Agricultural Economics, 7 (1992) 267–287
Elsevier Science Publishers B.V., Amsterdam

Soil, water and crop management alternatives in rainfed agriculture in the Sahel: an economic analysis

John C. Day [a], David W. Hughes [b] and Walter R. Butcher [c]
[a] *Economic Research Service, U.S. Department of Agriculture, Washington, DC, USA*
[b] *Louisiana State University, Baton Rouge, LA, USA*
[c] *Washington State University, Pullman, WA, USA*

(Accepted 13 February 1992)

ABSTRACT

Day, J.C., Hughes, D.W. and Butcher, W.R., 1992. Soil, water and crop management alternatives in rainfed agriculture in the Sahel: an economic analysis. *Agric. Econ.*, 7: 267–287.

Most agriculture in the Sahel Region is carried out under rainfed conditions where low and uncertain soil moisture levels limit productivity. Improved soil, water and crop management practices are required to reverse the steady decline in per capita food production and sustain output over the long term. Several technological innovations and related farm management practices are evaluated in a case study of a typical farm in Mali. Through use of a soil–water balance model and a whole-farm economic model an optimal mix of these measures is identified. Compared to a base case where no modern inputs are utilized, the combination of animal traction (oxen team), low levels of NPK fertilizer, tied-ridges, traditional long-season food grain crops and early planting was most effective: food grain output was 35% higher than with the traditional base case; soil erosion was reduced by 72%; and even with residual future soil erosion damage capitalized into current income, net farm income was larger by a factor of almost 45.

INTRODUCTION

One of the most serious problem areas in the developing world today is the Sahel region of West Africa. Senegal, Gambia, Mauritania, Mali, Burkina Faso, Niger and Chad are among the poorest countries in the

Correspondence to: J.C. Day, USDA Economic Research Service, 1301 New York Avenue NW, Washington, DC 20005-4788, USA.

0169-5150/92/$05.00

world. In 1981 income in the Sahel averaged just over US$300, food intake was below minimal requirements, falling as low as 1500 calories per day in some locations, and life expectancy was about 44 years (FAO, 1986a; MacDonald, 1986). The 1960–81 GNP growth rate was essentially zero (MacDonald, 1986).

Agriculture is the dominant economic sector in the Sahel, supporting 80–90% of the present population (World Bank, 1985). Yet total food grain production in the region grew only about 1% per year from 1970 to 1984, due mainly to expansion of cultivated area. Real productivity actually declined as average yield per ha fell. Food grain yields are now very low: 400–700 kg per ha compared with 2000–4000 kg in developed regions (FAO, 1985).

On the other hand, population growth has been high – close to 3% for some time, with the result that production per capita declined 1.6% per year over the 1962–83 period (Jayne et al., 1989). The situation is such that 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, rainfed agriculture must be the source of change. Farmers in the rainfed sector simply must achieve sustained increases in production if general well-being within the region is to improve.

This study addresses the issue of technological change within traditional farming systems of the Sahel. Several improved soil, water and crop management strategies are evaluated in the context of a typical farming situation in Mali. The objective of the analysis is to estimate changes in farm income, food production and resource conservation associated with these production practices. Given the similarity between agro-climatic conditions in Mali and other Sahelian countries, the results of the analysis are thought to be relevant to those locations as well.

BACKGROUND

Farming conditions in Mali

Water resources. Agriculture in Mali is almost completely dependent on seasonal rainfall for moisture. Surface water supplies exist, but irrigated land makes up less than 1% of the total. The geographic distribution and amount of rainfall is shown in Fig. 1, while the long-term trend appears in Fig. 2.

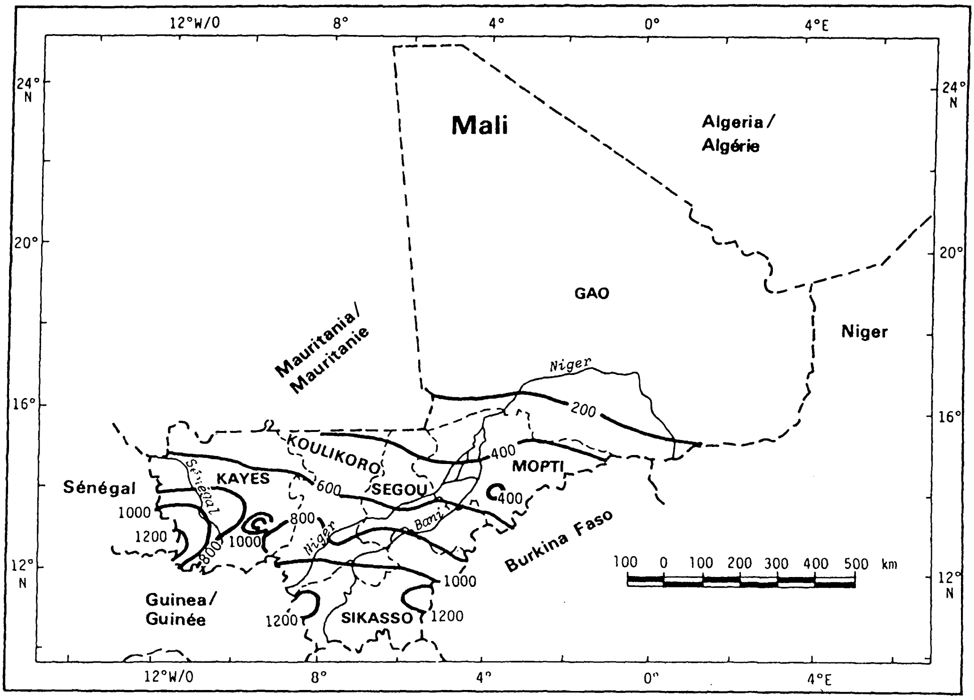

Fig. 1. Spatial distribution of mean rainfall, rainy season, Mali. Source: Sivakumar et al., 1984.

A full two-thirds of the country receives insufficient rainfall for crop production. In the remaining area rainfall is highly uncertain. Extensive droughts are quite common and even during non-drought years the year-to-year variability in rainfall is significant: coefficients of variation in total annual rainfall for 81 weather stations (30–70 years of record) range from 20% to as high as 50% (Sivakumar et al., 1984).

Rainy seasons generally begin in late spring–early summer and last 2–3 months in the north and 4–5 months in the south. The start of the rainy season is also highly variable: onset dates at many locations differ by 2–3 months from year to year.

Temperatures. Year-round high temperatures and solar radiation exacerbate the low rainfall situation. Elevated temperature and radiation mean that potential crop water use (potential evaporation) is high and often exceeds rainfall at critical times during the growing season (Table 1). When potential crop water use exceeds moisture availability plants experience stress and optimal plant growth is unlikely.

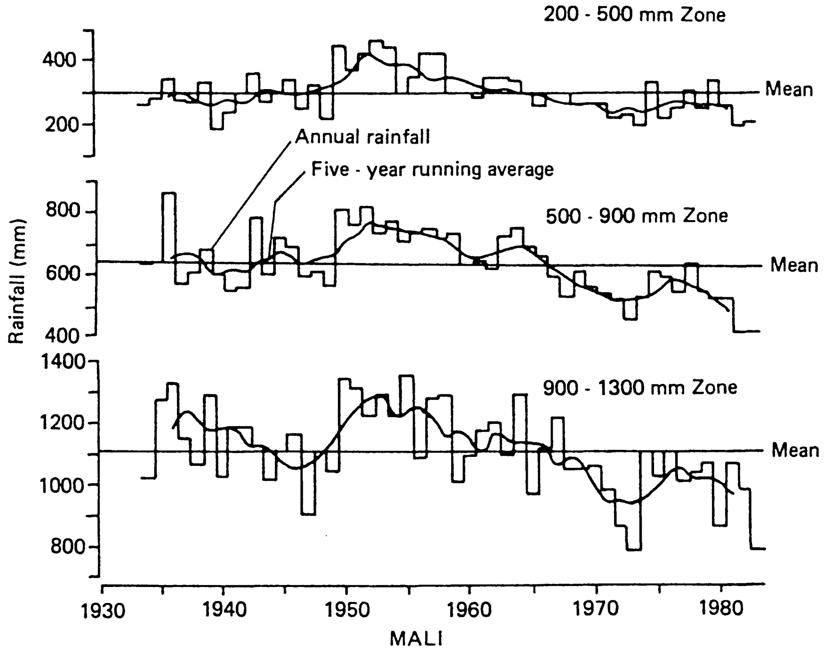

Fig. 2. Annual rainfall, 5-year running average and mean annual for last 50 years, Mali. Source: Biswas, 1986b.

Land resources. Along with climate, land resource endowments play a major role in land use. In Mali this means that only a very small proportion of the total land area (1.6%) is suitable for the cultivation of crops. Soils tend to be highly weathered and of low inherent fertility. Organic matter is generally lacking and soils are deficient in natural nitrogen, phosphorus, and sulphur. Acidity and aluminum toxicity are common problems. Weak 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. Low infiltration rates and low soil water holding capacity make the situation even worse. Water erosion on steeper slopes, wind erosion and sand encroachment are common problems.

The relationship between rainfall, soil water holding capacity and soil moisture level is particularly important, but is often ignored by analysts. Its significance can be illustrated by the following example. If infiltration is 40% of rainfall and 20% of infiltration is lost to deep percolation (not unreasonable numbers for the Sahel), then no more than 32% of rainfall is

TABLE 1

Climate in selected locations in Mali, average conditions over 37 years

Station	Mean monthly data												12-month total	Mean annual PET	Mean annual temperature
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec			
Rain/PET (mm)															
Mopti															
Rain	0	0	0	3	24	61	139	169	95	24	0	0	515	NA	NA
PET	152	166	215	220	224	199	177	154	147	159	157	140	NA	2151	NA
Sikasso															
Rain	1	3	15	45	106	152	253	326	217	84	19	4	1225	NA	NA
PET	173	177	211	192	185	163	152	142	147	163	164	165	NA	2003	NA
Tessalit															
Rain	1	0	1	0	2	23	55	27	1	1	0	118	118	NA	NA
PET	114	126	181	205	234	236	237	227	201	173	131	103	NA	2774	NA
Temperature (°C)															
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. PET, Potential evaportranspiration. Source: Hargraves and Samani, 1986.

available for crops. At an annual rainfall of 1000 mm only 320 mm is effective moisture, which is getting close to water requirements for many crops. Hence, given timing problems, even high rainfall zones can experience serious moisture constraints. It is a mistake, therefore, to base recommendations, and perhaps even serious discussions, on the concept of rainfall as the 'supply' of water for crop production.

Farming practices. Malian farmers tend to rely on local, long-season cereal varieties tolerant of low moisture, low nutrient levels and high pest infestations, but also of low productivity under good or even average weather conditions and 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. 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 re-seed; 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 top soil 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 that farmers face, it is the generally low and always unpredictable rainfall that 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. The rainfall situation, therefore, causes many problems for the typical Malian farmer and coping with it is a major concern.

Strategies do exist which can increase agricultural productivity. Soil and water conservation measures that enhance productivity include bunds, micro-catchment basins, mulching, small scale soil erosion and runoff retention devices (diguettes) and tied-ridges, i.e., 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). Considerable experimental research and on-farm trials at various sites indicate that crop yields can be increased with these methods; however, economic and financial analyses are not widely available for the Sahel.

CASE STUDY

As indicated, this analysis is focussed on technological change in a traditional rainfed farming system. A representative Malian farm is the unit of analysis. The primary methodologies followed are two: a linear-programming economic model of the representative farm, and a soil–water balance/crop yield response model of the bio-physical relationships involved in farm production technologies. The potential impacts of improved soil, water and crop management practices for the traditional farm are simulated and compared. In the remaining portion of the paper the steps followed in the analysis and the results obtained are described.

Characteristics of the representative farming situation

Representative Malian farming system. In 1978 and 1979, Fleming conducted a series of farm interviews on 55 farms in nine 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 and input/output prices for farms in the area. The basic characteristics of a representative traditional farm are shown in Table 2. Published summaries of the Fleming farm surveys and other secondary information formed the data-base for the linear-programming model.

Rainfall patterns in the study area. Rainfall in the study area is similar to the general pattern exhibited throughout the Sahel region, i.e., unimodal, normally beginning in late spring–early summer and terminating in early fall, but uncertain as to amount and timing (Fig. 3). Rainfall data from the Kita Weather Station formed the basis for the weather scenarios utilized in the analysis.

TABLE 2

Farm characteristics

Agro-climatic zone:	Sudano-Guinean	Technology:	Traditional with no modern inputs
Rainfall zone:	800–1 000 mm	Home consumption:	Per capita–food grains 185 kg vegetables 20 kg
Soils:	Alfisols		
Farm size:	8 ha	Crops:	Sorghum, Millet, Groundnut, Maize, Vegetables, Rice, Sorghum–Groundnut intercropped
Family size:	12 members		
Family labor pool:	5 adults (FTE)		

Source: Fleming, 1981.

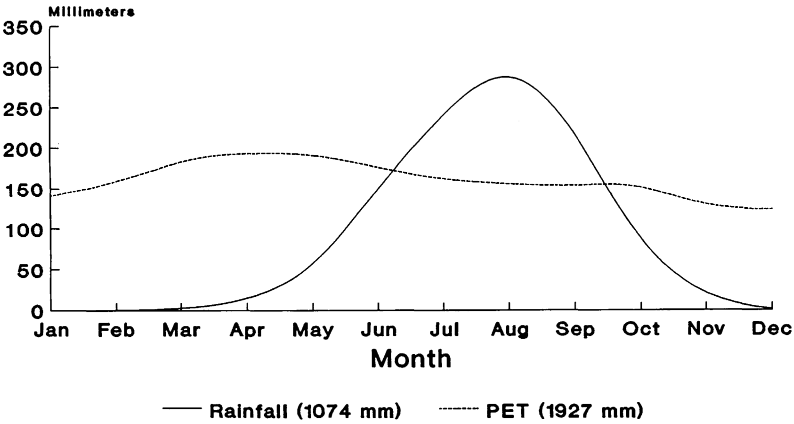

Fig. 3. Average rainfall and PET, Kita, Mali (25 years record).

Technological options examined. Any number of farm management options might be suited to the general conditions of the representative farm. Alternatives most likely to be adopted, however, are those that are consistent with the farm setting and call for modest adjustment to established practice as opposed to wholesale change. Given this, certain of the technological options examined were chosen on the basis of special considerations: NPK fertilizer levels were not allowed to exceed the amount typically used as revealed in the Kita farm surveys; oxen are superior to other animals for traction; cultivar selection does not require significant change in the production process aside from timing; and planting date is a key factor in that farmers everywhere adjust their planting schedules according to the onset of rains, other climatic variables, and availability of labor.

TABLE 3

Soil, water and crop management strategies for case study

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

The complete set of technological options chosen for evaluation, therefore, are: (1) use of small amounts of fertilizer, viz., up to 24, 8 and 32 kg NPK, respectively, per ha to increase 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 of millet, sorghum, maize and groundnut as a response to onset; (4) the use of alternative planting dates for all crops including rice and vegetables (15 May, 1 June, 15 June, or 1 July) as another response to rainfall; and (5) the use of a single team of oxen for tillage and ridge construction. The combinations (Cases) of these selected for analysis are shown in Table 3.

Analytical procedures

The analytical procedures involve estimating crop yields and soil erosion associated with each technological Case in the context of the soil, weather and crops of the representative farming system. When fitted with appropriate data, the soil–water balance/crop response model provided this information. Output from this model, in turn, became input data for the production activities in the whole-farm economic model. The whole-farm model, run for each Case situation, identified the production plan that maximized net farm income subject to various farm-level resource and behavioral constraints. By comparing these results, the likely effects of moving from traditional production practices to more advanced technologies can be seen. A more specific description of these procedures follows beginning with the farm model.

Representative farm model. The model is a single year linear-programming formulation of primary objectives, production activities and resources characteristic of the Kita typical farm. There are two behavioral objectives active: the first is to choose a farm plan such that cereal production will meet family food requirements; the second is to maximize net income from sales. One innovative aspect is the fact that while home food consumption needs are specified as a 'safety-first' constraint this production level is tied to what might be expected even if very unfavorable rains were to occur. Another innovation is inclusion in net farm returns of the present value of future lost productivity due to soil erosion associated with each technology mix and related current year production plan. A mathematical statement of the model appears in the Appendix.

Soil–Water balance / Crop response model. This model is the second primary analytical tool utilized. It is designed to reflect the relationship between rainfall, soil moisture, and crop yield – a fundamental consideration when evaluating soil and water management options.

For a given amount of rainfall, infiltration rates and the water holding capacity of the soil determine soil moisture availability. Soil moisture (or the lack thereof) in turn plays a significant role in crop yield. A basic objective of on-farm water management, for example, is to raise crop yields by improving soil water balance, that is, by bringing soil water availability more into line with plant water requirements. Other management practices such as the use of fertilizers and conservation tillage can do the same thing. In addition, the timing of operations in relation to rainfall and available soil moisture can change the soil–water balance situation either positively or negatively. Thus, whatever production practices are followed, if the timing is not good and plant water demand at any time still exceeds available soil moisture supply, plants will experience moisture stress. In most cases moisture stress will decrease crop yield.

According to methods described by Doorenbos and Pruitt (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:

$$\mathrm{SWB}^t = (R^t I^t) - (\mathrm{ET}_0^t \cdot k_c^t) + \sum_t \left[(R^{t-1} I^{t-1}) - (\mathrm{ET}_0^{t-1} \cdot k_c^{t-1}) \right] \qquad (1)$$

$$\mathrm{MD}_f^t = \frac{|\mathrm{SWB}^t|}{\mathrm{ET_m}} \quad \text{when} \quad \mathrm{SWB}^t < 0 \qquad (2)$$

$$y_r^t = \mathrm{MD}_f^t \cdot \mathrm{K}_y^t \qquad (3)$$

$$\mathrm{CY_r} = \sum_t (y_r^t) \cdot (\mathrm{CY_m}) \qquad (4)$$

$$\mathrm{CY_a} = \mathrm{CY_m} - \mathrm{CY_r} \qquad (5)$$

where

SWB^t = soil water balance in time period t, i.e., 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 carry-over 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 equation (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. Lastly, equation (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. Two-week time steps were used here.

Equations (1)–(5) become a simple model of soil water balance and crop response to resource conditions and management practices. 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, water and crop technologies examined. The data used to calibrate the model are now outlined.

Rainfall. Two rainfall patterns were used in this study: 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. These yields were estimated using equations (1)–(5) for each annual weather pattern in 43 years of record at the Kita Weather Station. Once these particular rainfall patterns were identified, equations (1)–(5) were again used to estimate potential yields for all crops and management practices examined. 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.

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 insure food supplies, farmers must also plan for this rainfall pattern. Our whole-farm model actually takes these two weather possibilities into account simultaneously to identify farm plans that are economically optimal under average yield conditions as well as satisfying food needs should the worst year occur. The two rainfall scenarios examined are shown in Table 4.

TABLE 4

Rainfall, Kita Station, Mali

Time period	Average rainfall		Average yield	Lowest yield
	Amount (43 years)	St. Dev. (43 years)	Rainfall (1968)	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, KS.

Infiltration. Estimates of rainfall infiltration were generated from rainfall–runoff curve data reflecting soil characteristics, ground cover and rainfall intensities in the Kita area (USDA/SCS, 1986). Two alternative infiltration rates were considered, viz., 40% and 80%. Alternative rates arise from the different soil water conservation practices considered. Traditional farm practices in the study area result in low (about 40%) infiltration rates, whereas tied-ridges are assumed to improve upon this considerably and lead to 80% infiltration.

Crop coefficients. 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 5). k_y coefficients reflecting crop yield response to moisture stress during plant growth stages are shown in Table 6. 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. Base long-season crop yields are taken from actual field survey data (Fleming, 1981) and are considered to be quite accurate. The field survey reported no short-season varieties in use during the sample years. These yield estimates were, therefore, derived from information in technical manuals and from expert opinion (Doorenbos and Pruitt, 1975; FAO, 1986b; Hatfield, personal communication, 1989). As such, they may not be fully precise estimates of likely yields. Sensitivity analysis of short-season yields could have been carried out; however, given the poor 'response' of these varieties in our analysis this was judged to be unnecessary.

TABLE 5

Crop water requirement coefficients (K_c) by crop growth stage

Growth stage	Crop							
	Sorghum		Millet		Maize		Groundnut	
	S-S	L-S	S-S	L-S	S-S	L-S	S-S	L-S
Establishment	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Vegetative	0.50	0.40	0.50	0.40	0.70	0.60	0.60	0.50
Flowering	0.80	0.70	0.70	0.60	1.00	1.10	0.90	1.00
Yield formation	0.90	1.00	0.80	0.90	0.80	0.90	1.00	1.10
Ripening	0.50	0.70	0.50	0.70	0.60	0.70	0.70	0.70

S-S refers to short-season (90-day growth) crops and L-S refers to long-season (130-day growth) crops. Source: Doorenbos and Pruett, 1975; FAO, 1986b; Hatfield, 1989.

TABLE 6

Crop yield–Moisture stress coefficients (k_y) by crop growth stage

Growth stage	Crop			
	Sorghum	Millet	Maize	Groundnut
Establishment	0.20	0.20	0.40	0.20
Vegetative	0.20	0.20	0.40	0.20
Flowering	0.55	0.55	1.50	0.80
Yield formation	0.45	0.45	0.50	0.60
Ripening	0.20	0.20	0.20	0.20

Source: Doorenbos and Kassam, 1979; FAO, 1986b; Hatfield, 1989.

Soil erosion and declining productivity. 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, based on Lal's soil plot data for Ibadan, Nigeria (Lal, 1987a) a maximum erosion rate of approximately 60 t/ha for a bare fallow field of variable length with 5% slope was used. 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), i.e., MPE $\cdot PC$. 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% ($P = 0.2$) (Roose, 1977).

The effect of soil erosion on crop productivity can be estimated by comparing yields on eroded and non-eroded fields. 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 t in corn yields and a 0.03 t decline in cowpea yields per 10 t loss in soil. It was assumed 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, and that the erosion-induced yield decline for groundnuts is 5% of the estimated yield decline for cowpeas. The productivity decline due to one year of erosion is small but it is a virtually permanent loss. All future yields will be slightly lower as a consequence of erosion during one crop year. Thus, the economic cost of one year's erosion will appear as a series of yield losses in future crops.

t, metric tonne = 1000 kg.

TABLE 7

Case study impacts of soil, water and crop management strategies

Impact category	Traditional case	Case I	II	III	IV	V
Net farm income (1 000 MF) [a]	8.4	35.5 (323)	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 (t/ha)	32	33 (5)	9 (−72)	33 (5)	9 (−72)	12 (−62)
Erosion damage (1 000 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	0.1	0.3
May 15	5.5	3.8	4.1	3.8	3.9	3.1
June 1	0.1	3.1	3.3	3.1	3.4	3.4
June 15	2.4	1.1	0.6	1.1	0.7	1.5
July 10	0	0	0	0	0	0
Animal Traction Utilized (h)						
Rented Ox team	23	38	0	38	0	0
Owned Ox team	0	0	400	0	351	370
Hired Labor (h)	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

Figures in parenthesis represent percentage changes compared to the base case. [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 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.

In this study, the cost of erosion associated with one year of a crop production activity is estimated as the present value of a 10-year stream of crop production value lost due to soil having been eroded during the single cropping year.

In summary. A soil–water balance/crop yield response model was employed 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 resource constraints and the safety-first constraint of producing sufficient food to satisfy home consumption requirements under the worst rainfall–production scenario.

CASE STUDY RESULTS

Solution values for the optimal production plan associated with each strategy are shown in Table 7. In this description of results the farm-level impacts, including long term consequences of soil erosion, associated with Cases I, II, III and IV are compared to those of the Traditional Case. The effects of ignoring the loss in productivity due to erosion is brought to light in a comparison between Case IV and Case V.

The analysis indicates 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 Traditional Case net farm income is not very high because there is little saleable surplus beyond basic family food needs. Moreover, real farm income is depressed by the present value of future productivity lost 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 well over two. 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. 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. The potential advantage of the short-season varieties did not come into play because onset under both scenarios was 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 compared to 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, 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, 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 t/ha. 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 as compared to the Base Case.

CONCLUSIONS

Our analysis indicates that even in the relatively humid Sudano-Guinean zone of the Sahel improved soil, water and crop management technologies can be cost-effective and yield high benefits in the form of increased income, production and erosion control. Even with traditional cultivars the combination of chemical fertilizer, tied-ridges, and animal traction proved most effective. Of major significance in these results is the potential for increased stability in year-to-year output made possible by the water conserving tied-ridge technology. Similarly, the erosion control benefits of the practice increase the possibility for sustainable farming in the Sahelian environment.

On the other hand, short-season (90-day) cultivars made no significant difference in farm output or income. However, in situations where seasonal distribution of rainfall is less favorable than the scenario examined here, such as later onset/earlier cessation, short-season cultivars would very

US$1.00 = 450 MF (Mali franc) in 1979 prices.

likely be a better choice, ceteris paribus, than traditional varieties. This would be particularly true in the drier northern regions of the Sahel where growing season length is normally shorter. Also, in the drier regions where water is even more scarce the economic returns to water conservation may be larger than estimated here.

Farms and farmers in other locations with characteristics similar to those of our representative Malian farm could experience similar gains, certainly in the short run. Clearly, there seems to be a strong economic incentive for adoption of new practices. However, given these results, how does one explain the relatively slow adoption rates for these sorts of innovations as reported in the literature. It must be remembered that farmers do put weight on non-economic considerations when evaluating technologies. For example, farmers may be unwilling to shift to ownership of oxen because of unfamiliarity with the care and maintenance of animals and/or because of a reluctance to take on the added burden of such a responsibility. Also, new technologies may be seen as too difficult to plan and implement given farmer's perceived returns, which may not be accurate.

Farmers may also put more weight on short term weather induced yield variability than was assumed to be the case in our analysis. Here, yield variability was handled by requiring protection against a worst-case yield scenario. This may not be a sufficiently accurate representation of the way Malian farmers perceive their environment if one wishes to explain farmer behavior. A Target-Motad analytical model utilizing a weather distribution–yield variability minimization approach with farmer's risk aversion included might provide a more precise representation of weather variability and farmer preferences. Whether the basic conclusion, viz., soil and water conserving technologies appear to be very profitable and sustainable in the long-run, would be any different is open to question. Future work will explore other modelling approaches and compare the results to these findings. Similarly, the extent to which conclusions will change with possible input and output price changes coming into the picture as a result of widespread technological diffusion is the subject of another analysis. In future studies we will attempt to take into account demand and supply elasticities.

Public policies and programs should be much more soil and water resource oriented than they have been to date in most instances. Vigorous action is needed to remove impediments to diffusion of better resource management technologies at the farm level and creation of a healthy setting for long-term sustainable growth in the farm sector. At a general level, economic policies that artificially distort agricultural prices thereby creating disincentives for technology adoption must be changed, and weak rural education, training, and infrastructure systems must be improved.

Research and extension programs need to stress expansion of the knowledge base pertaining to soil and water management in a setting where traditional practices can no longer cope with population-induced pressure on the land. Integrated crop and livestock farming systems that incorporate modern soil and water management principles are urgently needed in all parts of the Sahel.

Farmers should be the target of all this because most resource-use decisions are made by them, and the farm is where most management improvements will take place. In the long run Sahelian society-at-large stands to benefit from a more productive agricultural sector.

REFERENCES

Biswas, A., 1986a. Irrigation in Africa. Land Use Policy, 3(4): 269–85.

Biswas, A., 1986b. Land use in Africa. Land Use Policy, 3(4): 247–258.

Doorenbos, J. and Kassam, A., 1979. Yield response to water. FAO Irrigation and Drainage Paper, 33. Food and Agricultural Organization of the United Nations, Rome. 1979.

Doorenbos, J. and Pruitt, W., 1975. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper, 24. Food and Agricultural Organization of the United Nations, Rome.

FAO, 1985. Production Yearbook – 1984. Food and Agricultural Organization of the United Nations, Rome.

FAO, 1986a. African Agriculture: The Next 25 Years. Food and Agricultural Organization of the United Nations, Rome.

FAO, 1986b. Early agrometeorological crop yield assessment. Plant Production and Protection Paper, 73, Food and Agricultural Organization of the United Nations, Rome.

Fleming, A., 1981. Agricultural productivity and the use of labor in alternative enterprises in the circle of Kita, Mali. M.S. thesis, Purdue University, West Lafayette, IN.

Hargreaves, G. and Samani, Z., 1986. Rainfed and water requirements manual for Mali. International Irrigation Center, Department of Agricultural and Irrigation Engineering, Utah State University, Logan, UT.

Jayne, T., Day, J. and Dregne, H., 1989. Technology and agricultural productivity in the Sahel. Agric. Econ. Rep. 612, USDA Economic Research Service, Washington, DC.

Lal, R., 1981. Soil erosion problems on alfisols in western Nigeria, VI. Effects of erosion on experimental plots. Geoderma, 25: 215–230.

Lal, R., 1984. Productivity assesment of tropical soils and the effects of erosion. In: F.R. Rijsberman and M.G. Wolman (Editors), Quantification of the Effects of Erosion on Soil Productivity in an International Context. Delft Hydraulics Laboratory, The Netherlands.

Lal, R., 1987a. Effects of soil erosion on crop productivity. CRC Crit. Rev. Plant Sci., 5(4): 303–367.

Lal, R., 1987b. Managing the soils of sub-Saharan Africa. Science, 236: 1069–76.

MacDonald, L., 1986. Natural resources development in the Sahel: the role of the United Nations Systems. NRTS/UNUP-422, United Nations University, Tokyo.

Matlon, P., 1986. Orienting millet improvement objectives to fit clients needs: Improved genotypes and traditional management systems in Burkina Faso. Paper Presented at International Pearl Millet Workshop, ICRISAT, Hyderabad, April 1986.

Roose, E., 1977. Use of the Universal Soil Loss Equation to predict erosion in West Africa. In: G. Foster (Editor), Soil Erosion: Prediction and Control. Soil Conservation Society of America, Ankeny, IA, pp. 60–74.
Sivakumar, M.V.K., 1988. Predicting rainy season potential from the onset of rains in southern Sahelian and Sudanian climatic zones of West Africa. Agric. For. Meterol., 42: 295–305.
Sivakumar, M.V.K., Konate, M. and Virmani, S.M., 1984. Agroclimatology of West Africa: Mali. Inf. Bull. 19, International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradash, India.
Steiner, J., Day, J., Papendick, R., Meyer, R. and Bertrand, A., 1988. Improving and sustaining productivity in dryland regions of developing countries. Advances in Soil Sciences, 8. Springer, New York, pp. 79–122.
USDA/SCS, 1986. Hydrology for small watersheds. Technical Release 55, Washington, DC.
Wischmeier, W., 1959. Cropping-management factor evaluations for a Universal Soil-Loss Equation. Soil Sci. Soc. Am. Proc., 23: 322–26.
World Bank, 1985. Desertification in the Sahelian and Sudanian zones of West Africa. IBRD, Washington, DC.

APPENDIX

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

$$\text{MAX } I = \sum_i P_i(Y_i X_i - D_i - \text{HC}_i) - \left[\sum_f P_f\left(\sum_i F_f X_i \right) + \sum_i \text{CC}_i \cdot X_i + \sum_t W_t \cdot \text{HL}_t \right. \quad (1)$$

$$\sum_i L_{ti} X_i - \text{HL}_t \leqslant \text{LA}_t \quad (2)$$

$$\sum_i X_i \leqslant \text{HA} \quad (3)$$

$$\sum_i Y_i X_i - D_t \geqslant \text{HC}_i \quad (4)$$

$$\sum_i B_i X_i \geqslant \text{HC}_i \quad (5)$$

$$X_i \geqslant 0 \quad (6)$$

where

i = crop type
t = time period
P_i = price of the ith crop
Y_i = expected yield per ha of ith crop
X_i = hectares of ith crop
D_i = deductions (kg) of ith crop for seed, gifts, and crop loss

HC_i = home consumption of ith crop
PF_f = price of fth fertilizer
F_{fi} = fth fertilizer use per ha of ith crop
CC_i = cash cost per ha of ith crop
W_t = hourly wage rate of labor in tth time period
L_{ti} = labor hours in tth time period per ha of ith crop
LA_t = family labor hours available in time period t
HL_t = hired labor in tth time period
HA = hectares of land available for crop production
B_i = safe minimum assured yield of ith crop