A generic model of shifting cultivation

Kjeld Rasmussen & Lasse Møller-Jensen

Abstract

A generic computer model of shifting cultivation system is presented, with the objective of showing how a simple description may explain important characteristics of such agricultural systems. Based on a brief account of some of the fundamental mechanisms of shifting cultivation, a simple model is formulated, focusing on (1) the flow of nutrients, and in particular the use of fallow vegetation for collecting and storing nutrients, (2) the allocation of labour with the purpose of satisfying subsistence needs and maximizing labour productivity, and (3) the management of agricultural land, in particular the opening of new fields and abandonment of old ones. In relation to (2) and (3), a 'decision rule' has been formulated, expressing how farmers select between a number of options in order to obtain the goals of satisfying food needs and maximizing labour requirements. It is demonstrated how this simulation model produces the expected behaviour of a shifting cultivation system, which indicates that the most fundamental mechanisms are represented in the model. Finally, a test of the response of the model to an increase in the population density is carried out. It demonstrates that increasing population density will lead to a shortening of the cultivation-fallow cycle and to a decrease in labour productivity.

Keywords

Shifting cultivation, mathematical models, simulation, agricultural systems.

Kjeld Rasmussen & Lasse Møller-Jensen: Institute of Geography, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K., Denmark. E-mail: kr@geogr.ku.dk; lmj@geogr.ku.dk

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Objectives

This paper will present a computer model of a certain class of agricultural systems, termed 'shifting cultivation' systems. The model will represent what is believed to be the most fundamental principles and mechanisms of this class of agricultural systems, that is the management of land, nutrients and labour in such a way that subsistence needs are met and labour productivity maximized. It is argued that most of the observable behaviour of shifting cultivation systems may be explained as the aggregated effects of rational choices made by farmers. The objective of modeling is to demonstrate how such decision rules control overall system behaviour, and to study the response of the system to an increase in population density.

The model to be presented is a purely theoretical construct, yet inspiration and certain input data have been extracted from the study of the agricultural system on Bellona island by Christiansen (1975).

The rationale of shifting cultivation

Shifting cultivation systems are characterized by the use of fallow periods longer than cultivation periods. It is generally assumed that the rationale of this system is that the 'nutrient capital' (stored in the soil and the fallow vegetation) is being built up during fallow periods, resulting in higher yields and labour productivity than possible in a permanent or short-fallow cultivation system. Alternatively, abandonment of fields/plots/gardens after few years of cultivation may be related to the invasion of weeds, causing a reduction of labour productivity. These two explanations are not mutually exclusive, of course, yet only the first possibility will be discussed here.

The practice of shifting cultivation is often associated with remote areas with subsistence-oriented agriculture. While this may not be generally correct, we will, in the present context, limit the discussion to cases where shifting cultivation is the main agricultural system and the main occupation of the individual households, and where the production is predominantly for subsistence.

In the case of subsistence oriented shifting cultivation, the common denominator of the two abovementioned possible explanations is that a field, plot or garden, cultivated in the preceeding season, is given up if two conditions are fulfilled: (1) The projected benefit stream of continued cultivation, calculated over a certain period (and with a certain discount rate), is less than that associated with the alternative options of concentrating efforts on the other fields or opening a new field, and (2) the total food production/benefit stream will not fall below the household requirements (including a 'normal surplus' for security (Christiansen, 1975)) because of the abandonment of the field.

Shifting cultivation may be seen as a special case of 'concentrational agriculture', as suggested by Christiansen (1992). In agricultural systems relying primarily on local resources of plant nutrients and not using machines to any great extent, high labour productivity may be obtained by concentrating plant nutrients and water in time and space. Concentration of nutrients in time implies that nutrients, gradually released from the soil, added from the atmosphere or from dust or silt deposition, are stored in the fallow vegetation or in the soil and utilized over a shorter period than the period of accumulation. This is the case of fallow- and shifting cultivation systems.

Objectives of modelling

Models are simplified representations of 'real systems'. The simplification may have many different purposes, the most general being the highlighting of the key properties and mechanisms of the system, as seen from a certain perspective. A model may be perceived as a hypothesis: The model suggests that the system behaviour may be explained on the basis of those few mechanisms, structures or principles, which are represented in the model, whereas those mechanisms not included in the model are suggested to be of less significance. The purpose of modelling may vary, however, and this will influence what is considered as the 'key properties and mechanisms', and the same system may therefore be modelled in a multitude of ways. In the present context the objective will be to develop a model suitable for studying issues such as (1) the relationship between decision rules applied by the farmer and the behaviour of the system, and (2) the general response of the system to increased population density. No attempt will be made to build a model useful for practical planning or prediction. The model will be extremely simple and generic.

Models may be classified in several dimensions, including:

- Static versus dynamic
- Descriptive versus normative
- Deterministic versus stochastic
- Spatially distributed versus spatially aggregated

Real, human systems are always dynamic, normative (in the sense that they are operated with specific objectives in mind), do have stochastic elements and are spatially distributed. Nevertheless, it is likely that a 'good' model (seen in relation to a specific modelling objective) must neglect some of these complexities.

In the present context we will choose to represent a shifting cultivation system by a model which is dynamic, deterministic and spatially aggregated. It is dynamic because temporal concentration of nutrients is a fundamental feature of shifting cultivation, and in order to describe this properly, the time dimension must be explicitly included. It is deterministic, since stochastic elements (such as climatic variability), however important they may be, are not believed to determine system structure. It is spatially aggregated, simply because setting up a spatially distributed model will be much more complex, and since data-requirements will be great. In the final section we will discuss how the presented model may be developed into a spatially distributed model. The presented model is descriptive, yet designed to test the effects of the human decision rules, especially as concerns labour allocation and the opening up of new fields and abandonment of old ones.

Previous modelling studies

Two previous studies on modelling of shifting cultivation, yet with somewhat different objectives, will be briefly introduced and discussed.

Shantzis and Behrens III (1973) develop a 'system dynamics' model of the Tsembaga system in New Guinée, described by Rappaport (1968). The model aims at providing an explanation of the cyclic behaviour of the system, associated with the role of pigs and rituals in the system. The description implies that the pig-population, recurrent ritual pig festivals (in which the major part of the pigs are slaugthered and eaten) and periodic wars play a role in the maintenance of equilibrium. However, this role is not described as a conscious 'strategy' of the farmers, merely as an automatic regulation mechanism. Thus the model represents a particular case of societal regulation, rather than the dynamics of a general shifting cultivation system. The model does not include a representation of the mechanisms of nutrient concentration and maximization of labour productivity, assumed to be fundamental here.

Gilruth et al (1995) develop a model of the spatial dynamics of a shifting cultivation system in the Fouta Djalon of Guinée Conakry. The model, organized in a 'geographical information system' (GIS) has the main objective of simulating the spatial spread of cultivated lands in a situation of population increase. Whereas its representation of the (non-spatial) decisions in a shifting cultivation system is relatively simplistic, its strength is in its predictions of spatial change. The model is very interesting seen from a methodological point of view, and the ideas may be used as a basis for expanding the present model to include spatial aspects as well. This would allow that distance from a village, as well as spatial variations in soil conditions affecting productivity, may be taken into account.

Model structure

Main themes and state variables

As indicated above, the present model will focus on three main - and strongly interlinked - themes, nutrient flows, land use and labour. The 'state variables', have been chosen to be

- population size, determining both food requirements and labour availability in a subsistence system
- the nutrient status of the fields
- the cultivated area

The model will be formulated as a set of 'difference' (or differential) equations in these three state variables. Thus, changes in state variables between time t and $t + dt$ will be calculated on the basis of values of the state variable at time t. This will allow simulation of the changes in the system state, also termed 'system behaviour'. dt has been chosen to be one year.

The system boundary

All systems are 'open' in the sense that they exchange energy with the environment. Human systems, such as those discussed here, are invariably interacting strongly, in terms of exchange of energy, matter, information, 'value' and people, with other systems. Localized systems are embedded in larger regional systems. This does not, however, rule out the fruitfulness of identifying a (sub-)system and studying its internal dynamics. To do this a system boundary must be defined, however arbitrary this may be. This implies that certain factors are defined as external, which means that they may influence (or even control) the system, yet the feed-backs from the system to these external factors are disregarded. In the present model such factors include:

- Climatic variation, drought
- Import and export of produce and production factors
- Im- and emigration, external demand for labour
- Birth- and death-rates

Considering these factors as 'external' to any real-world system is obviously not correct. In model-building simplification is required, however, and it is argued that the fundamental logic of a shifting cultivation system is independent of these factors. This system boundary is consistent with the initial assumption that a subsistence oriented system is being modelled. The choice of population in-/decrease as an external factor deserves special mentioning. Food output from the shifting cultivation system may, of course, control population, yet external factors are often of greater importance, when considering relatively short periods of time. By assuming a certain growth rate of the population, the effects of population increase on land use, nutrient status and labour productivity may be tested.

A first graphical model

The complex interrelationships in a shifting cultivation system may be represented verbally, as attempted above, graphically or by mathematical equations. The graphical representation may be one stage on the way to a full, formal mathematical representation. The graphical representation may either be made in an informal 'boxes-and-arrows' style or using a standardized graphical 'language', e.g. that suggested by Forrester (1968). In the following a mixture of the two alternatives will be used.

A first simple graphical model of a shifting cultivation system is shown in Fig.1, next page.

Structure and functional relationships

The land resources are described as a finite number of

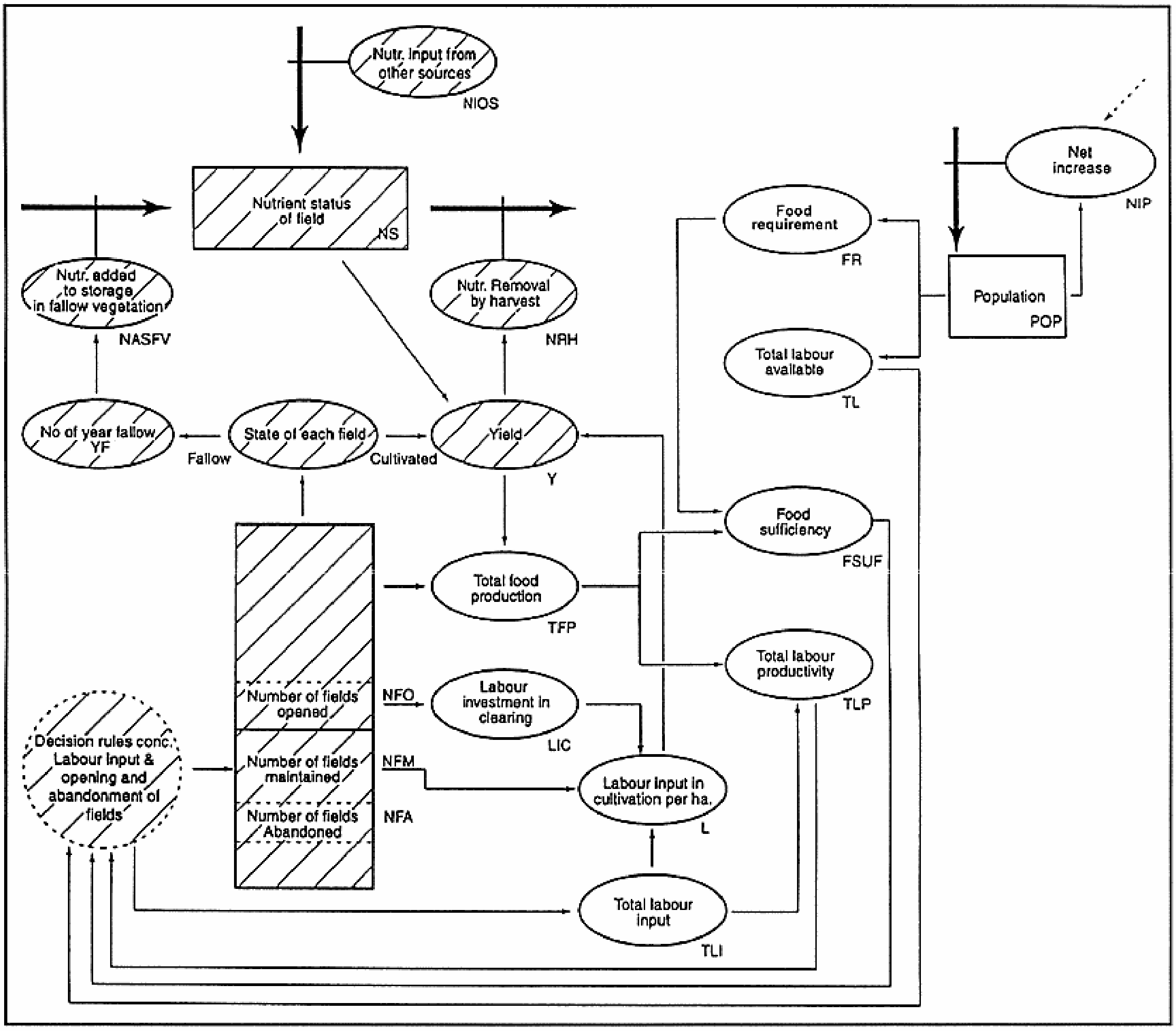

***Figure 1:** Overall system structure. Hatched parts indicate operations, carried out for each field, or variables, for which values exist for each field. Thick arrows denote flows (of nutrients or people), thin arrows denote influences or functional relationships.*

fields (in the model run described below: 15) of which a certain part, *NFC*, is cultivated. *NFC* is comprised of the number of fields maintained from the last growing season, *NFM*, and the number of new fields opened, *NFO*. Each field has the same area, *s*. The graphical model in fig.1 contains a hatched part, in which all variables have values for each of these 15 fields. For each time step one additional field may be opened and added to the fields already cultivated, and one field may be abandoned. Whether or not fields are opened or abandoned is determined by use of the decision rules, mimicking the rational choices of the farmers, aggregated to the village or island level. This will be described below.

The nutrient status of each field, *NUTR*, is updated for each time step by assuming that nutrients are added during fallow periods (at a rate depending on the number of years of fallow and the actual nutrient status at the time)

$$\mathrm{NUTR}(t+dt) = \mathrm{NUTR}(t) + k_1 * \left(1 - e^{-\frac{(maxnutr - NUTR)}{k_2} * \frac{k_3}{(YF+1)}} \right)$$

This equation expresses that the nutrient status in the next time step, *t+dt*, of a field, which is not cultivated, is determined as the sum of its nutrient status in the previous time-step *(t)* plus a term, representing the cumulation in the fallow vegetation and in the soil. This latter term becomes large if the nutrient status is far below the maximum level *(maxnutr)* and if the fallow is young (the number of years which the field has been fallowed, *YF*, low). The term decreases exponentially towards zero as *YF* increases, and *NUTR* approaches *maxnutr*. To sum up, the parameters and variables of the equation should be interpreted as follows:

- k_1 controls the maximum addition to *NUTR* per time step
- k_2 and k_3 control the rate of recovery of *NUTR* during a fallow period
- *maxnutr* controls the maximum value, which may be obtained by *NUTR* after a long period of fallow
- *YF* is the number of years that the field in question has been fallowed

Likewise nutrients will be removed during cultivation by harvesting

$$\mathrm{NUTR}(t+dt)=\mathrm{NUTR}(t)-k_4*\mathrm{Y}(t)$$

- *Y(t)* is the yield (in tons of dry matter per hectar)
- k_4 determines how much the nutrient status is reduced per unit of yield

In addition, a certain inflow of nutrients (e.g. from the atmosphere) may be assumed to occur during cultivation.

The total labour available, *TL*, is determined by the population size, *POP*, as

$$\mathrm{TL}(t)=\mathrm{POP}(t)*t_1*WH$$

- t_1 is the fraction of the population constituting the agricultural labour force
- *WH* is the number of working hours per year, which may, as a maximum, be supplied by each member of the agricultural labour force

The labour input to agriculture, *TLI*, is determined by use of the decision rules, aiming at maximizing labour productivity, *TLP*. If a new field is opened, a certain investment is made in clearing the field, *LIC*, and this is subtracted from the labour available for cultivation in order to obtain a value for the labour input per hectar in cultivation:

$$\mathrm{L}(t)=\frac{TLI-LIC}{NFS*S}$$

Given the labour investment in cultivation per unit of area and the nutrient status of each individual field, the yield may be determined from the production function:

$$\mathrm{Y}(t)=Y_0*\left(1-e^{-c_1*\mathrm{NUTR}(t)}\right)*\left(1-e^{-c_2*\mathrm{L}(t)}\right)$$

This equation expresses that the yield will increase asymptotically towards a yield ceiling, Y_0, as the nutrient status, *NUTR*, and the labour input per unit of area, *L*, increase. The constants c_1 and c_2 determine how sensitive the yield, *Y*, is to the nutrient status and the labour input. Further, the expression implies that the marginal utilities of both nutrient and labour inputs are assumed to be decreasing.

If the yield is summed over all fields, the total production, *TFP*, is determined. On the basis of *TFP* and the total food requirement (including 'normal surplus'), *FR*, the food sufficiency, *FSUF*, may be calculated:

$$\mathrm{FSUF}(t)=\frac{\mathrm{TFP}(t)-\mathrm{FR}(t)}{\mathrm{FR}(t)}*100\%$$

FR is calculated as *p* * *POP*, where *p* is the food requirement per person (including 'normal surplus').

Further assumptions made

In the process of implementing the model a set of further simplifying assumptions are made. These include:

- The variety of crops grown in any shifting cultivation system has been represented by only one. This rules out the use of the model for studying crop rotations and changes in crop choices over time (e.g. due to population increase). It further implies that the model will not provide a framework for understanding the importance of seasonal variations in labour demands and availability, caused by cropping calendars.
- As mentioned, the land available has been subdivided into a number of fields of equal size, among which a variable number is cultivated at any time. This implies that the model functions at 'village-' or 'island-level', and that individual households farmers and farms are not represented. This further means that some sort of common property land tenure system is assumed to exist.
- It is assumed that the nutrient status can be described by only one parameter, which implies that one single nutrient is assumed to be globally limiting.
- Technology is assumed to be constant.

Modelling human decision making in shifting cultivation

The rationale of shifting cultivation was discussed initially: Labour is allocated, fallow land is assumed to be brought into cultivation and cultivated land left fallow according to certain decision rules, involving factors such as labour productivity (*TLP*) and food sufficiency (*FSUF*). The simplest rule, which may be imagined, will be the following:

> *The farmers will choose the option (with respect to labour input and to the number of fields cultivated, opened and given up) which is expected to provide just enough food (including 'normal surplus') and give the highest obtainable labour productivity within the next year(s)*

The model presented applies this rule at the level of a village or island. It is assumed that the overall behaviour of the system at village/island level can be explaned by this simple decision criterion.

The rule given above has been implemented in the model in such a way that a number of strategies are defined, and the one which is optimal, according to the two criteria, is selected for each time-step. A strategy is defined by a certain total labour input, and by whether or not a new field is opened or an old field abandoned in the next time step. Only the simplest version of the rule will be tested here: It is assumed that the 'planning horizon' of the farmers is only one year, and that only one (out of a total of 15) 'fields' may be opened and abandoned in each time-step. In order to test the optimality of each strategy, a 'forecast' for the next timestep is required. This means that, for each strategy, the likely yield of each field must be estimated. This allows the calculation of a production forecast and a labour productivity forecast for each strategy. On this basis the optimal strategy may be selected, and this is in turn applied as a basis for calculating all variables in the next time step.

The implementation of this decision rule is made in the following way:

(1) 6 different *TLI*-levels in the interval between 80% of the current *TLI*-value and the total labour available, *TL*, are selected.

(2) For each of these levels, 4 strategies with respect to opening and abandonment of fields are defined: (1) No changes will be made. (2) One new field is opened, no fields are abandoned. (3) No fields are opened, one is abandoned. (4) One new field is opened, one is abandoned.

(3) If a field is to be opened, the field with the highest value of *NUTR* is identified as the candidate. If a field is to be abandoned, the field with the lowest value of *NUTR* is identified as the candidate.

(4) For each of the 24 'strategies' (6 levels of labour input, *TLI*, combined with 4 land use strategies) a production forecast is made by assuming that the yield, for already cultivated fields, will be a certain fraction, n_1, of the yield in the preceeding year, t. To this the production of any newly opened field is added, and the production of any abandoned field subtracted. The labour input in the cultivation of each field is adjusted for changes in the area cultivated and for the labour invested in clearing a new field.

(5) The strategies giving a positive value of food sufficiency *(FSUF)* are selected.

(6) Among these, the strategy giving the highest forecasted value of total labour productivity (calculated as *TFP/TLI*, yet based on forecasted rather than 'real' values) is selected.

(7) Finally, all model variables are recalculated for the time step $t+dt$.

Input data: The (mis-)use of the Bellona case

In order to test the model, which has been briefly presented above, input data are required. These may be purely speculative or derived from an empirical case. Few - if any - empirical studies provide the necessary data for such an exercise, yet the Bellona-study by Christiansen (1975) comes close, since it has from the outset been designed as 'systemic' study. However, many of the mechanisms described in the detailed account of the agricultural system of Bellona are not represented in the present model, and data on a number of mechanisms, required by the model, are not provided by the study, making direct use of the empirical data difficult. Very 'generalized' empirical findings - combined with purely speculative 'data' - therefore constitute the input.

The values of parameters, used in the model run shown below, were:

k_1	= 5 'nutrients units'
k_2	= 100 'nutrient units'
k_3	= 20 years
maxnutr	= 120 'nutrient units'
k_4	= 8 'nutrient units'/tons dry matter

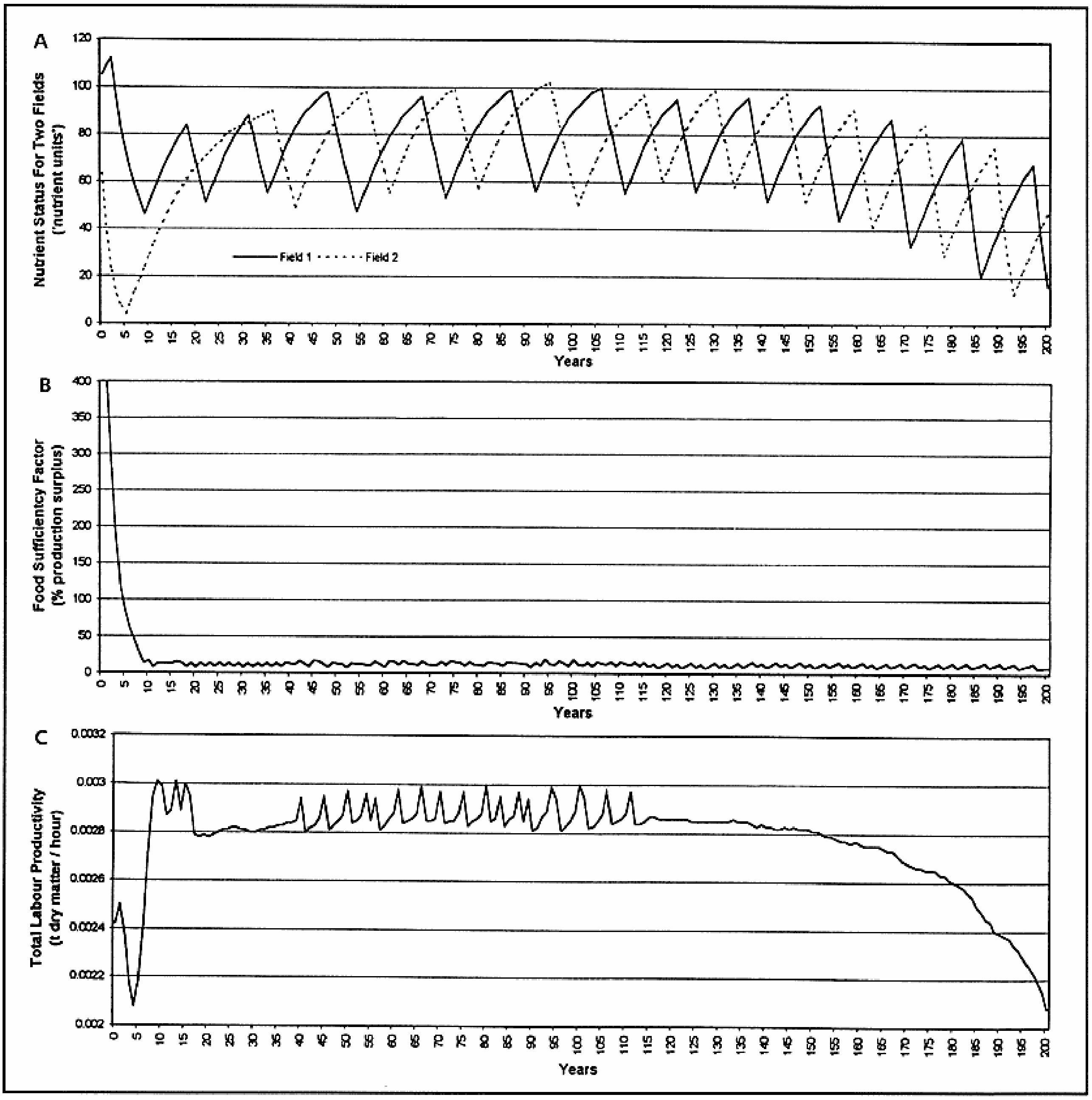

Figure 2: The behaviour of the (a) the nutrient status of two fields (one initially cultivated, one initially fallow), (b) the food sufficiency, and (c) the labour productivity. The x-axis gives the number of time steps (= years) the model has run. The first 40 years may be described as an adjustment to a stable equilibrium, due to that the initial values given are arbitrary. The period from year 40 to year 100 demonstrates a stable equilibrium with a constant population. The cropping/fallow cycle has a length of approximately 20 years. From year 100 and onwards a population increase of 0.7 % per year has been introduced. This gradually destabilizes the system, resulting in shorter cycles (15 years, which is the minimum possible in the present version of the model), declining nutrient status and decreasing labour productivity.

s	= 26.7 ha	t_1	= 0.4	c_2	= 1/3000 (hours/hectar)$^{-1}$
Y_0	= 10 tons dry matter/hectar	WH	= 2000 hours	LIC	= 2000 hours/hectar
n_1	= 0.9	c_1	= 0.04 ('nutrient units')$^{-1}$	p	= 0.25 tons dry matter/person

The initial values of model variables, used in the model run shown below, were:

POP = 400
NUTR = 100 'nutrient units' (for all fields)
NFC = 5

Model behaviour

Constant population
The basic behaviour may be described as stable, if the population is kept under a certain threshold, which may be termed the 'carrying capacity'. The various state variables will move asymptotically towards a stable equilibrium, which is the state in which the the food requirements are fulfilled and the labour productivity is at a maximum. This is illustrated by fig. 2 in the period between year 40 and year 100.

Increasing population: The Boserup case
If the population is increased gradually, corresponding to a 'doubling time' of 100 years, from a 'equilibrium level', the nutrient status and the labour productivity will change as demonstrated in Fig.2, in the period year 100 to year 200.

The behaviour, shown in Fig.2, corresponds well with the pattern suggested by Boserup (1965). The rotation period will become shorter than it was in the equilibrium case, nutrient levels will decrease, as will labour productivity, and eventually the system will collapse.

Conclusion and options for further developments

The presented simple model of shifting cultivation has been proven to simulate well the basic behaviour of such systems, both in an equilibrium situation and when exposed to increasing population pressure. The expected 'Boserupian' decrease in labour productivity and eventual collapse are observed.

The model may be further developed along (at least) three axes, in order to allow simulation of other important elements of the system's behaviour:

(1) By further elaborating the decision rules, represented in the model, it will be possible to relate more specific aspects of system behaviour to these rules. Strategies of farmers may be based on time-horizons substantially longer than one year, which has been assumed here, and this may have profound effects on behaviour.
(2) The model may be expanded to include more than one crop. This would make it realistic to study the rationale of intensification (under population pressure) through changes in crop choices. The Bellona case would be an ideal basis for such an expansion
(3) The model may be further developed into a spatial model, running in a GIS. The extensive map material, provided by Christiansen (1975), would form an ideal basis for this. This would further allow for the introduction of distance effects, as suggested by Christiansen (1977).

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