 1979, basic characteristics of traditional farms in the area were identified (Table 1).

TABLE 1: REPRESENTATIVE KITA FARM (TRADITIONAL)

Agro-Climatic Zone	: Sudano-Guinean	Technology	: Traditional, with no modern inputs
Rainfall Zone	: 800 - 1000 mm	Home Consumption	: Per Capita - food grains 185 kg; vegetables 20 kg
Soils	: Alfisols		
Farm Size	: 8 hectares	Crops	: Sorghum, Millet, Groundnut, Maize, Vegetables, Rice, Sorghum-Groundnut Intercropped
Family Size	: 12 members		
Family Labor Pool	: 5 adults (FTE)		

Source: Fleming, 1981

The Representative Farm Model with Technical Innovations

In general form the model is:

(1) $\text{Max } I = \Sigma_i P_i X_i$

Subject to the following constraints

(2) $\Sigma_i X_i a_{ij} \leq C_j \quad j = 1..., m$

(3) $X_i \geq 0 \quad i = 1..., n$

where I is net income, P_i = net revenue per unit of the i-th activity, X_i is the level of the i-th activity, a_{ij} is the amount of j-th constraint per unit of i-th activity, and C_j is the limit of the j-th constraint.

The objective function, equation (1), is maximization of gross revenue of farm crop production less crop losses, seed stock and family/village gifts in the form of produce and home consumption, minus costs for tied-ridges, fertilizer, seed, and labor. The constraint set refers to labor availability, land availability, a requirement that production less deductions must meet minimum family food consumption requirements, and the usual non-negativity requirements on production activities. This same framework was utilized for four alternative production-harvest schedules so that the optimal planting period and related calendars of operations were integral decision variables in the model.

Rainfall Patterns

Data obtained at the Kita weather station, the official station nearest the study site, were used as the basis for rainfall levels and associated probabilities, the number of rainfall events per month and other climatic information utilized in the study (Sivakumar, et al., 1984; Hargreaves and Samani, 1986). Rainfall patterns at the 75 (approximately one standard deviation below the mean) and 50 percent probability of occurrance were selected to represent two likely rainfall conditions facing farmers in the area.

TABLE 2. RAINFALL AT KITA STATION MALI, mm (51 YEARS OF RECORD)

Time Periods	Probability Levels (%) 75	50	Percent Difference
04/23-5/20	9	21	133
05/21-6/17	75	104	39
06/18-7/15	135	175	30
07/16-8/12	224	271	21
08/13-9/09	237	287	21
09/10-10/07	103	145	41
10/08-11/04	20	40	100
Total	803	1043	30

Infiltration, Evapotranspiration and Crop Response

Estimates of rainfall infiltration for the 75 and 50 percent rains were generated from rainfall-runoff curve data reflecting the soil characteristics, ground cover, and rainfall intensities in the area (USDA/SCS, 1986). Crop water requirements, or evapotranspiration (ET), during each phase of crop growth was derived from information

reported in Doorenbos and Pruett (1975). Data pertaining to crop yield response to moisture stress during growth stages was drawn from empirical crop-yield relationships developed in an FAO study by Doorenbos and Kassam (1979).

The relationship between moisture stress and crop yields is a fundamental consideration when evaluating soil water conservation options in rainfed agricultural systems. This relationship, as described by FAO, can be expressed as follows:

(4) $$\left(1 - \frac{Ya}{Y_m}\right) = k_y \left(1 - \frac{ETa}{ET_m}\right)$$

where:

Y_a = actual crop yield

Y_m = maximum crop yield

ET_a = actual crop evapotranspiration

ET_m = maximum crop evapotranspiration

k_y = crop yield response factor relating $\frac{Y_a}{Y_m}$ to $\frac{ET_a}{ET_m}$

In words, equation (4) says that the percentage decline in crop yield from a maximum potential of Y_m is proportional to the percentage decline in ET from a maximum potential of ET_m, where k_y is the proportion. Doorenbos and Kassam report k_y values generated from empirical observations on Y_a, Y_m, ET_a, and ET_m for each crop examined in this study.

If soil water uptake by a plant does not match optimum plant water requirements, a water deficit may be said to exist. A water deficit percentage, expressed as the ratio of actual evapotranspiration (ET_a) to maximum evapotranspiration (ET_m), may occur during any one of the individual plant growth periods, i.e., the establishment, vegetative, flowering, yield formation, or ripening period. In the case of moisture stress during growth periods, equation (4) is, therefore, specified for the period(s) affected. As different crops have different sensitivities to moisture stress during their various growth stages, k_y factors vary from crop to crop and stage to stage.

The k_y values reported by Doorenbos and Kassam, calibrated to reflect crop varieties and farming practices traditionally followed by farmers included in the Kita survey, formed the basis of the moisture stress-crop yield computations carried out in the case study.

The Analytical Approach

The first step in the analysis was to construct the farm linear-programming model. The initial model was based on characteristics of the traditional Kita area farms where no modern inputs or cultivation practices are followed. Four alternative crop planting-harvesting schedules were included in the model as "coping strategies" for dealing with poor rains. Also, fertilized crop activities were added to reflect better soil fertility management options.

The next step was to compute crop yields associated with different levels of soil moisture available for plant uptake through the growing season. In a general sense soil moisture is largely a function of rainfall and infiltration. As indicated our case study examined two rainfall patterns. One rainfall pattern was that expected 5 out of 10 years (probability .5). The other was a more frequent, but also drier, pattern occurring 7 out of 10 years (probability .75). Three infiltration rates were also considered, viz., 40, 60, and 80 percent of rainfall. Implicit in each rate is a level of soil water conservation, i.e., low, medium, and high. Current rates as practiced by the traditional farmer are at the low end of the scale. Crop yields were therefore, derived for combinations of rainfall, infiltration, and crop production activities in the four planting-harvesting schedules. Crops considered are: sorghum, millet, maize, rice, groundnuts and vegetables. Planting dates are May 15, June 1, June 15, or July 1. In all, 72 rainfall-infiltration-crop calendars were examined.

Basic features of the LOTUS spreadsheet used to carry out the computations resulting in crop yield estimates as described above are illustrated in Table 3.

RESULTS

Potential net farm income associated with water conservation is shown in Table 4. Farm returns with tied-ridges are largely dependent on construction costs, rainfall, and infiltration efficiency achieved. If the ridging is done during peak labor demand periods when wage rates are high and the infiltration rate is not significantly raised, net farm income gains could be low to negative.

However, tied-ridges are generally effective water conservation measures and can reasonably be expected to achieve 80 percent infiltration levels. At this level of infiltration farm income increases range from 119 to 374 percent. Benefits are 80,000 Malian Francs with high labor costs and about 100,000 MF at low labor costs ($178 to $222 U.S. at 1979 prices) with either rainfall scenario.

The analysis indicates, also, that during the low rainfall years farmers could economically increase production of basic food staples (sorghum, millet, rice, maize) from 41 to 57 percent if they were able

TABLE 3. SOIL-WATER BALANCE/YIELD REDUCTION COMPUTATIONS, LONG-SEASON SORGHUM, KITA REPRESENTATIVE FARM

Time Period	Plant Growth Stage a/	Plant ET mm	Rain-fall mm	Infil-tration b/ percent	Soil Moisture c/ mm	Crop Yield d/ kg
						1250 max
04/01-15			6.4	40	3	1250
04/16-30			8.5	40	6	1250
05/01-15			17.0	40	13	1250
05/16-31			28.7	41	25	1250
06/01-15	1	35	74.3	41	20	1250
06/16-30	2	42	79.3	33	4	1250
07/01-15	2	38	109.1	33	2	1250
07/16-31	3	56	141.0	38	0	1250
08/01-15	3	66	160.1	38	-5	1244
08/16-31	4	88	180.3	33	-29	1215
09/01-15	4	86	127.6	33	-43	1170
09/16-30	4	73	87.5	40	-38	1130
10/01-15	5	59	55.1	40	-37	1113

a/ Growth stages are: 1 - establishment; 2 - vegetative; 3 - flowering; 4 - yield formation; 5 - ripening
b/ Assumes no tied-ridges
c/ Soil moisture includes rainfall infiltration less plant ET in current time period plus carry-over moisture not used by plants during previous periods. Water holding capacity in root zone is 60 mm with 90 percent of excess carried over to the next period.

TABLE 4. NET FARM INCOME WITH TWO RAINFALL PATTERNS AND THREE INFILTRATION RATES, KITA REPRESENTATIVE FARM (1000 MF)

	.5 Rain Infiltration - %			.75 Rain Infiltration - %		
ITEM	BASE	60	80	BASE	60	80
Income w/o Tr	70	-	-	27	-	-
Income w/Tr						
Labor slack		91.8(31)	173.6(148)		29.2(8)	128.0(374)
Peak labor		74.1(6)	153.2(119)		9.4(Neg)	107.4(298)

Figures in parentheses are percentage increases over base case. Base infiltration rate is 40 percent. Tr refers to tied-ridges.

to do a better job of capturing more rainfall in the soil (Table 5.) Under rainfall conditions closer to what would be expected half of the time, production could increase almost 90 percent with additional water conservation efforts. Since fertilizer was held to very low levels (24-32 kg per hectare) to reflect the low resource conditions of traditional farmers in the Sahel, a large proportion of these production (and income gains) are attributable to water conservation.

TABLE 5. FARM PRODUCTION CHANGES WITH TWO RAINFALL PATTERNS AND THREE INFILTRATION RATES, KITA REPRESENTATIVE FARM

FOOD ITEM (kg)	.5 Rain Infiltration - %			.75 Rain Infiltration - %		
	BASE	60	80	BASE	60	80
Grain	3781	5257(40)	7120(88)	3630	5115(41)	5709(57)
Groundnut	777	1216(5[illegible])	1558(100)	316	782(147)	1770(460)
Vegetables	329	329(0)	329(0)	329	329 (0)	329(0)

Figures in parentheses are percentage increases over base case. Base infiltration rate is 40 percent.

CONCLUSION

Utilization of soil-water balance relationships for the soils, agro-climatology, and crop cultivars of Western Mali, together with economic farm modeling, has proven to be a useful approach to assessment of water conservation in a highly risky rainfed agricultural system. The analysis has shown that water conservation through tied-ridges can result in significant increases in crop output and substantial economic benefits to farmers; however, the gains are sensitive to the cost of the ridging, seasonal rainfall and infiltration efficiency achieved.

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