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An Economic Analysis of Farm Management Practices and Improved Technologies in the Sahel*

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I. Introduction

The seven West African countries of the Sahel (Senegal, Gambia, Mauritania, Mali, Burkina Faso, Niger, and Chad) are among the poorest in the world. In these countries, per capita income in 1981 averaged just over $300 (U.S. dollars), food intake was below the minimum requirements, falling as low as 1500 calories

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Table 1. Average annual growth rates, 1962–1983 (%): Cropped area, yield per hectare, and per-capita production of the principal food crops for the Sahel Region and selected countries

Country and commodity	Cropped area	Yield per hectare	Per-capita production
Sahel region	−0.3	−1.3	−1.6
Mali			
Maize	−1.01	−2.46	−3.47
Rice	−0.27	0.32	0.05
Millet	0.28	−1.96	−1.68
Niger			
Sorghum	4.18	−1.89	2.29
Rice	5.15	−1.38	3.77
Millet	3.51	−1.56	1.95
Senegal			
Rice	−1.83	−0.50	−2.33
Millete	−0.85	1.67	0.82

Source: Jayne et al., 1989.

per day in some locations, and life expectancy was about 44 years (FAO, 1986a; MacDonald, 1986). The GNP growth rate for the region during the 1960–81 period was essentially zero (MacDonald, 1986).

Agriculture is the dominant economic sector in the Sahel, supporting roughly 80 to 90% of the present population (World Bank, 1985). About 80% of the total land area is located in arid and semiarid zones where annual rainfall is less than 25 inches and over 98% of all cultivation is carried out under strictly rainfed conditions (World Bank, 1985; FAO, 1985; MacDonald, 1986).

Total food grain production in the region grew by approximately 1% per year from 1970 to 1984, predominantly because of cultivated area expansion; however, yield per hectare generally fell. During this same period population growth rates in the various countries ranged between 2 and 3% with the result that production per capita also declined (Table 1). Average grain yields are very low: 400 to 700 kg per hectare compared with 2000 to 4000 kg per hectare in developed regions (FAO, 1985). If current trends continue, the carrying capacity of the land in the year 2000 will be exceeded by about 30 million people (World Bank, 1985).

Given the limited potential for large gains in output from the irrigated sector (Biswas, 1986a) and the difficulty of attaining dramatic reduction of population growth in traditional societies, the rainfed systems of the Sahel must achieve sustained increases in productivity and production for positive changes in general well-being to take place.

A number of factors (biological, environmental, managerial, and socioeconomic) are responsible for the low agricultural productivity. Among the most important are adverse climatic conditions and poor soils (Sivakumar, 1988). In this study we evaluate several improved soil, water, and crop management strate-

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Table 2. Land use in Mali and the Sahel (m/ha)

Region	Total land area	Arable cropland[a]	Permanent pasture	Forest woodland	Other land[b]	Irrigated land[c]
Mali	122.0	2.0 (1.6)[d]	30.0 (24.6)	9.0 (7.4)	81.0 (66.4)	.1 (neg)
Sahel	525.2	16.9 (3.2)	139.3 (26.5)	59.9 (11.4)	308.9 (58.8)	.4 (neg)

Source: FAO, 1984.
[a] Arable cropland is land under cultivation, including tree crops.
[b] Other land is unused land, wasteland, and barren land.
[c] Irrigated land area is also included in other land-use categories.
[d] Figures in parentheses are percentages.

gies in the context of a typical farming situation in Mali. The objective is to estimate potential farm income, production, and resource conservation impacts of innovative farming practices. Given the similarity between conditions in Mali and other Sahelian countries, the results of the analysis are relevant to those locations as well.

II. Farming Conditions in Mali

A. Land Use

Only a very small proportion of the total land area of Mali (1.6%) is used for the cultivation of crops (Table 2). On the other hand, a relatively large share (32%) is devoted to permanent pasture, range, or woodlots. The largest share (66.4%) is land generally unsuited to food and fiber production. Irrigated land is a minor component in the total land use picture. This distribution of land use, very much the same for the Sahel as a whole, is largely due to the nature of the soil resources and the rainfall patterns of the area.

B. Soils

As in West Africa generally, Malienne soils are diverse and soil types are widely scattered. Within arable regions the predominant soils are Alfisols (32%), Entisols (28%), Aridosols (16%), and Ultisols (10%) (TAMS, 1983). The balance are stony, gravelly, and lateritic soils. All soils are highly weathered and of low inherent fertility. Organic matter is generally lacking, and soils are deficient in natural nitrogen, phosphorus, and sulfur. Acidity and aluminum toxicity are common problems. Weak soil structure and the presence of clay in many soils leads to crusting, compaction, and sealing during and following rains. The combination of soil crusting and intense storms typical of the rainy season cause high runoff and low infiltration. Water-holding capacities are low, particularly in the deep sandy soils so prevalent in much of the country. Water erosion on steeper slopes, wind erosion, and sand encroachment are common problems.

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Table 3. Land distribution by climatic zones, Mali and Sahel

Region	Saharan Sahelo-Saharan (<NLC)(%)[a]	Sahelo-Sudanean and Sudanean (NLC−800 mm)(%)	Sudano-Guinian (>800 mm)(%)	Total land area (million ha)
Mali	66.7	20.8	12.5	122.0
Sahel	66.4	26.1	7.5	525.2

Source: World Bank, 1985.
[a]NLC is the northern limit where rainfall is sufficient for crop cultivation, that is, about 300 mm.

C. Climate and Weather

Two-thirds of the country receives insufficient rainfall for crop production (Table 3). In the remaining area, over 99% depends on rainfall as its source of moisture. The spatial distribution of mean rainy-season precipitation in Mali is shown in Figure 1.

Climatological studies have shown a continuous decline in total annual rainfall since the 1950s (Fig. 2). Droughts are common. The most recent case, extending from the late 1960s to the early 1980s, was a severe, but not an unusual, occur-

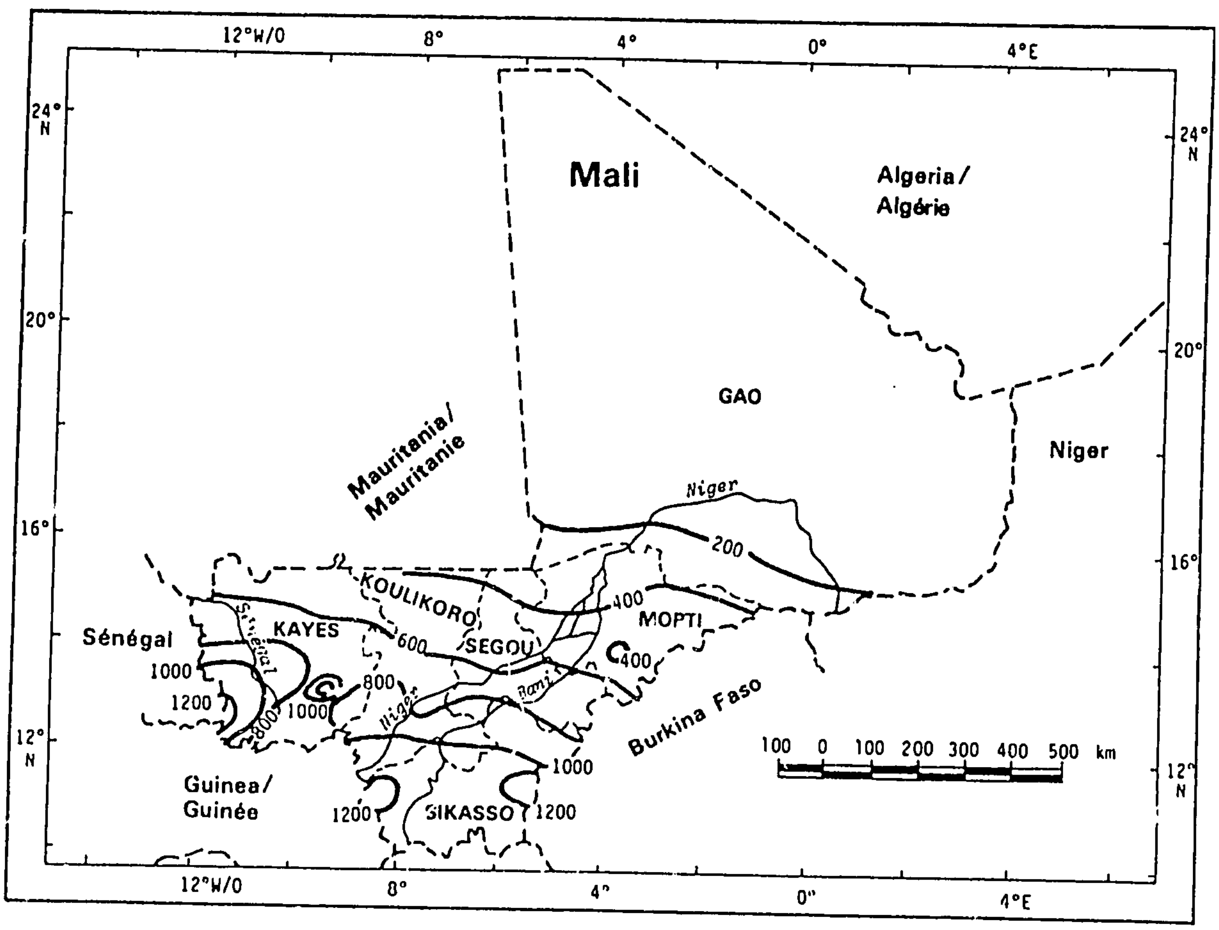

Figure 1. Spatial distribution of mean rainfall, rainy season, Mali. (From Sivakumar et al., 1984.)

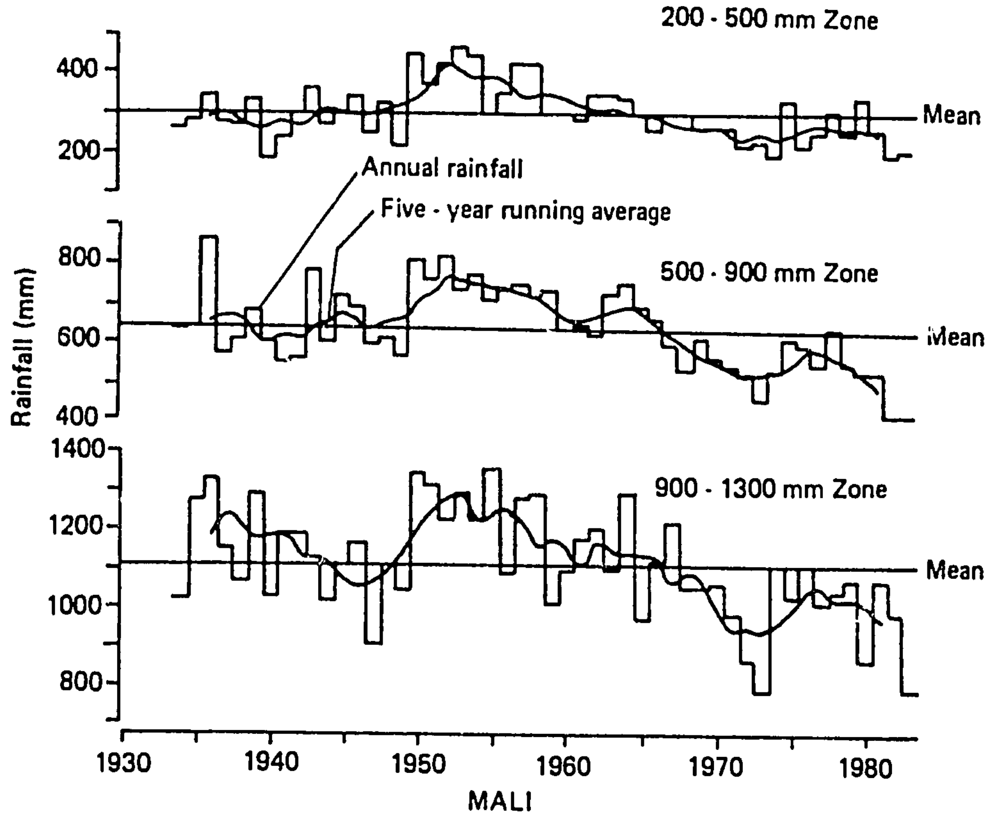

Figure 2. Annual rainfall, five-year running average and mean annual for last 50 years, Mali. (From Biswas, 1986b.)

rence in the long-term weather record. Of major significance is the year-to-year variability in rainfall that exists all across the country: coefficients of variation in total annual rainfall for 81 weather stations (30 to 70 years of record) range from 20 to as high as 50% (Sivakumar et al., 1984).

As in other Sahelian countries, rainfall in Mali is also highly variable in terms of date of onset and length of rainy season (Table 4). Rainy seasons generally begin in late spring–early summer and last 2 to 3 months in the north and 4 to 5 months in the south. Late onset is highly correlated with short rainy seasons and low total seasonal precipitation. The use of crop cultivars with short growing season requirements can be an effective response to late onset of rain (Stewart, 1987; Sivakumar, 1988).

Table 4. Mean annual rainfall and variation in onset, three locations in Mali

Location	North latitude	Mean annual rainfall (mm)		Range of onset dates		
		to 1970	from 1971	Earliest	Median	Latest
Ansongo	15°40′	334	214	6/02	7/27	8/27
Kayes	14°26′	749	546	5/21	6/23	7/28
Kolokani	13°35′	848	742	5/11	6/20	8/09

Source: Kanemasu et al (Chapter 14 of this publication).

Year-round high temperatures and solar radiation levels exacerbate the low rainfall situation. Elevated temperatures, coupled with high solar radiation, means that potential crop water use (potential evaporation) is high and often exceeds rainfall at critical times during the growing season (Table 5). Whenever potential crop water use exceeds precipitation, optimum plant growth is not achieved because of water stress. Low infiltration rates and low soil water-holding capacity make the already poor crop water demand–rainfall situation even worse.

D. Farming Practices

Malienne farmers tend to rely on local cereal varieties tolerant of low moisture, low nutrient levels, and high pest infestations. But the traditional varieties are also of low productivity under good or even average weather conditions and are generally less responsive to higher input levels than improved cultivars (Matlon, 1986). Eighty-five percent of all cultivated land is in food grains, primarily sorghum, millet, maize, and rice. These cultivars tend to be long-season varieties. Planting occurs in late May, June, or early July depending on location, and takes place only after sufficient rain (about 40 mm) has fallen to provide enough moisture in the upper soil profile to ensure seed germination. False starts in the rainy season may mean that farmers lose their initial planting and must reseed; hence farmers tend to plant late rather than early.

Fertilizer and manure applications are too small to replace nutrients withdrawn through crop growth, and long rejuvenating bush fallow is being shortened or eliminated altogether because of land use pressure. Erosion of topsoil and failure to return organic matter contributes further to soil deterioration. Many of the tillage, cultivation, and harvesting operations are done manually. Crusting makes it difficult to work the soil and land preparation must wait until early rains soften the ground. The need to both till and plant as soon as possible after the rains begin creates special demands on labor that may delay the planting. Labor is usually in short supply not only during planting/land preparation, but also during weeding and harvest periods.

Farm prices are typically low relative to production costs, and can fluctuate widely depending on the size of the harvest, which in turn is a function of rainfall. Marketing channels for both farm inputs and outputs are poorly developed except in scattered areas and for state-supported cotton and groundnut production. 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.

Of all the difficulties farmers face, the generally low and always unpredictable rainfall is probably the most serious. Farmers cannot be certain when first rains will occur or when there will be sufficient moisture in the soil for land preparation, planting, and seed germination. Likewise, they cannot be sure of the amount of rain they will receive for the season nor its distribution throughout the season. Coping with the rainfall situation is, therefore, a fundamental concern to

Table 5. Climate in selected locations in Mali, average conditions over 37 years

Station	Mean monthly data													Mean annual PET[a]	Mean annual temperature
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	12-month total		
	Millimeters														
Mopti:															
Rain	0	0	0	3	24	61	139	169	95	24	0	0	515	NA	NA
PET[a]	152	166	215	220	224	199	177	154	147	159	157	140	NA	2,151	NA
Sikasso:															
Rain	1	3	15	45	106	152	253	326	217	84	19	4	1,225	NA	NA
PET[a]	173	177	211	192	185	163	152	142	147	163	164	165	NA	2,003	NA
Tessalit:															
Rain	1	0	1	0	2	7	23	55	27	1	1	0	118	NA	NA
PET[a]	114	126	181	205	234	236	237	227	201	173	131	103	NA	2,774	NA
	Degrees Celsius														
Temperature:															
Mopti	32	35	38	40	40	38	34	32	32	34	35	31	NA	NA	27.8
Sikasso	34	36	38	37	36	33	31	30	31	33	34	33	NA	NA	27.2
Tessalit	27	30	34	37	41	43	42	40	40	38	33	26	NA	NA	28.6

NA = Not applicable.
[a]PET = Potential evapotranspiration.
Source: Hargreaves and Samani, 1986.

Table 6. Strategies to overcome major limitations in production of sorghum and millet

Limitation	Strategy
Crop establishment	Planting technique, timely planting, superior varieties
Nutrient stress	Timely planting, fertilizers, rotations, weed control, efficient varieties
Moisture stress	Timely planting, appropriate plant densities, mixed cropping, weed control, efficient varieties, soil erosion control, water conservation
Pests/diseases	Seed treatment, insecticides/pesticides, good husbandry, genetic resistance, rotations
Birds	Uniform maturity, short plant height, tannins/pearling (sorghum)
Postharvest losses	Good storage techniques, rodent/insect control
Market stability	Government policies, support prices, infrastructure

Source: D.J. Andrews et al., 1984.

farmers and a paramount concern for researchers, extension workers, and policy officials searching for ways to help these farmers.

III. Technological Options for Dryland Farming

Strategies do exist to increase agricultural productivity in the Sahel (Table 6). Soil and water conservation measures that enhance productivity include bunds, microcatchment basins, mulching, small-scale soil erosion and runoff retention devices (diguettes), and tied-ridges, that is, ridges with cross-ties to form furrow dikes. Other productivity-increasing technologies include chemical and organic fertilizer, various conservation-oriented tillage and cultivation schemes with and without animal traction, and better crop selection and scheduling of crop calendars (Lal, 1987b; Steiner et al., 1988). Experimental research and on-farm trials indicate that crop yields can be increased with these methods.

Economic studies of soil and water management alternatives (Delgado and McIntire, 1982; Nicou and Charreau 1985; Roth and Sanders, 1984; Sanders et al., 1985) have shown that farm-level benefits of animal traction, chemical fertilizer, and tied ridges can be quite high. Gains of 50 to 70% in both farm income and food production have been reported. While either tied ridges or fertilizer can be economically profitable, when both are combined the interactive effect increases yield by more than the sum of the yields when the two techniques are used alone (Roth and Sanders, 1984). However, with insufficient soil moisture, fertilizer may not be profitable.

Traditional cereal cultivars in West Africa are becoming less satisfactory in the face of the tendency toward lower and more variable rainfall, shorter rainy seasons, and the extension of farming onto marginal land (Matlon, 1986). Breeding programs currently underway emphasize short-season varieties (ICRISAT, 1984), which allow farmers more flexibility in planting, replanting, intercrop-

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ping, and relay-cropping rotations. However, variety selections must be made relative to other production practices and the seasonal rainfall pattern.

As Stewart (1987) and Sivakumar (1988) have shown, the amount of rain and the duration of the rainy season can be strongly correlated with date of onset. For that reason important farming decisions, such as planting date, varietal choice, and fertilizer applications, should be made in response to onset date and the early season pattern of rain. In a similar vein, Krause et al. (1987) demonstrate that significant economic benefits can be obtained by choosing appropriate plant densities in combination with sole-cropping, intercropping, and fertilization. Few if any published studies, however, have evaluated short-cycle versus long-cycle crops in combination with soil and water management options.

The literature review also revealed that economic research on technological innovations for the Sahel has addressed the rainfall variability issue mainly from the year-to-year perspective. Yet, as we have seen, the intraseasonal variation in rainfall is also very important. It is the intraseasonal 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 cycles. For example, if infiltration rates are 40% of rainfall, and 20% of infiltration is lost to deep percolation, then no more than 32% of rainfall is available for plant use.

If the amount of moisture in the root zone during any particular stage in a plant's phenological growth process falls below water requirements during that same stage, yield will be reduced. Even if there is excess moisture in later stages, the loss in yield is not likely to be recovered. Adjusting planting dates and crop variety can bring water requirements more into line with water availability. This interaction between rainfall, timing of crop planting, and soil properties must be taken into account when evaluating soil, water, and crop management practices.

The principal conclusions from the literature review are that (1) appropriate combinations of soil, water, and crop management practices 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 methods that reflect both soil characteristics and weather-related variability within a crop growing season.

IV. Soil, Water, and Crop Management Case Studies

Farming systems research underway by the authors is focused on soil, water, and crop management technologies for dryland areas. A major objective in this work is to be able to produce more accurate estimates of farm-level impacts of improved resource management by better integration of soils, weather, agronomic, and economic information. To that end an analytical procedure combining soil water balance–crop yield response relationships and whole-farm economic models has been developed. This method was tested in case studies of one or two management options drawing on data from Mali (Butcher and Day,

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Table 7. Farm characteristics

Agroclimatic 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
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: Flemming, 1981

1987; Day and Aillery, 1988; Day, 1988). This particular analysis uses the same basic methodology but examines a much wider range of options—soil moisture conservation, erosion control, short-season and long-season cultivars, alternative planting dates, animal traction, and fertilizers. The focus remains that of a typical nonirrigated farm in western Mali. The procedures followed and the results obtained in this latest case study are described in this section.

A. The Typical Rainfed Farming System

In 1978 and 1979, Fleming conducted a series of farm interviews on 55 farms in 9 villages in the Kita Region of western Mali (Fleming, 1981). These surveys generated information on farm family characteristics, farm size, input utilization, equipment complements, cropping patterns, crop calendars, and crop yields of farms in the area. The basic characteristics of a representative traditional farm are shown in Table 7. Published summaries of the farm surveys and other secondary information formed the data base for construction of a linear-programming model of the typical farm. A mathematical statement of the farm model appears in the Appendix.

B. Rainfall, Soil Moisture, and Crop Yields

The relationship between rainfall, soil moisture levels, and crop yield is a fundamental consideration when evaluating soil and water conservation options. Given rainfall, infiltration rates, and the water-holding capacity of the soil determine soil moisture availability. Plant response to soil moisture (or the lack thereof), in turn, plays a significant role in crop yield. The basic purpose of on-farm water management practices is to raise crop yields by improving soil water balance, that is, by bringing soil water availability more into line with plant water requirements. Timing of planting and of management practices in relation to rainfall and available soil moisture is, therefore, extremely important. If plant demand for water exceeds available soil moisture levels, plants will experience moisture stress, and in most cases yields will be negatively affected.

According to methods described by Doorenbos and Pruett (1975) Doorenbos and Kassam (1979) and FAO (1986b) soil water balances and resulting crop yield response to moisture stress can be estimated by the following equations:

$$SWB^t = (R^t \times I^t) - (ET_0^t \times k_c^t) + \Sigma_t[(R^{t-1} \times I^{t-1}) - (ET_0^{t-1} \times k_c^{t-1})] \quad (1)$$

$$MD_f^t = \frac{|SWB^t|}{ET_m} \quad \text{when } SWB^t < 0 \quad (2)$$

$$y_r^t = MD_f^t \times k_y^t \quad (3)$$

$$CY_r = \Sigma_t(y_r^t) \times (CY_m) \quad (4)$$

$$CY_a = CY_m - CY_r \quad (5)$$

where

- SWB^t = soil water balance in time period t, that is, the amount of moisture in the root zone,
- R^t = rainfall in time period t,
- I^t = rainfall infiltration rate in time period t,
- ET_0^t = reference crop evapotranspiration in time period t,
- k_c^t = proportion of ET_0^t required by the crop of interest,
- MD_f^t = soil moisture deficit factor in time period t,
- ET_m = total evapotranspiration demand of crop,
- y_r^t = crop yield reduction factor for moisture stress in time period t,
- k_y^t = crop stress factor for moisture deficits in time period t,
- CY_r = total yield reduction per unit of land due to moisture stress in all time periods,
- CY_m = maximum potential yield of crop per unit of land, and
- CY_a = actual crop yield per unit of land.

The first equation says that the amount of moisture in the soil (SWB^t) during any period is equal to infiltration less plant water loss during the period plus carryover moisture from previous periods. Within the root zone, SWB^t is bounded by the water-holding capacity of the soil to that depth. Equation 2 indicates that for any period in a plant growth cycle, a moisture deficit factor (MD_f^t) can be defined equal to the ratio of the absolute value of SWB^t for that period and the total plant water requirements (ET_m) for the entire season when SWB^t is less than zero. The moisture deficit factor indicates the degree to which water was insufficient for plant needs. In Eq. 3, the product of a moisture deficit factor and a crop stress factor, k_y, gives a yield reduction factor for each period of stress. Equation 4 means that the total reduction in crop yield per unit of land (CY_r) is equal to the summation of the periodic yield reduction factors, times the maximum potential yield (CY_m) per unit of land. Last, Eq. 5 shows that actual yield (CY_a) is maximum yield less the stress-induced reduction in yield. The time steps in these calculations are arbitrary; for example, these steps can be daily, weekly, or monthly, depending on data availability and the precision desired.

Table 8. Rainfall, Kita Station, Mali (mm per time period)

Time period	Average rainfall (43 years) Amount	St. deviation	Average-yield rainfall (1968)	Lowest-yield rainfall (1972)
5/16–31	29	24	43	14
6/01–15	74	33	73	141
6/16–30	79	39	38	83
7/01–15	109	52	81	27
7/16–31	141	46	192	164
8/01–15	160	55	114	147
8/16–31	180	71	161	100
9/01–15	128	50	198	55
9/16–30	88	42	52	34
Total season	988	–	952	765
Total annual	1103	205	1069	825

Source: Rainfall data was supplied by the Evapotranspiration Laboratory, Kansas State University, Manhattan, Kansas.

Equations 1 through 5 become a simple model of soil water balance and crop response relationships that can be used to estimate changes in crop yields resulting from various soil and water conservation measures. This model may also be used to evaluate crop management alternatives such as different planting schedules (crop calendars) or crop cultivars that alter plant water demand in the soil water balance equation.

A LOTUS 1-2-3 spreadsheet routine was developed to solve the soil water balance–crop yield response model for the soils, weather, cropping alternatives, and improved soil and water technologies examined in the Kita case study. The data used to calibrate Eqs. 1 through 5 are now outlined.

1. Rainfall Patterns

For any location with high interseasonal and intraseasonal variability, the number of possible rainfall patterns that might occur could be extremely large. For that reason, in technology appraisal one must select a particular pattern or some reasonable number of alternative patterns to analyze.

In this study we use two rainfall patterns: one that could conceivably produce average yields and one that could produce only the lowest yields for a reference crop, in this case 130-day sorghum with traditional technology. Equations 1 through 5 were employed to estimate potential sorghum yields for each annual weather pattern in 43 years of record at the Kita Weather Station. Average and poor seasonal rainfall, per se, were not used because neither parameter takes into account the distribution of the rain throughout the season: a year with low rain, for example, could still produce good yields if the moisture fell during critical plant growth stages.

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Table 9. Crop water requirement coefficients (K_c), by crop growth stage

	Crop[a]							
	Sorghum		Millet		Maize		Groundnut	
Growth stage	S-S	L-S	S-S	L-S	S-S	L-S	S-S	L-S
Establishment	.30	.30	.30	.30	.30	.30	.30	.30
Vegetative	.50	.40	.50	.40	.70	.60	.60	.50
Flowering	.80	.70	.70	.60	1.00	1.10	.90	1.00
Yield formation	.90	1.00	.80	.90	.80	90	1.00	1.10
Ripening	.50	.70	.50	.70	.60	.70	.70	.70

Source: Doorenbos and Pruett, 1975; FAO, 1986; Hatfield, 1988.
[a] S-S refers to short-season (90-day growth) crops and L-S refers to long-season (130-day growth) crops.

The two chosen rainfall patterns, therefore, represent average and poor *production* years. The average production year embodies a rainy season which could be expected to result in average crop yields, and thus becomes an approximation of the weather pattern farmers are most likely to plan for at the beginning of the season. The poor production year, on the other hand, is the worst-case rainfall scenario with which the farmer may have to cope. To ensure food supplies, farmers must also plan for this rainfall pattern. Our farm model actually takes these two weather possibilities into account simultaneously to identify farm plans that are optimal under average yield conditions as well as satisfy food needs should the worst year occur. The two rainfall scenarios examined along with the long-term seasonal average and its standard deviation are shown in Table 8.

2. Soil Moisture and Crop Yield Response

Estimates of infiltration were generated from rainfall–runoff curve data, which reflect the soil characteristics, ground cover, and rainfall intensities in the Kita area (USDA/SCS, 1986). Three alternative infiltration rates were considered: 40, 60, and 80% of rainfall. For a given soil and climate, alternative infiltration rates arise from different soil conditions and soil water conservation practices. Traditional farm practices in the study area result in low (about 40%) infiltration rates.

Crop water requirements were based on water requirements for a reference crop (ET_0) and k_c coefficients for the crops examined in this study (Table 9). K_y coefficients reflecting crop yield response to moisture stress during plant growth stages are shown in Table 10. Assumed levels of maximum potential crop yield (kg/ha) in the Kita area for 90-day and 130-day cultivars, respectively, under traditional practices with no water stress were sorghum – 1130/1250; millet – 820/1000; maize – 1080/1200; and groundnuts – 1290/1400.

C. Soil Erosion and Declining Productivity

Soil erosion, which can reach high levels in the Kita area, can have a sizable impact on crop productivity (Stocking and Peake, 1986). Since it would be too

Table 10. Crop yield-moisture stress coefficients (K_y), by crop growth stage

Growth stage	Crop			
	Sorghum	Millet	Maize	Groundnut
Establishment	.20	.20	.40	.20
Vegetative	.20	.20	.40	.20
Flowering	.55	.55	1.50	.80
Yield formation	.45	.20	.50	.60
Ripening	.20	.20	.20	.20

Source: Doorenbos and Kassam, 1979; FAO, 1986; Hatfield, 1988.

time-consuming and expensive to collect primary field data on rates of soil erosion under all the various crop and land-use conditions, we turned to synthetic erosion prediction models.

There are several soil erosion estimates for West Africa, but none for the Kita area, and no method for predicting erosion is as widely accepted as the Universal Soil-Loss Equation (USLE; Wischmeier, 1959). Therefore, using Lal's soil plot data for Ibadan, Nigeria (Lal, 1987a), we assumed a maximum erosion rate of approximately 60 mt/ha for a bare fallow field of variable length with 5% slope. The effectiveness of physical erosion control structures, tillage practices, and crop cover in reducing erosion to less than the maximum value was computed using the USLE approach of multiplying the maximum potential erosion (MPE) by the factors for physical structure (P) and crop cover (C), that is, MPE $\times$ P $\times$ C. Crop cover factors in western Africa range from 0.9 in early growth stages to 0.4 for a good stand of fully grown millet, maize, or sorghum. Tied ridges, the only structural erosion control practice analyzed, are assumed to reduce erosion by 80% (P = .2) (Roose, 1977).

The effect of soil erosion on crop productivity can be estimated by comparing yields on eroded and noneroded fields, by monitoring rates of erosion and yields over time, and by using biological plant growth models that predict the effect of erosion-caused changes in the growth environment on yield (Lal, 1987a). Linearized regressions of maize and cowpea experimental plot yields and soil loss, as estimated by Lal (1981;1984), indicate an approximate decline of 0.2 metric tons in corn yields and a 0.03-metric-ton decline in cowpea yields per 10-ton loss in soil. We assume that the 1% yield decline in corn from Lal's plots applies to the much lower maize, millet, and sorghum yields realized on farms in the Kita area. We further assume that the erosion-induced yield decline for groundnuts in the Kita area is 5% of the estimated yield decline for cowpeas. The present value of the permanent economic loss from unchecked erosion is entered in the farm model as a cost of erosion.

D. Management Strategies Examined

The farm-level soil and water management strategies and related farm management decisions examined in the case studies are (1) the use of small amounts of

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Table 11. Soil, water, and crop management strategies for case study

Strategy	Base case	Case I	Case II	Case III	Case IV	Case V
Fertilizer	–	X	X	X	X	X
Tied ridges	–	–	X	–	X	X
L-S cultivars	X	X	X	X	X	X
S-S cultivars	–	–	–	X	X	X
Four plant dates	X	X	X	X	X	X
Animal traction	–	X	X	X	X	X
(Long-term erosion accounted for)	X	X	X	X	X	–

fertilizer – up to 24, 8, and 32 kg per ha NPK, respectively, to improve soil fertility; (2) the use of tied ridges to increase rainfall infiltration and reduce soil erosion; (3) the choice of long-season (130 day) or short-season (90 day) cultivars for millet, sorghum, maize, and groundnut; (4) the use of alternative planting dates for all crops including rice and vegetables (May 15, June 1, June 15, or July 1); and (5) the use of animal traction. The complete set of options represent strategies that a farmer may carry out singly or in various combinations.

In summary, a soil water balance–crop yield response model was used initially to predict crop yields under various combinations of management strategies. These yield predictions became input data to the whole-farm planning model. Also included in the whole-farm model were crop production input/output coefficients and cost-return data for each management strategy. The farm model was then used to identify the most economically profitable farm production plan given farm level constraints on land, labor, capital, and the safety-first constraint of producing sufficient food to satisfy home consumption requirements under the worst rainfall-production scenario.

V. Case Study Results

The specific soil and water management strategies examined are outlined in Table 11. Farm-level impacts, including the long-term consequences of soil erosion, associated with Cases I, II, III, and IV are compared to those of the base case. The effect on farm income, production, and soil erosion whenever the farmer ignores the loss in productivity due to erosion is brought to light in a comparison of Case IV and Case V.

The analysis is designed to evaluate impacts of soil and water management options within the framework of actual fertilizer availability and use; hence, NPK fertilizer levels in each case situation were not allowed to exceed the amount typically used, as revealed in the Kita farm surveys. The impact of higher amounts of chemical fertilizer in combination with tied ridges and short-season cultivars was not examined. Animal traction (oxen) was considered an appropriate output-enhancing technological option, particularly for construction of tied ridges, in all

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Table 12. Case study impacts of soil, water, and crop management strategies

Impact category	Base case	Case I	Case II	Case III	Case IV	Case V
Net farm income (1000 MF)[a]	8.4	35.5 (323)[d]	375.1 (4365)	35.5 (323)	377.1 (4389)	345.9 (4018)
Food production (kg)						
Grain	7105	7954 (12)	9605 (35)	7954 (12)	9620 (35)	9452 (33)
Groundnut	120	120	120	120	120	120
Vegetables	240	240	240	240	240	240
Erosion (tons per ha)	32	33 (5)	9 (−72)	33 (5)	9 (−72)	12 (−62)
Erosion damage (1000 MF)[b]	343	360 (5)	94 (−72)	360 (5)	94 (−72)	130 (−62)
Area planted (ha)						
With tied ridges	0	0	7.4	0	7.4	6.6
With long-season crops	8.0	8.0	8.0	8.0	7.9	7.7
With short-season crops	0	0	0	0	.1	.3
May 15	5.5	3.8	4.1	3.8	3.9	3.1
June 1	.1	3.1	3.3	3.1	3.4	3.4
June 15	2.4	1.1	.6	1.1	.7	1.5
July 1	0	0	0	0	0	0
Animal traction used (hr)						
Rented ox team	23	38	0	38	0	0
Owned ox team	0	0	400	0	351	370
Hired labor (hr)	80	88	434	88	434	278
Soil/water conservation benefits						
Damage prevented (1000 MF)	0	0	249	0	249	213
Net benefits (B–C)[c]	–	–	157	–	157	131
B/C ratio	–	–	2.7	–	2.7	2.6

[a] Net farm income equals current net returns minus future income loss caused by yield losses resulting from current soil erosion.
[b] Present value of 10 year stream of lost productivity due to erosion in current year.
[c] Costs include labor and animal feed associated with mechanical tied ridging, but not a share of the fixed costs of oxen ownership. This somewhat understates the cost of tied ridges, but benefits are also underestimated since only a 10-year time horizon was considered.
[d] Figures in parenthesis represent percentage changes compared to the base case.

cases except the base case. Another common strategy option is the choice of planting date. Farmers everywhere adjust their planting schedules to the onset of rains and other climatic variables, and also to the expected availability of labor for planting and other farm operations. This analysis examines the question of how planting date might be affected by the introduction of tied ridges, short-season crops, and soil erosion.

Given the technical and economic input data associated with each technology mix, the whole-farm model was solved for each situation to identify the production plan that maximized net farm income subject to the various farm-level constraints. As indicated, the constraints included the need to produce enough food for yearly family needs in the event a poor production year occurs. Solution values for the optimal production plan associated with each situation are shown in Table 12.

A comparison of Cases I through IV with the base case reveals that the use of fertilizer, tied ridges, and animal traction could result in beneficial changes in farm income, production, and the natural resource base. In the base case, net farm income is not very high because there is little saleable surplus beyond basic family food needs. Moreover, real farm income is further depressed by the loss in present value of future productivity caused by erosion during production of the current crop. Fertilizer (even in small amounts) plus animal traction (Case I) could increase net farm income by more than 300% and food production by 12%, but soil erosion would also increase slightly. Introducing tied ridges (Case II) significantly increases net farm income and production and at the same time decreases soil erosion by about 72%. In this case the large increase in income arises from additional current-year food production (due to higher yields), which in turn permit a large increase in saleable surplus, plus increased present value of future productivity due to less erosion with the current crop. The soil and water conservation benefits of tied ridges alone in this comparison amount to 249,000 MF in present value terms for a benefit–cost ratio of almost 3. By increasing yields, the tied-ridge strategy supports the purchase of an oxen team, makes greater use of early-season rains through earlier planting, and permits the hiring of additional labor.

Short-season cultivars (Case III) make no contribution over Case I. Short-season crops have a yield advantage over long-season varieties when late onset or early cessation of rains result in a short growing season. Given the seasonal pattern of the rainfall data used in this study, the potential advantage of the short-season varieties did not come into play as expected primarily because early-season rains under both scenarios were generally sufficient for early planting. It is likely, however, that in a year with late onset the short-season crops would be a better choice. For the same reason the new combination of short-season varieties and tied ridges (Case IV) makes no significant difference from tied ridges alone (Case II).

The production plan of Case V represents a situation in which the farmer gives no weight to the long-term benefits of soil conservation. The first-year gain in productivity due to soil moisture conservation with tied ridges is accounted for,

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but the long-term loss in *future* soil productivity because of erosion caused by current farming practices is not. In Case IV, on the other hand, the long-term soil-conserving benefit of tied ridges is recognized, as are the immediate moisture-retaining advantages. Accordingly, the reduced use of tied ridges in Case V compared to Case IV results in somewhat lower profits and increased erosion rates of 4 tons per hectare. Case V represents a situation of misperception by the farmer, who ignores erosion costs. In both Case IV and Case V, however, the adoption of yield-boosting technologies results in higher profits and improved treatment of the soil resource base compared to the base case.

VI. Conclusions

This analysis evaluated various farming practices for managing soil, water, and crops to identify the most desirable combination on economic grounds. Land, labor, and capital resources available on a typical farm in western Mali helped to determine which technologies were feasible and the extent of their use. Food consumption needs of the farm family were additional constraints on the mix of productivity-enhancing measures selected. In this framework, increments of new technology and management decisions were evaluated and compared to the traditional farming situation in which options are limited. Soil moisture conservation and soil erosion control benefits of the tied-ridge technology were explicitly taken into account.

The whole-farm economic model used proved to be a simple but effective tool for integrating agronomic, agroclimatic, and socioeconomic data associated with the many alternative farm production decisions examined. Farm modeling efforts now underway, however, will attempt to reflect more directly statistical rainfall probabilities and effect of rainfall variability on crop yield and farm income. This will improve our ability to describe the "riskiness" of rainfed agriculture, how that risk can be reduced through improved resource management, and, coupled with information on farmers' attitudes toward risk, the likelihood of technology adoption.

The complex relationship between crop yields and rainfall distribution throughout the growing season, infiltration, soil water-holding capacity, and soil water management practices was simulated with a soil water balance model. The amount and timing of rain and the capacity of the soil to collect and hold water jointly determine the amount of moisture actually available for plant uptake. This water supply can be altered by appropriate technology and good management. Similarly, crop management can alter plant water demands to more closely match soil water availability. These basic relationships, and how they can be beneficially changed, are at the core of rainfed farming. The soil water balance model, therefore, played a major role in this economic analysis of the problem. The practicality of using simple crop growth models to perhaps generate more accurately this necessary physical-biological data for the Sahel region is being explored.

Even in the relatively humid Sudano-Guinean zone where our representative farm is located improved soil and water management could lead to significant

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differences in farm production, income, and soil erosion. The combination of chemical fertilizer and tied ridges proved most effective, as did the long-season (130 day) cultivars of food grain crops and groundnuts. The short-season (90 day) cultivars made no significant contribution to farm output or income. In situations with less favorable seasonal distribution of rainfall, such as, later onset/earlier cessation, the short-season options would very likely replace the traditional varieties. This is particularly true as one moves northward from our study area into the arid and semiarid regions of the Sahel, where growing season length tends to be shorter.

Our analysis indicates that the benefits of public programs and policies that stimulate better soil and water management in the rainfed areas of the Sahel are potentially very large. Farms and farmers with characteristics similar to our representative case could experience similar gains; however, this depends on the extent to which the collective actions of many individual farms affects the total demand for inputs, commodity supplies, and related input/output price ratios in general. If a large number of farmers were to adopt technologies that significantly increase output, farm gate prices could be depressed. Similarly, a large shift in demand for production inputs might raise costs. The net effect on net farm income should such changes occur, therefore, depends on input-output supply and demand elasticities. Thus, although farm-level studies provide valuable insights regarding the feasibility of new practices the aggregate effects of technology adoption should be examined as well before particular policy prescriptions are made.

Appendix

A simplified description of the linear-programming model employed in this analysis may be written as follows:

$$\text{MAX } I = \sum_i P_i\,(Y_i X_i - D_i - HC_i) \tag{1}$$

$$- [\sum_f P_f (\textstyle\sum_i F_{fi} X_i) + \sum_i CC_i X_i + \sum_t W_t\, HL_t$$

$$\sum_i L_{ti} X_i - HL_t \leq LA_t \qquad t = 1 \ldots n \tag{2}$$

$$\sum_i X_i \leq HA \tag{3}$$

$$\sum_i Y_i X_i - D_i \geq HC_i \tag{4}$$

$$\sum_i B_i X_i \geq HC_i \tag{5}$$

$$X_i \geq 0 \tag{6}$$

where

i = crop type,
t = time period,
P_i = price of the i^{th} crop,
Y_i = expected yield per hectare of i^{th} crop,
X_i = hectares of i^{th} crop,
D_i = deductions (kg) of i^{th} crop for seed, gifts, and crop loss,
HC_i = home consumption of i^{th} crop,
P_f = price of f^{th} fertilizer,
F_{fi} = f^{th} fertilizer use per hectare of i^{th} crop,
CC_i = cash cost per hectare of i^{th} crop,
W_t = hourly wage rate of labor in t^{th} time period,
L_{ti} = labor hours in t^{th} time period per hectare of i^{th} crop,
LA_t = family labor hours available in time period t,
HL_t = hired labor in t^{th} time period,
HA = hectares of land available for crop production,
B_i = safe minimum assured yield of i^{th} crop.

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