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Food security problems in sub-Saharan Africa: Operations Research as a tool of analysis

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Abstract

For many years, the author has been involved in teaching and research in the use of Operations Research as a tool of analysis to study food security problems in sub-Saharan Africa, in particular, grass root problems of poor farmers. The paper presents an introduction to the way Operations Research methods have been applied in case studies and research projects, and discusses in retrospect the author's views on the strengths and limitations of the application of Operations Research. The paper has in particular been written for people who are not familiar with applications of Operations Research in agriculture, and are interested to learn about its potential usefulness in practice. The retrospective part is largely based on food security studies in e.g. Tanzania, Burkina Faso, Bénin, Togo and Eritrea and on participation in several interdisciplinary research programmes in Africa.

Keywords: food security; operations research; risk in agriculture; agriculture in Africa; stochastic programming

1. Introduction

This paper[1] has in particular been written for people who are not familiar with applications of Operations Research in agriculture, and are interested to learn about its potential usefulness in practice. The paper deals with agriculture in Africa. In many African countries, agriculture is the backbone of the economy, because it produces food for the population, creates employment and generates income by export of cash crops. It is expected that agricultural development will contribute to the elimination of poverty and to economic growth. In many African countries, the majority of farmers are peasants, who on their small farms produce primarily for their own consumption. Their situation can be very vulnerable, particularly if agricultural production depends on rainfall. Failing rainfall can lead to poor harvests. Another reason for the peasants'

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vulnerability is the deterioration of soil conditions. Demographic pressure may be so high that not enough fertile land is available for farming. The shortage of land may lead to changing practices of cultivation. For instance, farmers no longer apply the traditional system of leaving land fallow to restore soil fertility. This may lead to a degradation of soils and decreasing production levels. The consequences can be disastrous, especially in situations where the farmers lack the financial means to purchase fertilizers to maintain soil fertility. These factors of uncertainty and deteriorating environmental conditions are the reason that in many African countries food security is of great concern. This fact is reflected in this paper. Food security is a major issue.

We will begin with a section on food security in an African historical context. It serves as background information, positioning problems to be discussed in this paper in a proper context. It also reveals the multitude of factors, which at various levels influence farmers' strategies and perspectives.

A second section introduces the features of mathematical modeling and Operations Research as instruments to study certain problems of agricultural development. It articulates the typical nature of Operations Research models by also discussing other types of mathematical models. Farmers' strategies to cope with risks receive special attention.

The last section is of a retrospective nature. We look back upon the role of Operations Research in various food security projects in Africa. We also discuss strong and weak points of the use of mathematical modelling, and comment on the sometimes strong criticism and doubts expressed concerning the usefulness of mathematical modelling in the field of socio-economic problems of development.

2. Food security

2.1. Period of decolonization

During the years after World War II, the period of de-colonization, food security was hardly an issue in the debates on economic growth and development. The debate was much centred on industrialization. It was widely believed[2] 'that industrialization was the unique key to development and that the industrial sector, as the advanced sector, would pull with it the backward agricultural sector'. These views were consistent with the traditional views on development, fashionable in the years of the 1950s and early 1960s: 'development' was synonymous with 'modernization'. Gradually these views changed, and the role of the agricultural sector became increasingly important in the debate on economic growth and development. A strong agricultural sector was seen as a prerequisite for industrial development, because only the agricultural sector could generate a financial surplus to invest in industry. Export of cash crops generated an important source of income for the state and became, in many developing countries, the backbone of the economy. Cash crop production was therefore much boosted, sometimes at the expense of food crop production. However, food production was necessary for domestic consumption: in the 1960s and 1970s almost all developing countries wanted to be self-sufficient in food production. There were strong reasons for that. The young nations aspired to be

[2]See Thorbecke (1969, p. 3). These views were particularly popular in the 1950s and early 1960s. Soon after, the views were criticized.

independent, not only politically but also economically. Food was a vital good. If they had to rely on foreign countries for food, it would restrict their political independence.

2.2. Green revolution

The importance of food production also became an issue of great international concern. In the 1960s and 1970s, initiatives were taken to carry out agricultural research on an international scale. In these years, several international research institutes were established in order to develop improved technologies to increase agricultural production. An example is the International Rice Research Institute (IRRI) on the Philippines, established in 1960 with strong support from the Ford and Rockefeller Foundations. New, so-called high-yielding varieties were developed. They usually required high levels of inputs. The introduction of these high-yielding varieties was welcomed as the 'Green Revolution'. In several Asian countries, the Green Revolution was a success.[3] In sub-Saharan Africa the results were less promising. Rates of adoption of high-yielding varieties were low. For crops like millet, sorghum and cassava, which are the main food crops in many regions of Africa, high-yielding varieties did not prove successful.

Moreover, in many African countries the supply of agricultural inputs was not adequate, and a proper infrastructure for agricultural research, extension services and planning was lacking. In fact, the growth of agricultural output during the last 25 years in sub-Saharan Africa has stagnated. The growth of food production lags behind demographic growth. Moreover, the export of cash crops has not been a motor for industrial development in Africa.[4]

2.3. State as the main actor

There have been many debates on why agricultural growth stagnated in Africa. Important causes were certainly the food policies by national governments. During the 1970s and 1980s, the political spectrum of regimes in Africa varied widely. Independent of the ideological color of the regimes, the governments in almost all African countries appropriated a central role in the field of food policies. There were many reasons for that. As in the colonial days, the governments wanted farmers to supply food to the urban centers. Moreover, they wanted to extract a surplus from the farmers in order to finance infrastructure, the government's administration and welfare services. In many countries, food was produced by peasants, who lived scattered all over the country. They applied traditional methods of cultivation, with land, labor and rainfall being the main inputs. Production levels were accordingly low. The governments wanted to change these traditional

[3]In India and Indonesia, for instance, introduction of high-yielding varieties in combination with appropriate fertilizer and water inputs resulted in an impressive increase in rice output over the last three decades. See e.g. Parikh et al. (1993), and Ellis (1993). For a critical review of the Green Revolution, see e.g. Lipton and Longhurst (1989), and Hazell and Ramasamy (1991).

[4]In the last 30 years the sub-Saharan's agricultural export earnings remained almost the same (whereas in south Asia, they were tripled); see IFPRI/USAID (2002, p. 13).

farming systems. It was necessary to increase agricultural production and to introduce improved modes of production. How to do that, was a major question in the offices of Ministries of Agriculture and funding agencies like the World Bank. And it is still a major question, as will be seen in this paper.

In the early days of independence, different approaches were adopted. Some implied *radical changes*, such as the establishment of large state farms on which the work had to be done by wage laborers. This would facilitate the introduction of new agricultural methods, investment in equipment, access to markets, and the large farms could benefit from an economy of scale. Although in the beginning some state farms were successful, for instance sisal estates, many of them failed. The enforced establishment of co-operatives was another radical approach. A well-known example is the Ujamaa village program in Tanzania in the late 1960s and early 1970s as part of the Ujamaa policy[5] of Nyerere (1968). It aimed at a transformation of rural areas into Ujamaa villages, wherein all political and economic activities would be collectively organized. The creation of Ujamaa villages was a failure. The term 'socialism from above', which has often been used as a paraphrase for Ujamaa policies, reflects the main contradiction of Ujamaa. Originally, the Ujamaa policy was supposed to be based on the initiatives of the farmers themselves. Self-help and mutual co-operation were the key words. The role of the government was to support such initiatives. Gradually, the government took the initiatives. Ujamaa became a process from above.

A second approach to introduce improved methods of cultivation, applied in most African countries, was *less radical*. It envisaged a gradual improvement of practice on existing farms. It was acknowledged that the farmers wanted to stick to their family-based farming systems, on land inherited from their forefathers. The main problem was how the government could reach the individual farmers in an efficient way. Transfer of technology became the key concept. At agricultural experimental stations, agronomists tested new technologies. After successful trials, extension officers tried to introduce the innovations to the farmers. Sometimes field tests at the farm level were also carried out. Most of the time such transfer of technology did not work well. The approach was too much top down and the role of the experts as exclusive actors was increasingly challenged. It was realized that the farmers' conditions and local knowledge should be taken as a starting point. 'Farmers first' became a key word and interactive learning the leading principle.

During the 1960s and 1970s the governments of most African countries wanted to have a firm control on the food market, to satisfy consumers in the urban centers and to be sure that the farmers would produce enough food. Governments were often main actors on the national food markets and they imposed official prices, both for consumers and for producers. National marketing boards were installed, which bought from farmers via intermediaries[6] and subsequently sold to consumers, at fixed producer and consumer prices. In most African countries the management of these large organizations was not successful. Farmers were not paid in time, transport was delayed, etc. The price policies were also problematic. Because consumer prices were set low and levies had to be paid to government controlled intermediaries, the farmers

[5] For a review and analysis of the failed Ujamaa policies in Tanzania, see Schweigman (2001).

[6] The intermediaries were governmental departments in the regions, government controlled co-operatives, or merchants authorized by the government. See e.g. Bryceson et al. (1999, pp. 25–27), Bassolet (2000, pp. 10–12).

received a price that was too low. This discouraged farmers from investing in improved technology in order to increase production.

2.4. Structural Adjustment Programs

In the 1980s and 1990s the ideas on the exclusive role of the state changed. By accepting the Structural Adjustment Programs, recommended or rather imposed by the IMF and the World Bank, in most developing countries the role of the state in the food market was severely reduced: markets were liberalized, marketing boards dismantled and prices were no longer fixed by the government. The role of national governments was restricted to creating optimal conditions (infrastructure, transparent rules and regulations, etc.) for a private market, to keeping a food safety stock and to organizing food aid. According to neo-liberal thinking, the free-food market would reduce marketing costs, decrease consumer prices and increase producer prices, allowing farmers to invest in agriculture and to improve productivity. Many developing countries are now in the transition process to the free market.

The extent to which the private market can indeed contribute to food security is one of the crucial questions for the coming decades (see e.g. Lutz et al., 1999): in many vulnerable regions in Africa the environmental conditions for agricultural production are deteriorating, possibilities of off-farm employment are limited and the purchasing power of the local population is low; inputs may be expensive; traders may not be interested in buying or selling in these regions, so the effect of the privatization of the market to attain food security is very uncertain.

In the 1990s, it was recognized that the Structural Adjustment Programs also had negative effects and did not lead to improvement of the conditions of life of the poor people. It was particularly felt that there were no proper ways for the poor people to participate in the imposed processes of change. The World Bank started to emphasize the importance of institutions (rules, enforcement mechanisms and organizations (see World Bank, 2002, p. 6)) in order to enhance opportunities to participate in markets and to reduce poverty. In studies and initiatives to make public and private institutions work, accountability, transparency, participation, and decentralization became key issues.

In the near future, much research will be required concerning institutions and their functioning to improve the competitiveness and participation on food markets.

3. Mathematical modeling

The mathematical models to be illustrated in this paper aim at describing processes of agricultural change and development. Such processes are influenced by climatic, environmental, economic, and social factors. The models for such complex socio-economic processes are quite different from those applied in the natural sciences such as Newton's laws, the ideal gas law and Avogadro's law. Many of those models can be tested experimentally. Experimental conditions can be reproduced. The mathematical models of this paper are different in nature. Owing to changing environmental conditions and human intervention, socio-economic processes cannot be reproduced. Lacking the possibility of rigorous experimental verification, such models are developed on the basis of a mixture of inputs: observed human behavior, interpretation of historical and economic processes, data on changing environment, and assumptions. Prejudices and wishful thinking should be avoided, but are not always absent.

3.1. Econometric models

Empirical econometric models are examples of mathematical models describing socio-economic phenomena. Here a typical example of an econometric model is illustrated. It deals with the supply of an agricultural product as a function of prices. This 'supply function' has played a role in discussions about the influence of price policies as discussed in Section 2. It deals with the question whether higher prices for the farmers would lead to higher production levels. It is still an important issue. Here, the production of one crop in a certain region is taken into account. In textbook examples, the supply[7] in year t, here called s_t, is supposed to depend on the price p_{t-1} during the previous year[8] in the following way:

$$s_t = a_1 + a_2 p_{t-1} + a_3 z_t + \varepsilon_t. \tag{1}$$

z_t is a variable representing other observed exogenous factors influencing supply, for instance total rainfall in year t or any other rainfall indicator, ε_t is a stochastic disturbance representing unobserved factors influencing supply. a_1, a_2 and a_3 are parameters, the values of which have to be estimated on the basis of observed data of supply, price, and e.g. rainfall during a series of years. The first econometric models to estimate such supply response on prices were developed by Nerlove (see e.g. Nerlove, 1958, 1979) and later applied in many macro-economic studies (see e.g. Askari and Cummings, 1976, 1977; Bond, 1983; Yonli, 1988; Fosu et al., 1997), for various crops, regions, and periods of time.[9] The Nerlove models were slightly different from (1), but for illustrative purposes, (1) will do. Estimation of the values of the parameters in (1) was attempted. This was done in such a way that a best fit to the observed data was obtained. In some situations the model did fit fairly well to the data, in other situations the results were not convincing. The fact that such data did not always fit is not surprising: in developing countries, regional data on production (i.e. on cultivated areas and yields per hectare) are often not very accurate; prices may be volatile; rainfall dependence may be much more complicated than one or two rainfall indicators may suggest; and many other factors may interfere such as deteriorating soil conditions, introduction of new crop varieties, changing markets, etc.

If the calculated prices and supplies in model (1) were a good fit to the observed data, and if the coefficient a_2 in (1) were significantly positive, then it could be concluded that the farmers would respond positively to price incentives.

[7]For cash crops to be sold on the market, production equals supply (on the market). For food crops cultivated for both home consumption and sales, a distinction has to be made between production and supply on the market.

[8]It is beyond the scope of this introductory example to discuss the meaning of 'price in year t'. It may refer to official prices, average prices on one market throughout the year, average prices on local markets, prices at harvest times, etc.

[9]A recent study used Nerlove models for different periods of time, to try to assess the influence of Structural Adjustment Programs on supply responses in Ghana and Burkina Faso; see Fosu et al. (1997).

It is not obvious that higher prices for farmers will lead to higher production. It is possible that the opportunities to increase the production are constrained, for example by a shortage of fertile land, of labor, or a lack of capital to invest in improved methods of cultivation. Even if land and labor are not restrictive, higher cash crop prices do not necessarily result in higher cash crop production, for instance if farmers grow food crops as well and if it is too risky for them to rely too much on cash crop production. Such issues are not addressed in the simple econometric models (1). If in a certain region a database could be set up consisting of primary data for a large sample of households, the setting up of more comprehensive econometric models would allow us to address some of these issues. But usually, especially in developing countries, such databases do not exist. In such situations it may be preferable to have recourse to Operations Research models. They can take such issues explicitly into account. Rather than looking for empirical statistical relations, Operations Research models describe farmers' strategies and factors influencing them. An analysis is made of farmers' decisions at the grass root level, for a representative farm household. Also the Operations Research models require a lot of data, but, as we will see below, these can be obtained from various sources.

3.2. Operations Research analysis

An Operations Research analysis of farmers' decisions at the household level and the way important factors influence them may start with the application of a 'Systems Approach'. As we have seen in Sections 1 and 2, agricultural development and food security are complex phenomena. So are farmers' strategies. Climatic, environmental, economic, and social factors play a role, at various levels. They may be strongly interrelated. A 'systems approach' may help:

- to disentangle all factors that influence the farmers' decisions and to clarify their interrelationships,
- to establish a reference framework as basis for the Operations Research models to be developed,
- to direct the step-by-step process of building Operations Research models and discussing preliminary results.

In a 'systems approach', an organism or organization is conceived as a system (see e.g. Garcia, 1984; Fresco, 1986; Luning, 1991; Van Duivenbooden, 1995; Maatman et al., 1996, Ch. 3; Maatman, 2000, Ch. 5), which consists of constituent elements. Between these elements relations exist. In a system various sub-systems may be distinguished. Each system has its specific characteristics, in terms of both its constituent elements and mutual relations. The holistic systems approach explores how changes in one constituent element may change the other elements in the system. For an analysis of farmers' strategies in a representative household, this household and its strategies could be considered as a system. The constituent elements may consist of the members of the household as *actors*, crop and livestock production as *acitivities*, land and labor as *physical resources*, fertilizers as *inputs* to be bought, and harvested produce as *outputs* to be sold or consumed. Between these elements *relations* exist. An illustration of such a system and the various elements is presented in Figs A1 and A2 in the Appendix to this paper. Such diagrams may be useful to identify all actors, activities, resources, inputs, and outputs and clarify what type of decisions have to be taken into account.

In the Operations Research models, to be illustrated below, *decision variables* and *parameters* occur. Each *decision variable* corresponds to a specific question to be answered or decision to be taken. In a 'systems approach' such questions and decisions have to be precisely formulated, acquiring an accurate definition of concepts to be used. Each *parameter* corresponds to a specific factor influencing farmers' decisions directly or indirectly. The *exogenous* nature of various factors is of special importance. In this paper, a parameter is called *exogenous* if the farmers' decisions have no influence on the values of the parameters. The estimation of parameters is of imminent importance and may require many efforts. Sometimes one can rely on existing results of village-level studies, carried out by agricultural research institutes; on results of agricultural tests at agricultural stations or with farmers; on new field studies by interviews and discussion with farmers; and by all sorts of reports on climate, rainfall, prices, etc. In a 'systems approach' it will also be necessary to discuss which factors will have to be taken into account explicitly, and which not or not yet. 'Systems approach' is a 'preparatory analysis' anticipating the development of Operations Research models. There is a characteristic difference between empirical econometric models like (1) and such Operations Research models. The first ones are *descriptive* in nature; they describe empirical relations between entities. Operations Research models as discussed in this paper are *normative* in nature. They simulate farmers' actual and potential strategies and investigate what the 'best' decisions are. On the basis of chosen criteria it is defined what 'best' decisions are, and how they are influenced by various constraints. In the next section we will illustrate an example of such a model.

3.3. A linear programming model

Anticipating a discussion of complex case studies, we will first illustrate the application of a linear programming model for a simplified situation. The model allows us to illustrate many issues, which are also at stake when modeling the more complex case studies. Our model will describe decisions of a farmer, who cultivates only three rainfed crops, for instance cotton, sorghum, and millet. There is only one growing season in the year, which coincides with the rainy season. A surplus of food crops may be sold and food may also be purchased. We number the crops cotton, sorghum, and millet $i = 1, 2, 3$, respectively, and define

x_i area where crop i is cultivated, in ha. (2)

y_i yield of crop i, in kg/ha. (3)

u_i purchased amount of crop i, in kg. (4)

v_i sold amount of crop i, in kg. (5)

The x_i's are decision variables, the values of which have to be determined. The y_i's are exogenous parameters, their values have to be estimated and are inputs in the model. If we want to explore the feasibility of the application of fertilizers, we could, for instance, introduce millet grown without the use of chemical fertilizer as crop 3, and millet with a prescribed dose of chemical fertilizer as crop 4. The corresponding yields of crops 3 and 4 may then be considered exogenous. By introducing new decision variables in this way, various technologies can be handled, for instance, early and late sowing, intensive and less-intensive weeding, deep ploughing by oxen, mulching, application of organic manure, etc. Needless to say, for each technology the corresponding yields, costs, etc., have to be estimated.

Crop production may be constrained by available land and labor. If the farmer has an area of land of size A at his disposal, then we may write for the *land constraint*:

$$x_1 + x_2 + x_3 \leqslant A. \tag{6}$$

If soil types on the farm are very different, then different land constraints can be formulated. Labor can be a limiting factor, in peak periods of sowing, weeding, and harvesting. To handle labor constraints for a situation where only family labor is used, we divide the growing season into periods (of length of 1 or 2 weeks), number them $\tau = 1, 2, \ldots$ and introduce the exogenous parameters:

$$\begin{array}{l} l_{\tau i} \text{ labor required in period } \tau \text{ to cultivate 1 hectare with crop } i, \text{ in mandays} \\ L_\tau \text{ total number of mandays of family labor, available in period } \tau \end{array}. \tag{7}$$

For each period τ, the following *labor constraint* can be formulated:

$$l_{\tau 1}\, x_1 + l_{\tau 2}\, x_2 + l_{\tau 3}\, x_3 \leqslant L_\tau, \tau = 1, 2, \ldots. \tag{8}$$

The left-hand side of (8) represents the total required labor in period τ, which may not exceed the available labor. If the possibility of hiring labor is to be explored, decision variables can be introduced, representing the number of mandays to be hired in period τ, and the variables have to be included in the right-hand side of (8). The expressions (6) and (8) are technical constraints and are due to the limited availability of resources. Similar constraints could be formulated to model that the farmer has only a limited amount of money to spend on agricultural inputs, costs for hiring labour, etc.

Certain conditions to be formulated are not the result of the limited availability of resources, but reflect certain aspirations. An example is, for instance, the aspiration that enough sorghum and millet is to be available for consumption by the household members. If we define:

$$\rho_i \text{ the household's annual consumption requirement of crop } i, \text{ in kg} \tag{9}$$

then this aspiration can be formulated as

$$y_i x_i + u_i - v_i \geqslant \rho_i, i = 2, 3. \tag{10}$$

Food requirements such as (10) are sometimes called 'normative' or 'aspirational' constraints. Usually, the food requirements are expressed in terms of nutrients such as calories and proteins. Based on the composition of the household, the annual requirement of calories and proteins can be estimated. Also the (average) contents of calories and proteins in 1 kg of sorghum and of millet can be estimated. Using these estimates, the formulation of the requirement that enough nutrients should be available is fairly straightforward. If such nutrient requirements are included, it is advisable to include as well some constraints about food habits, otherwise one may arrive at a consumption pattern, which is optimal from a nutritive point of view, but such that nobody likes the suggested diets (see e.g. Schweigman, 1979; Maatman et al., 1996).

Apart from the constraints (6), (8), and (10), other constraints may be of importance as well, for instance that part of sorgum is used for the consumption of beer, that a safety stock is to be kept to anticipate a possible poor harvest next year, that certain activities such as ploughing can be done by male people only, etc. Usually the formulation of such constraints is fairly straightforward. The handling of multi-year crop succession requirements is more complicated (see e.g. Schweigman, 1985, 1993; Klein Haneveld and Stegeman, 2005); it will not be discussed here.

The following constraints are trivial; note that cotton is a cash crop for sales only:

$$v_1 = y_1 x_1; u_1 = 0; \tag{11}$$

$$x_i \geqslant 0; u_i \geqslant 0; v_i \geqslant 0; i = 1, 2, 3. \tag{12}$$

Decision variables x_i, u_i, v_i, $i = 1, 2, 3$, which satisfy all constraints, constitute a feasible solution. It is customary in linear programming to try to find an 'optimal' feasible solution, which maximizes or minimizes a so-called objective function. If we introduce the parameters

$$\begin{aligned} &p_i \text{ selling price per kg of crop } i \\ &\pi_i \text{ purchasing price per kg of crop } i \\ &k_i \text{ costs per hectare to cultivate crop } i, \end{aligned} \tag{13}$$

then for our example we could try to find a feasible solution, which maximizes the net income, i.e.:

$$\text{Maximize:} \sum_i (p_i v_i - \pi_i u_i - k_i x_i), \tag{14}$$

where x_i, u_i and v_i, $i = 1, 2, 3$ have to satisfy (6), (8), (10), (11), and (12).

The prices p_i are called the producer prices, or farmgate prices, the prices π_i are consumer prices. Are the prices exogenous parameters? It is well known in agricultural economy that an individual farmer will not influence prices, but the aggregated supply does have an influence. The relation between aggregated supply and prices was dealt with in the econometric model (1). In our linear programming model, prices are supposed to be exogenous parameters. We have not yet specified when the surplus is sold, and when food crops are purchased. In several countries in West Africa, farmers sell their produce immediately after harvest, because they need urgently to earn some money to pay daily expenses or because traders are only then interested in buying from the farmers (at low prices). This phenomenon is called 'forced sales'. It is certainly not optimal for the farmers, who could better sell their produce later, when prices are higher. Sometimes, farmers are obliged to sell and then later purchase the same food during the lean period at much higher prices. Consumer prices are higher than producer prices, due to e.g. transaction costs for traders, hence $\pi_i > p_i$.[10]

In linear programming much value is generally attached to the objective function. One should not forget, however, that the constraints, both the technical and the normative constraints, can be very demanding and determine to a large extent farmers' strategies.

The maximation problem (14) is a linear programming problem, because the objective function in (14) and all constraints (6), (8), (10), (11), and (12) contain linear expressions in the decision variables.[11]

[10]From this condition it follows that for our example, either $u_i = 0$, or $v_i = 0$, implying – see (10) – that only a surplus is sold.

[11]Crop yields depend in a very non-linear way on doses of chemical fertilizers applied. Such non-linearities can easily be handled in a linear programming model by an appropriate choice of variables and parameters as discussed in this paper underneath the definitions (2)–(5).

Several computer programs are available, which allow solution of such linear programming problems, even if they contain many variables and constraints.

Before we discuss the question of what use has been made of such linear programming models in practice, we first consider an illustration of some models, which can be used to handle *risks*.

In a discussion on risk-reducing measures, a distinction can be made between (see Maatman, 2000, p. 393):

(a) *prevention or reduction of risks* by reducing the risky nature of certain specific activities
(b) *dispersion of risks* by diversification of risky activities
(c) *control of risks* through sequential decision-making
(d) *'insurance'* against risks

A classical example of (a) is the application of irrigation. It *prevents risks* due to water shortage. Growth of the plant is no longer dependent on rainfall hazards. Another *risk reduction* method from category (a) is the replacement of a common crop variety by a drought-resistant variety, again reducing the risk of crop failure due to poor rains. Another example is the construction of stone bunds on the land to reduce water runoff and to improve water infiltration in the soil; it *reduces the risk* of shortage of water for plant growth and thus of crop failure.

Dispersion of risks, can be obtained by diversification, i.e. by a combination of different (risky) activities, for instance, the cultivation of different crop varieties, different methods of cultivation, early and late planting, etc. The idea is that if one variety is doing not well due to poor weather conditions, another variety may do better; if an early planted crop fails due to poor early rainfall, a later planted crop will do better. It can be shown that diversification does indeed reduce farmers' risks if and only if the outcomes of different risky activities are not too strongly positively correlated.[12] In traditional farming, diversification is a well-known phenomenon, widely applied.

If farmers or members of the farmers' household are able to combine on-farm activities with off-farm activities to earn some money, this certainly may reduce farmers' risks of food shortages or other deficits.

Risk control, by sequential decision-making, is an important way of dealing with risks of poor rainfall. Farmers react on observed rainfall and plant growth during the growing season. Decisions of sowing and re-sowing, of intensive or less-intensive weeding, etc., are taken at times when information about rainfall until then, germination of plants, appearance of weeds, etc., becomes available. The further the growing season proceeds, the more information will be available. In fragile agricultural systems in Africa, farmers' strategies can differ much in bad, average, or good rainfall years. Farmers also take other decisions of a sequential nature, for instance the quantities of agricultural output to be sold, or food to be purchased. These decisions are usually taken after harvest levels have become known. The selling and purchasing strategies may be very different in bad, average, or good rainfall years.

[12]See e.g. Klein Haneveld and Schweigman (1985), who for the cultivation of two different crop varieties show under what conditions of the simultaneous probability distribution of the yields of the two crop varieties, in case the correlation between the random yields, the cultivation of both varieties together reduces indeed farmers' risks. The authors specify various definitions of risk. The theory of risk reduction by diversification of agricultural practice has much in common with risk reduction in portfolio selection in finance theory.

'Insurance' strategies do not refer to 'official' insurance systems as in industrialized countries, nor to experimental 'crop insurance' and 'rainfall insurance' systems as exist in some countries (see Hazell et al., 1986; Bakker, 1992). They refer to existing farmers' strategies, which are applied in a 'good' year to anticipate risks in the next year(s), for instance by installation of a food security stock, or keeping livestock as 'insurance' against a poor harvest, or by strengthening social relations. Although livestock is also kept for other reasons, its role as financial reserve in case crop harvests fail is of great importance. Social expenditures, often postponed to good years, may strengthen ties with other households and may create a basis for mutual help in cases of need.

In most farming systems in Africa, all such risk reduction strategies may be important elements of farmers' strategies.

3.4. Modeling strategies to cope with risks due to uncertain rainfall

We will now illustrate a method of modeling farmers' strategies to cope with risks due to uncertain rainfall. We recall that our linear programming model (6), (8), (10), (11), (12), and (14) was set up to describe farmers' strategies under specified conditions of rainfall, for instance average conditions. We extend this model to be able to handle the random nature of rainfall during the growing season and consequently the random nature of the crop yields. We define the random variable R as:

$$R \text{ total rainfall during the growing season, in mm,} \tag{15}$$

and for the crops $i = 1, 2, 3$, introduced above, the random yields are written as

$$y_i(R) \text{ yield of crop } i, \text{in kg.} \tag{16}$$

We shall discuss below how the random yields $y_i\,(R)$ can be handled. When the farmer has to take decisions about planting and sowing, he does not know what the rainfall R will be. This implies that in the model the values of x_i, $i = 1, 2, 3$, as introduced in (2), are to be determined before the realization of R is known. The decisions about sales and purchases are taken during the year after the harvest (sometimes called the target consumption year,[13] see Fig. 1), when the realization of R is known. So in the model the values of u_i and v_i, as introduced in (4) and (5), are to be determined after the realization of R is known.

The reasoning is now as follows. Assume that the values of x_i, $i = 1, 2, 3$ are known and are feasible, so satisfy (6), (8), and (12). Assume that the realized rainfall is known as well, say r. The corresponding realized yields are called $y_i(r)$, $i = 1, 2, 3$. The values of the decision variables u_i and v_i, $i = 1, 2, 3$ depend as well on r, so $u_i = u_i(r)$ and $v_i = v_i(r)$, $i = 1, 2, 3$. Referring to (10), (11), and (14), their values can be determined by solving the maximization problem:

$$\text{Maximize: } \sum\nolimits_i (p_i v_i(r) - \pi_i u_i(r) - k_i x_i), \tag{17}$$

[13]The name indicates that food produced during the growing season is supposed to be consumed in the year after harvest.

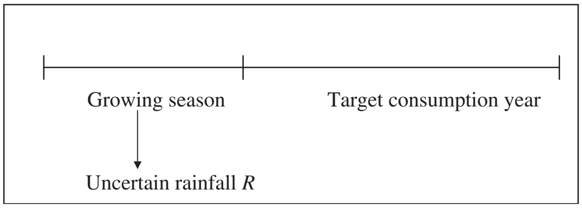

Fig. 1. The planning period.

where the variables $u_i(r)$ and $v_i(r)$, $i = 1, 2, 3$, have to satisfy, see (10), (11), and (12):

$$\begin{aligned} & y_i(r)\,x_i + u_i(r) - v_i(r) \geqslant \rho_i, i = 2, 3 \\ & v_1(r) = y_1(r)x_1; u_1(r) = 0 \\ & u_i(r) \geqslant 0, v_i(r) = 0, i = 1, 2, 3. \end{aligned} \tag{18}$$

It is assumed here that the exogenous prices p_i and π_i in (17) do not depend on r. There may also be reason to assume a decreasing relationship between prices and r: in years with poor rainfall, production may be low and prices high; in good rainfall years, prices may be low.

We define

$$z(x_1, x_2, x_3, r) \text{ the maximum value of (17),} \tag{19}$$

i.e. the value of (17) for the optimal solution of (17) and (18). It is emphasized that $z\ (x_1, x_2, x_3, r)$ is a function of given values of x_i, $i = 1, 2, 3$ and of realized rainfall r. Because rainfall is a random variable R, so also $z\ (x_1, x_2, x_3, R)$ is a random variable. The values of x_i, $i = 1, 2, 3$ are now determined in such a way that the maximum of the expectation of $z\ (x_1, x_2, x_3, R)$ is found, i.e.

$$\text{Maximize:} \sum [z(x_1, x_2, x_3, R)], \tag{20}$$

$$\text{where } x_i, i = 1, 2, 3 \text{ have to satisfy (6), (8), and (12).} \tag{21}$$

We will take for the probability distribution of R a simple discrete distribution. We assume that only three realizations of R are possible: r^- refers to a poor rainfall season, r^0 to an average one, and r^+ to a good rainfall season. We call the set of realizations of R:

$$\Omega = \{r^-, r^0, r^+\}. \tag{22}$$

For the empirical probability distribution of R, we write:

$$\Pr(R = r) = f(r), r\,\varepsilon\,\Omega \quad \text{with} \quad \sum_r f(r) = 1, f(r) \geqslant 0. \tag{23}$$

By making use of (23), the expression (21) may be written as

$$\text{Maximize: } \sum_r f(r) z(x_1, x_2, x_3, r). \tag{24}$$

It can be shown that finally we arrive at the following maximization problem, see (17), (18), and (24):

$$\text{Maximize: } \sum_r f(r) \sum_i (p_i v_i(r) - \pi_i u_i(r) - k_i x_i), \tag{25}$$

where the variables x_i and $u_i(r)$, $v_i(r)$, $i = 1, 2, 3$ have to satisfy:

$$(4), (6), x_i \geqslant 0, i = 1, 2, 3, \text{ and } (18) \text{ for all } r \in \Omega. \tag{26}$$

The model (25) and (26) is an example of a two-stage recourse model, belonging to an important class of stochastic programming models. (25)–(26) is again a linear programming problem, so it can usually easily be solved by way of standard software (although the number of variables and constraints in (25) and (26) is considerably larger than in the original deterministic linear programming problem). In this paper, a simple empirical distribution for rainfall R is taken. Although more appropriate distribution functions can be derived, for instance by making use of time series data of total seasonal rainfall, it is nevertheless advisable to use a simple empirical distribution here. The reason is that in the models a great number of parameters have to be estimated for all sorts of crops and applied agricultural technologies, for instance yields. To estimate yields for various rainfall patterns is very difficult, in particular if in addition new technologies are to be considered. In such cases, the estimation of yields in poor, average, and good rainfall years is already a difficult task (see e.g. Maatman et al., 2002).

The model to handle risks due to uncertain rainfall as illustrated in (25)–(26) is only one out of many approaches. It is beyond the scope of this paper to discuss various other risk issues, such as different risk attitudes of poor and rich farmers. Poor farmers may be risk averse,[14] because in a situation of survival they are not in a position to run risks. Rich farmers, on the contrary, may accept higher risk levels.

4. Application of Operations Research models in practice

After the illustration of some Operations Research models, we will now turn to some experiences in practice. The building of Operations Research models is a step-by-step process. As will be seen below, the development of the model is an interactive process[15] between researchers, local experts, farmers' organizations, and farmers. Usually, first a base model is set up, which aims to describe actual farmers' strategies. Once such a model has been constructed and verified, it can be extended to study new strategies.

[14]Risk aversion could, for instance, be handled by replacing the net revenues in (17) and (20) by utility functions, see e.g. Klein Haneveld and Schweigman (1985), and Ruszczynski and Shapiro (2003a, b).

[15]For a detailed discussion on such interactive processes and the 'systems approach', see Maatman (2005).

Operations Research models as illustrated above have been applied on a fairly large scale, for instance in several Ph.D. projects, which were supervised by the author of this paper. These Ph.D. projects were carried out in Burkina Faso, Bénin, Togo, and Eritrea. Some of the Ph.D. researchers were agricultural economists, working at national agricultural research institutes, others were staff members at economic or agricultural faculties of universities. In all cases the researchers were or became very familiar with the farmers' problems and their conditions of life. Characteristic of all projects was the interaction of the researchers with farmers, farmers' organizations, and local or national authorities. In some cases, this interaction was due to the mandate of agricultural research institutes to monitor agricultural development in some 'target villages' or to carry out field tests with farmers. In other cases extensive village-level studies were carried out during a couple of years in order to study farming systems and farmers' strategies in an integrated way.

Three Ph.D. projects were carried out in Burkina Faso. The project by Maatman (see Maatman, 2000) concentrated on strategies of survival of farmers in the north-west region of Burkina Faso. Special attention was given to farmers' response to uncertain rainfall, in particular to farmers' methods to adapt their farming to observed rainfall patterns. Another Ph.D. project, by Yonli (see Yonli, 1997), dealt with the role of cereal banks in villages in the North of the Central Plateau in Burkina Faso. A cereal bank may increase food security in the village, by keeping a communal safety stock. It may also allow alternative strategies of selling and buying cereals preventing 'forced sales' (see also Section 3). The third project in Burkina Faso by Ouédraogo (see Ouédraogo, 2005) was focused on the adoption of new agricultural technologies on the Central Plateau. In order to illustrate the role of such Ph.D. projects in practice, this project will be discussed below in more detail. In the Ph.D. project in Bénin by Adegbidi (see Adegbidi, 2003), the influence of rainfall uncertainty on farmers' strategies in the cotton region in the North of Bénin was studied. He came to the conclusion that due to rainfall uncertainty 'a flexible package of crops and agricultural technologies' is preferable to a strong reliance on cotton as the sole main cash crop. The Ph.D. study by Djagni in Togo (see Djagni, 2007) explores what, in the cotton region in the North of Togo, farmers' best response can be to the privatization of the market for inputs and outputs of cotton production. The Ph.D. project in Eritrea by Araya (see Araya, 2005) deals with the integration of crop cultivation, keeping livestock, and cutting and planting of trees in the Highlands of Eritrea. Trees have become a precious good in the Highlands, because almost all native forests disappeared due to the 30 years war between Eritrea and Ethiopia between 1961 and 1991.

For reasons of illustration, the Ph.D. project by Ouédraogo will be discussed in more detail. In the aftermath of the Green Revolution (see Section 2), the national agricultural research institute INERA in Burkina Faso, in collaboration with international research institutes, developed many 'promising' new agricultural technologies. During the last decades, extension offices of ministries, non-governmental organizations and farmers' organizations have taken initiatives to help to introduce these new technologies. Many projects were launched. The efforts were hardly successful. These disappointing results were, for Ouédraogo, who is himself a researcher of INERA, reason to inititate an integrated study where the possible technical merits of the 'promising' technologies were assessed in a socio-economic context. He wanted to investigate under what conditions the adoption of the 'promising technologies' could be feasible and attractive for the farmers. His approach was as follows.

He studied in detail 17 'promising' technologies; the new technologies were a combination of the use of modern inputs with application of improved local methods of water and soil management to increase soil fertility and water infiltration in the soil.[16] He made use of all results of extensive field studies initiated by INERA in two site villages on the Central Plateau in 1991/1992 and 1993. In these studies, in which much detailed information was collected on the farming systems, a distinction was made between poor, average, and 'rich' households.

Stepwise Operations Research models were developed for the two site villages, for the three categories of households and also at the village level where exchange of land and labor between the households was also taken into account. Many parameters in the model could be estimated by making use of the results of the field studies in the two site villages. Ouédraogo extended his model to handle rainfall risks in a similar way as sketched in (25)–(26) above.

First he developed a base model, which described actual strategies. The modeling results corresponded 'fairly well' to actual practices in the two site villages. Subsequently he extended his models by including the 17 new 'promising' strategies. By including a 'soil-nutrient balance' in his model, he could also assess the sustainability of the various agricultural practices. He divided the 17 new technologies into 'less intensive' and 'intensive' technologies; the latter require high doses of chemical inputs.

Ouédraogo arrived at the following conclusions: at present price levels of chemical inputs, farmers can only afford to adopt 'less intensive' methods. These are better than actual practices, but the methods are not sustainable in the long term. Only 'intensive technologies' will result both in considerably higher production levels and in sustainable agriculture. Farmers will only be able to afford the use of chemical inputs, if they can get access to (micro-) credits. The development of a competitive market for chemical inputs will be required as well. It may be expected to result in lower prices of chemical inputs for the farmers.

Finally, Ouédraogo touches a controversial discussion point. In the traditional societies of the Central Plateau, farmers do not own land, they have only the right to use it depending on approval by the clan or village community. According to Ouédraogo, this impedes farmers' investment in agriculture. He supports the idea of privatizing land ownership.

4.1. *Comments*

The example of Ouédraogo's Ph.D. project has been discussed here in more detail, in order to illustrate the nature of results of the use of Operations Research models. The results do not provide a blueprint for a strategy to solve farmers' problems. Far from that, Operations Research models constitute a tool of analysis, by which the rationale of farmers' actual strategies and the feasibility of adoption of new technologies can be better comprehended. This allows the researcher to participate actively in discussions with farmers and local and national authorities on how agricultural development can be realized in practice. The studies can strengthen the basis of policy making.

[16]In the 1980s and 1990s in Burkina Faso, in particular on the Central Plateau, on a large scale local measures were applied to improve water infiltration and to stop erosion, for instance by the construction of stone bunds. A widely applied local method to improve soil fertility is the technique of *Zaï*, where planting pits are dug and filled with organic matter, see e.g. Kaboré et al. (1994, 1997), Maatman et al. (1998), Reij and Thiombiano (2003).

4.2. Criticism

The use[17] of mathematical models has been criticized severely by social and political scientists, who are very aware of the complexity of problems of development, which depend to a large extent on power relations, social organization and human factors, which cannot be framed in mathematical models. Gunnar Myrdal (1970, p. 11) formulated his criticism as follows: "In presenting their concepts, models and theories, economists are regularly prepared to make the most generous reservations and qualifications indeed, to emphasize in the last instance development is a 'human' problem and that planning means 'changing men.' Having thus made their bow to what they have become accustomed to call the 'non-economic' factors, they thereafter commonly proceed as if those factors did not exist". All this criticism is justified to a certain extent. Mathematical models deal with partial problems only, the solution of development problems depends usually much more on political power than on research findings, and economic researchers are often more preoccupied by theory than by the complex reality. Nevertheless, the criticism is not convincing enough as will be discussed below.

4.3. Expectations

Many development problems are very complicated, because all factors of importance are strongly interrelated. It is very difficult if not impossible to deal with these interrelationships. In such situations mathematical modeling can play a role. In this paper, we have seen, for instance, that food security at the household level may depend on various factors, such as methods of cultivation, rainfall and soil conditions, access to credits, marketing strategies, risks, etc. With the aid of mathematical modeling, many of these factors can be studied and made coherent. Moreover, the influence of the change of conditions can be explored without the immediate necessity to carry out new field studies or experiments. The weakness of mathematical models, namely that they are only simplifications, is their strength as well. The structure of the model can be well understood; concepts and assumptions are well defined. For that reason it can structure the discussions and the understanding of the issues considerably. Each scientific analysis of complex situations is based on simplifications, each research approach on mental 'models' and perceptions. The contribution of mathematical modeling to solve problems can only be modest like the contribution of other scientific disciplines. Its contribution can be important though, if the modeling activities are integrated in an interdisciplinary approach in interaction between farmers, policy makers at the local level, and researchers.

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[17]Parts of this section were published in Schweigman (1994, p. 118).

has much been inspired by the intensive collaboration with Anselme Adegbidi, Bereket Araya, Kokou Djagni, Daniel Kaboré, Clemens Lutz, Arno Maatman, Souleymane Ouédraogo, Arjan Ruijs and Ernest Yonli. I owe much to them. I thank David Cappitt, Arno Maatman, Maarten van der Vlerk and three anonymous referees for their comments on this paper.

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Appendix A

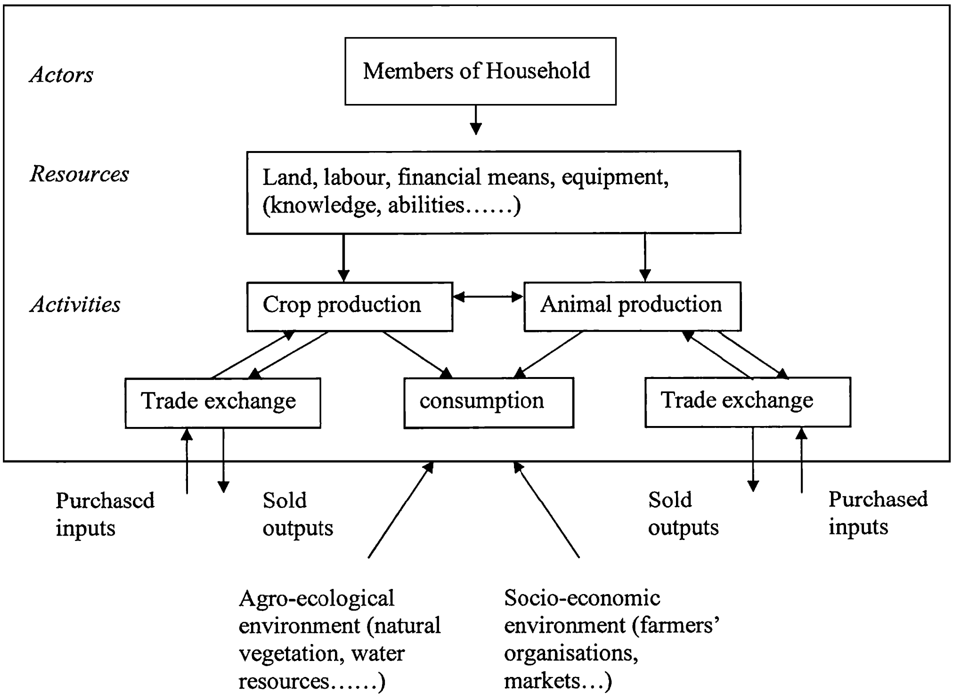

Fig. A1. Illustration of a system of a rural household.

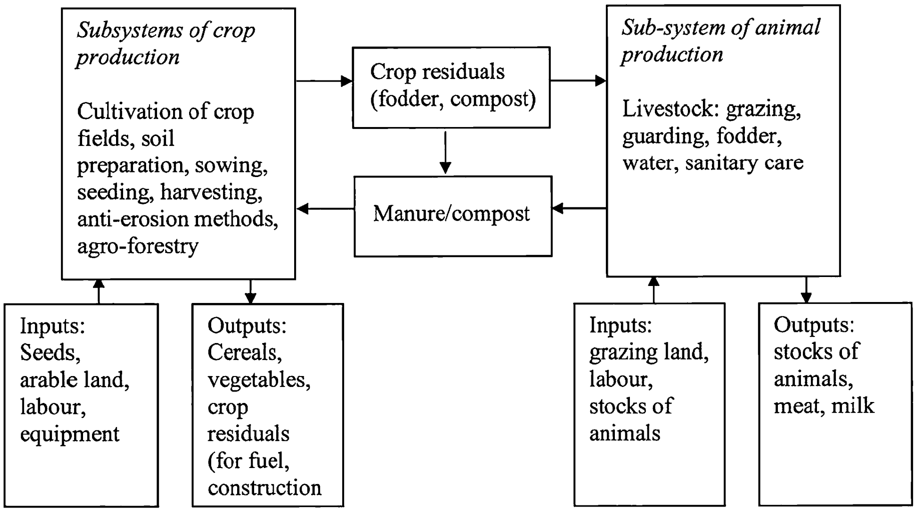

Fig. A2. Subsystems of crop and animal production and their interrelations (adapted from Maatman, 2000).