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Agricultural Economics, 2 (1988) 209-222
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Soil and Moisture Management in Mali: A Case Study Analysis for West Africa

John C. Day and Marcel P. Aillery

Resources and Technology Division, Economic Research Service, U.S. Department of Agriculture, 1301 New York Avenue, N.W., Suite 524, Washington, DC 20005-4788 (U.S.A.)

(Accepted 23 February 1988)

Abstract

Day, J.C. and Aillery, M.L., 1988. Soil and moisture management in Mali: a case study analysis for West Africa. *Agric. Econ.*, 2: 209-222.

In order for farmers to accept improved soil and water management practices, new technologies must be appropriate to the specific site conditions found in the farm setting and be consistent with farmers' objectives and available resources. A whole-farm modeling analysis of this problem is described. Preliminary estimates of the benefits of increased soil moisture conservation for representative low-resource farmers in Mali are presented. If farmers could improve rainfall infiltration from currently low rates of about 40% up to 60%, and use small amounts of chemical fertilizers, disposable income could increase two to four times depending on rainfall. Income could be increased another 50% if the infiltration rate was raised to 80%. Food grain production could increase 60 to 90% with improved moisture conservation and fertilizer use.

Introduction

Better soil and moisture management are the two most important factors affecting future agricultural productivity in rainfed areas of West Africa. If farmers are to adopt improved soil and water management practices, however, technologies must be appropriate for the specific physical site conditions found on the farm and be consistent with the farmer's objectives and the land, labor, capital and other resources he has available. New technologies must also be affordable.

In this paper changes in production, farm resource use, and income associated with economically optimal farm production plans including water conservation are estimated for a representative rainfed farm in western Mali.

The paper begins by summarizing the physical characteristics of rainfed agriculture in Mali. Next, a brief assessment of soil water management technol-

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ogy and information is provided. Finally, the results of a whole-farm analysis of improved resource management are presented.

General background: Rainfed farming in Mali

As in other Sahelian countries, rainfall is a major determinant of crop production in Mali. Unfortunately, rainfall is highly variable in location, timing, and amount. Rainy seasons last from 2 months in the north to 4–5 months in the south. In these areas total seasonal precipitation averages 100 mm or less to about 1400 mm. Coefficients of variation (CVS) in seasonal rainfall totals range from 20 to 40% in most locations. Year-round temperatures are always high with peaks of 35–45 °C during the late spring–early summer periods. Yet, 95% of the arable land in Mali is cultivated under these difficult conditions.

Exacerbating the rainfall situation is the generally poor quality of soil resources. Crusting and sealing is a widespread problem. Natural moisture infiltration is poor due to the combination of high rainfall intensity and low absorptive capacity of the soils; and, farmers do not usually practice soil and water conservation methods that could be effective. In addition, the natural fertility of soils is low; organic matter is lacking and soils are deficient in nitrogen, phosphorous and sulfur. Clay soils tend to be neutral to alkaline, slowly permeable, susceptible to flooding, and difficult to manage with traditional tillage practices. Sandy soils tend to be acidic. Gravelly and stony soils are generally infertile due to intense leaching. Aluminum and manganese toxicity may also exist in Malian soils (TAMS, 1983; Jaynes, Day and Dregne, 1988).

Eighty-five percent of all cultivated land is in food grains, primarily sorghum, millet, maize, and rice. The principal cash crops are peanuts and cotton accounting for approximately 15% of all cultivated land. Irrigation, mostly in rice, accounts for less than 5% of land in cultivation.

Rapid population growth and expansion of cultivation onto marginal lands has meant that average annual per-capita production of food grains in Mali declined during the period from 1966 to 1983 (Shapouri et al., 1986). With population increases projected at 3% annually, it is doubtful that Malian agriculture can sustain its future population with current production practices (World Bank, 1985). Limited potential for major yield gains and/or area expansion in the irrigated sector (Eicher, 1986) means that the productivity of rainfed farming must be raised.

Technological options for soil/water management

Improved soil and water management options are available for the agroclimatic regions of West Africa (Lal, 1987; Steiner et al., 1988). These options include: conservation oriented tillage; ridging; fertilization; mulching; water harvesting techniques such as micro-catchment basins, bunds, ridges with cross-ties to form furrow basins, small terraces; cultivation with animal traction; and agro-forestry inter-cropping. All of these are potentially operational in Mali. Experimental research and on-farm trials indicate that crop yields can be increased with these methods.

Economic studies of soil and water management alternatives in the Sahel also exist for selected practices and countries (Delgado and McIntire, 1982; Roth and Sanders, 1984; Nicou and Charreau, 1985; Sanders et al., 1985). For example, the use of animal traction, chemical fertilizer, and tied ridges in Burkina Faso has been examined using both partial budgeting and whole-farm modeling approaches. These studies consistently show that the potential farm level benefits of new practices can be high providing their use is consistent with farm labor availability.

Few published studies of this nature, however, are to be found for Mali. A number of agronomic research projects dealing with improved farming practices have been conducted, but not enough attention seems to have been given to economic aspects of the problem. As a result little published information is available on the farm level costs and returns of specific soil-water conservation practices, and the extent to which such practices fit conditions on the typical Malian farm. The lack of data on costs and labor requirements is particularly troublesome.

Mali case study

In simple terms, the case study is designed to estimate possible farm level impacts of alternative ways of coping with soil and water limitations in Mali. Procedures are employed which take into account intra-seasonal variation in weather as well as differences in annual rainfall patterns.

If new technologies are to be effective, they must be compatible with the setting in which they are to operate (Matlon and Spencer, 1984). Soil and water management technologies in particular must be suitable for the soils, rainfall and biological plant growth conditions at the farm site. These technologies must also help the farmer increase his income and satisfy other objectives given the land, labor, and capital he has available.

In rainfed farming the importance of the timing of rain as well as the total amount received cannot be overemphasized. In a given year annual precipitation may be enough to satisfy total plant water requirement; however, 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 stage, then yield will be reduced. Even if there is excess moisture in later periods, the loss in yield may never be recovered. In our case study soil-water balance conditions and the intraseasonal variation in agro-climatic variables were given special attention.

Whole-farm modeling is widely recommended as a useful methodology for farm level technology appraisal (Ghodake and Hardaker, 1981; Nagy et al., 1985). 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.

In the remainder of this paper input data utilized, analytical procedures followed and results obtained in the case study are summarized.

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).

Rainfall patterns. Data obtained at the Kita weather station, the official station nearest the study cite, 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% probability of occurrance were selected to represent two likely rainfall conditions facing farmers in the area. A complete distribution of Kita area rains is shown in Table 2.

Infiltration, evapotranspiration and crop response. Estimates of rainfall infiltration for the 75 and 50% rains were generated from rainfall-runoff curve data re-

TABLE 1

Representative farm (traditional)

Location	Kita Region, Western Mali
Agro-climatic zone	Sudano-Guinean
Rainfall zone	800-1000 mm
Soils	Alfisols (32% of cultivable lands in Mali)
Farm size	8 ha
Family size	12 members
Family labor pool	5 adults (FTE)
Crops	sorghum, millet, groundnut, maize, rice, vegetables, sorghum-groundnut intercropped
Technology	Traditional, with no modern inputs
Home consumption	Per capita — food grains 185 kg; vegetables 20 kg

Source: Fleming, 1981.

TABLE 2

Rainfall at Kita Station Mali (51 years of records)

Four-week period	Weeks	Rainfall (mm)					
		Probability level (%)					
		90	75	50	25	10	Mean
01.01-28.01	1- 4						
29.01-25.02	5- 8						
26.02-25.03	9-12						
26.03-22.04	13-16						
23.04-20.05	17-20	4	9	21	39	62	27
21.05-17.06	21-24	48	75	104	135	162	104
18.06-15.07	25-28	98	135	175	216	253	175
16.07-12.08	29-32	181	224	271	320	364	271
13.08-09.09	33-36	198	237	287	344	401	294
10.09-07.10	37-40	74	103	145	195	250	154
08.10-04.11	41-44	10	20	40	68	103	49
05.11-02.12	45-48						
03.12-31.12	49-52						
Total[a]		831	941	1074	1219	1360	1080

Source: Sivakumar et al., 1984.
[a]Totals include minor precipitation throughout the year.

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

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:

$$(1-Y_a/Y_m)=k_y\,(1-\mathrm{ET}_a/\mathrm{ET}_m) \qquad (1)$$

where Y_a is actual crop yield, Y_m maximum crop yield, ET_a actual crop evapotranspiration, ET_m maximum crop evapotranspiration, and k_y crop yield response factor relating Y_a/Y_m to $\mathrm{ET}_a/\mathrm{ET}_m$. In words, equation (1) 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 (1) 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.

Analytical approach

Soil moisture conservation impacts were estimated for two alternative rainfall patterns a typical farmer in West Mali might experience in the course of time, and three levels of soil moisture conservation that he might carry out.

The first step in the analysis was to construct the farm linear-programming model. The 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. (A mathematical statement and description of the model is shown in the Appendix.)

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 and three infiltration rates. One rainfall pattern was that expected 5 out of 10 years (probability 0.5). The other was a more frequent, but also drier, pattern occuring 7 out of 10 years (probability 0.75). Three infiltration rates were considered, viz., 40, 60, and 80% 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 15 May, 1 June, 15 June, or 1 July. In all, 72 rainfall–infiltration–crop calendars were examined.

The LOTUS spreadsheet routine used to carry out the computations resulting in crop yield estimates as described above is illustrated in Table 3.

The lack of appropriate cost information on water harvesting and soil mois-

TABLE 3

Water balance/yield reduction computations, Kita Region, Mali

Base data

Crop:	sorghum and millet	Rainfall:	1008 mm	Soil:	Alfisol	Days/T:	15
Yield (Y_m):	1250 kg	Infiltration:	low (40%)	Plant Date:	15 May	ET_0/day:	7

Time Period, T	Plant growth stage	Crop water requirement coefficient[a], k_c	ET_m (mm/T)[b]	Moisture availability					Yield reduction data				
				Rainfall (mm/T)	Infiltration coefficient[c]	Effective rainfall[d] (mm/T)	Soil moisture deficit		k_y[e]	Calibration coefficient[f]	Yield reduction		Actual yield (kg)
							(mm/T)	(%)			(%)	(kg)	
T-09 5/01- 5/15		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	—
T-10 5/15- 6/01	Establishment	0.30	31.50	33.00	0.60	19.80	11.70	0.37	0.20	0.21	0.02	19.50	1231
T-11 6/01- 6/15	Vegetative	0.75	78.75	70.00	0.40	28.00	50.75	0.64	0.20	0.21	0.03	33.83	1197
T-12 6/15- 7/01		0.75	78.75	80.00	0.40	32.00	46.75	0.59	0.20	0.21	0.02	31.17	1166
T-13 7/01- 7/15	Flowering	1.00	105.00	95.00	0.41	38.95	66.05	0.63	0.55	0.21	0.07	90.82	1075
T-14 7/15- 8/01		1.00	105.00	130.00	0.41	53.30	51.70	0.49	0.55	0.21	0.06	71.09	1004
T-15 8/01- 8/15	Yield Formation	0.75	78.75	140.00	0.33	46.20	32.55	0.41	0.45	0.21	0.04	48.82	955
T-16 8/15- 9/01		0.75	78.75	155.00	0.33	51.15	27.60	0.35	0.45	0.21	0.03	41.40	913
T-17 9/01- 9/15		0.75	78.75	130.00	0.38	49.40	29.35	0.37	0.45	0.21	0.04	44.03	869
T-18 9/15-10/01	Ripening	0.50	52.50	75.00	0.38	28.50	24.00	0.46	0.20	0.21	0.02	24.00	845
T-19 10/10-10/15		0.00	0.00	70.00	0.33	23.10	0.00	0.00	0.00	0.21	0.00	0.00	845
T-20 10/15-11/01		0.00	0.00	30.00	0.33	9.90	0.00	0.00	0.00	0.21	0.00	0.00	845
T-21 11/01-11/15		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	845
T-22 11/15-12/01		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	845
T-23 12/01-12/15		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	845
			687.75	1008.00		380.30	340.30				0.32	404.66	845

[a]Adjustment coefficient to convert evapotranspiration for a reference crop (ET_0) to ET_m for crop of interest, in this case sorghum and millet.
[b]Evapotranspiration requirements for respective growth periods, i.e., $(k_c) \times ET_0/\text{day} \times \text{No. days}/T$).
[c]Ratio of infiltration to rainfall. Values based on rainfall-runoff curve data (USDA/SCS, 1985).
[d]Soil moisture available for plant uptake; i.e. (rainfall × infiltration coefficient). In this analysis, the simplifying assumption is made that deep percolation is negligible.
[e]Moisture stress-yield reduction coefficient to apply to maximum potential yield (Y_m).
[f]Yield reduction adjustment coefficient to reflect local conditions.

ture management techniques in the Kita area, as alluded to earlier, precludes analysis of the financial and economic feasibility of particular water saving technologies. It is possible, however, to look at the benefit side of soil moisture conservation. In that context, our estimates of the changes in net farm income associated with various rainfall–infiltration scenarios and farm production plans may be taken as possible upper bounds on the annual economic benefits of increased soil moisture. These benefit estimates may also give one an indication of the upper limit on the *annual* expenditures the farmer could afford to pay for equipment, labor, and other moisture conserving inputs.

By comparing the full set of solution values obtained with each scenario we can also assess other farm-level impacts of improved water conservation and associated farm management plans. Utilizing the statistically estimated 50% and 75% rainfall probability estimates provides a picture of what the typical farmer might actually face (and how he might react) 5 years out of 10 vs. 7 years out of 10.

Results

Overall results of the analysis are summarized in Table 4 and Figs. 1, 2, and 3.

The analysis indicates that if farmers could increase rainfall infiltration from the current rate of about 40% to 60% through moisture (water) conservation practices, disposable income could be expected to rise by about 125,000 Mali Francs (MF), or about $278 based on 1979 prices (Table 4). This translates into a two-fold increase in the case of the 0.5 probability rain, and four-fold with the drier 0.75 probability rain. Increasing infiltration from 60% to 80% would result in an additional income gain of slightly less than 100,000 MF. It should be pointed out that possible price-decreasing effects of a large number of farmers adopting yield-increasing water conservation technology was not considered in this analysis.

If one assumes, for example, that 10% of total disposable farm income is necessary to cover returns to management, then the amount of annual income gain available to cover annual moisture conservation costs (capital, interest, OMR and associated labor charges) is in the neighborhood of 100,000 MF per increment of infiltration rate change from 0.4 to 0.6 or from 0.6 to 08. These estimates represent a first approximation of the on-farm cost-range the R&D community and the local credit institutions must be working toward when developing and distributing soil moisture management equipment in the Kita Region.

To the extent, however, that farmers choose to allocate some portion of these income gains to other needed purchases (e.g., food, clothing, medicine, schooling), the amount they may be *willing* to spend on conservation payments may be less than these estimates. Similarly, farmers' perceptions of and attitudes

TABLE 4

Optimal farm impacts associated with two rainfall probabilities and three rainfall infiltration rates, Kita Region, Mali

Farm impacts	Rainfall Probability-Infiltration Efficiency					
	0.5 Rain			0.75 Rain		
	Infiltration			Infiltration		
	0.4	0.6	0.8	0.4	0.6	0.8
Disposable income (1000 MF)	70	198	296	27	148	246
Food consumption (kg/capita)						
sorghum	120	80	80	80	80	80
millet	40	80	80	80	80	80
groundnuts	10	10	10	10	10	10
maize	20	20	20	20	20	20
rice	5	5	5	5	5	5
vegetables	20	20	20	20	20	20
Crop output (kg)						
sorghum/millet	3358	4073	3858	3219	4097	4437
groundnuts	777	1216	1558	316	782	1770
maize	423	1102	3180	329	936	1190
rice	0	82	82	82	82	82
vegetables	329	329	329	329	329	329
straw	282	338	320	280	348	368
residue	735	982	1270	694	951	1094
Land use (ha)						
sorghum/millet	3.9	3.6	3.0	4.3*	4.3*	4.0
groundnuts	0.9	1.0	1.1	0.5*	0.8*	1.4
maize	1.0	1.3	2.7	1.1	1.5	1.2
rice	0	0.2	0.1	0.3	0.2	0.1
Vegetables	1.1	0.7	0.6	1.3	0.9	0.7
Total	6.9	6.8	7.5	7.5	7.7	7.4
Labor use (1000 MF)	31	35	106	36	52	55
Fertilizer use (kg)						
N	56	72	60	29	52	78
P	33	39	37	10	26	48
	89	111	97	39	78	126
Cash expenditures (1000 MF)	50	60	128	45	69	84

*Mixed crop sorghum with groundnuts.

toward risk will influence their actions regarding soil moisture technology adoption. With more accurate data on management opportunity costs, household expenditure patterns, and risk-related parameters, predictions of adoption and willingness to pay can be improved.

The analysis indicates, also, that while the combination of increased soil moisture, fertilizer use, and optimal planting schedule can be expected to increase crop yields significantly, at some level of fertilizer application moisture increases alone may have this same effect (Fig. 1). This appears to be the case, in particular, with maize. In fact, increased maize yields are possible without any fertilizer, i.e., no fertilized maize is included in any of the optimal farm production plans yet yields increase by almost 4 times.

Overall farm crop output levels are related to land use allocation decisions as well as to the use of yield-increasing technologies. In the farm situation examined, the total area of cultivated land does not change appreciably with different moisture levels; however, the mix of crops does. With initial increases in soil moisture groundnut area almost doubles but then remains fairly constant as moisture availability continues to increase. This is in contrast to the area devoted to maize and sorghum/millet, which remains stable until the highest moisture levels are reached. At that point maize area increases dramatically while sorghum/millet area decreases by almost one-third. Vegetable area declines as more moisture becomes available, reflecting increasing yields and a shift toward the food grains and groundnut crops. Increased soil moisture can help increase food grain output (i.e., sorghum, millet, maize, rice) from 3630 kg to 5709 kg (57%) during the low rainfall years, and from 3781 kg to 7120 kg (88%) about half of the time (Table 4). The effect of all these dynamic factors on production of major crops and income is shown in Fig. 2.

One land-use allocation decision of special interest is that of adapting planting dates to seasonal moisture availability. With the relatively lower rainfall scenarios, and/or lower rainfall infiltration rates examined, it appears to be

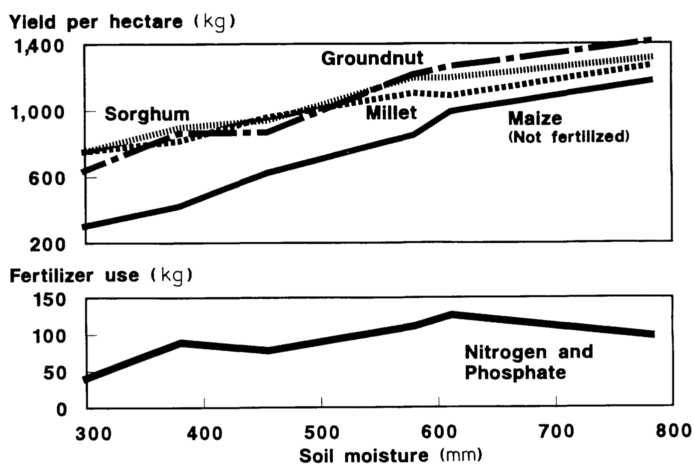

Fig. 1. Soil moisture, fertilizer use, and crop yields, representative farm. Kita Region, Mali.

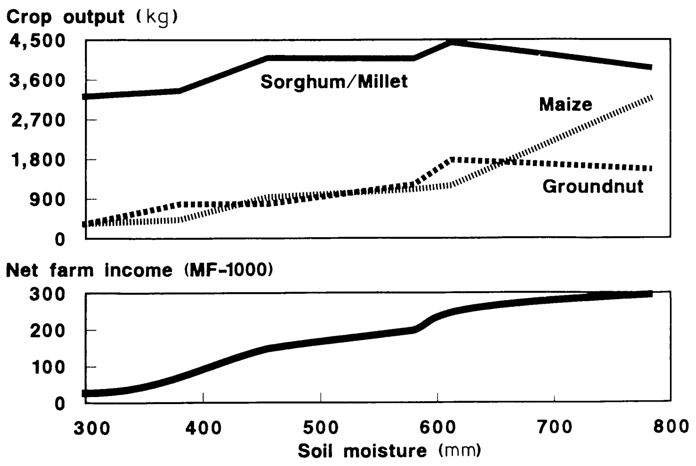

Fig. 2. Soil moisture, crop production, and farm income. Representative farm, Kita Region, Mali.

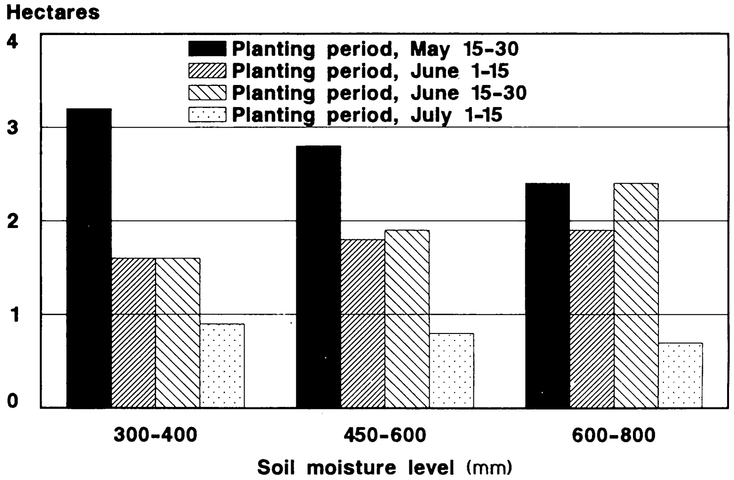

Fig. 3. Soil moisture, cropland area, planting period. Representative farm, Kita Region, Mali.

advantageous for farmers to begin planting early subject, of course, to the availability of sufficient moisture for preplant tillage and seed germination. With improved soil moisture levels planting could be spread out over the first part of the season (Fig. 3). One explanation for this is that it appears to be more profitable to plant inter-cropped sorghum/groundnut early rather than later. In addition, as soil moisture increases, the optimal production plan calls for a shift away from early sorghum/millet to maize planted later in the season, resulting in a planting pattern spread more evenly acrosss the four alternative planting periods considered.

A major advantage of spreading out the planting operation is that it also spreads out the demand for labor (land preparation, tillage); however, it may also create further bottle necks if weeding associated with early-plant crops coincides with late-plant tillage, etc. Our analysis assumed that labor supply was not an absolute constraint on the construction/implementation of water saving measures. For practical applications, Kita area labor supply elasticities and wage rates during the crop season need further research.

Summary

In dryland regions soil fertility and soil moisture levels are primary factors that determine agricultural productivity. Improved soil and water management practices, however, must be appropriate to the site conditions found at the farm level, e.g., soil quality and rainfall patterns, as well as be consistent with farmer's economic objectives and available resources. A good example of the situation in rainfed zones of Africa is found in the Kita Region of Western Mali.

The Kita Region is characterized by low and erratic rainfall, high temperature, soils of generally poor quality, and a short growing season. Low rainfall combined with low natural levels of infiltration result in low soil moisture levels. Crops are frequently under moisture stress during some or all of the various stages of plant growth leading to less than potential yields. At issue is the question of what technologies and/or management practices should be applied that would capture more rainfall in the soil profile, thereby increasing crop yields by reducing plant stress, and raising economic returns.

Using secondary data from farm surveys conducted in the Kita Region, a linear-programming model of a representative farm was developed. This model was used to identify optimal farm management plans associated with various levels of soil moisture, i.e., with alternative rates of rainfall infiltration that might be obtainable with soil moisture conservation technologies. Since little data exist on the costs and returns of specific technologies in the study area, our analysis estimates only potential farm income benefits (after usual production expenses and returns to management have been deducted) associated with soil moisture conservation. These benefit estimates represent first approximations of the annual costs the typical farmer in Kita may be able to pay for soil moisture conservation practices. Labor availability and cost may affect the feasibility and or timing of water conservation efforts.

A basic feature of the analytical framework employed is a crop-water balance LOTUS spreadsheet sub-routine that predicts crop yields as a function of crop evapotranspiration, rainfall, infiltration, and moisture stress during each stage of the crop growth process through the entire growing season.

The analysis shows that by increasing rates of rainfall infiltration from 40 to 60%, farmers could increase disposable income 2 to 4 times depending on rainfall. Income can be increased another 50% if the infiltration rate was raised

to 80%. Food grain production could increase from 60 to 90% with improved soil moisture conservation practices in place.

While information on the economic returns to conservation can be improved with more complete data, these estimates provide an indication of farmers' ability to pay for soil moisture conserving technologies and the productivity gains that might be expected. Hopefully, information of this type can stimulate researchers, policy makers, and development planners to devote greater attention to soil and water management options for rainfed areas of the world.

Appendix

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

$$\text{MAX } Z = \sum_i P_i \left[Y_i X_i - (D_i + \text{HC}_i) \right] - \sum_f \text{PF}_f \left[\sum_i F_{fi} X_i \right] + \sum_i \text{PS}_i \left[S_i X_i \right] + \sum_l \text{PL}_l \left[\sum_i L_{li} X_i \right] \tag{1}$$

subject to:

$$\sum_i \sum_l L_{li} X_i \leqslant \text{LA}_l \tag{2}$$

$$\sum_i X_i < \text{HA} \tag{3}$$

$$\sum_i \left[Y_i X_i - D_i \right] > \text{HC}_i \tag{4}$$

$$X_i \geqslant 0 \tag{5}$$

where i is crop type, $i=1, ..., 6$; P_i price of ith crop; Y_i yield per hectare 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, $f=1, ...,$ 3; F_{fi} fth fertilizer use per hectare of ith crop; PS_i price of seed for ith crop; S_i seed use per hectare of ith crop; PL_l price of lth labor type, $l=1, ..., 3$; L_{li} lth labor hours per hectare of ith crop; LA_l hours of lth labor type available; and HA hectares available.

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 production costs for fertilizer, seed, and labor. An imputed value of home consumption is also made explicit in the objective function. Constraint equations refer to labor availability (2), land availability (3), a requirement that production less deductions must meet minimum family food consumption requirements (4), and the usual non-negativity requirements for crop area (5). 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.

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