Economic Analysis of Soil and Moisture Management on Marginal Croplands

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Abstract

A linear programming model for a typical dryland farm in the 1000mm rainfall zone of Mali, West Africa indicates that, despite substantial variability in yields due to weather, a "safety-first" condition on staple food production constrains profit maximization only in the case of much smaller than average farms. Tied-ridge cultivation methods will reduce erosion damage, improve food security for small farms, and increase incomes if expected costs and yields are realized. Even without an immediate yield gain, tied-ridge cultivation would be economically justified by the reduction provided in future erosion-caused losses in soil productivity.

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Introduction

In many developing countries, pressure of food needs for growing populations has led to increased reliance on dryland crop production from lands that are inherently low in productivity due to low rainfall and low levels of soil fertility. Often, these lands are also subject to wide variation in yield from one year to the next and to deterioration over time. Because of low yield per unit of land area, traditional methods of cultivation that use large labor input per unit of land result in low marginal productivity of labor and generally in low ~~levels~~ standard of living for the farmers.

Low levels of income are also common among farmers in agricultural areas where the problem arises due to dividing undersized shares of the admittedly fertile land among too many farmers. Farmers in both the heartland and the marginal agricultural areas share a need to make careful choices in combination of crops to produce, in rates of application for fertilizer and other variable inputs and in general optimal allocation of land, labor, and capital resources. But in marginal dryland farming, questions regarding optimal soil and moisture management over time and feasible strategies to avoid disastrous impacts of random adverse weather conditions assume much greater importance than in fertile, well-watered heartlands.

Improved soil and moisture management are two important actions that can lead to increased agricultural productivity on marginal croplands. In this paper, farming practices that enhance fertility, reduce the rate of productivity decline due to soil erosion, and increase soil moisture through improved rainfall infiltration are examined in the context of the whole-farm operation of a typical dryland farmer in Mali, West Africa. In order for farmers to adopt recommended soil and water management practices, technologies must be both appropriate to the specific physical conditions found on the farm and consistent with the farmer's available resources and income and risk-avoidance objectives.

The paper begins by summarizing the physical characteristics of dryland agriculture in Mali. Next, a brief description of emerging soil- and moisture-conserving technology is provided. Lastly, a whole-farm planning model is presented and initial results of a case study involving the economics of improved resource management are given.

The economic investigations reported here are part of a larger research program that also includes agronomic studies of soil-moisture-crop management relationships in dryland farming areas.

General Background: Dryland Farming in Mali

Agriculture in Mali is oriented to staple food production. Eighty-five percent of all cultivated land is in food grains, primarily sorghum, millet, maize, and rice. The principal cash crops--peanuts and cotton--account for only approximately 15 percent of all cultivated land. Yet, from 1966 to 1983, total food production in Mali declined at a rate of .5 percent per year (Shapouri et al., 1986). With a projected annual population growth rate of 3 percent, resulting in a doubling of the population in 25 years, the future ability of Malian agriculture to feed its population is in question.

As in other Sahelian countries, soil moisture is a primary determinant of crop production in Mali. Ninety percent of Mali's arable land is farmed under strictly rainfed conditions; only ten percent is irrigated, mostly for rice production. Most of the crop production is in the 40 percent of the country where rainfall averages from 400mm up to as much as 1400mm. Throughout the area, rainfall is highly variable in timing of onset of the summer rains, in length of the summer rain season, and in the amount of rainfall that occurs.[1] Thus, there is considerable uncertainty connected with agricultural production and with the returns to new technologies or investment in agricultural improvements that may be sensitive to moisture conditions.

Exacerbating the rainfall situation in Mali is the generally poor quality of soil resources. Crusting and sealing of the soil is a widespread problem. Natural moisture infiltration is poor due to the combination of high rainfall intensity and low absorptive capacity of the soils. In addition, the natural fertility of soils is low; organic matter is lacking and soils are deficient in nitrogen, phosphorous and sulfur.

Land fertility and productivity are declining at both the intensive and extensive margins (Lallement, 1986). Fertilizer and manure applications are too small to replace nutrients withdrawn through crop growth, and the long rejuvenating bush fallow is being greatly shortened or eliminated in many cases. Erosion of topsoil and failure to return organic matter to the soil contributes further to deterioration of soils. Limited potential for major productivity increases or area expansion in the small irrigated sector (Eicher, 1986) suggests that measures must be adopted at the farm level that will enable low-resource dryland farmers to improve management of available land and water resources (Stewart et al., 1986).

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[1]The long-run average rainfall at Kita, for example, is 1080mm per year, but the standard deviation is 205mm. Lower rainfall zones tend to have proportionately greater year-to-year variability. At Hombori, the mean is 401 mm and the standard deviation is 110mm.

Economics of Soil and Moisture Management

Soil and moisture management technologies produce economic values in three ways. First, the technologies improve infiltration and increase moisture storage in the root zone where it can be utilized by the crop. In marginal dryland areas, increased soil moisture has a direct effect upon yields during the cropping season in which the practice is applied. Increased infiltration of water has a corollary effect of reducing the movement of water over the soil surface and lessening or eliminating yield damage due to washing out or silting over of plants.

Second, the erosion of soil that is caused by surface run-off has a long-run effect through loss of the productive topsoil layer. The third effect of improved soil and moisture management technologies is the downstream effect on the timing and quality of outflows from watershed. With improved infiltration and retention on the land, peak flows following a storm are not as high and the water that is retained tends to support a higher level of flow during the period between rainstorms.

The economic analysis of the immediate effects of improved soil and moisture management is not significantly different from the economic analyses that would be applied to other innovations and alternative management practices. Appropriate approaches would include a benefit-cost analysis comparing the value of increased yield to the cost of adopting the alternative management technology. Marginal analysis of increase in yield from alternative levels of application of the technology would also be appropriate. These techniques are a well-known part of farm economic analysis, and in fact are widely used with considerable skill by farm operators themselves. The primary reason for agricultural economists to conduct analyses of the immediate effects of soil and moisture management technologies is that they are innovations and farmers may not have the knowledge required to make a judgement about whether they are economically viable for their farms or not.

The long-run productivity gains (productivity losses averted) are a return to investment in improved soil and moisture management and erosion prevention. Economic analysis of long-run productivity effects requires first a determination of the effect that the soil and moisture management technologies will have on the rate of erosion. Next, the relationship between rate of erosion and productivity of the land must be determined. The given amount of erosion causes a permanent, for all practical purposes, deterioration in the productivity of the soil. Figure 1-A represents a typical path of crop yield or productivity at different remaining depths of topsoil. The figure represents a soil that is deep to begin with, and hence can incur some erosion without any measurable decline in yield. Eventually, however, further erosion leads to decline in yield until a yield is reached that can be sustained even when the entire topsoil has been eroded away. This would be the case for soil with a subsoil that can also support, albeit at a lower level, crop production.

Figure 1-B illustrates the erosion-productivity relationship for a soil that has no margin of safety. Thus, any erosion/decline in topsoil depth results in decrease in yield. Figure 1-B is also representative of a soil that cannot sustain crop production without more than some minimum level of topsoil.

Basic information on soil erosion and crop productivity is published in Follett & Steward (1985), and in American Society of Agricultural Engineers (1984). A recent review that provides more complete coverage outside the United States is Lal, 1987. The critical point is that erosion occurring

Figure 1-A. Yield/Soil Depth Relationship for A Deep Soil with Arable Subsoil

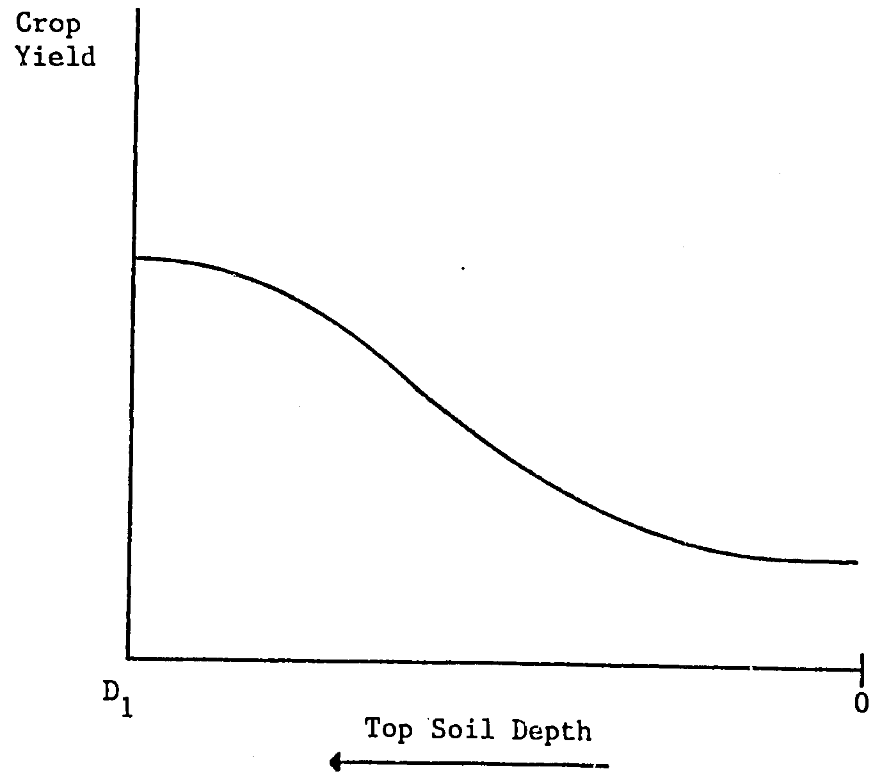
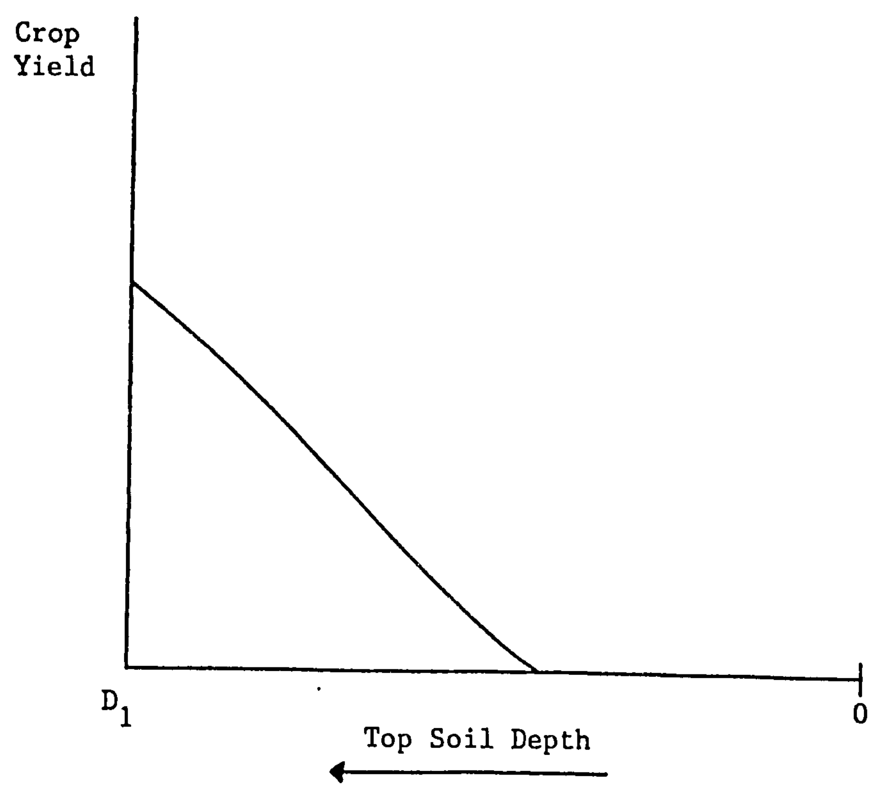


Figure 1-B. Yield/Soil Depth Relationship for an Eroded Soil with Non-tillable Subsoil



during one cropping season has a permanent impact upon the future productivity of the soil. Thus, crop production in the one season imposes a cost in a form of reduced productivity that extends indefinitely into the future. The value of that cost stream is the appropriate measure of the productivity costs of erosion, and the value of the stream of changes in future productivity is the relevant measure of the soil conservation contribution of an improved soil and moisture management technology.

The most straightforward way to evaluate the benefit of soil erosion avoided is to consider the soil to be an income earning asset. The decision that may be taken at the present time as to whether to employ soil conserving practices or not depends upon the value attached to preventing the future loss in productivity of that asset as compared to the value attached to labor and other costs that must be expended in order to carry out the conservation practices. The value of erosion prevented and productivity decline averted is the present value of the expected perpetual decline in yield coming about as a result of erosion occurring in the given year. The consequences of erosion caused in that particular year will be incurred over a much longer period of time. The present value of the future decline depends upon the number of years in the planning horizon and the discount rate. Peasant farmers are apt to have a very high discount rate because of pressing need for money for production and family living expenses. Moreover, pressure of supplying food to meet immediate nutrition needs of the family may cause the time horizon to be relatively short. Society may take a much longer view, recognizing that there must be provision to produce and feed future generations as well as the current generation. Society may also employ a much lower discount, reflecting relatively greater concern about the future as opposed to the present.

In recent years, there have been several applications of the theory of optimal control to the problem of choosing an appropriate level of soil conservation (Burt; McConnell; Bhide and Heady; Segarra). Optimal control provides a means of choosing the path of conservation to be employed over all future time periods. Depending upon the discount rate and the relative values of the productivity that will be lost in the future if erosion takes place compared to the cost of adopting soil-conserving techniques, the optimal path may call for a steady and high rate of conservation input in order to preserve the soil over time, for a low input of conservation with consumption of the soil and eventual abandonment, or for a changing rate of conservation application over time. The ability to model a changing optimal rate of conservation in view of the path of costs and returns throughout all future time periods is a definite strength of the optimal control approach. The disadvantage of optimal control is that it is not easily combined with the need to choose among many alternative soil and moisture management technologies and to fit those into an overall farming operation that has as well many alternative choices for combinations and levels of other activities.

Technological Options for Soil/Water Management

A number of recent studies have demonstrated the potential of practices such as animal-traction powered tillage operations, tied-ridging, dikes, and mulching to improve water use and crop yields in dryland environments of Africa (Delgado and McIntire, 1982; CRED, 1976; Nicou and Charreau, 1985; Roth and Sanders, 1985; Sanders, Nagy and Shapiro, 1985; Roth et al., 1986; Purdue Univ., 1986). These studies, mostly from Burkino Faso, also indicate a positive interactive effect of moisture management technologies and fertilization. The combination of tied ridges and fertilization will increase yield by more than either fertilizer or tied ridges alone. A more assured supply of adequate water to the crops' root zone means higher and more certain production increase from hard earned money spent on commercial fertilizer.

The slow adoption of potential technologies may be explained in part by the farmers' learning curve for "technology packages" and a lack of adequate extension support, and by the cost and inavailability of purchased inputs and equipment maintenance and repair services. Moreover, studies point out that new technologies may have certain characteristics which restrict their adoption on particular farms. Animal traction plowing may accelerate erosion and conflict with labor requirements for planting. Fertilization may be ineffective or even counterproductive without adequate moisture. Tied-ridge construction may increase labor requirements at critical times and may not be successful on all sites. However, the greatest deterrent to the adoption of what appear to be desirable technologies may be a lack of empirical data on the costs and returns associated with new soil/water management practices and a lack of analysis of whether adoption of new soil and water management technologies will contribute to or detract from the family's short and long-run subsistence, income, and stabilization objectives.

The objectives of this research are to: (1) estimate the cost and productivity effects of existing practices and new technologies, given the various soil, rainfall, and other resource conditions of the dryland farmers, and (2) evaluate the acceptability of alternative farm practices given the subsistence, risk avoidance, and income enhancement goals of typical farmers.

The Mali Case Study

A basic pre-condition if improved soil and water management practices are to be widely adopted is that they must be compatible with the farm-level setting in which they are to operate (Matlon and Spencer, 1984). Management practices must be suitable for the particular soils, rainfall patterns, and biological conditions at the farm site. They must be effective in helping the farmer to increase his income and satisfy subsistence, security and other objectives given the capital and labor resources he has available.

Whole-farm modeling is widely recommended as a useful methodology for appraisal of small-farm technology options (Ghodake and Hardaker, 1981; Nagy, Ames and Ohm, 1985; Roth, Abbott, Sanders and McKenzie, 1986), and this approach was adopted for our assessment. A farm programming model was designed based on typical farming operations in the Kita region of western Mali. The model has a number of features that should make it a useful prototype for analyses in other dryland agricultural areas.

The Farm Planning Model

A linear programming model was designed to reflect the perspective of a farmer seeking to optimize in the face of given production possibilities and limited resources. The general form of the model is

$$\text{Max } I = \sum_i P_i X_i \qquad i = 1, \ldots, n$$

subject to:

$$\sum_i X_i a_{ij} \leq C_j \qquad j = 1, \ldots, m$$

$$X_i \geq 0$$

where I is the income objective, P_i is the price or revenue per unit of the i^{th} activity, X_i is the level of the i^{th} activity, a_i is the amount of the j^{th} constraint used per unit of i^{th} activity, and C_j is the limit of the j^{th} constraint.

This programming model considers two objectives that are important to small farmers in the dryland areas of Africa. The first objective is a secure supply of staple food. Farmers are generally seeking to acquire adequate land resources and follow a management program that will have a fair probability of meeting their family's basic supply of food requirements under any adverse weather conditions. The safety criterion in the model is a constraint that the optimal farm plan must contain activities that will provide minimum food requirements even in a year with weather such that a higher crop yield would be expected in about nine years out of ten.

The second objective is to maximize profit, subject to the safe minimum food supply constraint. This arrangement is consistent with the "safety first" rules for decision making under conditions of uncertainty (Robinson, et al., 1984).

The food producing, and income-generating, activities in the model include sorghum, millet, maize, groundnuts, and vegetables.[2] Alternative planting schedules for the crops permit an evaluation of interaction between the timing of moisture requirements for the plant and susceptibility to moisture stress during the growth of the plant with the timing of rainfall and moisture availability. Shifting of planting dates can also help to fit farm operations in line with the availability of labor.

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[2]Sorghum and millet may be planted in the first, second, or third two-week period after the normal start of the rainy season. Maize may be planted in the second or third period, and groundnuts may be planted in the second, third or fourth period. Vegetables may be planted in the third or fourth period.

Methods of cultivation include traditional cultivation with human labor only and oxen cultivation. There is an option with either method of cultivation to fertilize the crop or to leave it unfertilized.

The constraints on the cropping activities include land, which is limited in the typical farm case to eight hectares, family labor, and temporary labor available for hire. Oxen labor of 104 hours per month is available if the fixed cost of owning and caring for the oxen has been included. Maintenance of the oxen requires labor and feed supply throughout the year.

The model has a section that accounts for the disposition and use of grain and fodder produced by the cropping activities. The family's staple food requirement, measured in Kcal of energy requirement per year, must be supplied out of the crop production. Dietary diversity restrictions require a variety of grains to meet the family's requirement. Grain must be supplied to the oxen during heavy working seasons and at times of the year when the fodder supply is not adequate for maintenance.[3] Additional grain over and above the family's living requirements and the requirements of livestock may be sold at the market price.[4]

Potential future additions to the model include use of improved short-season crop strains, dry season vegetable production (with some supplemental irrigation), forages intercropped with grain, cowpeas, and

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[3]The feed requirement for oxen is split into early dry, late dry, and wet seasons. Fodder is supplied from weeds and growth around the edge of the field and from crop residues.

[4]The farm family would have a choice as to whether they wish to sell all of the grain above subsistence or to use some of the additional surplus to provide a better-than-minimal diet.

agroforestry for producing firewood or other wood products. Future versions of the model will include cattle, sheep, and goat production activities. Livestock activities common in this area include small numbers that are owned by the local farmers and kept on the farm. More commonly, livestock owned by local farmers are taken by migrant herders to common grazing areas during the rainy season. The largest numbers are in herds of livestock that are owned by the migrants that pass through and spend some time grazing in the fields of the farmers.

Water-Yield Relationships

Crop yields in dryland farming areas of Mali and throughout West Africa are very strongly affected by the amount and timing of rainfall. A water-yield model was designed to estimate yield under various weather conditions. The model is used not only to estimate the distribution of crop yields over a range of different weather conditions but also to estimate the change in average yield and in distribution of yield that would be realized with changes in planting date, tillage practices, soil moisture management practices and measures, or crop growing season.

Crop yield response to moisture stress during growth stages was estimated using relationships developed by the Food and Agricultural Organization of the United Nations (Doorenbos and Pruett, 1975; Doorenbos and Kassam, 1979). The basic relationship between crop yield and moisture stress is assumed in the FAO methodology as:

$$(1) \qquad \sum_{t=1} 1 - \frac{Y_a}{Y_m} = k_{yt} \quad 1 - \frac{ET_{at}}{ET_{mt}} \qquad (t = 1, \ldots, 24)$$

where:

Y_a = actual harvested yield;

Y_m = maximum potential yield;

ET_{at} = actual moisture available for crop evaporation in time period t;

ET_{mt} = maximum potential crop evaporation in time period t;

k_{yt} = response factor relating decline in Y_a to the moisture deficit in time period t; and

t = half-month time periods.

Calculation of the yield decline due to moisture stress is carried out separately in each time period during the growing season. The moisture stress response factor, k_{yt}, varies from period to period as the plant exhibits different degrees of impact on ultimate yield due to water stress occurring at different stages in the growth of the plant. For example, maize is very sensitive to moisture stress during the flowering period. Thus, the k_y factor for maize during that stage of its growth is relatively high. Millet and sorghum also are sensitive to moisture stress at the flowering stage of growth, although not as sensitive as is corn. During time periods before the planting of the crop and after all growth is completed, the k_{yt} values are zero.

The FAO indicates that the relationship between moisture stress and yield production is approximately linear. That is to say, the k_{yt} values are constant for moisture deficits ranging up to about 50% of maximum potential evapotranspiration. A LOTUS spreadsheet was used to estimate the actual yield that would be realized under various alternative moisture availability regimes. Table 1 is an example of that spreadsheet calculated for sorghum and millet at the Kita location with a rainfall pattern that equals the long term average and a low rate of infiltration of precipitation into the root zone of the soil.

Rainfall and Infiltration

The yield-moisture stress model was used to estimate yields under weather situations such as occur at three locations in Mali. Kita, located in southwestern Mali, has a long run average precipitation of 1080mm per year. Segou, in central Mali, has a long run average rainfall of 720mm per year. Hombori, located in eastern Mali, has an average rainfall of 412mm per year. Daily precipitation records for each of these locations were obtained from the Evapotranspiration Laboratory at Kansas State University, and other climatic information was obtained from Hargreaves and Samani, 1986. The daily precipitation record was aggregated into half-monthly time periods that correspond with the twenty-four periods in the yield-moisture stress estimating model.

The yield-moisture stress model was used to predict yields at each of the planting dates for the crops for each of the years of weather record. Thus, there was an estimate of the yield that could be expected from early, mid-season, or late plantings of each crop if weather occurred that was practically equal to that in one of the years during the period of record. The resulting yields were arrayed from lowest to highest over the entire period of record and summarized by quartiles. The yields of sorghum associated with weather at the Kita station are presented in Table 3.

Estimates of yield that could be expected if patterns of precipitation recur provide a weather rating index that incorporates much more information than can be gleaned from, for example, the total seasonal precipitation or the precipitation in a critical time period during a cropping season.

Season-by-season yields recognize that the pattern of rainfall occurring during the season has an effect on yield over and above the effects that may arise from the total rainfall. The difference shown in Table 3 between the yield averaged over all the years and the yield that would be expected if exactly average weather occurred throughout the year illustrates this principle. The long run average of yields expected to occur given the various uneven weather patterns experienced at Kita is approximately 8 percent less than the yield that would be expected if exactly the long run average weather occurred in a given year.

The amount of moisture available for plant growth is affected by the infiltration and water-holding capacity of the soil as well as by the amount of precipitation that falls. The serious crusting problems that occur, especially in the rainfall zones of 700mm and above, are reflected in a very low set of infiltration rates being appropriate for conventional farming practices in the higher rainfall zones. The low infiltration rate assumes that approximately 40 percent of the moisture that falls is actually available in the root zone for the plant. The infiltration rate varies somewhat from one time to the next during the year as normal tillage and groundcover from a growing crop tend to improve the rate of infiltration over what would be the case on bare, untilled ground. Medium (approximately = .6) and high (approximately = .8) infiltration rates are also investigated. These higher rates might be obtained through improved tillage or through structures such as tied ridges or other devices that hold the water on the land and allow more time for infiltration.

Soil Erosion and Declining Productivity

It is very time-consuming and expensive to collect primary field data on rates of soil erosion under all the various soil and land-use conditions that may or could exist. Therefore, synthetic erosion estimating models, such as the Universal Soil-Loss Equation (USLE) (Wischmeier, 1959), are widely used in the temperate zone for estimating the change in erosion that will occur with a change in management practices or cropping patterns. The USLE and similar models have been widely used in recent years to link with crop yield forecasting models and estimate the effect of soil loss on long-run future yield potential of the land.

There are several soil erosion estimates for West Africa, but none for the Kita region, and no method for predicting erosion in these tropical areas that is as widely accepted as is the USLE in temperate areas of the U.S. Therefore, we adapted from Lal's soil plot data for Idaban, Nigeria (Lal, 1987), a maximum erosion rate of approximately 60 tm/ha for a bare fallow field of variable length and 5 percent slope. The effectiveness of physical erosion control structures, tillage practices, and crop cover in reducing erosion to less than the maximum value is estimated in the USLE by multiplying maximum potential erosion by physical structure (P) and crop cover (C) factors. According to Roose, crop cover factors in Western Africa range from 0.4, in early growth stages, to 0.9 for millet, maize, and sorghum and from 0.4 to 0.8 for groundnuts. Actual factors used in the model vary within these ranges according to seeding schedule. Tied ridges, the only structural erosion control practice used in the model, are assumed to reduce erosion by 80 percent (P = .2).

The effect of erosion upon crop productivity has been estimated by comparison of yield on eroded and non-eroded fields, by monitoring rates of erosion and yields over time, and by biological plant growth models that account for the effect that erosion has upon the growth environment for the plant, and hence the anticipated effect upon plant yield. Lal (1987), in a general review of the effects of soil erosion on crop productivity, has presented findings for the tropical zone as well as the much more heavily researched and recorded temperate zone. Regressions of maize yield on soil loss estimated by Lal (1976; 1984) provide an estimate of between 70 and 90 kg decline in yield on experimental plots with a ten ton soil loss. The loss amounted to approximately 1.5 percent of the yield on the plots. Assuming that the same percentage rate applies to the much lower yields realized in the Kita area, yield decline from ten ton loss of soil there would equal approximately 15 kg per year. Where soil erosion rates are around thirty tons per hectare per year, as they are on some soils under conventional farming practices, the projected decline in yield would be approximately 5 percent. It should be remembered that this is a permanent decline that will be reflected in lower yields until action is taken to rebuild and restore the soil, if that is in fact possible.

Soil and Moisture Conservation Technology

There are no definitive data for several conservation technologies. However, there is a growing body of information about the technique of "tied ridges." Field data reported from Burkina Faso indicate increases in yields from tied ridging alone in the range of 15-40 percent (Roth, et al.). When tied ridges were combined with fertilization, the increase in yield was in the neighborhood of 100 percent over the control plot with traditional farming methods. The advantage of tied ridging is that it retains the moisture and thus not only lowers moisture stress but also creates a situation in which there is more productivity gain from fertilizer applied to the crop. Tied ridges also cut off the surface flow of water and reduce erosion, decreasing the adverse impacts on future productivity. In this analysis, the effect of tied ridges is represented through the increase in the infiltration efficiency and reduction in the annual rate of erosion. Low infiltration rate is approximately appropriate for present practice in the area. The medium infiltration rate gives a lower limit of what might be achieved with tied ridging. The higher rate of infiltration is a somewhat more optimistic but still very realistic estimation of gains that might be achieved through tied ridging.

The tied ridging technology is very labor intensive. Additional labor of approximately 100 hours per hectare is required to construct the tied ridges even when there is animal traction available to assist in the operation. If the work is done entirely by hand, the labor requirement may be as much as 50 percent higher.

Results

The optimal plan for the 8 hectare farm with all parameters and variables at baseline expected values are presented in the first column of Table 5. The profit maximizing plan calls for most of the cropland to be used to produce millet and maize. Long-run average expected yields are used as the basis for optimization. However, even a yield low enough to be expected only one year out of eight would provide more than enough grain to meet the minimum safety subsistence standard. Grain surplus to subsistence requirements is expected to average 7000kg per year. If the entire surplus is sold at market price, net income of the farm is expected to be 512,000 Mali francs (MF).

It would be profitable, and contribute to food security, if tied-ridging technology was used on all of the grain cropland, assuming that the expected 25 percent increase in yield can be realized. Because of the tied ridges, erosion is expected to average less than 8 tons per hectare per year. It is indicated to be profitable to fertilize about two-thirds of the grain crop.

Despite having five adult family workers, it is necessary to hire temporary labor during the midseason periods when weeding, cultivation, and construction of tied-ridges is at a peak. Had temporary labor not been available, the farm plan would of necessity have been changed to reduce labor demands during the peak seasons.

The baseline solution for the smaller 5-hectare farm is similar, but much less surplus grain would be available on average. Some rearrangement of the production plan is necessary to insure that subsistence requirements will be met even in a bad crop year. Providing one more kilogram of subsistence safety margin would reduce net income by about 6MF, and probably reduce the long-run average grain production of the farm.

The results of parametric variation on the subsistence safety requirement (Table 4) indicate how important that constraint is to the small landholder with a large family to be fed. In solution C the safety first condition is relaxed by 10 percent. Instead of being willing to accept no more than a one-eighth chance of not meeting their subsistence requirements out of their crop (solution B), they are hypothesized to be willing to accept an equal chance of meeting only 90 percent of their requirements. The result is freedom to reorganize production so as to increase by 440kg their average salable surplus of grain and increase by 40,000MF average net income. Further relaxing the subsistence safety requirement (solution D) would allow a further increase in expected value of grain production and net income.

Another series of analyses explored the effect of increased consideration of the present value of future productivity lost due to erosion during the current year of farming. Tied-ridges are assumed to give no increase in current yield in these solutions, so there is no reason to employ the slightly more expensive technique other than to protect the land from long-term productivity decline. When no value is attached to soil lost (solution F), income in the profit maximizing plan is expected to average 411,000MF per year, but soil erosion averages 36 tons per acre per year. If the soil loss is considered to have a value equal only to the present value, at a discount rate of 9 percent, of the erosion-caused productivity losses incurred during the next 5 years, a change to tied ridges would be profitable. Net income in the current year would decline by about 20 percent, but the savings in future productivity losses averted would be very large, even if valued at the above conservative basis.

Conclusions

The complexities of interactions between soil and moisture management technologies, resource limitations and multiple objectives of typical dryland farmers are sufficient to make whole-farm analysis a preferred analytical approach. Even relatively simple yield-weather simulation approaches can be helpful in translating weather data into estimates of the expected distribution of yields over a long series of weather years.

In the relatively high rainfall Kita study area, tied ridges are a promising technology if the yield gains reported in field experiments in similar areas can be obtained by farmers in their own fields.

Even moderate consideration of the apparently large erosion-caused losses in future soil productivity would be sufficient to induce adoption of tied ridges or other soil conserving technologies even though there were no immediate yield gains to be realized.

Extension of the model to include livestock enterprises, other soil and moisture conserving technologies and additional crop management alternatives would be appropriate. Better delineation of interaction with and reaction to weather conditions as they emerge during the cropping should be added to the model. Estimation for regions with lower rainfall and more moisture stress should proceed.

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Appendix

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

(1) $$\text{MAX } A = \sum_i P_i \sum_i Y_i X_i - \sum_i (D_i + HC_i) + \sum_i P_i \sum_i HC_i - \sum_f PF_f \sum_i F_{fi} X_i + \sum_i PS_i S_i X_i + \sum_t PL_t \sum_i L_{ti} X_i$$

subject to:

(2) $$\sum_i L_{ti} \geq LA_t$$

(3) $$\sum_i X_i \geq HA$$

(4) $$\sum_i Y_i X_i - D_i \geq HC_i$$

(5) $$\sum_i B_i X_i \geq \sum_i HC_i$$

(6) $$X_i \geq 0$$

where:

i = crop type
t = time period
P_i = price of the i^{th} crop
Y_i = 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
PF_f = price of f^{th} fertilizer
F_{fi} = f^{th} fertilizer use per hectare of i^{th} crop
PS_i = price of seed for i^{th} crop
S_i = seed use per hectare of i^{th} crop
PL = price of labor
L_{ti} = labor hours in t^{th} time period per hectare of i^{th} crop
LA_t = labor hours available in time period t
HA = hectares of land available for crop production
B_i = safe minimum assured yield of i^{th} crop

Table 1. Water balance and yield reduction computations for Sorghum and Millet, with schedule S1 (early planting) and low efficiency of water infiltration (+-40%)

TM	DATES	GROWTH STAGES	DAYS PER GROWTH STAGE:	DAYS PER TIME PERIOD:	ETo PER DAY: (MM/TM)	ETo PER TM (MM/TM)	Kc FACTOR	ETm (MM/TM)	RAIN-FALL (MM/TM)	INFILTR. FACTOR (LOW)	EFFRAIN (MM/TM)	MOIS. DEF. (% TM)	MOIS. DEF. (%Tot.)	kY YIELD FACTOR	ADJ. YIELD FACTOR	YIELD RED. (%)	BASE YIELD (KG/HA)
TM-07	12/1-4/15			135	8.9	1201.5	0	0	0	0.60	0	0	0	0	0.25	0	1250
TM-08	- 5/1			15	9.0	135.0	0	0	14.3	0.60	8.58	0	0	0		0	
TM-09	- 5/15			15	8.7	130.5	0	0	5.2	0.60	3.12	0	0	0		0	
TM-10	- 6/1	ESTABLISH	15	16	8.3	132.8	0.30	39.84	19.9	0.60	11.94	0.70	0.044	0.20		0.0350	
TM-11	- 6/15	VEGETATIV	30	15	7.7	115.5	0.75	86.63	94.7	0.40	37.88	0.56	0.077	0.20		0.0281	
TM-12	- 7/1	"		15	7.0	105.0	0.75	78.75	68.0	0.40	27.20	0.65	0.082	0.20		0.0327	
TM-13	- 7/15	FLOWERING	30	15	6.3	94.5	1.00	94.50	35.0	0.41	14.35	0.85	0.127	0.55		0.1166	
TM-14	- 8/1	"		16	5.8	92.8	1.00	92.80	173.7	0.41	71.22	0.23	0.034	0.55		0.0319	
TM-15	- 8/15	YIELD FOR	45	15	5.5	82.5	0.75	61.88	205.3	0.33	67.75	0	0	0.45		0	
TM-16	- 9/1	"		16	5.5	88.0	0.75	66.00	176.4	0.33	58.21	0.12	0.012	0.45		0.0132	
TM-17	- 9/15	"		15	5.7	85.5	0.75	64.13	101.3	0.38	38.49	0.40	0.041	0.45		0.0449	
TM-18	-10/1	RIPENING	15	15	6.1	91.5	0.50	45.75	18.4	0.38	6.99	0.85	0.061	0.20		0.0423	
TM-19	-10/15			15	6.5	97.5	0	0	30.5	0.33	10.07	0	0	0		0	
TM-20	-11/1			16	6.8	108.8	0	0	2.5	0.33	0.83	0	0	0		0	
TM-21	-11/15			15	6.8	102.0	0	0	3.0	0.40	1.20	0	0	0		0	
TM-22	-12/1			15	6.7	100.5	0	0	0	0.40	0	0	0	0		0	
TM-23	-12/15			15	7.0	105.0	0	0	0	0.60	0	0	0	0		0	
			135					630.265	948.2		349.24		0.479			0.345	

Table 2 Precipitation by time period. Kita weather station

	ANNUAL PRECIP	PRESEAS RAIN	FIRST + SECOND	REST SEASON	PRE-TM-8	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
					PRECIPITATION by HALF-MONTH INTERVALS															
Quartil 1																				
MIN.forS1	825.0	21.8	224.0	579.2	0.3	6.9	1.0	13.6	141.2	82.8	26.9	163.9	146.6	100.0	55.3	34.2	25.0	19.4	0.0	7.9
MAX.forS1	1005.5	38.0	77.0	890.5	5.0	33.0	63.0	14.0	102.0	46.0	48.0	110.0	123.0	138.5	157.0	82.0	68.0	16.0	0.0	0.0
Avg.	889.9	36.9	136.6	716.3	5.1	8.7	15.1	23.2	67.0	65.9	63.2	110.5	131.1	126.5	116.2	84.6	56.7	13.9	0.0	0.0
STD	96.1	21.0	39.1	111.2	7.6	13.5	19.8	29.1	36.1	20.1	22.9	41.8	43.1	34.2	62.7	51.7	45.7	10.1	3.1	2.3
Quartil 2																				
MIN.forS1	1052.4	42.6	259.8	750.0	0.0	5.0	21.0	16.6	130.0	129.8	50.0	189.0	55.0	244.0	75.0	45.0	80.0	9.0	3.0	0.0
MAX.forS1	1069.5	118.9	111.3	839.3	54.8	13.1	8.3	42.7	73.3	38.0	80.6	191.7	114.3	161.5	198.3	52.1	18.4	0.7	0.0	21.7
Avg.	1030.1	56.3	186.8	786.9	8.5	8.0	13.0	17.9	77.5	88.2	95.1	131.8	142.2	186.3	121.8	67.8	45.5	21.8	2.1	2.5
STD	116.9	33.0	44.0	109.9	15.4	10.4	10.7	11.3	34.5	32.1	32.2	43.4	44.4	60.6	37.8	39.7	51.0	50.4	2.9	6.3
Quartil 3																				
MIN.forS1	1084.7	39.5	275.8	769.4	16.5	0.0	0.7	22.3	74.9	200.9	50.6	146.5	183.7	121.3	162.1	68.3	31.8	5.1	0.0	0.0
MAX.forS1	1268.5	36.0	206.0	1026.5	2.0	2.0	28.0	4.0	93.0	113.0	196.5	128.0	180.5	183.5	108.0	77.0	52.0	59.0	42.0	0.0
Avg.	1170.2	42.5	146.1	981.7	2.0	4.4	17.6	35.0	62.1	76.5	140.6	140.9	184.2	196.8	131.2	89.2	53.1	21.1	15.6	0.0
STD	111.5	27.4	52.4	139.0	4.6	9.3	15.1	23.6	18.7	53.5	56.1	31.6	58.5	79.0	39.2	29.4	42.7	23.1	23.9	0.0
Quartil 4																				
Min.(S1)	1258.5	11.5	102.6	1144.4	0.0	0.0	4.5	7.0	64.6	38.0	162.5	145.2	191.0	300.9	110.7	156.1	55.0	23.0	0.0	0.0
Max.(S1)	1507.6	49.8	217.2	1240.6	3.5	12.6	4.2	29.5	149.5	67.7	208.0	235.4	222.1	224.6	129.5	128.9	49.9	13.5	28.7	0.0
Avg.	1347.5	53.1	158.1	1136.3	10.2	13.4	22.7	39.6	92.0	87.4	140.6	184.7	185.1	214.7	142.8	110.7	66.4	27.9	8.0	1.3
STD	148.4	25.7	43.6	168.9	13.5	24.4	19.7	22.6	29.6	38.9	45.1	30.1	49.7	69.3	51.4	29.5	32.7	32.3	11.0	2.8
TOTALS																				
AVERAGE	1103.9	47.1	156.9	899.9	6.4	8.5	17.0	28.7	74.3	79.3	109.1	141.0	160.1	180.3	127.6	87.5	55.1	21.0	6.7	1.2
MINIMUN	766.0	2.0	77.0	569.3	0.0	0.0	0.0	0.0	4.0	7.0	26.9	30.7	41.3	44.0	22.8	15.6	2.1	0.0	0.0	0.0
MAXIMUN	1619.8	118.9	275.8	1448.8	54.8	82.6	73.3	107.6	149.5	200.9	254.9	235.4	296.0	324.1	278.6	168.0	187.7	180.0	77.1	21.7
ST. DEV.	205.4	28.3	48.9	210.7	11.6	15.6	17.1	24.2	32.5	39.2	52.4	45.8	55.0	71.0	49.8	41.7	44.4	32.8	14.6	3.8

Table 3. Estimated yield and yield reductions by quartiles at three planting times, low infiltration efficiency rate, and long run average weather at three infiltration rates. Kita weather region in MALI (West Africa)

	Yield S1	Yield S2 (kg)	Yield S3	Reduction S1	Reduction S2 (percent)	Reduction S3	Precipitation (mm)
Quartil 1							
MIN.	703	712	628	0.44	0.43	0.50	825
MAX.	774	818	746	0.38	0.35	0.40	1006
AVG.	739	763	714	0.41	0.39	0.43	890
STD.	21	54	72	0.02	0.04	0.06	96
Quartil 2							
MIN.	777	810	724	0.38	0.35	0.42	1052
MAX.	880	855	732	0.30	0.32	0.41	1070
AVG.	829	831	777	0.34	0.34	0.38	1030
STD.	41	56	73	0.03	0.05	0.06	117
Quartil 3							
MIN.	882	894	784	0.29	0.28	0.37	1085
MAX.	939	918	854	0.25	0.27	0.32	1269
AVG.	906	894	840	0.28	0.28	0.33	1170
STD.	19	40	67	0.02	0.03	0.05	112
Quartil 4							
MIN.	939	971	937	0.25	0.22	0.25	1259
MAX.	1105	1075	956	0.12	0.14	0.24	1508
AVG.	982	979	901	0.21	0.22	0.28	1347
STD.	55	57	70	0.04	0.05	0.06	148
Totals for Efficiency 1							
AVG.	861	864	806	0.31	0.31	0.36	1104
MIN.	703	700	627	0.12	0.14	0.21	766
MAX.	1105	1075	991	0.44	0.44	0.50	1620
STD.	97	95	99	0.08	0.08	0.08	205
Totals for Efficiency 2							
AVG.	1038	1062	989	0.17	0.15	0.21	
MIN.	878	910	788	0.04	0.02	0.06	
MAX.	1197	1221	1171	0.30	0.27	0.37	
STD.	90	90	101	0.07	0.07	0.08	
Totals for Efficiency 3							
AVG.	1111	1136	1067	0.11	0.09	0.15	
MIN.	960	985	884	0.01	0.00	0.01	
MAX.	1234	1250	1241	0.23	0.21	0.29	
STD.	74	77	91	0.06	0.06	0.07	

Table 4. Effect of Varying Subsistence Safety Requirement

	A	B	C	D
SITUATION				
Farm Size (ha)	5	5	5	5
Tied Ridges Yield Ratio	1.25	1	1	1
Present Value Soil Loss (1000 mf/mt)	0	1.3	1.3	1.3
Subsistence Constraint (1000 kcal)	11.2	11.2	10	9
LAND USE				
Sorghum	1.23	3.51	2.23	2.21
Millet	1.43	0.55	0.55	0.45
Maize	1.76	0.35	1.63	1.76
Groundnuts	0.10	0.11	0.11	0.10
Vegetables	0.48	0.48	0.48	0.48
Fallow				
TECHNOLOGY USE (ha)				
Tied ridges	4.42	4.41	4.41	4.42
fertilized	1.43	0	0	1.81
Animal Traction				
CROP OUTPUT (kg)				
Sorghum	1347	3090	1966	2107
Millet	1897	480	480	480
Maize	2545	405	1884	2036
Groundnuts	120	120	120	120
EROSION				
Gross (tons/ha)	7.09	6.25	6.86	6.86
Prest. value of Prod. loss (1000 mf)	0	41448	45638	45747
INCOME (1000 mf)	252315	80542	121409	142726

Table 5. Effect of Varying Subsistence Safety Requirement

SITUATION	E	F	G	H
Farm Size (ha)	8	8	8	8
Tied Ridges Yield Ratio	1.25	1	1	1
Present Value Soil Loss (1000 mf/mt)	0	0	1.3	3.5
Subsistence Constraint (1000 kcal)	11.2	11.2	11.2	11.2
LAND USE				
Sorghum	0.38	0.48	0.48	5.35
Millet	4.15	5.12	5.14	0.45
Maize	2.89	0.89	1.74	1.61
Groundnuts	0.10	1.02	0.17	0.10
Vegetables	0.48	0.48	0.48	0.48
Fallow				
TECHNOLOGY USE (ha)				
Tied ridges	7.42	0	7.36	5.80
fertilized	4.53	6.62	5.62	5.80
Animal Traction				
CROP OUTPUT (kg)				
Sorghum	480	480	480	5285
Millet	5429	4973	5376	480
Maize	4170	1034	1988	1864
Groundnuts	120	1182	201	120
EROSION				
Gross (tons/ha)	7.75	35.81	7.81	6.90
Prest. value of Prod. loss (1000 mf)	0	0	83630	196805
INCOME (1000 mf)	512071	410863	332359	312250