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Dynamic modelling of resource management for farming systems

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Abstract

With the rapid development of computer technology, numerous simulation models have been developed for agricultural systems and farms. Nevertheless, most of them are rather appropriate for developed countries as they have considerable data requirements and often aim at optimizing farm resources, excluding the farmer's household from the system. Yet, the latter is crucial for the understanding of semi-subsistence systems such as those found in developing countries.

We present a dynamic model of an agricultural system in the Central Highlands of Nicaragua. It aims at giving a deeper insight into the functioning of the system and the constraints the latter is subject to. Such an approach helps to explain why farmers make certain choices. Although for the study area few data are available, a robust model with a one-day resolution could be designed.

For simulation two groups of scenarios were chosen:

(a) Minimum farm sizes for the production of a certain food supply (e.g. basic staples) were assessed and the impact of increased fertilizer use was estimated. (b) Monoculture farms were simulated with the main crops of the region. The production of calories, protein and added value were chosen as indicators.

We determined the labour requirements for both groups of scenarios.

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Simulation results show that the latter is a limiting factor. This is true even for farming systems aiming at covering minimum needs (food, elemental health care and schooling) only. We can show that farmers' strategies (e.g. crop mix, fertilizer application) are crucial for the system. Last but not least, we produce some evidence for the advantage of the current crop mix in the study region.

Keywords: Resource management; Simulation; Farming systems; Nicaragua

1. Introduction

Food resources become scarcer on a global scale. Should this trend continue, prices for food will inevitably start to rise and, on the long run, importing any significant proportion of staples must be regarded as impracticable for many developing countries. For nations with a rapidly growing population, considerable agricultural improvement and development will be indispensable if sufficient food of satisfactory quality and the energy to prepare it are to be provided. The understanding of the main agricultural regions as entities with their own specific resource endowments and constraints, characteristic socioeconomic patterns and cultural values is therefore crucial.

With the development of computer technology, the simulation of agricultural systems and their components has gained importance. Numerous publications are available on this topic and sophisticated models have been developed (for a review see Jones et al., 1997). They can be grouped into three categories:

1) Crop simulation models;
2) Optimization models;
3) Models supporting decision making by farmers and policy makers.

The first group operates mostly at a field scale in order to predict yields under varying conditions (e.g. Jones and Kiniry, 1986; McKinion et al., 1989; Matthews and Hunt, 1994; for a review see Sinclair and Seligman, 1996). Nevertheless, there are many resource constraints farmers are not able to deal with at the field level (e.g. such as labour availability). Moreover, although new, modular models allow for more flexibility and are system-oriented (e.g. Keating and McCown, 2001; McCown et al., 2002), the important role of the farmer's household and its needs concerning food, health care and education are often neglected. As most of these models concentrate on crops, the animals and the contribution of animal products to the farm family's nutrition are not accounted for. Yet, these are crucial points for developing countries, where many farmers aim at self-sufficiency. Castelán-Ortega et al. (2003a,b) have considered many of these factors for smallholders in Mexico by combining two biological (CERES maize and a cow model) and one socio-economic model and a survey database.

The second group of models optimises the use of farm resources, minimises costs, or determines the minimum requirements for a specific farm income, and can analyze farm response to policy change, mostly under the hypothesis that farmers are profit maximisers (e.g. Caillavet et al., 1994). Yet, agricultural producers may be highly influenced by cultural values (Lee et al., 1995). Furthermore, smallholders in developing countries often try to avert risk in the first place.

The third group of models supports farmers' decision making. These models may need considerable amounts of data, describing the management practices of interest under the soil and weather conditions of the particular farm studied (e.g. Williams, 1995). Yet, for many regions of the developing world such information is not available. To generate it, a time-consuming and costly measurement program is required. Secondly, models set up for high-input systems in temperate regions may not be appropriate to simulate the low-input situations in most developing countries. In general, characteristics of some existing models may not be ideal, for example having a time resolution of one year (Shepherd and Soule, 1998). Nevertheless, seasonal oscillations are essential in systems oriented towards self-sufficiency. Farmers have to manage stocks and carefully plan ahead. Thus, in order to understand such constraints, models need to have an appropriate time step.

The key questions of the study were the following:

1. How can an agricultural region of a developing country where data are scarce be modelled dynamically in order to gain insight into the resource management of farmers?
2. Which factors are limiting the performance of the system?
3. What may be reasons for the fact that farmers have followed certain patterns (e.g. crop mix) for decades and centuries?

In this study we present a dynamic model of a specific agricultural system. The model used to describe the latter is based on material and substance flow analysis and considers the agricultural system as a whole and not just a specific part of it. We focused on the management of production and consumption of plant and animal products. The objective of the study is to gain deeper insight into the functioning of the system and the factors constraining it. Such an approach helps to explain why farmers make certain choices and why others are not successful. Although in the study region few data are available, a robust model with a one-day time resolution could be designed.

2. Study region

Nicaragua was chosen to be our subject of study because of several reasons. Firstly, its population grows rapidly (INEC, 2003). Secondly, the country's agricultural sector is important for the domestic economy. Thirdly, the agricultural sector consists of many smallholders. Last but not least, the first author has considerable experience in this country. San Dionisio, in the department of Matagalpa, is located in the central hillside range of Nicaragua. The municipality is the main staple producer of the so-called grain basket in the strip between Matagalpa and Esquipulas (FAO, 1995). Its topography is hilly with steep slopes and altitudes between 350 and 1250 m.a.s.l. Rainfall totals 1100–1600 mm/year and the rainy season lasts from May to October. The temperature ranges from 22 to 25 °C all year round.

The population density is about 250 inhabitants/km^2. The predominantly rural municipality of San Dionisio ranks among the very poor in Nicaragua (SETEC, 2001). Farmers cultivate mostly small plots: 70% of the farms are smaller than 6.5 ha (FAO, 1995). The main crops of the region are the staples maize (*Zea mais* L.) and beans (*Phaseolus vulgaris* L.). If farmers have access to enough land they may additionally raise livestock and grow coffee (*Coffea arabica*). Only few farmers opt for other crops such as sorghum (*Sorghum bicolor* (L.)), tomatoes (*Solanum lycopersicum* L.) or potatoes (*S. tuberosum* L.). Staple crops may be grown in both of the two harvest seasons *primera* (May–August) and *postrera* (September–December). Yet, there is a clear preference for planting maize and some beans in the first season, while in *postrera* mostly beans are grown. Maize is mainly produced for home consumption and fodder. Beans are partly sold and are considered to be the cash crop of the poor. Generally, agricultural work is done by hand. For field preparation, almost all farmers were found to burn crop residues and weeds. The herbicide *Gramoxone* (active ingredient Paraquat) is applied after sowing. Mineral fertilizers are widely used for the growing of maize, while usually none is applied to bean crops. Urea is the most popular mineral fertilizer, followed by 15-15-15 formula fertilizer. Although the use of inputs is common, application rates are modest. As a consequence, and as no alternative cultivation methods are used, yields tend to be low. In the region of San Dionisio chicken, pigs, cattle, horses and mules are raised. Most of the farmers in San Dionisio own at least some hens. Flocks are usually held in a free-range system. They are fed with maize grain and pick a large variety of leaves, grasses and insects. A big problem for poultry production is exotic Newcastle disease, which can cause a death rate of almost 100% in unvaccinated flocks. Exotic Newcastle can even affect vaccinated birds (United States Department of Agriculture, 2003). According to farmers, this disease causes significant losses every year.

Pigs and livestock are also raised in an extensive way. Nevertheless, the latter are fattened with maize during the last two months before slaughtering or selling. Cattle feed only on natural pasture, which leads to fodder shortage and severe bovine malnutrition during the dry season. As a consequence, fertility rates and milk yields of cows are low. Before the onset of rains in May most farmers burn their pastures, at least once every three to five years. Coffee is mainly grown above 800 m.a.s.l. under shade trees. Often it is not well maintained and the plants are old. After the dramatic collapse of coffee prices on the world market, farmers stopped using fertilizer for coffee production. For these reasons, yield tends to be low. Yet, the coffee forest also supplies firewood, the main energy source, which is predominantly used for cooking.

3. Methods

Material flow analysis (MFA), applied in this study, is described in detail in Baccini and Bader (1996). Various studies based on dynamic MFA models have been carried out in developed (Real, 1998; Zeltner et al., 1999; Hug et al., 2003; Müller et al., 2003) and developing countries (Binder et al., 2001; Bader et al., 2003; Pfister, 2003). The procedure is as follows:

a) System analysis, which includes the definition of the system's border, its processes and flows.
b) Mathematical description, including the definition of the system variables and the formulation of the equations that describe the behaviour of the system.
c) Calibration
d) Simulations and uncertainty analysis.

3.1. System analysis

The system (Fig. 1) represents a farm household in our study region. Its borders are the land managed by the farmer and it is composed of 13 internal processes: five represent crop production (coffee, beans, maize, pasture, and forest), four stand for animal production (chicken, pigs, cows, horses/mules), three for storage (coffee storage, bean storage, maize storage), and one corresponds to consumption and labour supply (household). There are 35 flows associated with those processes. For a better overview, in Fig. 1 similar flows are aggregated and numbered. In the model, however, they are calculated separately. The groups of flows are fertilizer (#1), animals purchased (#2), harvest (#3), seeds (#4), produce sold (#5), animals and animal products consumed (#6), firewood consumed (#7), additional food bought (#8), staples and coffee consumed (#9), fodder produced and consumed on-farm (#10), animals sold (#11) and grass (#12). Labour input is represented by a grey arrow. A dash-and-dot line represents the flows that are not relevant for describing the present functioning of the farms in the study region. However, they may be important for the simulation of scenarios.

3.2. Data collection

The data derive from an original field study, mainly based on interviews with farmers and key persons in Susulí, one of the 15 communities of San Dionisio (Pfister, 2003). After a first field-trip, which deepened the system understanding and provided basic data and local contacts, a second field-trip took place. Farmers were split into four groups, namely landless, smallholders, medium and big farmers. They are defined according to local categories: landless farmers own less than 0.35 ha, smallholders between 0.35 and 3.5 ha, medium farmers between 3.5 and 10.5 ha and big farmers more than 10.5 ha. Fifteen farmers of each category were sampled randomly and the following information was gathered in semi-structured interviews: farm

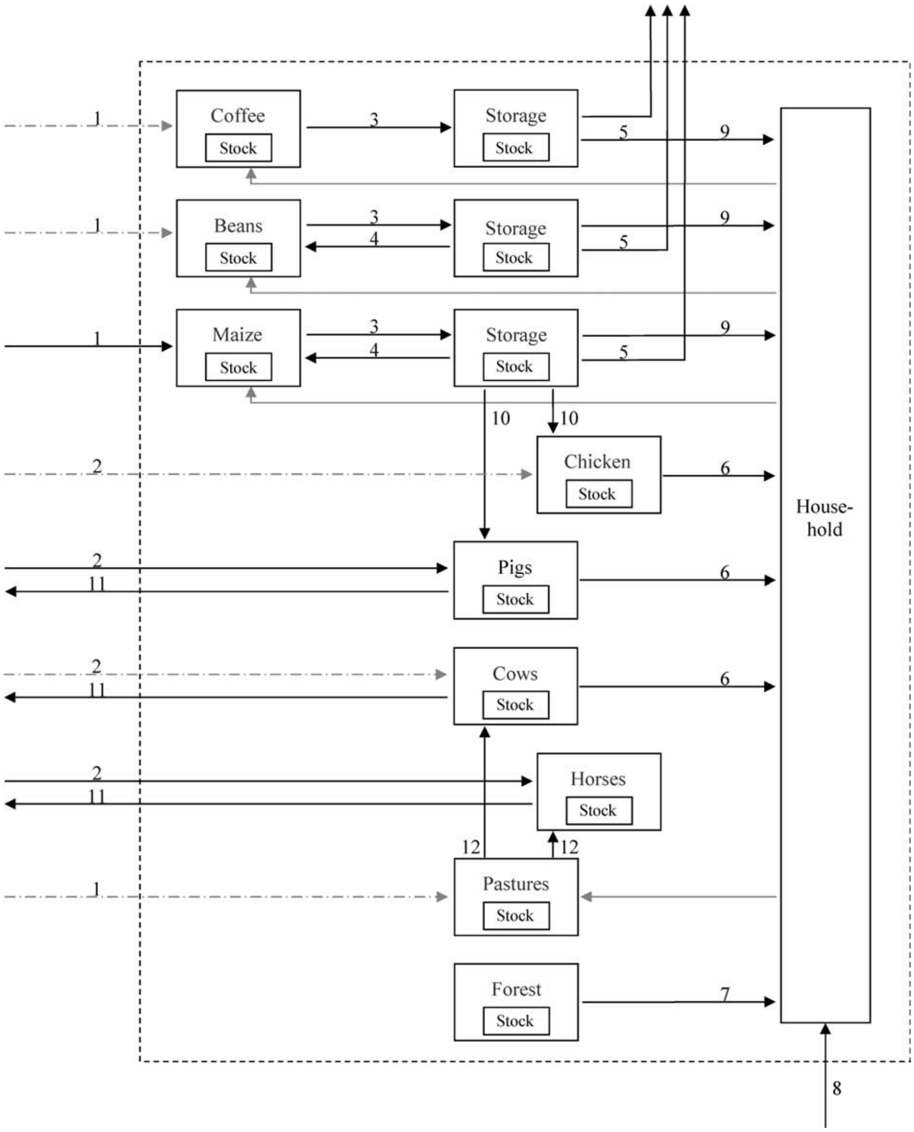

Fig. 1. System of the Dynamic Model.

management, fertilizer and pesticide use, different categories of yields (poor, average, good), storage and sale of grain, home consumption, human nutrition, fodder, animal holding and firewood source. Further data were obtained from interviews with key persons and from literature.

Despite the limited database, the results proved to be quite accurate in a cross-checking with data collected in a parallel study in the area of San Dionisio (Leemann, forthcoming). Further checks were carried out with the uncertainty analysis.

4. Mathematical model

Resource growth and use largely determine the resource management of an agricultural region. In order to account for both, we identified two groups of subsystems:

a) Subsystems regulated by biological growth patterns
b) Subsystems regulated by agents' decision patterns

4.1. Subsystems regulated by biological growth patterns

As early as 1837 Verhulst showed that in biological systems growth can be described by logistic functions. In the beginning they are exponential, then linear, until they reach a saturation level, arising from competition between plants or animals for water, nutrition and – in the case of plants – light. This effect becomes manifest when a population reaches a certain threshold. The logistic growth function has proven to be adequate for many biological and industrial applications (Fischer and Pry, 1970; Overman and Scholtz, 2002). Here we applied it to the following biological subsystems:

a) Maize
b) Beans
c) Coffee
d) Forest and
e) Individual animals.

The maize subsystem is described in detail in Section 4.4 in order to explain the design of the mathematical model. The other subsystems are built up analogously. Some important differences are discussed below.

For coffee, beans and maize only the harvest product is considered while plant material is ignored. Therefore, stocks on the fields build up periodically during the cropping season and are depleted with the harvest. In other words, when the grain is gathered, the stock on the fields drops to zero until the next cropping season. The impact of nitrogen fertilizer application on the saturation level of the growth curve for maize, beans and coffee cultivation was accounted for. The nitrogen input from burning plant residues is ignored. The modelling approach is similar to that discussed by Overman and Scholtz (2002).

Forest density at starting time t_0 is assumed to correlate with that of the coffee shade forest (Rivas, 2000), which is what most woodlands in the study region are. Their growth is slow and it takes hundreds of years to reach the level of saturation of the growth curve. The dynamics of the forest stock depends on the ratio between its growth and firewood extraction.

Animal subsystems are more complicated than plant subsystems. First, for plant subsystems such as maize or beans in contrast to animal subsystems, population is more or less in the same growth state, conditioned by the seasonal climate. Second, the number of individuals in plant populations is far larger than in animal populations, especially in smallholder farming systems. Therefore, for plant populations it is a good approximation to consider only the population as a whole and not the individuals. This is different for animal subsystems. Farmers consume only animals with a certain weight, which depends on their development stage and on other factors. Therefore, in principle, a model for the individual animal should be used. As a first approximation, age-class models have been applied for the animal subsystems. The number of age classes for each animal species is such that the important decisions of the farmer, such as the regulation of reproduction, consumption, sale and purchase, may be taken into account. The growth of each class is logistic, characteristic for the type of animal considered. As in our study region only few farmers breed pigs and horses, in the model they are all purchased. Chicken and cows, however, are bred on the farm. For the latter two species, a maximum number of animals has to be pre-determined by the user. Thus, we simulated farmers' knowledge about the ideal flock size for their farms. The surplus animals are consumed (chicken) or sold (cows).

4.2. Subsystems regulated by agents' decision pattern

4.2.1. Storage stocks

The stocks in the storage processes are replenished with the harvest produce and then depleted through on-farm consumption (gradually diminishing stock) (Fig. 2, top) and sales (immediate drop of stock). The storage processes may thus have two shapes: if the harvest is stored and consumed slowly, it takes shape (a) in Fig. 2, e.g. in the case of maize, or if part of it is sold immediately and the rest consumed, it takes shape (b), such as in the case of beans.

4.2.2. Consumption patterns

The consumption behaviour is modelled with three patterns (Fig. 2, bottom). Type (a) is the pattern for e.g. firewood, where consumption is constant. For food, either type (b) or type (c) is foreseen. Both are coupled with the stock, as farmers described in the interviews that consumption patterns adapt to the size of the food stocks. Furthermore, uptake does not drop below a certain level until provisions are exhausted, because of the minimum physical requirements of the human body. In option (b) the adaptation to the stock occurs in steps, while for (c) it is continuous. Nevertheless, simulations have shown that the difference between (b) and (c) is irrelevant. This indicates that this feature of the model is robust.

4.3. Assumptions

The following assumptions have been made for the dynamic model:

a) The natural conditions are similar for all plots.
b) There are no harvest oscillations due to climatic impacts.
c) Farmers harvest average yields.
d) All bad grain is fed to the chicken (no harvest losses).

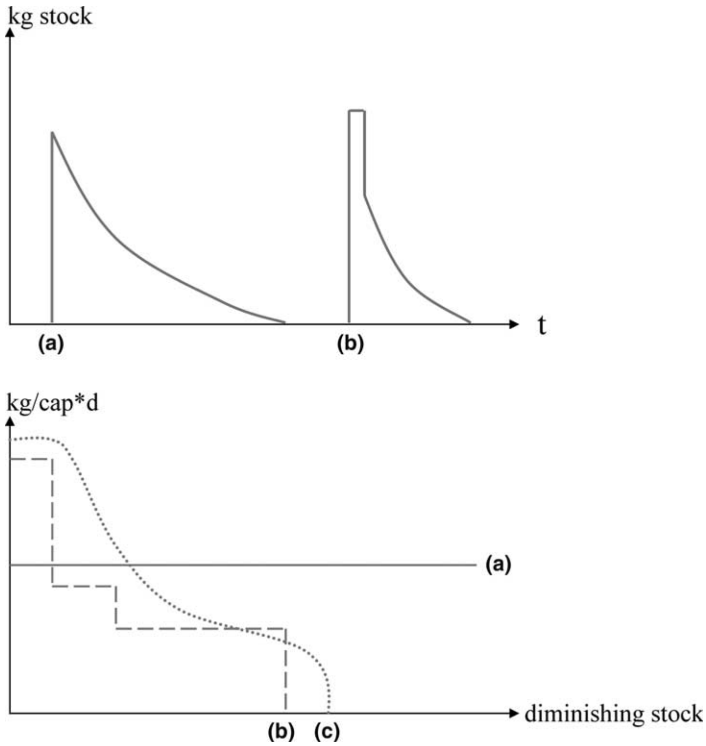

Fig. 2. Modelling of storage processes (upper part) and consumption patterns (lower part).

e) Horses and pigs are purchased and not bred on the farm.
f) Fertilizer application is carried out under ideal conditions having an optimal effect.
g) Once every three years Newcastle disease affects chicken flocks.

4.4. Mathematical description

Here the mathematical description is given for the maize module (Fig. 3). Other modules are mostly analogous. The most important differences are listed in Section 4.1.

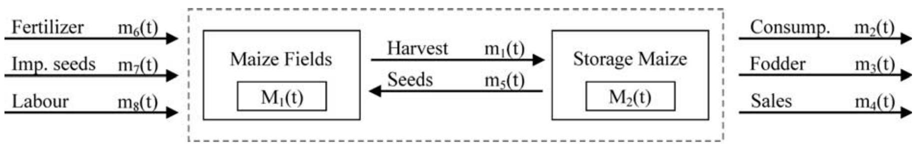

Fig. 3. Module maize and its variables.

4.4.1. Variables in the maize module

$M_1(t)$:	Maize stock on the fields
$M_2(t)$:	Maize storage stock
$m_1(t)$:	Maize harvest
$m_2(t)$:	Maize consumption
$m_3(t)$:	Fodder maize
$m_4(t)$:	Maize sale
$m_5(t)$:	Maize seeds
$m_6(t)$:	Chemical fertilizer for maize
$m_7(t)$:	Import maize seeds
$m_8(t)$:	Labour input maize

4.4.2. Balance equations

$$\dot{M}_1(t) = Q_{m_1}(t) - m_1(t), \tag{1}$$

$$\dot{M}_2(t) = m_1(t) - m_2(t) - m_3(t) - m_4(t) - m_5(t) \text{ as long as } M_2(t) \geqslant 0 \text{ else } \dot{M}_2(t) = 0.$$

$\dot{M}_1$ is the derivative of $M_1(t)$ with respect to time (for $\dot{M}_2$ it is analogous). A growth term for maize $Q_{M_1}(t)$ was introduced. It describes the growth of maize as a function of several parameters (see below).

4.4.3. Specific model approach

1. Maize growth (kg/d)
A logistic growth has been assumed (Fig. 4):

$$Q_{M_1}(t) = \begin{cases} P_{F_1}\left(P_{1,1} + P_{1,2}\frac{M_1(t)}{P_{F_1}} - P_{1,3}\left(\frac{M_1(t)}{P_{F_1}}\right)^2\right) & \text{during growth season from mid} - \text{July} \\ & \text{until the beginning of September} \\ 0 & \text{rest of the year} \end{cases} \tag{2}$$

$P_{F_1}(t)$:	Area of Maize production
$P_{1,1}\ldots P_{1,3}$:	Parameters for growth function of maize (normalized per unit area)

Parameters influencing the growth of maize (e.g. fertilizer application) are included in $P_{1,1}\ldots P_{1,3}$. Eq. (2) describes the fact that cobs grow from about mid-July until the beginning of September. Then they are left to ripen and dry on the fields until the main harvest takes place in October (see maize harvest).

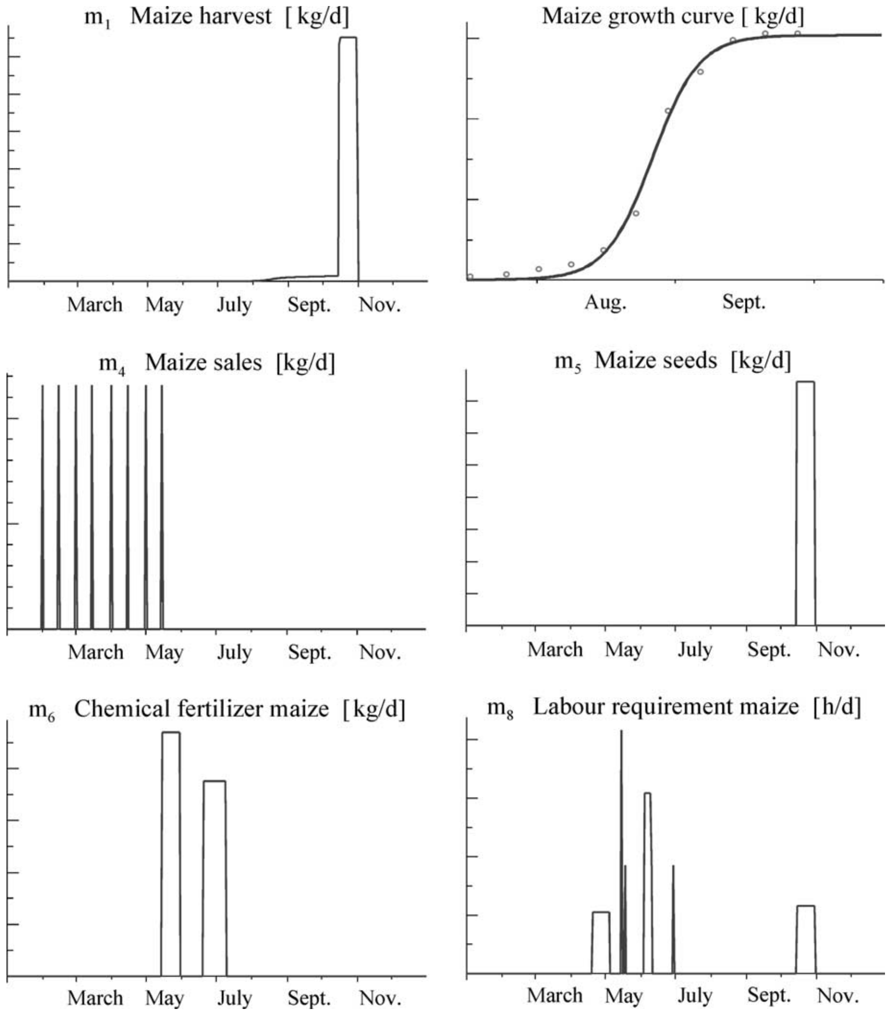

Fig. 4. Parameter functions of the module maize.

2. Maize harvest (kg/d)

$$m_1 = f_{m_1}(M_1, t). \tag{3}$$

The function f_{m_1}, as shown in Fig. 4, contains two parts: the pre-harvest and the main harvest. Maize pre-harvest starts in August, when all baby maize cobs except for one are taken off the plant and consumed. Farmers claim that this way the remaining cob develops much better. During ripening, maize cobs for daily consumption are gathered until the main harvest takes place from the middle until the end of October.

3. Maize consumption (kg/d)

$$m_2 = f_{m_2}(P_0, M_2, P_2). \tag{4}$$

The human maize consumption function f_{m_2} depends on the family size (P_0), the maize storage stock (M_2) and parameters for maize consumption, e.g. P_2. f_{m_2} is shown in Fig. 2, lower part. f_{m_2} has been parameterized by the maximum daily consumption, the stock threshold for zero consumption and by three parameters describing the shape of the function in Fig. 2.

4. Fodder maize (kg/d)

$$m_3 = f_{m_3}(T_1, M_2). \tag{5}$$

Fodder maize is a function of the chicken and pig population (e.g. T_1) and maize storage stocks M_2. It is similar to human maize consumption. Nevertheless, fodder maize uptake diminishes more rapidly than the latter.

5. Maize sales (kg/d)

$$m_4 = f_{m_4}(M_2, P_0, T_1). \tag{6}$$

Maize sales are a function of maize storage stocks M_2, family size P_0 and animal population T_1. We modelled the following simplified sale strategy observed among poor farmers: during the dry period, every two weeks a certain quantity of maize is sold in order to purchase salt, lime for the preparation of tortillas, oil etc. We kept the amount constant, as average family size does not differ considerably between farmers' categories (Pfister, 2003; Leemann, forthcoming). Maize selling takes place from the beginning of February until mid-May (see m_4 in Fig. 4).

6. Maize seeds (kg/d)

$$m_5 = f_{m_5}(P_{F_1}, P_3) = P_{F_1}\ 21\ \text{kg/ha}. \tag{7}$$

The function describing the flow of seeds depends on maize area P_{F_1} and seed-specific characteristics P_3. Based on our data, we assumed 21 kg/ha per harvest season (see m_5 in Fig. 4).

7. Chemical fertilizer maize (kg/d)

$$m_6 = p_x P_{F_1}. \tag{8}$$

As (a) nitrogen is the limiting nutrient in most parts of our study region (Orozco, P.P., personal communication) and (b) urea is by far the most popular fertilizer in the region, only the impact of N on the growth curve of maize was considered. Fertilizer nitrogen is applied at a quantity corresponding to the parameter p_x, which is chosen by the user (see m_6 in Fig. 4).

8. Import seeds (kg/d)

$$m_7 = 0. \tag{9}$$

Although traditionally farmers select seed grains from their own crop, in certain cases seeds might have to be imported. Yet, because of the financial constraints of farmers, we assumed this flow to be zero.

9. Workforce maize (person hours/day)

$$m_8 = f_{m_8}(P_{F_1}, P_4). \tag{10}$$

The function f_{m_8}, describes the labour required in person hours/day. It depends, among other things, on the total size of maize plots P_{F_1} and on the technology factor P_4. Nevertheless, the data gathered in the field already contain the technology factor. We assumed a certain time-span within which the tasks have to be carried out. Thus, the resulting labour requirements show how much labour is needed on the farm during this period (see m_8 in Fig. 4). If the available workforce of the family exceeds the demand on-farm, surplus labour can be sold. If it is insufficient, additional workers have to be hired or the task cannot be carried out as needed. Climatic events can severely impede the completion of agricultural activities, however, and thus family labour cannot be sold on all days when theoretically there is a surplus.

Eqs. (1)–(10) form a set of coupled non-linear equations for the 10 variables of the maize module. The parameters appearing in these equations are determined in the calibration procedure below. Assuming the starting values for the two stock variables, all other variables can then be calculated as a function of time.

4.4.4. Computer program

The dynamic model for the whole farming systems in Susulí consists of 130 variables. They are described in 130 coupled non-linear system equations, 98 parameter functions and by means of 353 parameters. The model was implemented in the program SIMBOX (Baccini and Bader, 1996; Bader and Scheidegger, 1996). All calculations were carried out on a PC with a Pentium(IV) 2 GHz processor and the operating system Windows XP.

4.5. Calibration and recalibration

Calibration is the procedure of fitting the parameters of the model equations to the available data. We did this module by module. The growth curves of maize, beans and coffee were calibrated based on data collected in interviews with farmers and key persons (technicians, NGO staff and researchers). The impact of mineral fertilizer nitrogen on crop growth was assessed as follows: for maize it was calculated with a rule-of-thumb provided by a researcher working in the region (Orozco, P.P., personal communication); for coffee it was established with information from farmers, while for beans it was based on information from the literature (Maingi et al., 2001) because of the lack of region-specific data. We determined the growth curve for pasture with the help of an expert (Schmidt, A., personal communication). For forest it was established with figures from El Salvador (Rivas, 2000) and for the individual animals with information from key informants (farmers, cattle traders and breeders). Data on flock and herd size were gathered in the farmer interviews and then used to determine the maximum number of animals. Storage and consumption patterns were based on our information and observations from the field.

In a second step, the model was recalibrated based on the system knowledge obtained in the interviews and the quasi-stationary model (Pfister, 2003). Some specific factors such as regulation of the chicken population and stock management had been assessed in the interviews. Each subsystem was recalibrated first independently. For maize and beans this was done by modelling specific farms. In the end the entire system was analyzed. It has some boundary conditions, which could also be included in the recalibration. Some of these are as follows:

a) The calorie consumption of humans and animals cannot exceed a certain maximum.
b) Many families (landless and small families) suffer from hunger at the latest in June/July.
c) Animal populations never grow above a certain threshold in non-specialized farming systems.

5. Simulation, results, discussion and uncertainty analysis

5.1. Scenarios

Access to land and crop choice are crucial to lowering the vulnerability of farming systems in the study region (Pfister, 2003). Therefore, these two factors were further investigated with the dynamic model.

The six scenarios chosen for analysis can be divided into two groups: minimum farms and monocultures.

For all scenarios the average family size was six adult persons (Pfister, 2003). For calorie consumption, children were set equal to 0.75 adults. Farmers were assumed to be free of debts and to own the land they work. Thus, in the simulations, they did not have to pay rent.

In order to estimate the confidence range of the results, an uncertainty analysis was carried out (see Section 5.4).

5.2. Minimum farms

5.2.1. Description of scenario group "minimum farms"

Pfister (2003) investigated the ability of different farmers' groups to purchase the basic consumer basket and the minimum needs. The latter were defined as staple foods, the most essential personal hygiene items (soap and toilet paper), one set of clothes per person and year, elementary school fees, and basic medicine. It has to be stressed, however, that the items considered as the minimum needs do not permit a dignified life for farmers' families.

As landless farmers are not able to produce their minimum needs on the little land they have access to (Pfister, 2003), they work as day-labourers to satisfy their vital requirements. This raises the question how much land a family needs to produce the staples needed for survival. Further, what is the surplus production required to purchase the minimum needs, and which factors limit the development of these farms?

On the one hand, the minimum farms scenarios try to assess the smallest possible size of a farm needed to

a) produce maize and beans for home consumption (farm "staples"), and
b) produce maize and beans for home consumption and a surplus of beans for sale to cover the minimum consumer basket (farm *canasta mínima*). On the other hand, we assessed the impact of fertilizer by modelling
c) a farm with the same size as a) but with higher fertilizer input for maize production and fertilizer for bean production (farm "higher input").

We assumed for all three options that maize was produced for home consumption and fodder for poultry. The field area necessary to satisfy this demand was assessed by modelling the storage stock with varying maize plot size and a given fertilizer application. Although the latter is quite high for semi-subsistence farmers by international standards, in the study region such quantities used to be common. Currently smallholders' fertilizer application rates are diminishing constantly due to lack of funds. For the assessment of the minimum maize field area, the maize stock was allowed to drop nearly to zero, but not altogether, in order to guarantee self-sufficiency. Under the given conditions, the corresponding size of the maize plot is hence the absolute minimum that can supply a family with this staple.

For scenario (a), the size of the bean plot was determined similarly. For (b), the amount of surplus beans necessary for the purchase of the minimum needs was computed and the size of bean plots for the production of home consumption and bean sales was assessed (Table 1). The price paid to producers was estimated as 250 Córdobas (39€)/100 kg. Option (c) has the same total farm size as (a), but higher fertilizer

Table 1
Minimum farm scenarios

Parameter	Minimum farm "staples"	Minimum farm "Canasta mínima"	Minimum farm "higher input"
Area maize (ha)	?	Same as "staples"	?
Area beans primera (ha)	?	?	?
Area beans postrera (ha)	?	?	?
Minimum total area per family per year (ha)	?	?	Same as "staples"
Fertilizer nitrogen applied to maize (kg/ha)	130	130	260
Fertilizer nitrogen applied to beans (kg/ha)	0	0	130
Maximum chicken (#)	6	6	6
Needs covered	Staples	Minimum needs	Staples + ?
Family size	6	6	6

Two minimum farms for a certain production level have been set up. In the case of "staple" the size of a farm that produces the staples needed to feed a family of six is determined. "*Canasta mínima*" assesses the land needed to supply a family of six with the minimum needs (food, few clothes, basic medicine), while "higher input" estimates the potential of a farm with the size of "staple" for doubled chemical fertilizer on maize, and fertilizing beans.

input – it is at the upper limit of current application rates by the farmers of the study region. Moreover, in option (c) beans are also fertilized. Thus the quantity of maize necessary to satisfy the family's needs is produced on a smaller plot and the rest of the land is used to grow surplus beans for sale. We assessed what this farmer could buy in addition to the basic staples. In all three cases, the fertilizer costs were accounted for. For all minimum farms, chickens were assumed to be the only animals owned.

5.2.2. Results of the scenario group "minimum farms"

Results of the simulation of minimum farms are presented in Table 2, Figs. 5 and 6. The main results are as follows:

a) In order to produce the minimum needs, a family needs almost twice the land needed to produce the basic staple needs.
b) Such a farm with four workers cannot produce their minimum needs without hiring outside labour.
c) By raising fertilizer inputs, farmers might increase output considerably.

The land needed for providing a family of six with the basic staple needs (food and fodder for chicken) is 1.25 ha. Of these, 0.75 ha are cultivated in *primera* and 0.5 ha in *postrera* (Table 2). Two-thirds of the former are used for maize cropping. The quantity of beans sold by these farmers is virtually zero. If the minimum needs are to be covered, then almost twice this amount of land is required, namely 3.25 ha – 1.75 ha in *primera* and 1.5 ha in *postrera*. Of the former, 0.5 ha is maize crop. Further calculations, not presented here, show that with this system, the farmer sells about 1300 kg of beans. Yet, he must obtain at least 250 Córdobas/qq (39€ per

Table 2
Results of minimum farms

Parameter	Minimum farm "staples"	Minimum farm "Canasta Mínima"	Minimum farm "higher input"
Area maize (ha)	0.5	0.5	0.5
Area beans primera (ha)	0.25	1.25	0.25
Area beans postrera (ha)	0.5	1.5	0.5
Minimum total area per family per year, Sum of two harvest seasons (ha)	1.25	3.25	1.25
Minimum total area per family per year for both seasons (ha)	0.75	1.75	0.75
Minimum total area per family per year with firewood supply (ha)	1.5	2.5	1.5
Fertilizer nitrogen maize (kg/ha)	130	130	260
Fertilizer nitrogen beans (kg/ha)	0	0	130
Maximum chicken (#)	6	6	6
Needs covered	Staples	Minimum needs	Staples + half of the minimum needs
Family size	6	6	6

In order to produce the staples needed by a family of 6, a farmer needs to possess 0.75 ha land. This figure rises to 1.5 ha if firewood has to be supplied by the farm. For "higher input", the same size of land is needed, while for the "*canasta mínima* " the demand rises to 1.75 and 2.5 ha respectively.

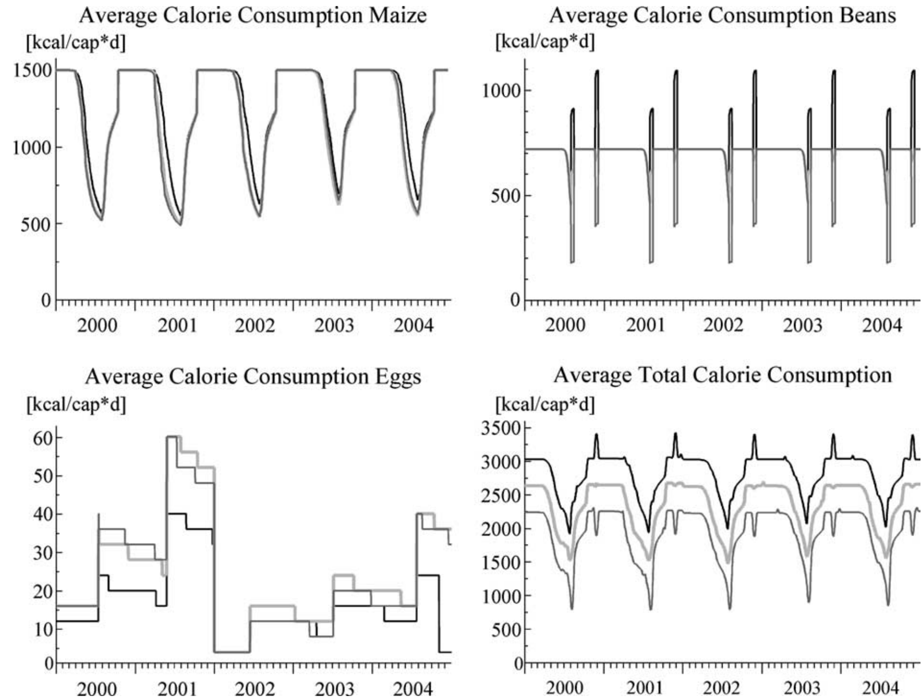

Fig. 5. Calorie production and consumption for the three minimum farms "staple", "*canasta mínima*" and "higher input".

100 kg) to pay the expenses for the minimum needs. The "higher input" farmer frees 40% of the land hitherto used for maize by doubling the fertilizer input. Thus, he may grow additional beans for sale. As fertilizer is applied to bean plots, he produces a surplus of roughly 800 kg. That way, about half of the *canasta mínima* may be purchased. Besides food, the families also require firewood. If we assume a production of 9 t/a of wood per hectare of forest, each family additionally needs a forest plot of 0.75 ha for energy self-supply. Hence, for the option "staples", a total of 1.5 ha is needed per family per year, which means that about 800 families could provide themselves with staples and energy on the area of Susulí. In order to obtain the minimum needs, only 480 families – roughly the current population – could live in the area. A precondition for these minimum sizes is stable, average yields. Nevertheless, in the study region, harvest losses due to droughts, floods and pest attacks are common and predictions indicate a further decrease of yields by about 20% due to climatic change (IPCC, 2001) and an additional decline because of deterioration of the soil resource base. In this paper harvest losses are not directly included in the model. They will be considered in further publications (Pfister et al., 2004). Nevertheless, we assume that real farms have to be larger in order to produce the staple or the minimum needs, e.g. by 20% if harvest losses are of this magnitude. In order to compensate for declining yields, plots would need to be enlarged constantly. As beans are

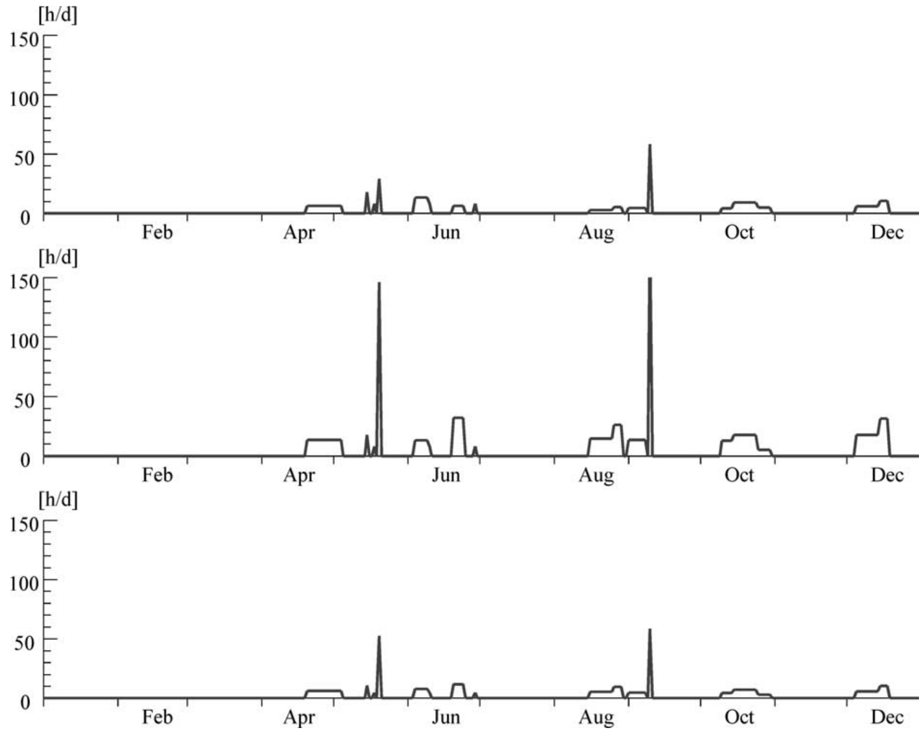

Fig. 6. Workforce needed for scenarios "staples", "*canasta mínima*" and "higher input".

especially vulnerable to the impact of the factors mentioned above, the size of bean fields would increase disproportionally as compared to maize.

For the calorie supply of the farmers' families, the following results were obtained (Fig. 5): Because of the setup of the model, maize consumption is equivalent for all three minimum farms. Randomized oscillations in the chicken stock cause small variations. The calories obtained from maize lie between 500 and 1500 kcal/cap*day and thus make up the most important share of the total supply. The range is wide because, with diminishing reserves, maize uptake drops considerably. The energy derived from beans amounts to 500–700 kcal/cap*day for the scenario "staples" and "higher input". For "minimum needs", it lies between 600–1100 kcal/cap*day. As eggs account only for a small share of the calorie input (maximum 60 kcal/cap*day), oscillations arising from different hen populations do not have a big impact (Fig. 5). Total energy uptake ranges from 800–2250 kcal/cap*day for the scenario "staple". During certain periods, therefore, energy supply is far below the minimum of more than 2000 kcal/cap*day. For "higher input" scenario calorie uptake lies considerably higher, namely between 1600 and 2600 kcal/cap*day, which indicates that even on these farms there are periods of severe food shortages. Last but not least, for the option *canasta mínima,* the calorie consumption ranges from 2000–3000 kcal/cap*day. During pre-harvest, for a short time it is even higher. The differences in calorie supply between minimum farms result mainly from the purchase of rice, sugar and oil with the revenue of the beans' sale.

The labour requirements for the three scenarios are shown in Fig. 6. Not surprisingly, those of the biggest farm *canasta mínima* are highest. During the period for sowing beans, the demand rises to 145 (*primera*) and 175 (*postrera*) h/day, corresponding to 18 and 22 labourers, if all plots are sown on the same day. This exceeds by far the manpower available from within the family. Even if smaller plots are sown, outside farm workers have to be employed. For the scenario "staples", the maximum labour requirements total 59 h/day in *postrera*, corresponding to 7.3 persons, the same as for the "higher input" scenario. The latter has in addition a similar peak in *primera*. If the normal workload apart from the peaks is analyzed (Fig. 6), it amounts to an average of about 6–13 h/day (staples), 14–18 h/day (*canasta mínima*) and 8–12 h/day ("higher input"), which corresponds to 1–1.5, 2 and 1–1.5 workers per farm.

In summary, with current technical levels, farmers cannot produce their minimum needs without employing outside labour. This implies the mobilization of further resources, many of them in the period between April and July, when cash and food are scarce.

5.3. Monocultures

5.3.1. Description of scenario group "monoculture farms"

When investigating a farming system, the following questions are raised among others: Why do farmers opt for a certain crop mix? How does each crop contribute to the system as a whole? Which advantages and disadvantages do monocultures have? In order to answer these questions, monoculture farming systems were set up in the model for the main crops or produce of the study region and compared (Table 3). We analyzed 1 ha plots for the following four options:

a) Maize, with animals being fed maize (chicken and pigs).
b) Beans,
c) Coffee,
d) Livestock.

The options were evaluated according to four criteria:

a) Current calorie supply per capita per day
b) Average protein production per capita per year
c) Average production of added value per year
d) Labour need (hours per day)

In an agricultural system in which a considerable amount of the produce is used for home consumption, the calorie yield of a crop plays a crucial role. We assumed that Nicaraguan farmers, who do physical work all day long, need at least between 2200 and 2700 kcal/cap*day. Women and children require somewhat less. Nevertheless, the calorie content of a food does not provide information about its nutritional

Table 3
Assumptions for setting up the monoculture farms

Parameter	Maize	Beans	Coffee	Pasture
Area maize (ha)	1	0	0	0
Area beans primera (ha)	0	1	0	0
Area beans postrera (ha)	0	1	0	0
Area coffee (ha)	0	0	1	0
Area pasture (ha)	0	0	0	1
Total area (ha)	1	1	1	1
Fertilizer nitrogen input [kg/ha]	130	0	0	0
Gramoxone (lt/ha)	4.1	2.8	0	0
Maximum chicken	11	0	0	0
Pigs	1	0	0	0
Maximum cows (cap/ha)	0	0	0	1
Family size	6	6	6	6
Maximum consumption (kg/cap*day)	0.4	0.4	0	0

The monoculture farms were designed such that each farm grows 1 ha monoculture of one of the main crops of the study region. Animal holding is included in the farm in the case of maize – as chicken and pigs are fed with maize – and pasture (cattle).

value. One important factor relating to nutrition is protein content. Therefore, calorie and protein production was investigated for each monoculture scenario. While these two indicators are directed mostly at products for home consumption, cash crops such as coffee are cultivated for generating income. Thus, the production of added value was chosen as a further indicator. Last but not least, most farms in our study region rely mostly on family workforce. Employing labour implies high costs at a time when cash is scarce. The need for day labourers was therefore estimated for each farming system and compared with the farms' possibilities. We assumed that one family has a maximum of four adult workers.

The following adaptations to consumption parameters had to be made for the monoculture farms. While usually 100–200 g/cap*day of beans are eaten, we raised this amount to 400 g/cap*day for the calculation of calorie production. Thus, an objective comparison of the potentials is possible, as maize is consumed up to 400 g/cap*day.

For pasture plots, figures are calculated for 7 ha and standardized to 1 ha. This allows for the assessment of realistic averages: NGO workers and experienced farmers recommend one local livestock unit per 0.7 ha of pasture. Thus, on 1 ha there is only livestock unit, while on 2 ha there are already three. As cow fertility rates are low, one cow calves on average once every two years and therefore, on a 1 ha plot, every two years no milk is supplied at all. Nevertheless, this does not represent the average milk production per hectare if more animals and more land are owned. As daily calorie consumption per capita is the focus of interest here, slaughtered cows have not been included in this analysis. The reasons for this are a lack of refrigeration facilities in the study region. Slaughtered cows have to be consumed quickly and therefore shared with many other families. In reality they are all sold.

For the coffee forest, the firewood was not priced, as currently most people gather it for free.

5.3.2. Results of the scenario group "monoculture farms"

The results of the scenario group "monoculture farms" are presented in Figs. 7–9. The main results are as follows:

a) Maize produces most calories per hectare per year, and beans the most protein and the highest added value. This enhances our understanding of farmers' current crop choice. Both crops also ensure a stable calorie supply throughout the year, while that of cattle ranching is highly variable.
b) Bean production is severely limited by labour shortage during sowing.
c) Cattle ranching and coffee production are not very labour intensive and are thus good options for farmers owning much land. Furthermore, important labour peaks occur mostly in periods when no workers are used for maize and bean production. Hence, there is much labour available.

When cultivating monocultures of 1 ha, most calories (1500–3000 kcal/cap*day) are produced with maize, including the supply with eggs and pig meat (Fig. 7). The main contribution to energy supply derives from the grain, although only one cropping season per year is modelled. Even though theoretically two crops can be grown per year, in the case of maize it is seldom done. For maize there are calorie consumption peaks as high as 4000 kcal/cap*day. They correspond to times when pigs are slaughtered, often when an important event is celebrated. They are shared with relatives and neighbours, and therefore the real energy consumption is not that

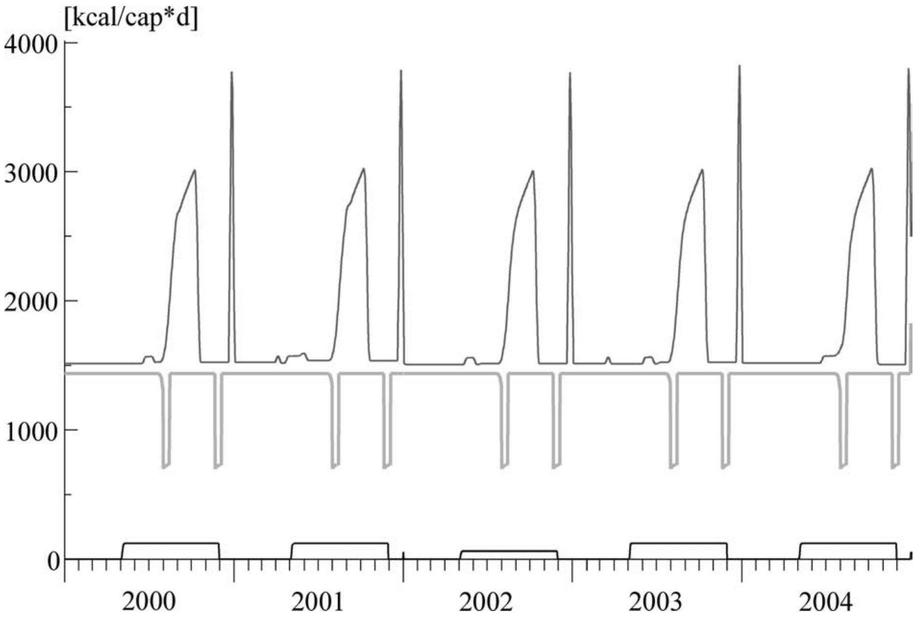

Fig. 7. Average calorie production of 1ha monocultures maize (dark grey), beans (light grey, thick line) and pasture (black) for a family of six.

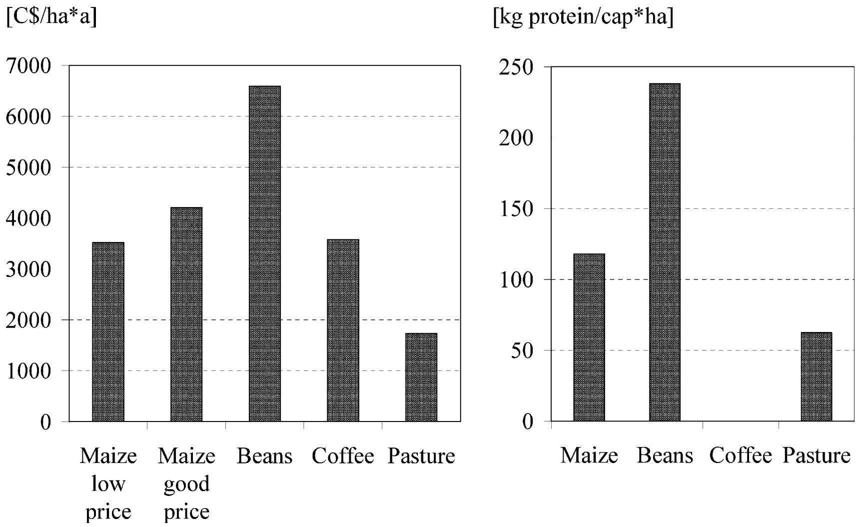

Fig. 8. Protein and added value production of monoculture scenarios.

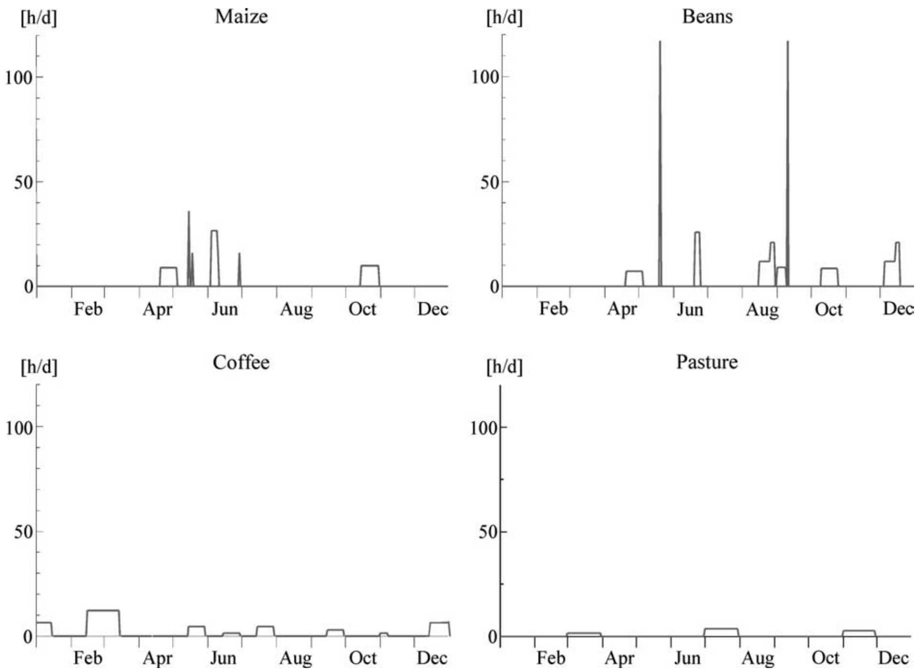

Fig. 9. Workforce needed for 1 ha monoculture scenarios.

excessive. Lower peaks represent pre-harvest of maize (smaller peaks). Second in calorie yield, with about 750–1400 kcal/cap*day per hectare, are beans. This is not enough to cover daily needs. Pasture plots generate merely an average of about 150 kcal/cap*day in the form of milk – due to poor fodder quality and quantity during the dry season at most during seven months a year.

Furthermore, the product can be stored at most for a few days, as in the study region virtually nobody owns refrigerators. There are thus periods without any calorie inputs from pasture plots, if no animals are slaughtered. Although these provide roughly 30,000 kcal per animal, their meat cannot be preserved because of the reasons mentioned above and does not contribute to long-term energy supply. Coffee plots do not yield any calories.

As regards protein, beans produce roughly 240 kg/ha*a (Fig. 8). This corresponds about to the yearly need of two families of six, if we assume a protein need of 50 g/pers*d, regardless of the amino acid composition. With 120 kg/ha*a, maize supplies exactly half this amount, whereof only 9% are animal derived. Pasture plots provide about 63 kg/a of protein in the form of milk and meat. Coffee plots produce none at all.

If beans are sold at a minimum of 250 Córdobas (C$)/qq (39€ per 100 kg), they generate the highest gains with about C$ 6500 (€ 464) per hectare per year (Fig. 8). Maize follows on rank two, if a good price is obtained. Yet, this implies that the grain can be stored for several months before selling. This option exists mainly for medium and big farmers. Small and landless farmers mostly sell maize – if at all – for 84% or less of the good price mentioned. This is about C$ 3600 (€ 255). The same amount can be earned at present with 1 ha of low input coffee. Pasture plots produce less than C$ 2000 (€ 143)/ha*a.

Labour peaks (Fig. 9) are highest for beans. They amount to 120 h/d*ha, or 15 persons. If we assume that the 1 ha plot is divided into three smaller units which have to be sown on one day each, the farmer needs five workers for three days. This means at least one person has to be hired. With maize, there are two critical periods for labour shortage. On one hand there is sowing in May, when requirements amount to 36 h/day and 4.5 persons. On the other hand, weeding is very labour-intensive and requires 3.4 workers (27 h/day) for eight days. For coffee, labour is required mainly for the harvest at the end of the year (less than 8 h/day, thus one worker) and pruning in February (about 13 h/day, 1.5 workers). Yet, the latter is often neglected and not carried out by the farmers. Last but not least, the peaks for pasture cleaning are less than 8 h/day. If farmers burn the pasture, the labour input is even less.

5.4. Uncertainty analysis

As the data have a relatively broad range of uncertainty, error propagation was carried out in order to estimate the effect of parameter uncertainty on the results. The minimum farm was chosen for analysis. As the consumption of sugar, rice and oil have a considerable impact on total calorie consumption, they were included.

Table 4
Parameter uncertainty

Parameter	Value	Unit	Estimated uncertainty (%)
Area maize	0.5	ha	20
Area beans *primera*	0.25	ha	20
Area beans *postrera*	0.5	ha	20
Threshold value of human consumption of maize	50	kg/cap	30
Threshold value of consumption of beans after *primera*	3.5	kg/cap	30
Threshold value of consumption of beans after *postrera*	8	kg/cap	30
Maximum consumption maize	0.4	kg/cap*day	25
Minimum consumption maize	0.12	kg/cap*day	25
Maximum consumption beans	0.2	kg/cap*day	25
Minimum consumption beans	0.1	kg/cap*day	25
Beans stored per cap/d after *primera*	0.2	kg/cap*day	30
Beans stored per cap/d after *postrera*	0.2	kg/cap*day	30
Nitrogen input of chemical fertilizer	130	kg/ha	30
Eggs per hen laying/brooding	6/4	kg/a	50
Number of chicken per brood	6	No./brood	67
Sugar consumption	36.5	kg/cap*a	30
Rice consumption	36.5	kg/cap*a	30
Oil consumption	2	l/cap*a	30

For analysis the minimum farm ‘‘staple’’ was chosen. Parameter uncertainty was estimated (right column). They were varied one by one in order to detect those with a strong impact on the results. In a second step, they were varied concurrently in order to calculate the effect of uncertainty on the results.

The parameters listed in Table 4 were first varied individually. Substantial impacts were generated by altering the cropping areas, the fertilizer input, and minimum and maximum consumption figures. Modification of threshold values or beans stored per capita did not have much impact on the results. For maize, the uncertainty of area and fertilizer input results in an error margin of about ±250 kg for production figures, which corresponds to ±500 kg/ha – roughly a third of the total harvest. Accordingly, maize reserves of the household vary by about 250–350 kg, thus 500–700 kg/ha. For beans, the stock on the fields oscillates by 30 kg in *primera* and 60 kg in *postrera* – roughly 15–20% of the total harvest.

In a second step, the uncertainty of all parameters was taken into account concurrently. The results are depicted in Fig. 10. The overalll uncertainty of the assessment criteria varies considerably. In the case of calorie input (Fig. 10) it amounts to about ±500 kcal/cap*day. Sometimes it is even higher. At the upper limit, farmers consume roughly 3500 kcal/cap*day for half a year. This figure is rather high, but it should be noted that the maximum consumption of maize and beans was assumed to be at the upper limit in the model. Therefore, our calculated results may well be the actual maximum consumption figures of farmers.

Total labour requirement was calculated to vary only according to plot size. Thus, the uncertainty range of data describing labour input/ha for the different tasks is not included. It may be as high as 30%, depending on topographic conditions, workers, vegetation, etc.

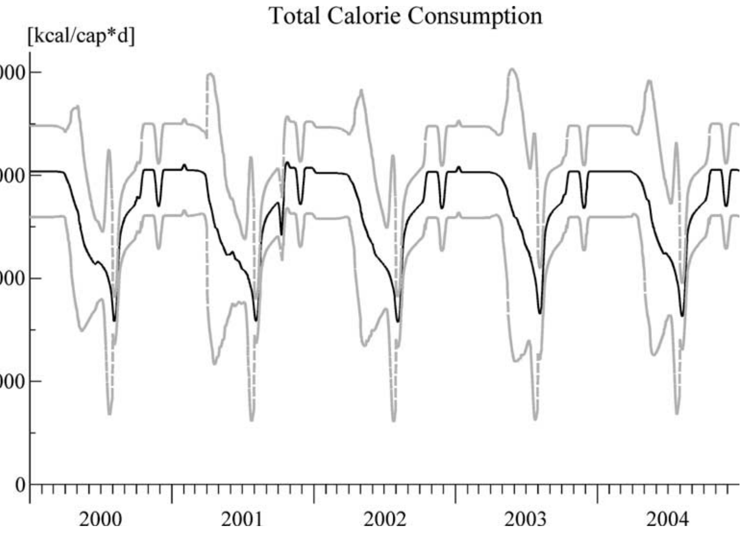

Fig. 10. Uncertainty margins for the assessment criteria "total calorie input" for the minimum farm "staples". All parameters were varied simultaneously. Total calorie input is depicted in black, uncertainty margins in grey.

6. Conclusions

A dynamic model based on MFA was set up to simulate a system of natural resource use by the inhabitants of a region. It is an agricultural system in a developing country for which data availability is poor. Good system knowledge and reliable key informants are indispensable for setting up a robust model.

By setting up the model we achieved the following: Firstly, insight into the functioning of the farms from the point of view of resource management can be gained. Secondly, the potentials and limitations of different management strategies can be discussed. Thirdly, understanding of how dynamic models can be developed in regions where data are scarce is improved.

Simulation showed that the key factors of the system studied are the crop mix, labour availability, and fertilizer application. Their interdependencies cannot be grasped without a dynamic model.

The crop mix is of central importance, as it determines calorie, protein and added value output, in addition to giving the option to hold animals as living bank accounts. Yet, the choice is severely limited by access to land, water scarcity during the dry period and labour shortages, as in the case of the sowing of beans. Not even the minimum needs can be produced without hiring additional labour. It thus becomes evident why farmers with land above a certain size sharecrop although they do not produce much surplus (smallholders): otherwise, they would suffer labour shortages. For medium and big farmers the cultivation of coffee and pasture, less labour-intensive crops, are options for avoiding bottlenecks in labour availability. Of course, these choices are also based on other strategies not studied with our model, such as risk aversion and seeking higher overall profits.

Raising the fertilizer input has considerable impact on the farming system. This is an interesting option in areas where land is scarce. For a sustainable system, organic fertilizer may be an attractive alternative.

Simulations also show that farmers have adapted to the local circumstances. Few of them have renounced to maize cultivation, despite the low price of this grain on the market, as it is crucial for calorie supply and animal holding. Beans provide the necessary protein and some cash, while coffee used to be the typical cash crop, even for smallholders, until its price drop on the world market. Livestock, as mentioned above, is mostly reared by farmers with bigger landholdings, as they can spare labour, and animals serve as bank accounts. Each crop thus contributes in one way or another to farm families' well-being and security. However, in order to understand agricultural systems oriented towards self-supply, seasonal oscillations are essential. Food supply, calorie and protein intake, labour offer and demand vary considerably throughout the year. As a result, farmers often make decisions that at first sight may seem disadvantageous from an economic point of view. They may become highly indebted between May and July, in order to purchase foodstuff and inputs and to pay workers. In order to repay the loans, farmers then have to sell part of their harvest when prices are low. Only with dynamic modelling, where we see that food shortages, input purchases and labour shortages occur concurrently, can we understand these actions.

In this paper we have omitted some important factors such as weather variability and pest attacks, which are responsible for substantial variations in yield. This was done to gain better understanding of the system's basic functioning. The latter may easily be reduced to input and output figures where too many factors are included in a system. Nevertheless, further steps for research would be to include climatic variation in the model and complement dynamic resource modelling with economic and anthropological studies about institutions, as these can give us further insight in the nature and dynamics of farming systems.

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