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Maatman, A.

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Modeling farmers' response to uncertain rainfall in Burkina Faso: a stochastic programming approach

Arno Maatman
Arjan Ruijs

Caspar Schweigman
Maarten H. van der Vlerk

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Abstract

This paper deals with strategies of farmers on the Central Plateau of Burkina Faso in West Africa. They cultivate under precarious conditions. A multi-objective linear programming model has been developed which describes farmers' strategies of production, consumption, selling, purchasing and storage. On the average, the outcomes of this model correspond fairly well to actual farmers' strategies with one major exception. The model is of a static nature, all decisions are assumed to be taken at one time, before the growing season starts. However, in practice production strategies are of a *dynamic* nature: decisions are taken sequentially. This process of sequential decision making is one of the most important ways to cope with risks due to uncertain rainfall. In this paper a stochastic programming model is presented to describe farmers' sequential decisions reacting on rainfall. The dynamic model describes farmers' strategies much better. The study illustrates how operations research techniques can be usefully applied to study grass root problems in developing countries.

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The study in this paper deals with farmers' strategies on the Central Plateau in Burkina Faso, West Africa. This Plateau covers almost a quarter of Burkina Faso's territory. Its population is almost half of the country's population. The rural people face a gloomy prospect. The prevailing systems of production and distribution do not prevent serious food shortages for the majority of the people, and, through force of circumstance, natural resources are depleted severely. Despite, or rather owing to this critical situation, farmers have taken important initiatives to try to improve production methods, in particular by making use of local resources. We refer to methods of water and soil management, to anti-erosion measures and to the use of organic manure by integration of keeping livestock and crop cultivation.

Our study aims at answering the questions to what extent actual strategies of farmers guarantee food security of their households and what changes are possible to ensure higher and sustainable levels of food security. The development of a linear programming model has been one of the main instruments of analysis. The modeling is focused on one farm household, which is representative of a large number of households on the Central Plateau. This representative (hypothetical) household is called here 'the Household'. It does not apply 'modern inputs', like chemical fertilizers. The farmers have at their disposal only local resources like land, labor and manure; almost no capital is invested in agricultural methods. No irrigation is applied. There is only one growing season in the year, which coincides with the rain season. Based on a thorough study of all important village level studies executed in the past on the Central Plateau, a linear programming model has been constructed for average climatological, environmental and socio-economic conditions. The development of the model has been a repetitive process of interpretation of results, comparison with actual practices and improvement of the model. The final model corresponds fairly well to actual farmers' strategies with one major exception: the model is of a static nature. All decisions are assumed to be taken at one time, before the growing season starts. However, decisions on e.g. sowing, resowing, timing of weeding and intensity of weeding are not taken at one time, but progressively during the first weeks of the growing season dependent on observed rainfall, germination of the seeds, appearance of weeds etc. In fact, production strategies are of a *dynamic* nature: decisions are taken sequentially. This process of sequential decision making is one of the farmers' most important ways to control risks due to uncertain rainfall. This paper deals with the modeling of this process of sequential decision making. The approach is as follows. Although the sequential decision taking by farmers is a continual process in time, basically decisions in three periods can be distinguished:

period 1. At the beginning of the growing season during the first rains. Given the actual observed rainfall in this period, what decisions on agricultural production should the farmer take anticipating uncertain rainfall patterns later in the

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growing season?

period 2. Later in the growing season: what decisions should the farmer take given the decisions taken in the first period, and observed actual rainfall patterns in the second period?

period 3. The year after the beginning of the harvest, called target consumption year. The decisions during this period concern consumption, storage, selling and purchasing. They are taken when harvest levels are known.

The periods are illustrated in Figure 2.1. Rainfall in periods 1 and 2 are important factors influencing farmers' sequential decisions.

In this paper we capture the dynamics of this decision making process by modelling it as a collection of so-called two-stage recourse models. Before presenting this approach in Section 3, we first describe the background and the features of the underlying problem in Sections 1 and 2. In Sections 4 and 5 we present results for a static model and the dynamic model, respectively. In Section 6 we evaluate how much is gained by using our composite model instead of a more simple deterministic one. Finally, in Section 7 we present conclusions and comment on the practical relevance of our results. A complete specification of the model and numerical results are given in the Appendix.

1. Risk and farmers strategies

Farmers on the Central Plateau face a lot of risks due to factors as rainfall, plagues of insects, uncertain yield prices of agricultural produce, uncertain off-farm incomes etc. The influence of the various risk factors on farmers' strategies differs much. Various methods of risk reduction exist. There are methods which aim at *prevention* of risks, *dispersion* of risks (by diversification of risky activities), *control* of risks (e.g. by sequential decision making) and *'insurance'* against risks. An example of a method of risk prevention is irrigation. Methods to prevent risks are not included in our study. Methods of dispersion of risks refer, for instance, to the cultivation of different crops (or varieties) on different soil types applying different agricultural methods. In general, dispersion of risk is only effective, if the effects of the different activities are not too much positively correlated (e.g. if a poor rainfall pattern does not have the same effect on yields on all plots). Methods of risk control refer in this study to sequential decisions on (re)sowing and weeding during the growing season, making use of information which becomes available (e.g. on rainfall, germination of plants, appearance of herbs). Livestock often functions as a method of 'insurance' against a poor harvest: if harvest fails, some of the animals can be sold to buy food. In this study methods of dispersion and control of risks take a central place. Insurance of

risks has only been dealt with by the possible installation of a safety stock of cereals at the end of the year.

2. Key elements of the models

The models describe crop *production* strategies during the *growing season* and *consumption, storage and marketing* strategies during the *target consumption year*, see Figure 2.1. Production decisions taken into account refer to:

a) crop choice: the crops maize, red sorghum, white sorghum, millet and ground-nuts, and the mixed crops red sorghum/cowpeas, white sorghum/cowpeas, millet/cowpeas;

b) land category: dependent on the location (low and high lands) and on the distance from the compound (less than 100 meters, between 100 and 1000 meters, more than 1000 meters);

c) land ownership: common or individual fields;

d) applied dose of organic manure (0, 800, 2000, 4000, 8000 kg per hectare);

e) sowing dates: dependent on crop and land category;

f) levels of intensity of weeding (intensive, or less intensive).

The harvest period consists of three months. Maize is a crop that is harvested early. An important feature in the developed models is the concept of *plot*. It is a piece of land with the following properties: one of the crops under a) is grown; it belongs to one of the land categories b); it is a common or an individual field c); one of the doses of organic manure d) is applied; sowing takes place at one of the dates e). Intensity of weeding f) is not included in the definition of a plot; it will be handled differently, see Section 3. In this way a large number of plots are distinguished. *Representative plots* refer to combinations of crops, land categories, and agricultural methods observed in practice, *alternative plots* to other combinations. The area of each plot is a decision variable. Their values correspond to the production decisions what, where, how much, how and when should be cultivated.

Key elements of the models describe the influence of the production factors land, labor and organic manure on the production decisions. The *constraints* of *land* (per category), of *labor* and of *organic manure* say that required amounts of resources cannot exceed available amounts. The growing season was split up in time intervals of two weeks or a month (see Figure 2.1) in order to formulate the labor constraints for the various time periods. In the labor constraints the required labor includes not only time of the work on the land, but also of the time-consuming walking from and to the fields. Specific labor constraints had to be introduced for sowing and land
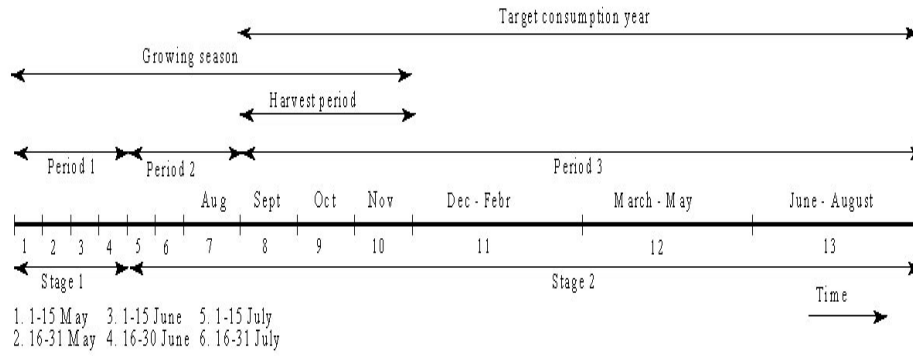
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Figure 2.1: Schematic representation of the planning period and the different decision stages.

preparation during the first weeks of the growing season, where labor availability had to be based on available time during days where the rainfall conditions were favorable for sowing. Organic manure is applied on the common fields. Individual fields belong to women. Fallow practice is another key element of the model. It is dealt with by postulating that supplementary to each plot a piece of land is left fallow. The size of this piece of land is supposed to be proportional to the size of the corresponding plot. Coefficients of proportionality are parameters, whose values depend on category of land, crop and manure level. By a choice of parameter values various scenarios of fallow practice can be analyzed. Here we use parameter values based on observation of actual practice.

Decisions on consumption, storage and marketing are taken during the target consumption year, which is divided in several periods of time to allow to analyze the strategies in different periods of the year. Decision variables on consumption correspond to consumption of the various produce in each period, decision variables on marketing to quantities sold and purchased. The nutritive balances express the cereal and the non-cereal consumption in terms of *nutrients* (calories and proteins). In the *stock equations* for all agricultural products, losses as well as seed reserves are included. *Financial balances* contain also interest rates, and non-agricultural incomes and expenses as exogenous parameters.

A few constraints are included in the models to ensure that calculated patterns of consumption correspond to observed patterns on the Central Plateau. For instance, a restriction is imposed on the consumption of red sorghum, which is mainly used

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for beer consumption. Another condition reads that part of the meals should consist of cereals. Such constraints are called *normative* constraints. The main objective of all strategies of the Household together is to attain a certain level of auto-sufficiency and to try to prevent, or if that is not possible, to minimize shortages of calories and proteins during the target consumption year. If these shortages can be avoided, then a stock is kept for the harvest period of the next year. If these stocks are sufficient, then the revenues are maximized. If revenues are obtained indeed, a fraction is spent on a food security safety stock for the next year. All these objectives are dealt with in one objective function and in the formulation of normative constraints.

Data of all studied sources[1] have been used to estimate 'average' values of parameters in the base model. For instance, yields and labor requirements for all plots, i.e. for all crops, categories of land, levels of applied manure, sowing dates, and for levels of intensity of weeding, have been estimated. For alternative plots the values of these parameters have been estimated by extrapolating results of village level studies, and by making use of data of experimental stations. Exogenous selling and purchasing prices refer to average observed producer prices during the harvest period, and to consumer prices during the 'lean time' before the next harvest. For a justification of the estimation of all parameters in the model and their estimated values, see Maatman et al. (1995, 1996). The losses due to the traditional grinding of grains play an important role in the analysis. Some grains are hard and difficult to grind unpounded on the millstone. They are therefore first pounded and skinned. The losses of nutrients thus incurred are estimated at 25%. In order to avoid such losses it is assumed that the Household can make use of a mill, which can grind the hard grains.

3.   Two-stage stochastic models

In practise, farmers make decisions sequentially, depending to a large extent on actual rainfall patterns. As explained below, two principal decision moments can be distin-

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1   Use has been made of: (i) secondary sources, in particular all village level studies previously effected in Burkina Faso: the studies of ICRISAT (e.g. Matlon and Fafchamps (1988); McIntire (1981, 1983); Kristjanson (1987)), ICRISAT and IFPRI (Reardon and Matlon (1989)); of the programme FSU/SAFGRAD (e.g. Lang, Roth and Preckel (1984); Nagy, Ohm and Sanders (1986); Roth et al. (1986); Roth (1986); Singh et al. (1984); Singh (1988)), of CEDRES of the University of Ouagadougou (Thiombiano, Soulama, Wetta (1988)), of the University of Wisconsin (e.g. Sherman, Shapiro, Gilbert (1987)); Delgado (1978), Broekhuyse (1982, 1983), M.J. Dugué (1987), P. Dugué (1989), Kohler (1971), Marchal (1983), Imbs (1986) and Prudencio (1983, 1987); the results of farming systems research published e.g. in Matlon et al. (1984) and Ohm and Nagy (1985) have been consulted as well; and (ii) primary sources: results of studies and interviews in three villages in the North-West region: Baszaïdo, Kalamtogo and Lankoé Ouédraogo et al. (1995, 1996), INERA/RSP/Zone Nord-Ouest (1995).

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guished. First decisions are made *after observing the dates of the first rains*, but under *uncertainty about rainfall later in the growing season*. Once also the latter rainfall data are known, a second set of decisions is made. We model this decision process by a collection of two-stage stochastic models: for each of a representative set of dates of the first rains, a corresponding two-stage stochastic model is formulated. Consequently, for each of these dates of the first rains, we obtain first-stage decisions that are optimal in a sense to be made precise below.

In principle, more stages could be distinguished, but it would make the analysis very complex. The demarcation of the stages 1 and 2 was not evident. If a clear-cut distinction could be made between a first period of sowing and a late period of weeding the demarcation would be easy. However, during the growing season late sowing and first weedings may coincide. Stage 1 has been chosen as the period in which most sowing decisions are taken, in stage 2 the most important weeding decisions (see Figure 2.1).

Observed rainfall in period 1 is called r_1. The set Ω_1 contains the distinguished outcomes of r_1. The uncertain rainfall in period 2 is considered as a random variable, called R_2, with realizations r_2 in Ω_2. The model for the sequential decision making is a so-called two-stage recourse model; stage 1 refers to period 1, stage 2 to the periods 2 and 3. Before the model will be elaborated in detail, first the structure will be presented. We introduce the following vectors:

x_1 first-stage variables, corresponding to decisions taken in stage 1;

x_2 second-stage variables, corresponding to decisions taken in stage 2.

For each $r_1 \in \Omega_1$ values of x_1 are computed which solve

$$\min_{x_1} \left\{ E_{R_2} z(x_1, R_2) \mid A_1(r_1)x_1 = b_1(r_1), \ x_1 \geq 0 \right\} \tag{1}$$

where z is the value function of the second-stage problem, i.e., for any realization $r_2 \in \Omega_2$,

$$z(x_1, r_2) = \min_{x_2} \left\{ c(r_2)^\top x_2 \mid B_2(r_2)x_2 = b_2(r_2) - B_1(r_2)x_1, \ x_2 \geq 0 \right\} \tag{2}$$

$A_1(r_1)$, $B_1(r_1)$ and $B_2(r_2)$ are matrices, $b_1(r_1)$, $b_2(r_2)$ and $c(r_2)$ are vectors with elements depending on r_1 and r_2, respectively. Their contents will be discussed below.

In stage 1, which covers the months May and June, production decisions deal with soil preparation, sowing, and early weeding. In practice, these decisions are progressively taken during these two months, in particular depending on dates of the first rains. In our model three situations are distinguished: the growing season starts *'late'*, *'normal'* or *'early'*. The three situations correspond to three different values of r_1.

The production decisions are different for each of these situations. If the growing season starts late, less time is available for land preparation and sowing. The number of days favorable for sowing (see above) in the labor constraints is a critical parameter: if planted during these favorable days the plants will come up, and early growth will be successful. It may be possible that also in other days fields are sown, but on these fields plants will not come through. These unsuccessful plots may have to be resown later. So, the number of favorable sowing days depends on r_1.

The rains in period 2, which covers the months July and August, can be *'bad'*, *'average'* or *'good'*, corresponding to 3 different values of R_2. The decisions during this period correspond to decisions of late sowing and especially of intensity of weeding. It can also be decided to abandon certain plots, planted during the first stage. Bad, average or good rainfall, i.e. the value of R_2, influences the values of various parameters: the time available for late sowing, and in particular the labor for intensive and less intensive weeding. Also the yield levels (of all plots) depend on R_2. The dependence of all these parameters on the three levels of R_2 could be derived from secondary data. Labor requirements for harvesting, which takes place in September, October and November, depend on yield levels. Decisions on consumption, storage and marketing during the target consumption year depend on realized harvest levels and prices, so depend on rainfall too.

Since there exist enough data of rainfall on the Central Plateau, more rainfall scenarios, both for r_1 and R_2, could be distinguished. However, relatively few data are available on the influence of rainfall on yields and labor times, as a function of crop, soil type and agricultural methods. The three scenarios for r_1 and R_2 reflect the division which is generally made by farmers in order to explain results of the agricultural season (see e.g. Dugué, (1989)). It makes not much sense to add more scenarios, if it is so difficult to estimate reliable values of the parameters. We note as well that it is not necessarily required to take into account extremely poor rainfall scenarios. Methods of risk insurance, see above, anticipate such situations.

Decision variables

The index $\tau = 1, 2$ refers to period 1 and 2. The plots are defined by a) – e) on page 4. We introduce the following sets:

$$J \quad = \quad \{ \text{ all plots defined by a) - e) } \} \tag{3}$$

$$J(\tau) \quad = \quad \{ \text{ plots to be sown in period } \tau \}, \quad \tau = 1, 2 \tag{4}$$

Note that $J(1) \cap J(2) = \emptyset$ and $J(1) \cup J(2) = J$. We define for $j \in J(1)$ the following first-stage decision variables:

$$SUR1(j) \quad \text{area of plot } j \tag{5}$$

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In the second stage, the decisions on sowing the plots $j \in J(2)$ and on weeding intensity depend on the observed rainfall r_2 during period 2, i.e. the second part of the growing season; note the difference between the uncertain rainfall R_2 and observed rainfall r_2. We introduce, for $j \in J(2)$, the following second-stage variables:

$$SUR2(j, r_2) \quad \text{area of plot } j, \text{ if rainfall in period 2 is } r_2 \tag{6}$$

and for $j \in J$:

$$
\begin{aligned}
SURi(j, r_2) \quad &\text{area of that part of plot } j \text{ which will be weeded} \\
&\text{intensively during period 2, if rainfall in period 2 is } r_2; \\
SURe(j, r_2) \quad &\text{area of that part of plot } j \text{ which will be weeded less} \\
&\text{intensively during period 2, if rainfall in period 2 is } r_2
\end{aligned}
\tag{7}
$$

For the plots which are sown in period 2, it is decided immediately which part will be weeded intensively and which part extensively. Hence,

$$SUR2(j, r_2) = SURi(j, r_2) + SURe(j, r_2), \quad j \in J(2). \tag{8}$$

In period 2 it will be decided whether parts of the plots sown in stage 1 will be weeded intensively or extensively or abandoned. This condition can be written as:

$$SUR1(j) \geq SURi(j, r_2) + SURe(j, r_2), \quad j \in J(1). \tag{9}$$

The inequality in (9) implies for the Household the possibility to abandon a part of the plots sown in period 1 (because of a lack of labor if labor requirements for weeding are too high).

The decision variables during period 3, see Figure 2.1, correspond to decisions on consumption, sales and purchases of the produce which are taken into account, see above. We define:

$$P = \{\text{maize, red sorghum, white sorghum, millet, groundnuts, cowpeas}\} \tag{10}$$

During period 3 the time intervals $t = 8, 9, \ldots, 13$ are distinguished, see Figure 2.1. For $p \in P, t = 8, 9, \ldots, 13$, and rainfall $r_2 \in \Omega_2$ the following decision variables are introduced:

$$
\begin{aligned}
CON(p, t, r_2) \quad &\text{consumption of produce } p \text{ during time interval } t \\
PUR(p, t, r_2) \quad &\text{quantity of produce } p \text{ purchased during time interval } t \\
SAL(p, t, r_2) \quad &\text{quantity of produce } p \text{ sold during time interval } t
\end{aligned}
\tag{11}
$$

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In Table 1 in the Appendix the definitions of parameters and variables are presented, in Table 2 the whole model. References to formulas below refer to this table. The constraints of land, including parameters to describe fallow practice, of organic manure and of labor, both for common fields and individual fields, are given in (17), (18) and (19) – (22), respectively. Production corrected for quantities of produce to be reserved as seeds for the next farming season is defined in (23). Stock equations for each produce and financial balances are formulated in (27) – (29). The constraints (24) – 26 state that farmers according to practice on the Central Plateau sell only during the months after harvest and purchase only in the period of the lean time just before the new harvest. This practice is much in the interest of the traders purchasing from and selling to the farmers on the local market, rather than in the farmers' interest. It often occurs that even in years of shortage farmers have to sell part of the production immediately after the harvest for daily expenses or to repay debts to traders, and then have to buy again later in the year when prices are much higher. This phenomenon is well known on the Central Plateau and in many other regions of Africa (see e.g. Yonli (1997)). The selling prices $prs(p, R_2)$, $p \in P$, refer to prices on the local market after harvest, purchasing prices $prp(p, R_2)$ to those prices during the lean time.

The objective of our model is to minimize (expected) deficits of various nutrients during the planning period, including the harvest period of the next farming season. Actually, the constraints (30) to (36) modelling nutritive and consumption requirements are formulated in terms of three different measures of possible deficits:

(i) deficits in each period of the target consumption year

(ii) deficits during the harvest period of next farming season

(iii) deficit of *auto-subsistence cereal production*, which is defined as the minimal quantity of staple cereals to be produced by the Household itself.

Since possible deficits depend on rainfall R_2 in the second period, they are modelled as second-stage or *recourse* variables with corresponding recourse costs. In addition, the objective function also contains a term for the (expected) net revenues during the target consumption year, which are to be maximized.

Although it may be possible to specify unit costs for deficits of type (i), (ii), and (iii) (the fourth term is already in monetary units), we have chosen the coefficients in the objective function in such a way that highest priority is given to minimization of shortages in the target consumption year, and further in decreasing order to (ii), (iii), and net revenues as mentioned above. That is, in the objective function (16), the coefficients satisfy $w(n) \gg w_1(n) \gg w_2 \gg w = 1$.

We recall that rainfall in period 2 can be 'bad', 'average', or 'good'. This is modelled

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by the discrete random variable R_2 which has this three possible realizations, denoted by $r_2 \in \Omega_2$. The discretization is chosen in such a way that all outcomes have equal probability, i.e., $\Pr(R_2 = r_2) = f(r_2) = 1/3$ for all $r_2 \in \Omega_2$.

Since R_2 is a discrete random variable, it follows that for each $r_1 \in \Omega_1$, the recourse problem (1)-(2) is equivalent to a deterministic large-scale linear programming problem of the following form:

$$\min_{x_2(r_2)} \Big\{ \sum_{r_2 \in \Omega_2} f(r_2)c(r_2)^\top x_2(r_2) \mid A_1(r_1)x_1 = b_1(r_1), \qquad (12)$$
$$B_2(r_2)x_2(r_2) = b_2(r_2) - B_1(r_2)x_1$$
$$x_1 \geq 0, \quad x_2(r_2) \geq 0, \quad r_2 \in \Omega_2 \Big\}.$$

This model is completely specified in Table 2. In (12), x_1 represents the first-stage variables SUR1 defined in (5), whereas x_2 takes the place of the second-stage variables in the model. (The vectors x_1 and x_2 also contain the appropriate slack variables.) The constraints $A_1(r_1)x_1 = b_1(r_1)$ correspond to the first-stage constraint (19), and $B_2(r_2)x_2(r_2) = b_2(r_2) - B_1(r_2)x_1$ for all $r_2 \in \Omega_2$ to the other constraints. The vectors $c(r_2)$, $r_2 \in \Omega_2$, contain the weighting coefficients in (16).

The number of variables of the two-stage model is 2724, the number of constraints 1252. The linear programming problems were formulated in GAMS and solved with MINOS5 (see Brooke et al. (1992)). In Table 3 some computational results are presented, which we will discuss in Sections 4 and 5. A comparison is made between the results of the two-stage stochastic models and *static models*. In a static model r_1 and r_2 are assumed to be *known*. It is given by (12) with Ω_2 replaced by r_2 and with $f(r_2) = 1$. So, for given r_1 and r_2 the static model can be written as:

$$\min_{x_1,x_2} \Big\{ c(r_2)^\top x_2 \mid A_1(r_1)x_1 = b_1(r_1), \qquad (13)$$
$$B_2(r_2)x_2 = b_2(r_2) - B_1(r_2)x_1,$$
$$x_1 \geq 0,\ x_2 \geq 0 \Big\}$$

For average rainfall $\bar{r}_1$ and $\bar{r}_2$, (13) is called the *average static model*.

Approximately, the computation times (on a Pentium 200 Mhz with 64MB internal memory) were 90 seconds (10000 iterations) for the two-stage models, and 10 seconds (1000 iterations) for the static models.

4. Results of static models

The results of the average static model show that in an average rainfall year the Household can just avoid shortages of nutrients (calories and proteins) during the

target consumption year. Production is not enough. All revenues from other sources are used to buy cereals during the 'lean time'. No reserve stocks can be kept. A remarkable feature is the *heterogeneity of agricultural strategies*, i.e. the cultivation of different crops, both sole-cropped and intercropped, on different soil types, and using a great diversity of growing methods (sowing periods, quantities of organic manure, intensive and less intensive weeding). The great diversity in agricultural activities, in response to a complex range of objectives and constraints, is a key element of the farmers' actual strategies on the Central Plateau. Another result that is conforming observations made in practice is the necessity to buy cereals later in the year.

Notwithstanding the heterogeneity of the cropping strategies of the Household, some general tendencies can be observed. Millet and white sorghum are cultivated on the high lands with no or very low levels of organic manure, red and white sorghum with moderate fertilization on the low lands and maize on some small plots at a short distance of the household with high doses of organic manure. Cowpeas are cultivated as intercrop on both millet and sorghum fields. Maize is an important crop, since it is harvested during the first weeks of the harvest period, just before the harvest of the (large) millet fields. Since no stocks are left from the year before, the cultivation of *early crops* like maize is urgently required.

We have also computed results for static models with other scenarios of r_1 and r_2. We mention only the major differences between the results of 'average' and 'bad' rainfall scenarios in period 2. For the average rainfall scenario a large part of production consists of white sorghum. For a bad scenario, however, white sorghum is almost all replaced by millet. This effect is explained in the next section.

5.   Results of the two-stage stochastic models

The results of the two-stage model for normal rainfall in the first period differ from those of the average static model in two important aspects:

- the increased importance of millet cultivation;
- the extension of the area sown in the first period.

The predominance of millet, both sole-cropped or intercropped with cowpeas, may be explained by its resistance to drought stress and its tolerance to weeds, which is important when rainfall in the second period is average or good (see below). Hence, it has properties that are favorable in all possible rainfall scenarios, so that millet cultivation increases flexibility.

With regard to crop choice, the results resemble much those of the 'bad' rainfall scenario discussed above. The resemblance with the pessimistic scenario can be well

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understood: in the objective function minimization of deficits gets high priority. The probabilities of bad rainfall in period 2 (low yields), and good rainfall (high yields) are the same. Since in good years deficits are avoided, minimization of expected deficits implies that strategies are found which minimize deficits in bad rainfall years.

For $r_1 = \bar{r}_1$, the outcome of the two-stage stochastic model is that 6% more land is sown during period 1 than in the average static model (see Table 3, for $r_1 =$ normal). Sensitivity analysis shows that the area sown in period 1 for a normal start of the rainfall season is very much restricted by the land constraints. If more land were available, the Household would extend the area sown in the first period even further. Again, the sowing of a large area in the first phase optimizes production levels when rainfall in period 2 is bad. In that case, poor rainfall conditions limit the growth of weeds and all weeding can be done intensively. However, when rains in period 2 are average or good, labor requirements for weeding become a problem. In that case, the Household is forced to start weeding for some fields later, and to weed less carefully. When rains in period 2 are good some fields cannot be weeded in time and must be abandoned.

Some important conclusions can be drawn from these results. First, the scope for diversification of cropping systems to reduce risks seems to be limited on the Central Plateau. As expected, intercropping with cowpea increases when risks are taken into account (although, when rains start late, the cultivation of cowpeas is limited: preference is given to sole-cropping of millet in order to reduce competition, see Table 3). However, already in the static model a large variety of cropping systems were chosen, with much intercropping too. The cultivation of millet and of large areas are the most important strategies to minimize risks. Both strategies increase the space for maneuver of the Household to anticipate rainfall, in particular bad rainfall, in period 2.

The production strategies differ much according to rainfall patterns, see Table 3. For the distinguished scenarios of r_1 and r_2 this variability can best be illustrated for two extreme situations:

1. A late start of the growing season and bad rainfall in period 2: time for sowing is limited. Poor rainfall conditions limit the growth of weeds, all weeding can be done intensively. Yields and production are low.

2. An early start of the growing season and good rainfall in period 2: much more labor time for sowing is available. Labor time for weeding is very restrictive. In fact, the Household is obliged to abandon part of its fields and another part is weeded less intensively. Yields and production are relatively high.

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The strategies for the various rainfall scenarios corresponds fairly well to observations made in field studies. The more realistic nature of the two-stage recourse models in comparison to the static models is to a large extent due to the more precise formulation of the labor constraints in period 1 and 2. The differences are considerable. For instance, the first-stage part of the solution of the average static model is not feasible in the two-stage stochastic model for a good rainfall year (due to the rise of labor requirements for weeding). It may be concluded that the two-stage stochastic model is more convincing than the static model with average parameter values. This last model does not lead to the preferred strategies. In various recent studies to explore alternative production techniques (see e.g. Maatman et al. (1998)) two-stage stochastic models are used instead of the average static model.

6. The value of using multiple recourse models

In this section we evaluate how much is gained by using our composite modelling approach, characterized by

   (i) separate models for each realization of r_1,
   (ii) two-stage recourse models to capture the uncertainty with respect to R_2,

instead of one deterministic model (the average static model). To this end, we utilize several concepts known from the literature (see e.g. Birge and Louveaux (1997)).

First of all, we remark that it is not surprising that the optimal values of the static models are lower (i.e., better) than those of the corresponding recourse models. Indeed, the static models are based on the false assumption that the future is known (deterministic), whereas the recourse models explicitly take into account uncertainty about future rainfall.

Assuming that the uncertainty with respect to the rainfall in the second period is adequately modelled by the random variable R_2, we can compute how much is lost (on average) if we neglect this uncertainty by using a static model. To compare the models, for example with $r_1 = \bar{r}_1$, we first compute a first-stage solution $\bar{x}_1$ of the average static model. The expected result of this solution, obtained by substituting it in the two-stage model, is given by

$$\min_{x_2(r_2)} \left\{ \sum_{r_2 \in \Omega_2} f(r_2) c(r_2)^\top x_2(r_2) \mid \begin{aligned} &B_2(r_2) x_2(r_2) = b_2(r_2) - B_1(r_2) \bar{x}_1, \\ &x_2(r_2) \geq 0, \quad r_2 \in \Omega_2 \end{aligned} \right\}. \tag{14}$$

The difference between (14) and the optimal value of the corresponding two-stage model (12) is known as the *value of the stochastic solution* (VSS), which is always

non-negative. This can be understood from the fact that a solution of a two-stage model anticipates the uncertainty in the future, whereas the model (14) only allows to react after the uncertainty resolves.

For our problem (with $r_1 = \bar{r_1}$), the VSS equals 15% of the optimal value of the objective function. For the models with early and late first rains, the VSS is 3% and 22%, respectively. These values indicate that it is indeed useful to use stochastic models for this problem. The VSS increases considerably when rainfall in the first stage becomes more favorable, illustrating the strong influence of first-stage rainfall on farmers' opportunities to anticipate bad rainfall in the second stage. Of course, when rainfall is late, the room for risk-controlling strategies (sowing of large areas) becomes limited.

Numerical experiments also corroborate our choice to use separate models for each realization of r_1. Indeed, as mentioned above, if the first-stage optimal solution $\bar{x}_1$ of the average static model is substituted in the two-stage model with r_1=late, this model becomes infeasible due to the labor constraints for the first period. This is a strong qualitative indication that our approach is preferable.

Finally, we use the concept of the *expected value of perfect information* (EVPI) to investigate how important the role of randomness is in our model. In other applications EVPI can sometimes be interpreted as the price one is willing to pay for complete information on future events. Because of the nature of the uncertainty in our problem (rainfall in the mid-term future), this interpretation does not make sense here. The (expected) value of perfect information has been treated in the literature in different contexts (see e.g. Kristjanson (1987), Chavas and Pope (1984), Chavas et al. (1991)). The concept of EVPI as we consider here is commonly used in stochastic programming (see e.g. Kall and Wallace (1994), Prékopa (1995)).

In order to compute the EVPI (with respect to R_2) for each of the two-stage models, we first determine solutions of all models under perfect information. That is, for a fixed $r_1 \in \Omega_1$, and each possible realization $r_2 \in \Omega_2$, we solve the deterministic problems

$$\min\{c(r_2)^\top x_2(r_1, r_2) \mid \quad A_1(r_1)\, x_1(r_1, r_2) = b_1(r_1), \qquad\qquad (15)$$
$$B_2(r_2)\, x_2(r_1, r_2) = b_2(r_2) - B_1(r_2)\, x_1(r_1, r_2),$$
$$x_1(r_1, r_2),\ x_2(r_1, r_2) \geq 0\}.$$

From this, we calculate the expected objective function value. The EVPI with respect to R_2 is given by the difference between the optimal value of the corresponding recourse model and the expectation of (15). It is easy to see that the EVPI is non-negative.

Computations for the various values of r_1 show (see Table 4), that the EVPI equals about 7–9% of the corresponding optimal value. It is not easy to interpret this result. On the one hand, EVPI measures the relative difference between expected values of the objective function, which in our models represents multiple objectives put on a common denominator by assigning to them more or less arbitrary weights. On the other hand, the careful modeling of the problem and estimation of the parameters justifies a certain degree of confidence in the outcomes of the model. In any case, when assessing the EVPI found, we should not forget that these percentages refer to food shortages. In a precarious situation 9 or even 5% less food shortage can be of crucial importance.

7.   Conclusions

First, it is important to note that the results we have discussed in this paper stem from studies which were entirely embedded in the national program for agricultural research in Burkina Faso, and carried out by various researchers from the national Institute of Agricultural Studies and Research (INERA), the CEDRES research institute of the University of Ouagadougou and the Department of Econometrics of the University of Groningen.

Second, mathematical modeling was used as an instrument of analysis, complementary to other types of studies. The models were developed in a step-by-step process, and results were carefully studied together with all researchers involved. The two-stage stochastic models – and not just their parameter values – presented in this paper have evolved from this approach, and are inspired by and based on numerous in depth studies on village-level, interviews with key-informants (farmers, extension agents, agronomists) and continuous experimenting together with farmers on their fields, but also on agricultural stations.

The research helped in explaining some important problems which confronted agricultural research and extension on the Central Plateau. All researchers involved became very much aware of the need for new technologies to preserve or if possible to increase the flexibility of agricultural production systems. This led to an increased use of short cycle varieties and of varieties with more resistance to drought spells, diseases, and weeds in on-farm experimentation (thereby justifying once more – but with other arguments – the increased attention for the breeding and selection of this kind of varieties). On-farm experiments were carried out which left more space for farmers to adapt technologies to their circumstances and which increased flexibility, for instance methods of cautious fertilization before and after sowing ('top-dressing').

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However, the potential for increased productivity through more flexible cropping systems and the breeding of drought resistant crops seems to be very limited, especially in those areas where rural density is relatively high. Two solutions are often proposed: land-use intensification (based – at least partially – on the use of modern inputs, in particular chemical fertilization), and migration. Since, as we have seen, risk-control strategies favor extensive methods of cultivation, with large areas per worker, intensive technologies will not be easily adopted on the Central Plateau. For land-use intensification to work, production-risks have to decrease considerably through the adoption of soil and water-conservation methods and by way of programs to restore the degraded soils. Recognition of this problem is rapidly increasing in Burkina Faso, as is shown among others by the reorientation of the national agricultural research program, empowering regional research on the management of natural resources on farm, village, and regional levels, and stimulating research on adequate methods to restore and to maintain soil fertility.

Acknowledgements

Appendix

Table 1: Definition of the variables and parameters of the model in Table 2.

The index τ corresponds to period 1 and 2, $t = 1, 2, \ldots, 13$ to the time intervals indicated in Figure 1, s to the categories of land defined by b), l to the mode of ownership in c) (see page 4), p to the produce introduced in (10), n to the nutrients, and j to the plots in (3) and (4). RS refers to the crop red sorghum. In addition to J and $J(\tau)$, defined in (3) and (4), we define the following sets:

S	= {land categories}
L	= {1,2}; 1 = common fields, 2 = individual fields;
$JS(s, \tau)$	= plots of land category $s \in S$, sown in period τ, $\tau = 1, 2$
$JL(l, \tau)$	= plots with mode of ownership $l \in L$, sown in period τ, $\tau = 1, 2$
$Pcer$	= {maize, red sorghum, white sorghum, millet}
N	= {kilocalories, proteins};

Definition of variables:
All decision variables have been defined in (5) – (7) and (11). For $r_2 \in \Omega_2$, the following additional second-stage variables are defined:

$PRO(p, t, r_2)$	harvest of product p (in kg) in period t, available for consumption or sale;
$ST(p, t, r_2)$	stock of product p at the end of time interval t (in kg);
$STR(p, r_2)$	volume of the stock of product p (in kg) saved at the end of period 13 to contribute to food needs in the harvest period of next farming season;
$SAFST(p, r_2)$	volume of the safety stock of product p (in kg) reserved at the end of period 13 to meet food requirements after the harvest period of the next farming season;
$FIN(t, r2)$	financial resources of the Household at the end of period t;
$REV(r_2)$	net revenues during the target consumption year;
$DEF(n, t, r_2)$	deficit of nutrient n in period t;
$DEFR(n, r_2)$	deficit of nutrient n during the harvest period of the next

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farming season, if the consumption of the Household was based only on the agricultural stocks at the end of period 13;

$DEFPR(r_2)$ deficit of auto-subsistence production;

Definition of parameters:

$av(s)$	available area of soil type s (in ha);
$\lambda(j)$	ratio between the area of the fallow supplement of plot j and the surface area of the cultivated plot $j \in J$;
$avman$	quantity of manure available to the farm in kg;
$man(j)$	quantity in kg/ha of manure applied on plot j, $j \in J$;
$avlab(l,t)$	available labor during period t for farming activities (in hours) on common fields ($l = 1$) or individual fields ($l = 2$);
$lab(j,t)$	required labor (in hours) in period t to cultivate 1 ha of plot j;
$labi(j,t,r_2)$	labor required to cultivate 1 ha of plot j intensively in period t (hrs/ha);
$labe(j,t,r_2)$	labor required to cultivate 1 ha of plot j extensively in period t (hrs/ha);
$labsow(j,t)$	labor required in period t for preparing and sowing 1 ha of plot j;
$sowday(t,r_1)$	number of favorable days in period t for preparing and sowing the fields if rainfall in period 1 equals r_1, for $t = 1,2,3,4$;
$sowdays(t,r_2)$	number of favorable days in period t for preparing and sowing the fields if rainfall in period 2 equals r_2, for $t = 5$;
$dur(t)$	duration (in number of days) of period t;
$yldi(j,p,t,r_2)$	quantity of product p harvested in period t on 1 ha of plot j if it is weeded intensively;
$ylde(j,p,t,r_2)$	quantity of product p harvested in period t on 1 ha of plot j if it is weeded extensively;
$\gamma(j,p,t)$	quantity of product p to be reserved per hectare of plot j in period t;
$f(p,t)$	fraction of the stock of product p lost in time interval t due to storage losses;

$\rho(t)$	interest rate in period t on the capital deposited;
$nci(t)$	non-cropping incomes received by the Household at the end of time interval t;
$nfe(t)$	non-food expenses of the Household during time interval t;
$prs(p, r_2)$	selling price which the farm expects to receive when selling 1 kg of product p;
$prp(p, r_2)$	purchasing price which the farm expects to pay for 1 kg of product p;
$fin(7)$	financial resources of the Household at the end of period 7;
$val(p, n)$	contents of nutrient n of 1 consumed kg of product p;
$dem(n, t)$	demand of nutrient n by the Household during period t;
$demr(n)$	demand of nutrient n by the Household during the harvesting period of the next growing season, i.e. in period 13;
$\theta_1(n)$	fraction of the demand of nutrient n to be satisfied by consuming products $p \in P$;
$\theta_2(n)$	fraction of the consumption of nutrient n by the consumption of the staple cereals, white sorghum, millet and maize;
$\theta_3(n)$	critical minimum fraction of the consumption of nutrient n;
α	fraction of the consumption of staple cereals (white sorghum, millet and maize) to be produced by the Household itself;
β	fraction of the revenues to be used to build up a safety stock;
$maxrs(t)$	maximum red sorghum quantity which can be consumed in time interval t;
$w(n), w_1(n), w_2, w$	weighting coefficients in the objective function.

Parameter values are taken from Maatman et al. (1995, 1996).

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Table 2: Stochastic linear programming models for sequential decision making by the Household in Burkina Faso

For each $r_1 \in \Omega_1$, choose decision variables as defined in (5) – (7) and (11), such that

$$\sum_{r_2 \in \Omega_2} \frac{1}{3} \left(\sum_{n \in N} \sum_{t=8,\ldots,13} w(n) \cdot DEF(n, t, r_2) + \sum_{n \in N} w_1(n) \cdot DEFR(n, r_2) \right.$$

$$\left. + w_2 \cdot DEFPR(r_2) - w \cdot REV(r_2) \right) \tag{16}$$

is minimized, subject to the following constraints: for all $r_2 \in \Omega_2$, $p \in P$, and $n \in N$,

$$\sum_{j \in JS(s,1)} (1 + \lambda(j)) \cdot SUR1(j) + \sum_{j \in JS(s,2)} (1 + \lambda(j)) \cdot SUR2(j, r_2) \leq av(s), \quad s \in S \tag{17}$$

$$SUR2(j, r_2) = SURi(j, r_2) + SURe(j, r_2), \qquad j \in J(2)$$

$$SUR1(j) \geq SURi(j, r_2) + SURe(j, r_2), \qquad j \in J(1)$$

$$\sum_{j \in J(1)} man(j) \cdot SUR1(j) + \sum_{j \in J(2)} man(j) \cdot \left(SURi(j, r_2) + SURe(j, r_2) \right) \leq avman \tag{18}$$

$$\sum_{j \in JL(l,1)} lab(j, t) \cdot SUR1(j) \leq avlab(l, t), \quad l = 1, 2, \ t = 1, \ldots, 4 \tag{19}$$

$$\sum_{j \in JL(l,1) \cup JL(l,2)} \left(labi(j, t, r_2) \cdot SURi(j, r_2) + labe(j, t, r_2) \cdot SURe(j, r_2) \right) \leq avlab(l, t),$$

$$l = 1, 2, \ t = 5, \ldots, 10 \tag{20}$$

$$\sum_{j \in JL(l,1)} labsow(j, t) \cdot SUR1(j) \leq sowday(t, r_1) \cdot avlab(l, t)/dur(t),$$

$$l = 1, 2, \ t = 1, \ldots, 4 \tag{21}$$

$$\sum_{j \in JL(l,2)} labsow(j, t) \cdot SUR2(j, r_2) \leq sowdays(t, r_2) \cdot avlab(l, t)/dur(t),$$

$$l = 1, 2, \ t = 5 \tag{22}$$

$$PRO(p, t, r_2) = \sum_{j \in J} \left(yldi(j, p, t, r_2) - \gamma(j, p, t) \cdot SURi(j, r_2) \right.$$

$$\left. + ylde(j, p, t, r_2) - \gamma(j, p, t) \cdot SURe(j, r_2) \right), \ t = 8, 9, 10 \tag{23}$$

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$$PRO(p, t, r_2) = 0, \qquad t = 11, 12, 13 \tag{24}$$

$$PUR(p, t, r_2) = 0, \qquad t = 9, 10, 11 \tag{25}$$

$$SAL(p, t, r_2) = 0, \qquad t = 8, 9, 10, 12, 13 \tag{26}$$

$$ST(p, t, r_2) = (1 - f(p, t)) \cdot ST(p, t - 1, r_2) + (1 - f(p, t)/2)$$
$$\times \Big(PRO(p, t, r_2) + PUR(p, t, r_2) - SAL(p, t, r_2) - CON(p, t, r_2) \Big),$$
$$t = 8, \ldots, 13 \tag{27}$$

$$ST(p, 13, r_2) = STR(p, r_2) + SAFST(p, r_2) \tag{28}$$

$$FIN(t, r_2) = (1 + \rho(t)) \cdot FIN(t - 1, r_2) + (1 + \rho(t)/2)$$
$$\times \left(\sum_{p \in P} \Big(prs(p, r_2) \cdot SAL(p, t, r_2) - prp(p, r_2) \cdot PUR(p, t, r_2) \Big) + nci(t) - nfe(t) \right),$$
$$t = 8, \ldots, 13 \tag{29}$$

$$REV(r_2) = FIN(13, r_2) - fin(7)$$

$$DEF(n, t, r_2) \geq \theta_1(n) \cdot dem(n, t) - \sum_{p \in P} CON(p, t, r_2) \cdot val(p, n), \quad t = 8, \ldots, 13 \tag{30}$$

$$DEFR(n, r_2) \geq \theta_1(n) \cdot demr(n) - \sum_{p \in P} STR(p, r_2) \cdot val(p, n) \tag{31}$$

$$CON(RS, t, r_2) \leq maxrs(t), \qquad t = 8, \ldots, 13 \tag{32}$$

$$ST(RS, 13, r_2) \leq maxrs(8) + maxrs(9) + maxrs(10) \tag{33}$$

$$\sum_{p \in Pcer \setminus \{RS\}} CON(p, t, r_2) \cdot val(p, n) \geq \theta_2(n) \cdot \sum_{p \in P \setminus \{RS\}} CON(p, t, r_2) \cdot val(p, n),$$
$$t = 8, \ldots, 13 \tag{34}$$

$$\sum_{p \in P} CON(p, t, r_2) \cdot val(p, n) \geq \theta_3(n) \cdot dem(n, t), \quad t = 8, \ldots, 13 \tag{35}$$

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$$DEFPR(r_2) \geq \alpha \cdot \sum_{p \in Pcer \backslash \{RS\}} \sum_{t=8}^{13} CON(p, t, r_2) - \sum_{p \in Pcer \backslash \{RS\}} \sum_{t=8}^{10} PRO(p, t, r_2) \qquad (36)$$

$$\sum_{p \in Pcer} prp(p, r_2) \cdot SAFST(p, r_2) \geq \beta \cdot REV(r_2)$$

$$SUR1(j) \geq 0, \quad j \in J(1)$$
$$SUR2(j, r_2) \geq 0, \quad j \in J(2)$$
$$SURi(j, r_2), \ SURe(j, r_2) \geq 0, \quad j \in J$$
$$CON(p, t, r_2), \ SAL(p, t, r_2), \ PUR(p, t, r_2), \ FIN(t, r_2), \ ST(p, t, r_2) \geq 0, \quad t = 8, \ldots, 13$$
$$STR(p, r_2), \ SAFST(p, r_2), \ DEF(n, t, r_2), \ DEFR(n, r_2), \ DEFPR(r_2) \geq 0, \quad t = 8, \ldots, 13$$

Table 3: Some results of the two-stage models

	Results average static model	Results of two-stage models (see (12))		
Rainfall period 1	(normal)	late	normal	early
Value of the objective function[1] ($\times 10^5$)	8.15	12.16	8.77	7.94
Cultivated area[2] (ha)	2.86	2.34	3.03	3.00
- Red Sorghum	0.19	0.18	0.18	0.11
- White Sorghum	0.77	0.30	0.11	-
- White Sorghum/cowpea	0.62	-	0.02	0.24
- Millet	-	1.05	0.19	0.19
- Millet/cowpea	1.28	0.81	2.53	2.46

Rainfall period 2	(aver.)	bad	aver.	good	bad	aver.	good	bad	aver.	good
Cultivated area[3] (ha)										
- Maize	0.13	0.13	0.16	0.10	0.13	0.15	0.10	0.13	0.15	0.08
- Millet	-	1.03	0.64	0.03	-	0.33	-	-	0.40	-
- Millet/cowpea	0.44	-	0.35	0.53	-	-	-	-	-	0.12
- Groundnuts	0.13	0.07	0.08	0.06	0.55	0.13	0.36	0.55	0.10	0.35
Cultivated area (ha)	3.56	3.57	3.56	3.06	3.72	3.64	3.26	3.68	3.64	3.54
Area cultivated int. (ha)	2.96	3.57	2.64	1.83	3.72	2.87	2.01	3.68	2.72	2.12
Area cultivated ext. (ha)	0.60	-	0.92	1.12	-	0.77	1.01	-	0.91	0.88
Area abandoned (ha)	-	-	-	0.11	-	-	0.24	-	-	0.54
Production (kg)										
- cereals	1510	1118	1337	1352	1051	1453	1431	1090	1492	1483
- groundnuts	42	12	109	239	107	41	163	103	29	157
- cowpeas	42	14	22	27	40	60	66	48	68	78
Sales (kg)										
- cereals	96	122	37	48	133	44	48	147	122	150
- groundnuts	30	-	64	77	2	38	51	-	-	2
- cowpeas	44	-	12	14	-	38	50	-	55	64
Purchases (kg)										
- cereals	437	280	408	506	346	405	334	347	420	523
- groundnuts	-	31	-	-	-	-	-	-	-	-
Shortages										
- in 100 kilocalories	-	1621	176	-	1276	23	-	1184	-	-
- in proteins (1000 g)	-	17	-	-	9	-	-	7	-	-
Reserve Stock (kg) (cereals)	-	-	-	221	-	-	223	-	-	247
Degree of autoproduction[4]	72%	51%	68%	78%	56%	70%	78%	57%	71%	80%

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1 The objective is a summation of variables measured in kilocalories, proteins and kilograms. Therefore, the units of the objective cannot be presented.
2 This refers only to the area cultivated in period 1.
3 This refers only to the area sown in stage 2.
4 Ratio of the value of (all) agricultural production in kilocalories to the energetic demand of the members of the Household.

Table 4: Some results of the perfect information models and the model in which the first-stage strategies correspond to the average static model strategies

	Perfect information models (15)			Static first-stage strategy
Rainfall period 1	late	normal	early	
Value of the objective function[1] ($\times 10^5$)	11.3	8.15	7.26	10.09
Rainfall period 2	bad aver. good	bad aver. good	bad aver. good	bad aver. good
Degree of autoproduction[4]	52% 68% 82%	57% 72% 84%	58% 75% 86%	53% 72% 80%

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