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Chapter 4

Shifting Cultivation and Tropical Deforestation

4.1 Introduction

Throughout the tropical belt, conversion of forest land into agricultural land is the most important direct cause of deforestation (Amelung and Diehl, 1992, p. 118; Myers, 1991; UNEP, 1992). Since the bulk of the agricultural activities in rainforests is small-scale agriculture, in this chapter an attempt is made to analyse the decision-making process of the peasant household. The focus will be on the intensity of land use, as this variable largely determines whether or not agriculture is undertaken sustainably. In general, the longer the fallow period and the shorter the cultivation period, the less the soil is depleted and the longer the vegetation is allowed to regenerate, and hence the better forests are able to perform their environmental functions (especially those related to biomass); see for example Herrera *et al.* (1981, p. 113). In terms of agricultural productivity, a long fallow cycle allows the soil to recover, thus restoring soil productivity. Therefore, sustainability requires a reduction in current output in order to achieve higher output in the future (Barrett, 1991a; Deacon, 1994). In the deforestation literature, attention is paid to factors that affect the peasant household's decision-making process with respect to sustainability. The literature focuses mainly on two phenomena: the role of tenure rights and the role of prices.

Regarding the prices of agricultural outputs, there has been a strong debate about whether or not higher prices for agricultural products improve the sustainability of agriculture: on the one hand it can be argued that higher prices increase the profitability of soil conservation, but on the other hand higher prices may also increase the profitability of current soil mining. The question therefore is whether indeed it should be attempted to increase agricultural output prices in order to stimulate soil conservation, or whether this policy measure would be counterproductive.

Regarding the role of tenure rights, peasant households are likely to invest in soil conservation only if it is reasonably certain that they themselves will benefit from the higher agricultural revenues in later periods. Thus, the tenure system is an important factor in land use decisions. Conceptually, a distinction can be made between the nature of tenure rights and their security. First, the nature of the tenure rights themselves may discourage sustainable agricultural use: if land rights are not permanent but only of a temporary nature (with or without predetermined length), the tenant is not stimulated to apply sustainable production techniques. Second, tenure rights can be permanent but may not be fully respected. Although the consequences of the first type of tenure insecurity are relatively straightforward, the consequences of the second type are more complex as peasant households do not have to accept land takeovers as they come.

In this chapter, both problems are addressed. To analyse the decision problem of peasant households in the right setting, the main characteristics of the practice of small-scale agriculture in rainforest areas are discussed first in section 4.2. It will be made clear that the current practice is to a large extent determined by the low agricultural potential of rainforest soils for permanent agriculture combined with the peasant household’s limited access to the various markets. The latter is caused mainly by the fact that distances in rainforests are long, especially because of lack of transportation; transaction costs can be such that it is not profitable for peasant households to participate. This phenomenon is found to have important consequences for sustainability of agriculture, both in the case of determining the effects of changing the agricultural output price and in determining the effects of land uncertainty. In section 4.3, the effect of changes in the prices of agricultural outputs on soil conservation are analysed. In section 4.4, the effects of uncertainty of land rights on the intensity of land use are discussed. Finally, conclusions are drawn in section 4.5.

4.2 The practice of small-scale agriculture in rainforests

Most agricultural activities in rainforest areas are carried out by small-scale peasant households applying shifting cultivation. As has already been explained in section 1.3, this is an agricultural technique in which a parcel of cultivated for only a limited period of time, after which the plot is left lying fallow to recover while the peasant household clears and cultivates another parcel of land. Therefore, agricultural practice in rainforest areas is very land extensive. In this section, it will be argued that this technique is well-adapted to both the agricultural potential of rainforests and the degree of integration of peasant households in the (inter)national economy.

Regarding their agricultural potential, it can be stated that rainforests are not suited for permanent cultivation of most crops. In spite of the presence of abundant vegetation, the agricultural potential in these forests is limited: generally, soil productivity in the first few years of cultivation is very high but falls drastically over the cultivation period. Basically, five reasons can be identified. First, natural fertility of rainforest soils is generally low because of adverse structural characteristics. These soils have only very low concentrations of major plant nutrients since they are severely weathered: they are not very deep and generally lacking in major plant nutrients. During the cultivation period, nutrient depletion can therefore take place quite quickly (Grainger, 1993, p. 30; Jones and O'Neill, 1993; Ruthenberg, 1980, pp. 23 and 25). Second, rainforest soils are generally acidic and characterised by high concentrations of aluminium and manganese (Grainger, 1993, pp. 30-32; Herrera *et al.*, 1981; Quan and Foy, 1994, p. 6). Third, the physical soil characteristics of land under cultivation tend to deteriorate as a result of erosion caused by excessive rainfall (Gijsman, 1992, p. 2). Fourth, weed competition increases as the natural revegetation process takes place, resulting in reduced agricultural productivity (Dvořàk, 1992; Sanchez, 1976, p. 383). Fifth, incidence of pests and diseases increases over the cultivation period, especially in continuous monoculture systems (Grainger, 1993, p. 50; Sanchez, 1976, p. 379).

In response to decreases in soil productivity over the cropping period, several options are available. First, in order to cope with the decreasing nutrient content of the soils, peasant households adapt their cropping sequence (Sanchez, 1976, pp. 376-378): in the first year of cultivation crops are planted that are most demanding in nutrients (such as grain crops), whereas in subsequent years less demanding crops are planted (such as cassava). The choice of crops is also adapted in response to increasing weed infestation: in subsequent years of cultivation crops with a higher canopy are chosen. Furthermore, multicropping can limit the incidence of pests and diseases.

Second, the decline in fertility as a result of nutrient depletion can be counteracted by the application of fertilisers. Indeed, *inorganic* fertilisers have been found to have a positive effect on soil productivity in rainforest areas (Sanchez, 1976, pp. 395-399). However, in practice this type of fertilisers is rarely used. The reasons are that they are expensive and often require skilled application so that they are generally beyond the reach of small-scale peasant households (Grainger, 1993, p. 34; Quan and Foy, 1994, p. 8; Ruthenberg, 1980, p. 60; Sanchez, 1976, pp. 383 and 399). *Organic* fertilisers (such as manure) are generally more readily available. However, the possibility of livestock keeping in rainforest areas is often limited because of the presence of diseases (such as sleeping sickness caused by the tsetse fly). Although this applies to a lesser extent to Latin-America, it is an important limiting factor for livestock keeping in Africa (Amelung and Diehl, 1992, pp. 54-55; Sanchez, 1976, pp. 386 and 400).

Therefore, for most crops (especially food crops) permanent agriculture is not viable in rainforest areas. The traditional agricultural technique applied in rainforest areas is shifting cultivation, which is well-adapted to the agricultural conditions in rainforests. By burning the vegetation, nutrients are released into the soil (Jones and O'Neill, 1993, p. 122). As often a large proportion of the nutrients is stored in the vegetation, topsoil fertility increases substantially (Grainger, 1993, p. 30; Ruthenberg, 1980, p. 45). Furthermore, fallowing is an integral part of the cropping system as it allows the forest to recover. Forest regeneration results in restoration of nutrients availability (both in the soils and in the vegetation), in improved control of the spreading of weeds, pests and diseases and in improved protection of the soils from erosion (Grainger, 1993, p. 50).

For these reasons, traditional shifting cultivation is based on cropping periods of only one to two years while subsequent fallow could be as long as eight to twenty years, and even longer (Gillis *et al.*, 1987, pp. 492-493;

Grainger, 1993, p. 50; La-Anyane, 1985, p. 3; López and Niklitschek, 1991; Sanchez, 1976, p. 348). Because of the length of the fallow cycle, shifting cultivation used to be itinerant: peasant households resettled, abandoning their houses near the old parcels and constructing new ones in the vicinity of the newly cleared plots. Depending on the local situation, this agricultural technique can sustain a population density of about 20-50 persons per km^2 with guaranteed subsistence (Geertz, 1963, p. 26).[1]

Regarding the economic environment in which shifting cultivation is carried out, traditional agriculture was aimed at satisfying the needs of the household. However, since the colonial era rainforest areas have become increasingly integrated into the (inter)national economy: nowadays, pure subsistence agriculture is rare (Jones and O'Neill, 1993; Ruthenberg, 1980, p. 30; UNESCO/FAO/UNEP, 1978, p. 429). In rainforest areas, the allochtonous population sells (part of) its agricultural produce at the regional and national markets, but the indigenous population also has increasingly become involved in market transactions. One of the main changes arising from this integration as compared to the subsistence situation is that new crops were introduced. Increased exposure to the needs of the national and international markets stimulated the production of so-called cash crops such as coffee, cocoa, rubber and palm oil. Their introduction has induced small-scale peasants to become sedentary because most cash crops are perennial crops. Thus, shifting cultivation in the *traditional* sense has been abandoned and replaced by sedentary long-fallow cropping systems: agriculture takes place in the neighbourhood of permanent housing. The construction of road networks has also affected the pattern of shifting cultivation: the desire of living close to the roads also resulted in permanent settlement.[2]

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[1] Assuming that 0.3 hectares per capita are needed for subsistence and assuming a cultivation period of two years and subsequent fallow of fifteen years, about 39 persons can be supported per square kilometre if land is used evenly (see also Ruthenberg, 1980, p. 62).

[2] Therefore, shifting cultivation in the traditional itinerant sense has almost become extinct: currently, the technique most often applied in rainforests would more appropriately be described as sedentary long-fallow systems. However, in the literature the term shifting cultivation is still widely used, and therefore the term will also be used throughout this study.

The fact that cash crops are very often perennial tree or bush crops, has environmental implications. For these crops, soil productivity is nearly constant over time: given a certain per hectare input of labour devoted to weeding and maintenance, output per hectare does not change much over time as permanent tree crops establish their own closed nutrient cycle (Pearce and Warford, 1993, p. 34; Sanchez, 1976, pp. 402-403). From an environmental point of view, these crops are preferable to food crops as they provide continuous canopy and root structure and are better capable of preventing soil erosion (Amelung and Diehl, 1992, pp. 87-88; Barraclough and Ghimire, 1990, pp. 15-16; Pearce and Warford, 1993, pp. 190-191; Repetto, 1989, p. 89; Sanchez, 1976, pp. 378-379; Southgate and Pearce, 1987, p. 12). Food crops are still produced by means of fallow systems: root and grain crops (such as cassava, peanuts, sorghum, and millet) are erosive (Hamilton and King, 1983, pp. 13-21; Pearce and Warford, 1993, p. 34; Repetto, 1989, p. 89).

From the increased integration into the national and even international economy it may be inferred that peasant households in rainforest areas have perfect access to all markets for inputs and outputs. However, this is generally not the case: households may be discouraged to participate in markets, for example due to prohibitive transaction costs (arising from travel costs, mark-ups by merchants or search costs), the shallowness of local markets or the existence of price risk and risk aversion (Padoch and De Jong, 1989, p. 110; Sadoulet and De Janvry, 1995, p. 149; Singh *et al.*, 1986, pp. 52-54).[3] Missing markets are actually a widespread phenomenon in developing countries (De Janvry *et al.*, 1991; Ellis, 1993; Githinji and Perrings, 1993; Sadoulet and De Janvry, 1995). Although peasant households in rainforests may produce for the national and international markets, food crop production is predominantly for autoconsumption: food markets are highly underdeveloped in developing countries (De Janvry *et al.*, 1991; Griffon and Ribier, 1996, p. 5; Koopman, 1992, pp. 3 and 5; Sadoulet and De Janvry, 1995, p. 154; World Bank, 1990, p. 60). In rainforest areas, travel costs are high, which implies that farmgate prices

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[3] Market failure, therefore, is not commodity specific but rather household specific (De Janvry *et al.*, 1991, p. 1401).

for the household’s output are low while the purchase prices (for manufactured goods or for food products) are high. The price band that arises between purchase prices and sales prices induces peasant households to rely on self-sufficiency in food production (Andreae, 1980, p. 157; Koopman, 1992, p. 5; Padoch and De Jong, 1989, p. 110). Furthermore, as most households in rainforest areas are essentially in the same situation vis-à-vis access to inputs whereas there is not much scope for specialisation, local food markets are also not likely to develop. In most tropical countries, marketing of cash crops is much easier because of the existence of parastatal organisations. Cash crops are an important source of foreign exchange, and hence governments of tropical countries recognise the importance of facilitating the marketing of these crops (La-Anyane, 1985, pp. 80-81). Therefore, cash crop production is the main activity to generate monetary income: by selling cash crops, income is earned that is needed to purchase manufactured goods. However, even though cash crop production often yields higher returns to land and labour, the introduction of these crops has not resulted in abandoning food crop production altogether because of various types of risks associated with cash crop production (such as price risks and production risks). Therefore, ’smallholder producers make a conscious effort to maintain subsistence food production alongside the ... cash crops’ (Von Braun, 1994, p. 62).

Regarding the peasant households’ access to production factors, the two main inputs are still land and labour. In areas with low population densities, labour is the factor that determines the size of the land area under cultivation. Generally, labour markets are underdeveloped in rainforest regions: to a large extent the peasant household can only mobilise its own labour (De Janvry *et al.*, 1991; Kaimowitz and Angelsen, 1997, p. 11; Koopman, 1992, p. 3; Sadoulet and De Janvry, 1995, p. 154; World Bank, 1990, p. 60). Most labour is dedicated to clearing and weeding, and therefore the decision how much land is to be cleared depends crucially on the amount of labour available for these activities: the decision to leave a plot lying fallow and to clear a new parcel of land is based on comparisons of the marginal productivity of labour devoted to either weeding or land clearing (Dvořàk, 1992).

As shifting cultivation is a very extensive production technique, in more densely populated areas not only the amount of labour available is important but also the land constraint can become binding. As has already been stated, most rainforest soils can sustain a population of 20 to 50 persons per square kilometre. However, this figure is derived under the assumption that land is used evenly. In practice, shifting cultivators have a strong preference for carrying out their agricultural activities alongside or at least near roads, so that output can be marketed more easily. This implies that even in rainforest areas that appear to have a low population density on average, actual pressure on the land can be very high.

In areas with perceived scarcity of land, labour is used to foster forest regeneration. In general, peasant households can undertake several activities that enhance natural soil regeneration (Ruthenberg, 1980, pp. 61 and 71; Southgate, 1990). For example, ridge and mound cultivation are labour demanding but soil conserving agricultural techniques. Furthermore, natural regeneration can be enhanced by planting specific species on land that is left fallow. Also, soil depth can be enhanced by mulching and by spreading manure and household refuse over the fields under cultivation (Jepma, 1995, p. 92; Ruthenberg, 1980, p. 48; Sanchez, 1976, pp. 380-387; Southgate, 1990; Southgate and Pearce, 1987, p. 3).

From this analysis it is clear that shifting cultivation is a technique well-suited for rainforest areas with low and medium levels of population density and with limited access to agricultural inputs. Given the importance of fallowing in this technique, it can be concluded that sustainable land use has distinct investment characteristics to it. Typically, the cultivation period should not be too long (the soils must not be depleted too much) and land should be left in fallow over a long enough period to allow it to revert to natural vegetation and to enable soil fertility and productivity to build up sufficiently to support adequate crop growth later (Barrett, 1991a; Jepma, 1995, pp. 86-87; La-Anyane, 1985, p. 3; Pearce and Warford, 1993, p. 149; Quan and Foy, 1994, p. 6; Ruthenberg, 1980, p. 25). Furthermore, as has already been explained above, peasant households can take several activities to enhance soil regeneration. Of course, as these measures can be seen as an investment, land right security plays an important role. In many rainforest areas customary land rights prevail; formal property rights are usually too expensive to obtain (Amelung and Diehl, 1992, p. 91; Lawry and Stienbarger, 1991; López and Niklitschek, 1991). Customary land rights are typically based on a claim of first settlement (Lawry and Stienbarger, 1991, pp. 10-11). As Angelsen (1995, p. 1717) states: '... a common feature in many areas is that forest clearing gives the farmer claims to the cleared land...'. These rights can be very secure, but increased population pressure may diminish social cohesion and customary land rights may no longer be respected, especially if immigration occurs (Cleaver, 1992, p. 70; López and Niklitschek, 1991; Mahar and Schneider, 1994). However, not all land is vulnerable to such invasions: land claims on cultivated land are usually secure.

4.3 The effects of prices on land use sustainability[4]

One of the most obvious indirect instruments to affect economic activity is intervention in the price structure. Direct government intervention in the price structure is not uncommon in developing countries: in many of these countries the prices of primary products (such as agricultural products and natural resources) have been set at an artificially low level in order to stimulate industrialisation and urbanisation, as an important part of a country's development strategy (see for example Ahmed and Mellor, 1988, p. 2; Krishna, 1967, p. 498; Pearce and Warford, 1993, pp. 189-191).

Intervention in the price structure of a country can be a powerful instrument in the battle against deforestation, at least if the response of a peasant household to price changes is known. As for the prices of agricultural outputs, there has been a strong debate about whether higher prices for agricultural products will improve sustainability of agriculture, or not. On the one hand, it can be argued that higher prices will result in higher returns on conservation, thus stimulating peasants to improve sustainability of their agricultural activities (see for example Pearce and Warford, 1993, pp. 189-190; Repetto, 1989; Southgate, 1990). On the other hand, higher prices may result in increased environmental degradation as the profitability of (current) soil mining increases (Lipton, 1987).

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[4] This section is based on Bulte, E.H. and D.P. van Soest (1997b), "A Note on Soil Depth, Failing Markets and Agricultural Pricing", University of Groningen, Groningen, mimeo.

In order to analyse the effect of price increases on sustainability, a model is constructed to represent the decision-making process of a smallholder household. It is attempted to include the main characteristics of smallholder agriculture in the model. One of the features that can have pervasive effects on price responses is that peasant households may not trade at all markets for inputs and outputs. In the first subsection, the reasons why higher prices for agricultural outputs may or may not result in improved sustainability are discussed in more detail. Next, the peasant household's price response is addressed in the case in which the household is assumed to face a complete set of markets (in section 4.3.2) and in the case in which one market is assumed to fail (in section 4.3.3).

4.3.1 Agricultural pricing policies and soil management

In the literature, both high and low prices for agricultural products have been proposed as measures to promote sustainable development. However, in a lucid paper Barrett (1991a) reconciled such conflicting claims by demonstrating that agricultural price reform will have only modest effects on soil conservation because the new price, either higher or lower than the old one, will affect both the marginal benefits *and* costs (in terms of forgone current production) of soil conservation proportionally. Hence, high prices will encourage current soil mining but will also provide an extra incentive to build up soil depth and fertility to increase future revenues. This finding implies that policies aimed at altering prices for agricultural output will have little impact on sustainable development in rural areas.

As acknowledged by Barrett, this result depends crucially on three assumptions: (i) farmers consider the new price to be permanent; (ii) the household produces one single crop; and (iii) the technical rate of substitution between nutrient extraction and soil conservation is constant. As regards the first point, when prices are expected to decline over time, supply will be concentrated in the period of high prices, hence short-run soil mining will be enhanced at the expense of future productivity. The second point pivots around the notion that if there are multiple crops that differ in their impact on the soil, changes in the relative prices of these crops will affect the crop mix and consequently soil conservation.[5]

The third assumption is crucial to this analysis. In general, the technical rate of substitution between nutrient extraction and soil depth is not constant as peasant households can affect the rate of soil regeneration. For example, peasant households do influence soil regeneration by levelling, terracing or irrigating their land (Repetto, 1989, p. 71), by mulching (Barbier, 1990; Tiffen and Mortimore, 1994) or by planting soil improving vegetation when land is left fallow (Quan and Foy, 1994, p. 8). In section 4.3.2, production is modelled under the assumptions that (i) peasant households can invest in soil regeneration and (ii) that there is a complete set of markets for inputs and outputs. It is, however, widely recognised that some markets are ’missing’ to certain households in developing countries: as has been argued in section 4.2, it may be beneficial for households not to participate in every market. Therefore, the assumption of a complete set of markets is relaxed in section 4.3.3.

4.3.2 The basic model with investment in soil conservation and a complete set of markets

In this section the basic Barrett model is extended in two modest ways. First, rather than assuming profit maximising behaviour, this section analyses the decision-making process of a representative utility maximising peasant household that acts both as a producer and as a consumer. Second, it is assumed that the household is able to combat soil erosion by investing in soil conservation. These investments consist of labour intensive measures (*e.g.*, mulching or building dams to capture run-off and stimulate on-site sedimentation). The peasant household is assumed to maximise the net present value of utility derived from consumption of (purchased) goods (c_G) and leisure (c_L). The model reads as follows:

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[5] An additional issue, not discussed by Barrett, concerns the observation that the discount rate may be a function of the ’wealth’ of a household (where the standard assumption would be that this discount rate becomes lower when income or wealth increases; see for example Ghatak, 1995). An increase in agricultural prices will result in more wealth, and thus in a lower discount rate which, *ceteris paribus*, will result in a thicker topsoil.

$$W = \max_{L_D, L_I, L_H, R} \int_0^{\infty} U(c_G(t), c_L(t)) e^{-rt}\, dt \tag{4.1}$$

$$c_G(t) = Pq(R(t), S(t), L_D(t)) - \omega L_H(t) \tag{4.2}$$

$$\bar{L} + L_H(t) = c_L(t) + L_D(t) + L_I(t) \tag{4.3}$$

$$\dot{S}(t) = Z(L_I(t)) - R(t) \tag{4.4}$$

In (4.1), U is the instantaneous utility function and r is the farmer's discount rate. The utility function is assumed to have the usual characteristics: the first derivatives of this function with respect to either argument (denoted as U_G and U_L) are nonnegative, whereas the second derivatives with respect to each argument (U_{GG} and U_{LL}) are negative. Equations (4.2) to (4.4) are the constraints the peasant household faces, where P is the price of the agricultural good produced; q is agricultural output which is a function of labour directly employed in the production process (L_D), soil depth (S, for example measured by the amount of nutrients stored in the soil) and the amount of nutrients extracted from the soil (R); L_H is the quantity of labour hired at the prevailing wage rate ω; $\bar{L}$ is the time endowment of the household itself; and L_I is the quantity of labour used in soil conservation. Finally, $\dot{S}$ denotes the change in soil depth (S) over time while Z is the soil regeneration function.[6] Equation (4.2) states that all net income (*i.e.*, after having paid the wage sum) is used for goods consumption. Consistent with Barrett, agricultural production is assumed to be a function of the soil depth (S) and the amount of nutrients extracted from the soil during cultivation (R), with q_R, $q_S > 0$ and q_{RR}, $q_{SS} < 0$. By choosing the appropriate technique or by selecting the appropriate crop variety, the peasant household is able to determine the nutrient extraction

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[6] Throughout this study, f_x denotes the first derivative of function f with respect to variable x; f_{xx} denotes the second derivative of function f with respect to variable x, and $\dot{x}$ indicates the time derivative of x.

(R) from the soil. In addition, labour is considered an input in the production function: L_D denotes direct labour ($q_L > 0$ and $q_{LL} < 0$). Equation (4.3) is the ’labour budget constraint’: the available quantity of time (consisting of the peasant household’s time endowment $\bar{L}$ and the quantity of labour hired) is allocated to leisure and labour used either directly in the production process (L_D) or indirectly to improve soil quality (L_I). Finally, equation (4.4) describes the development of soil depth over time ($\dot{S}$). In each period, an amount of nutrients Z is added to the soil, which, in contrast to Barrett’s model, is subject to labour devoted to conservation activities (with $Z_L > 0$ and $Z_{LL} < 0$). However, as a result of cultivation an amount of soil R is lost.

The current-value Hamiltonian of this maximisation problem reads as follows (suppressing time notation):

$$H(R,S,L_D,L_I,L_H,\lambda) = U(Pq(R,S,L_D) - \omega L_H, \bar{L} + L_H - L_D - L_I) + \lambda[Z(L_I) - R] \quad (4.5)$$

where λ is the costate variable associated with the equation of motion. This variable is akin to the Lagrange multiplier in a static optimisation problem and can be interpreted as the shadow price of a unit of soil depth: it reflects the marginal value of the state variable (S) at each moment t (see for example Kamien and Schwartz, 1981, pp. 151-153).

Upon applying Pontryagin’s maximum principle and assuming an interior solution[7], the necessary conditions for an optimum solution are:

$$\omega U_G = U_L \quad (4.6)$$

$$U_L = P U_G q_L \quad (4.7)$$

$$U_L = \lambda Z_L \quad (4.8)$$

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[7] Interior solutions are those solutions in which the nonnegativity constraints are not binding.

$$PU_G q_R = \lambda \tag{4.9}$$

$$\dot{\lambda} = r\lambda - PU_G q_S \tag{4.10}$$

Combining equations (4.6) and (4.7) yields the usual result that labour is applied in the production process up to the point where its value marginal product equals the wage rate. Equation (4.7) defines that for an optimal solution the marginal utility of leisure should be equal to the marginal utility of consumption of goods earned by working an extra unit of time. Similarly, the interpretation of (4.8) is that the increase in utility derived from consuming one extra unit of time in the form of leisure should be equal to the value of devoting this unit to soil regeneration. Equation (4.9) states that the immediate gain in utility of extracting an additional unit of soil should be equal to the marginal costs in terms of the forgone profits of extracting it currently rather than at a later point in time (λ); see also Dorfman (1969).

Equation (4.10) requires somewhat more explanation. Basically, the equation is an intertemporal nonarbitrage condition dictating that, for an optimal solution, no gain in utility can be achieved by reallocating extraction from one period to another. It indicates when the decision maker is indifferent between extracting an additional unit of soil depth and postponing extraction. In a simple mining model, the quantity extracted in each period should be such that the present value of a unit extracted is equal in each period, and hence the current-value shadow price (λ) should increase at discount rate r. This result is known as the Hotelling rule (Hotelling, 1931). The second term on the RHS of equation (4.10) arises from the benefits the decision maker derives from keeping an additional unit of soil depth: deeper soils result in increased agricultural productivity and hence increased consumption possibilities. Therefore, to be indifferent between extracting an additional unit of soil depth now rather than in the future, extraction should be such that the current-value shadow price of soil depth increases at the discount rate reduced by the marginal utility derived from soil depth.

Usually, intertemporal optimisation models are closed by adding a transversality condition to the first-order conditions. Transversality conditions are needed to specify end-point constraints (such as constraints that determine whether or not the stock should be depleted, whether the depletion period is fixed or free, etcetera). The transversality condition associated with problems in which there are only nonnegativity constraints on the size of the stock is that either the stock should be depleted in terminal period T or the *present*-value shadow price of the stock in this period ($\mu(T)$) should be zero. Indeed, if $\mu(T)$ is positive, extracting an additional unit would still be optimal and hence the stock would be depleted ($S(T)$ equals zero); if the soil is not depleted ($S(T)$ is larger than zero), the decision maker apparently does not attach a positive value to an extra unit of soil so that $\mu(T)$ is zero (Blanchard and Fischer, 1993, p. 43; Léonard and Long, 1992, pp. 22-23). In terms of the *current*-value shadow price ($\lambda(T)=\mu(T)e^{rT}$) evaluated at infinity, the transversality condition is (Léonard and Long, 1992, pp. 229-235):

$$\lim_{T\to\infty} S(T)\lambda(T)e^{-rT} = 0 \tag{4.11}$$

Therefore, either the soil should be depleted or its present-value shadow price should equal zero.

The model can be solved using the conditions (4.6)-(4.11) and the equation of motion (4.4). The steady state is defined as the case in which all variables have become constant: the time derivatives $\dot{S}$ and $\dot{\lambda}$ are set equal to zero (Kamien and Schwartz, 1981, p. 88). The optimum thus found satisfies the transversality condition: because the soil depth and the current-value shadow price λ become constant when the steady state is reached whereas the exponential term goes to zero as time goes to infinity, the transversality condition is met. The implications are that $Z(L_l)$ is equal to R (see equation 4.4) and that rq_R equals q_S (from combining equations 4.9 and 4.10).

Having derived an implicit expression for soil depth in equilibrium, comparative static analysis can be used to derive the effects of (exogenous) changes in P on equilibrium values of S. Under the assumption that all second cross derivatives are equal to zero, the comparative statics around the equilibrium situation are as follows (see appendix 4.1):

$$\frac{dS_c}{dP} = \frac{r q_{RR} q_{LL} Z_L q_L [\omega^2 U_{GG} + U_{LL}]}{D_C} > 0 \qquad (4.12)$$

In this equation, D_C is the determinant of the Hessian of the system describing equilibrium in the case of a complete set of markets (the subscript C refers to 'complete'). Appendix 4.1 shows that the sign of the determinant is strictly negative. On the basis of the fact that all first derivatives are positive and all second derivatives are negative, it can be concluded that dS_C/dP is positive: an increase in the price of agricultural products results in thicker soils. The reasoning behind this is simple. On the one hand, raising the price of agricultural output increases the marginal productivity of all inputs and hence the farmer's demand for all inputs. Thus, the peasant household would like to devote more labour to soil conservation. On the other hand, as a result of the fact that income is increased, demand for both consumption goods and leisure increases. In case of a complete set of markets, the increased demand for both (soil conserving) labour and leisure do not conflict as the household is able to reduce its own working hours (and increase its consumption of leisure) while increasing total labour input by hiring additional labour (at the current wage rate). Therefore, soil depth increases unambiguously in response to an increase in the price of agricultural output.

4.3.3 Investing in soil conservation assuming a failing labour market

We now consider the case in which labour markets fail so that the peasant household is not able to hire extra labour. This means that the peasant household faces a strict time constraint: given its time endowment $\bar{L}$, increased consumption of leisure can only be achieved at the cost of an equal decrease in the amount of time spent on either soil conservation or production. In the model, this implies that L_H is set equal to zero. Hence, for an optimum solution with a failing labour market, equations (4.2) and (4.3) should be replaced with $c_G = Pq(R,S,L_D)$ and $\bar{L} = c_L + L_D + L_I$, respectively.

Analogously to section 4.3.2, the model is solved by deriving the first-order conditions, setting all time derivatives equal to zero and applying

Cramer’s rule to the system of equations thus derived. Then, the impact of a change of the price level on long-run soil depth is (see appendix 4.2):

$$\frac{dS_F}{dP} = \frac{rq_{LL}q_{RR}Z_L q_L U_G \; [1 + \eta_G]}{D_F} \tag{4.13}$$

where the subscript *F* refers to ’failing’ and η_G is the elasticity of marginal utility of the consumption of goods with respect to quantity consumed (that is, $\eta_G = (c_G U_{GG})/U_G < 0$). Although the sign of the denominator is known (the determinant of the system is strictly positive, see appendix 4.2), the effect of price changes on soil conservation is now ambiguous. As is clear from the numerator, an increase in the price of agricultural output can result in an improvement or reduction in soil depth depending on the value of the elasticity of marginal utility of the consumption of goods with respect to quantity consumed. If the absolute value of η_G exceeds 1, the sign of dS_F/dP is negative whereas the reverse applies if the absolute value is smaller than unity.

The interpretation is as follows. Again, an increase in the price of agricultural products implies an increase in the demand for both labour and leisure. However, the peasant household is not able to relieve this tension by hiring additional labour: it has to clear its own market for labour and leisure. In this case, the environmental consequences of a price change depend on which demand function shifts out most: the demand for labour or the demand for leisure. If the absolute value of the elasticity of marginal utility of consumption goods is greater than unity (that is, an increase in the quantity of goods consumed results in a more than proportional decrease in marginal utility), marginal utility U_G falls substantially if goods consumption is increased in response to the agricultural output price increase. To restore equilibrium, marginal utility of leisure U_L must also decrease, which can only be achieved by taking more time off ($U_{LL} < 0$). This implies that more leisure must be consumed at the cost of hours spent on soil conservation and production.[8] Hence in equilibrium, *Z* (and, by definition, *R*) should fall. A reduction in *R* implies an increase in q_R

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[8] It is easily verified that the sign of dL_I/dP is positive (negative) when the absolute value of η_G is smaller (greater) than unity.

(because $q_{RR} < 0$). Since in equilibrium $r = q_S / q_R$ must hold, equilibrium is restored by increasing q_S as well, *i.e.* by running down soil depth (because $q_{SS} < 0$).

However, if the absolute value of the elasticity of marginal utility of consumption goods is less than unity (that is, an increase in consumption of goods results in a less than proportional decrease in marginal utility), marginal utility U_L falls only slightly and hence the demand function for leisure shifts out only marginally. Then the number of hours worked will increase at the cost of amount of time consumed as leisure, and soil conservation will be improved.

4.3.4 Conclusions

In this section the effects of increases in agricultural prices on soil conservation have been analysed using a model that describes the decision-making process of a peasant household. Since missing markets are fairly common in rural areas in developing countries, the peasant household's response has been analysed under the assumption that it faces a complete set of markets and under the assumption that it is not able to hire additional labour (*i.e.*, the labour market is assumed to be missing). The conclusion is that in a model in which soil regeneration can be enhanced by applying labour, higher prices will unambiguously contribute to thicker soils when agricultural producers face a complete set of markets for their inputs and outputs; additional labour will be hired to enhance soil conservation. However, when the restrictive assumption of access to all markets is relaxed, raising prices can have both positive and negative effects on soil depth, depending on the elasticity of marginal utility of purchased consumption goods. The adverse effect can occur if the absolute value of the elasticity of marginal utility of goods consumption with respect to the quantity consumed is large (*i.e.*, if it is larger than unity). Then, the increased consumption of goods (enabled by the increase in output prices) leads to a substantial fall in marginal utility of goods consumption. This implies that marginal utility of leisure should also fall substantially, resulting in a strong increase in demand for leisure. As the peasant household is not able to hire additional labour, time spent on soil conservation is reduced.

From a policy point of view, it is concluded that using prices of agricultural output as an instrument to increase sustainability is hazardous: unless peasant households are fully integrated in the market economy, undesired results may be obtained.

4.4 The effects of tenure security on land use sustainability[9]

In many tropical forests fallow periods are shortened mainly because of increased population pressure (Pearce and Brown, 1994, pp. 12-13). Population pressure increases because of natural population growth but often net migration into the rainforest area is also a factor. Although the underlying causes of migration may differ between countries, the main reason is economic hardship in other regions of the country: either overpopulation in the rural areas outside the rainforest areas forces people to migrate to the forests in search for arable land, or economic crises reverse the urbanisation trend and stimulate people to remigrate to the rural areas (Myers, 1980, p. 24; Panayotou and Ashton, 1992, p. 57; Repetto, 1990).

The increase in population density in rainforest areas affects land use sustainability in two ways. First, increasing pressure to meet the needs of the current generation results in increases in land use intensity (Jepma, 1995, p. 127). A growing population implies that the demand for agricultural products increases. The first response will be expansion of the area exploited, but if this is not possible land is likely to be used more intensively. Second, increased population pressure (especially if caused by a net inflow of migrants) may result in an increased frequency of land disputes, especially if customary land rights prevail. Customary rights can be very secure, but increased population pressure may reduce social cohesion so that these land rights may no longer be respected (Cleaver, 1992, p. 70; López and Niklitschek, 1991; Mahar and Schneider, 1994, p. 163; Pearce and Warford, 1993, p. 254).

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[9] This section is based on Van Soest, D.P. and V.C. Hoogenveen (1997), "A Parameterisation of a Shifting Cultivator's Response to Uncertainty of Land Rights", University of Groningen, Groningen, mimeo.

In this section the effect of land right uncertainty on the peasant household's decisions is analysed. In principle, the peasant household is able to signal land claims by keeping its land under cultivation. If a parcel of land is cultivated, there is no doubt that it is owned by someone. As Southgate (1990, p. 94) states: '...[peasant households] realize they risk losing land not in use for crop [...] production...'. Indeed, it is more difficult to uphold land claims on land lying fallow, especially in the last years of recovery: if forest regeneration is allowed to continue up to the point where regrowth starts to resemble (secondary) forests again, migrants may not be able to recognise that the parcel of land is already owned by someone else and may therefore decide to clear it for their own use. This means that an increased chance of land conflicts will stimulate the peasant household to increase the area of land under cultivation relative to the land area lying fallow, resulting in cultivation practices that may be too intensive from a sustainability point of view (Lawry and Stienbarger, 1991, p. 24; Pearce and Warford, 1993, pp. 31 and 254; Rudel, 1983; Schneider, 1992, pp. 23 and 27; Southgate, 1990; Southgate *et al.*, 1991; Westphal *et al.*, 1981, p. 53). Thus, the main coping mechanism identified in the literature is a reduction of the fallow period: since land claims on cropped land are easier to defend than on land lying fallow, peasant households are willing to accept a reduction in soil productivity in order to uphold their land claims.

The point of reducing the fallow periods in response to insufficiently enforced tenure systems has received some attention in the literature. The main focus has been on the consequences of treating forested land as an open access resource rather than as a privately owned resource. The result is that the shadow price of soil fertility (the marginal costs of nutrient extraction now in terms of future profits forgone) is largely ignored: mainly the instantaneous marginal costs and benefits of increases in land use intensity are taken into account by the decision maker (see for example López and Niklitschek, 1991). More specifically, Southgate (1990) analyses the consequences of the possibility to uphold land claims by keeping land cultivated; he finds that such a tenure mechanism does not only induce peasant households to clear more land but also to invest less in conserving soil fertility on existing farm land than would be the case under secure property rights (see also Southgate and Pearce, 1987). Thus, it is found that resource degradation can be the rational outcome of a peasant household's decision-making process.[10]

However, peasant households do not have to simply accept a decline in agricultural productivity; they tend to adapt the choice of crops to soil fertility (Amelung and Diehl, 1992, p. 74; Angelsen, 1995; López and Niklitschek, 1991; Pearce and Warford, 1993, pp. 159-160). The response is that peasant households switch to crops that depend less on fallow cycles to retain productivity. For example, cash crops (such as coffee, cocoa and oil palm) are perennial crops: they are better able to conserve soil fertility and are far less erosive than most food crops (see section 4.2). This implies that if peasant households are not constrained in the range of crops they have to produce, all land can be allocated to cash crops. In such case, the peasant households are able to prevent actual land invasion by allocating their land to cash crop production without the adverse consequences of reduced agricultural productivity.

Unfortunately, in reality peasant households are often confronted with constraints on the types of crops they grow. As has been argued in section 4.2, food markets are underdeveloped in many tropical forest countries: most peasant households are self-sufficient in food consumption. For example Koopman (1992, p. 5), who has studied the situation of peasant households in Southern Cameroon (Lekié department), states that '... markets for basic food items are vastly underdeveloped: rural households would encounter unacceptably high risks of severe undernutrition if most ... were to abandon food production in order to allocate their labor to more renumerative activities'.

This section analyses the response of a peasant household to the existence of land uncertainty, taking into account the fact that households can adapt the allocation of their land to different types of crops and emphasising the role of missing markets. In section 4.4.1, a model is presented which captures the main effects: the decision-making process of a peasant

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[10] Although, in general, yields decline over time if land is used too intensively under pressure of tenure uncertainty, this may not be the case for plots cultivated by migrants who have settled only recently in a rainforest region. As these migrants may not be familiar with rainforest cultivation techniques at the time of arrival, their yields may go up over time because of learning-by-doing effects (Schneider, 1992, pp. 6-7).

household is modelled under the assumptions that it aims to maximise utility, that it forms expectations about the future in a rational way and that food and labour markets are missing. Since the model cannot be solved analytically, it is solved numerically using a technique developed by Den Haan and Marcet (1990). Section 4.4.2 analyses and discusses the results.

4.4.1 The model

Just as in section 4.3, the model that is used in this section aims to capture the main characteristics of shifting cultivation as described in section 4.2. The common features are that the peasant household is assumed to maximise expected discounted utility derived from consumption of manufactured goods, food and leisure while the labour market is assumed to be missing. However, this section’s model differs from the one in section 4.4.1 in several respects, three of which are worth emphasising. First, the size of the land area that is owned is explicitly included in the analysis: the household is assumed to be faced with a limited supply of land. The reason is that if land were available in sufficient amounts, uncertainty of land rights would not be an issue. Second, the allocation of land is also explicitly modelled in this section: we distinguish between food crops and cash crops because of the difference in dependency on fallow. Third, not only the labour market is assumed to be missing but the food market as well. As has been described in section 4.2, food production is carried out mainly to satisfy the needs of the household itself while cash crop production is the main source of monetary income. The model in this section is based on the extreme assumption that all food produced is consumed by the household, whereas manufactured goods can only be bought with the revenues of cash crop sales.

The model used in this section is as follows:

$$W = \max E_0 \left[\sum_{t=0}^{\infty} \rho^t U(c_{Ft}, c_{Mt}, c_{Lt}) \right] \tag{4.14}$$

$$c_{Ft} = q_F(S_t, L_{Ft}, A_{Ft}) \tag{4.15}$$

$$c_{Mt} = P_C\, q_C(L_{Ct}, A_{Ct}) \tag{4.16}$$

$$c_{Lt} = \bar{L} - L_{Ct} - L_{Ft} \tag{4.17}$$

$$A_t = B_t + A_{Ft} + A_{Ct} \tag{4.18}$$

Equation (4.14) represents the peasant household's maximisation objective: the household aims to maximise the present value of the future stream of utility derived from consumption of food crops (c_F), manufactured goods (c_M) and leisure (c_L). Furthermore, t reflects time, E_t the expectation held at time t, and ρ the peasant household's discount factor (which is less than 1). Equation (4.15) represents self-sufficiency in food consumption: the quantity of food consumed is equal to the quantity of food produced (q_F) in each period. The production of food crops is determined by soil fertility (S_t), the amount of labour (L_{Ft}), and the area of land used (A_{Ft}). Basically, a unit of land is cultivated for just one period, after which it is abandoned to fallow. Equation (4.16) represents the assumption that manufactured goods can be bought only by selling cash crops (q_C is the quantity of cash crops produced, while P_C is the exogenous relative price of cash crops with respect to manufactured goods). Only two arguments are included in the cash crop production function, labour (L_{Ct}) and land (A_{Ct}). Because cash crops are perennial crops that establish their own closed nutrient cycle, soil productivity can be assumed constant. Output is therefore determined by the amount of time spent on maintenance and harvesting and by the area of land (Sanchez, 1976, pp. 402-403). Equation (4.17) shows that the amount of time consumed as leisure is by definition the household's time endowment ($\bar{L}$) minus the time spent on production of cash crops and food crops: the labour market is again assumed to be missing. Finally, equation (4.18) states that the total area of land available to the peasant household is either cultivated (with food crops or cash crops), or lying fallow. In this equation, A_t is the total area of land available to the peasant household at time t while B_t is the area of land lying fallow in the same period.

Up until now, the model is fully deterministic. Uncertainty of land rights can be introduced by letting the fallow area be vulnerable to land claims by migrant peasants: in each period there is a chance that part of the fallow land is invaded. However, it would not be realistic to assume all fallow land to be vulnerable to such invasions: only fallow land in advanced stages of recovery is liable to land take-overs by newcomers. Simplifying matters, it is assumed that the area vulnerable to take-overs is the area of land which has been lying fallow for more than one period. Thus, the entire area lying fallow in a particular period is vulnerable to land take-overs except for the area cultivated in the previous period: in period t the land area vulnerable to hostile land claims is $B_t - A_{Ft-1}$. Therefore, the total area of land available to the peasant at time t is assumed to be given by the following equation:

$$A_t = A_{t-1} - \mu_{t-1}(B_{t-1} - A_{Ft-2}) \tag{4.19}$$

Hence, it is assumed that the area of land currently available to the peasant household is equal to its land area in the previous period minus the part that is taken over by competitors for land. The fraction taken away from this area is represented by a stochastic parameter μ_t. It is assumed that at the end of each period the value of μ_t becomes known to the peasant so that he can calculate how much land is available to him at the beginning of the next period. Hence, A_t is given and known at the beginning of period t when the land allocation to fallow, cash crops and food crops has to be determined (see equation 4.18).

Regarding expectation formation, farmers in developing countries have been observed to respond reasonably prompt to changes in their environment: for example, rotational techniques were adapted relatively quickly to exogenous changes (Grigg, 1985; Jones and O'Neill, 1993). Therefore, in line with Jones and O'Neill (1993) farmers are assumed to have rational expectations about the likelihood and size of land take-overs. This implies that farmers do not make systematic, expectational errors.

In order to be able to solve the model, the utility function, the production functions and the stochastic process have to be specified. The utility function is assumed to have the following form:

$$U\,(c_{Ft},c_{Mt},c_{Lt}) \;=\; \left(\frac{c_{Ft}^{1-\tau}}{1-\tau} + \frac{c_{Mt}^{1-\tau}}{1-\tau} + \frac{c_{Lt}^{1-\tau}}{1-\tau}\right) \qquad 0 < \tau < 1 \tag{4.20}$$

The main properties of this function are that there are decreasing marginal utilities with respect to the different consumption goods and that the function is additively separable in its arguments. Therefore, this specification has the same properties as a log-linear utility function (with equal weights on its arguments). The reason for using the specification as presented in (4.20) is that it substantially facilitates the solution procedure.

The production functions are assumed to be of the Cobb-Douglas form. The cash crop production function is specified as follows:

$$q_{Ct} = \bar{\theta}_C\, A_{Ct}^{c}\, L_{Ct}^{1-c} \qquad 0 \le c \le 1 \tag{4.21}$$

in which $\bar{\theta}_C$ represents constant soil productivity.

As has already been stated, food crop production depends on fallowing to restore soil fertility. Soil productivity is assumed to be positively related to the length of the fallow cycle as measured by the current period's ratio of land lying fallow to the area of land under food crops.[11] Hence, soil productivity is modelled as follows:

$$S_t = \bar{\theta}_F \left(\frac{B_t}{A_{Ft}}\right)^{a} \tag{4.22}$$

In this equation $\bar{\theta}_F$ is exogenous (natural) productivity. Furthermore, soil productivity is assumed to be subject to decreasing returns to scale

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[11] The correct way to model soil productivity is to determine the fallow length of each parcel of land. However, mathematically this approach is extremely cumbersome. A second best description of reality would be to let current soil productivity depend on the rotation length in the past. Unfortunately, time interdependency increases and the model can no longer be solved. Therefore, we have to resort to the strong simplification of letting soil productivity depend on the current rotation period.

(Dvořàk, 1992). Inserting this specification into a Cobb-Douglas production function (which also includes land and labour), the following food crop production function can be specified:

$$q_{Ft} = \bar{\theta}_F \, B_t^a \, A_{Ft}^b \, L_{Ft}^{1-a-b}, \qquad a > 0,\ b > 0,\ (1-a-b) > 0 \tag{4.23}$$

Finally, the stochastic process is modelled as follows: in each period, the share of land vulnerable to land take-over by migrants (μ_t) is expected to have a value $\tilde{\mu}$ with probability P; $\tilde{\mu}>0$ and $0 \leq P \leq 1$.

Now the decision problem of the peasant household can be solved. The household has to allocate its land optimally to three uses, taking into consideration that land lying fallow is vulnerable to take-overs but also that it contributes to food crop productivity. Deriving an unconstrained maximisation function by inserting the constraints into the objective function (4.14) and taking the first derivatives with respect to the control variables, the following first-order conditions can be found (see for example Blanchard and Fischer, 1993, pp. 98-100)[12]:

$$A_{Ct}^{\gamma-1} = \frac{\alpha}{\gamma}\left(\frac{P_C\bar{\theta}_C}{\bar{\theta}_F}\right)^{\tau-1} L_{Ct}^{\gamma+\tau-1} \tag{4.24}$$

$$E_t\left[B_t^{\alpha-1}A_{Ft}^{\beta}L_{Ft}^{1-\tau-\gamma} - \rho\mu_t B_{t+1}^{\alpha-1}A_{Ft+1}^{\beta}L_{Ft+1}^{1-\tau-\gamma} - \rho^2\mu_t(1-\mu_{t+1})B_{t+2}^{\alpha-1}A_{Ft+2}^{\beta}L_{Ft+2}^{1-\tau-\gamma}\right]$$

$$A_{Ft}^{\beta-1} = E_t\left[\frac{\gamma}{\beta}\left(\frac{P_C\bar{\theta}_C}{\bar{\theta}_F}\right)^{1-\tau} B_t^{-\alpha}A_{Ct}^{\gamma-1}\left(\frac{L_{Ct}}{L_{Ft}}\right)^{1-\tau-\gamma} - \rho^2\frac{\alpha}{\beta}\mu_{t+1}B_t^{-\alpha}B_{t+2}^{\alpha-1}A_{Ft+2}^{\beta}\left(\frac{L_{Ft+2}}{L_{Ft}}\right)^{1-\tau-\gamma}\right] \tag{4.25}$$

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[12] For the sake of notational convenience, new parameters α, β and γ are introduced to denote $a(1-\tau)$, $b(1-\tau)$ and $c(1-\tau)$, respectively. Furthermore, for computational simplicity it is assumed that given the values of the other variables in the production functions, the coefficients on labour are the same in both cash crop and food crop production as it substantially reduces the nonlinearity of the model without affecting the general results. In other words, c is set equal to the sum of a and b.

$$L_{Ft} = \left[\left(\frac{P_C \bar{\theta}_C}{\bar{\theta}_F} \right)^{\tau - 1} B_t^{\alpha} A_{Ft}^{\beta} A_{Ct}^{-\gamma} \right]^{\frac{1}{\tau + \gamma}} L_{Ct} \tag{4.26}$$

$$c_{Lt} = \left[(1 - c)^{-1} \; (P_C \bar{\theta}_C)^{\tau - 1} \; A_{Ct}^{-\gamma} \; L_{Ct}^{\tau + \gamma} \right]^{\frac{1}{\tau}} \tag{4.27}$$

The first-order conditions with respect to land allocation (4.24 and 4.25) reflect that current decisions are affected by the stochastic term because current land allocation decisions influence the extent of future land invasion. As the allocation of the household's time endowment over its three different uses does not have direct consequences for the future, labour (used in either cash crop production or food crop production) and leisure only depend on current period variables (see 4.26 and 4.27). However, these equations must still be solved simultaneously with the land allocation problem. Hence, the model is complicated and analytical solutions cannot be derived.

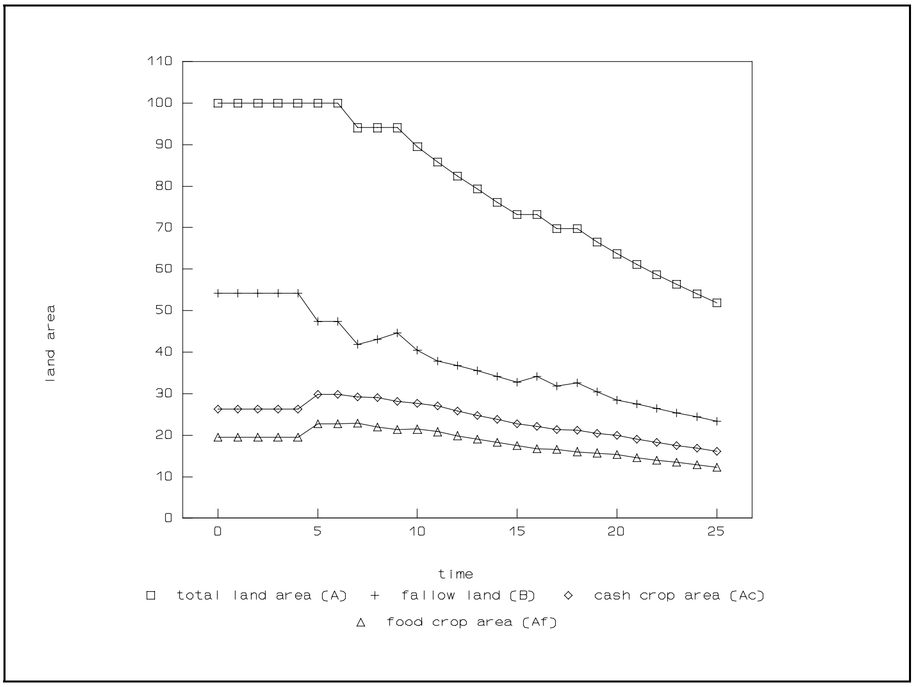
Therefore, a numerical solution method is applied as developed by Den Haan and Marcet (1990) and applied by Den Haan (1990). The method is based on reiteratively approximating the nonlinear first-order conditions by polynomials. These functions are referred to as the parameterisation functions; they describe the land allocation decisions using explanatory variables such as the area of land lost and the remaining area of land (current or lagged). In the solution method, the coefficients of the parameterisation functions are adapted so that these functions start replicating the optimising behaviour as represented by the model's first-order conditions. In essence, the approach can be summarised as follows. First, a series of land invasions (μ) are drawn and coefficient values are chosen for the parameterisation functions. Through simulation, the parameterisation functions yield time paths for all variables, which are fed into the RHS of the first-order equations (4.24-4.27) so that values for the variables on the LHS can be calculated. Thus, new 'observations' are found for these variables. On the basis of a regression analysis using these new observations, the coefficients of the parameterisation functions are adapted so that new time series can be calculated for the various variables through simulations. The resulting series are fed into the RHS of the model's first-order conditions, so that again a new set of 'observations' can be calculated for the variables on the LHS, after which the parameterisation equations are re-estimated on the basis of another regression analysis. The procedure is repeated so that the fit of the regression improves. Eventually, when the time series produced by the parameterisation functions start to approximate the paths derived from the first-order conditions, the parameterisation equations' coefficients are adapted only slightly. The procedure stops when the sum of the absolute differences between the coefficients found in the current and previous run is less than a certain predetermined small value. This solution procedure is described in more detail in appendix 4.3.

4.4.2 The results

Now the effects of land uncertainty on the allocation decisions of the peasant household can be analysed. However, as this model is a simulation model based on a stochastic process of land invasion, it is not possible to give one single solution: the results differ between runs because of differences in the occurrence of invasions. For example, if the μ series turns out to be such that the occurrences of land invasion are heavily concentrated in a particular period (*e.g.* in the first few years of the planning horizon) the approximation results are different than when the occurrences of land take-over are equally distributed over the entire planning horizon. Other factors that affect the outcomes in quantitative terms are the choice of the parameter values of the model and the initial endowments of time and land. However, the responses are reasonably stable especially in terms of direction. Therefore, as an illustration, a representative run of the simulation model is discussed.

As regards the peasant household's response to land uncertainty, a distinction can be made between the adaptations in the allocation of land and time to the *threat* of land invasion and these adaptations when land invasion actually occurs. Given the fact that rational expectations are assumed, the introduction of the *possibility* that the household may lose land is likely to induce it to reconsider the length of the fallow cycle and the choice of crops. By reducing the fallow cycle the area of potentially invadable land is reduced, while adaptations of the choice of crops limits the subsequent reduction in agricultural productivity. When land is actually lost to migrant peasants, the peasant household will reconsider its land allocation given the fact that land becomes increasingly scarce. A representative outcome of the model's land allocation predictions is depicted in figure 4.1.

Figure 4.1: Land allocation over time (P=0.5 and $\tilde{\mu}$=0.2)



Parameter values: A_0=100, $\bar{L}$=100, ρ=0.9, P_C=1, $\bar{\theta}_C$=1, $\bar{\theta}_F$=3, a=0.3, b=0.1, c=0.4, τ=0.5.

In this figure, in the first four periods the allocation of land is depicted *under certainty*. In the fifth period, land uncertainty is introduced: the jumps between the fourth and fifth period therefore reflect the adaptations in land allocation the peasant household makes under the *threat* of possible land invasion by competitors for land; the household is confronted with a fifty per cent chance of losing twenty per cent of its old fallow land in each period. After the fifth period, land invasion can actually occur: the top line in the figure depicts the area of land still available in each period.

The differences in the peasant household's response to the *threat* of land invasion and to *actual* land invasion are discussed in the following two subsections.

4.4.2.1 The peasant household's response to the introduction of land uncertainty

Confronting a peasant household with the possibility of losing land to migrant peasants induces a reallocation of the land area over its different uses, as can be seen from the jumps that occur between the fourth and fifth period in figure 4.1. The peasant household reacts to the threat of land take-over by reducing the area of fallow land and by increasing the area of cultivated land. Furthermore, from the first-order conditions (4.26) and (4.27) it can be derived that these changes in land allocation induce an increase in the number of hours worked compared to the case under certainty. The main adaptations are summarised in table 4.1:

Table 4.1: The initial values of land allocation and quantity of time consumed before and after introduction of land uncertainty ($P=0.5$ and $\tilde{\mu}=0.2$)

	Fallow land (B)	Food crop area (A_F)	Cash crop area (A_C)	Leisure (c_L)
Certainty	54.2	19.5	26.3	40.0
Uncertainty	47.3	22.8	29.9	22.3

Parameter values: $A_0=100$, $\bar{L}=100$, $\rho=0.9$, $P_C=1$, $\bar{\theta}_C=1$, $\bar{\theta}_F=3$, $a=0.3$, $b=0.1$, $c=0.4$, $\tau=0.5$.

Thus, in line with one's expectations, exposing the peasant household to land uncertainty induces it to decrease the area of land lying fallow; as cropped land is fully protected from land take-over, the peasant household decides to increase the area of land cultivated. Furthermore, as food crops require fallowing whereas cash crops are perennial crops, the peasant household is induced to increase cash crop production. However, the fact that the food market is assumed to be missing, the peasant household is not able to fully insure itself against land take-over: although it is willing to accept a decrease in land productivity by reducing the area of land lying fallow, some land must always be abandoned to allow the soil to regenerate.

Therefore, independent of whether or not the peasant household faces a complete set of markets, the threat of land invasion induces it to increase the area of land cultivated at the expense of the area of land lying fallow, while the resulting decrease in soil productivity induces a shift towards cash crop production. However, the magnitudes of the shifts are affected by the missing markets assumption: in case of missing food markets, the increase in land allocated to cash crops is smaller and the decrease in the length of the fallow cycle is larger than under the assumption of a complete set of markets.

The revisions with respect to land allocation also affect the peasant household's allocation of its labour time. The increase in the cultivated land area implies that the peasant household spends less time as leisure (c_L) and spends more time working. As for time spent on cash crop production, the increase in the area of land allocated to cash crops production implies that labour productivity on these parcels is also increased, and hence more labour is devoted to cash crop production. In terms of the quantity of labour applied in food crop production, the model predicts that the increase in this variable is substantial. The reasoning behind this is the following. The fall in food crop productivity resulting from the reduction in the fallow cycle implies that output falls and hence that marginal utility with respect to food consumption increases. By increasing the quantity of labour in the production function, the fall in food production can be limited. In other words, the increase in land cultivated results in a decrease in land productivity in food crop production, and the peasant household therefore increases the number of hours worked in this respect.

Therefore, the conclusion is that the *threat* of land invasion induces a peasant household that is self-sufficient in food production to increase the area of land allocated to cash crops but also to accept a strong reduction in the length of the fallow cycle (resulting in reduced agricultural productivity in food crops production), whereas the number of hours worked is increased.

4.4.2.2 The peasant household's response to actual land loss

If old fallow is actually lost to competitors for land, the peasant household is likely to adjust its allocation decisions for its endowments of both land and time. In the case of complete markets, land loss will induce the peasant household to shift allocation even more towards cash crop production (if land has not already been fully allocated in response to the threat of land invasion). Indeed, land loss leads to increased scarcity of land, resulting in a stronger bias against food crop production. Initially, a small area of land lost to migrant farmers does not affect the peasant household's utility very much: if the initial amount of land is relatively abundant, the peasant household can easily cope with the consequences of land loss. However, as land invasion continues, the peasant household's survival may come under threat: if land becomes relatively scarce, additional losses of land will have severe consequences for the peasant household's welfare. Thus, as land loss becomes increasingly more expensive in terms of its effect on utility, the relative profitability of food production vis-à-vis cash crop production increasingly declines when land invasion takes place. Therefore, if a peasant household is assumed to be confronted with a complete set of markets, cash crop production will gain in importance at the expense of food crop production.

In case of missing food markets, this may not be the case. In figure 4.1 the peasant household's response to actual land loss is shown from period 5 onwards. However, the figure is not very enlightening in terms of changes in land allocation *over time*. Therefore, we turn to the regressions underlying figure 4.1 (and table 4.1). Because the first-order conditions of the theoretical model are approximated by a regression model (the parameterisation functions), the regression results give insight into the behaviour of the peasant household especially over time as land invasion occurs. The explanatory variables in these two equations are both the (negative) changes in land area and the very size of the land area. If old fallow is lost to migrants ($dA_t = A_t - A_{t-1}$), the peasant household will reconsider its allocation of the remaining land to the three uses. As has already been argued, the household is also likely to respond to the actual size of the available land area (A_t).

The regression results are as follows (the *t*-values of the coefficients are presented in parenthesis):

$$\ln\left(\frac{B}{A_F}\right)_t = \underset{(120.824)}{1.067} - \underset{(-29.855)}{2.270}\ln(1-dA_t) - \underset{(-14.739)}{1.122}\ln(1-dA_{t-1}) - \underset{(-29.610)}{0.072}\ln(A_t) \qquad (4.28)$$

$$\ln\left(\frac{A_F}{A_C}\right)_t = \underset{(-10.925)}{-0.368} + \underset{(1.567)}{0.459}\ln(1-dA_t) + \underset{(2.212)}{0.021}\ln(A_t) \qquad (4.29)$$

Thus, these two equations give the ratio of the area of land lying fallow to the area of land allocated to food production (equation 4.28) and the ratio of land under food crops over land under cash crops (equation 4.29). On the basis of these two regression equations, the allocation of the available land area can be calculated, and then the allocation of time to its three different uses can be found. The *t*-values show that the variables included in the analysis are indeed able to explain the peasant household's response to land uncertainty as reflected by the first-order conditions. Although the value of the coefficients and their level of significance differ for different realisations of land invasion (*i.e.* different series of μ_t), the coefficients presented are always significant (at least at the 10% level) and have the same sign.

The main conclusion that can be drawn on the basis of these two parameterisation equations is that some of the adaptations that are observed initially (*i.e.*, when the threat of land uncertainty was introduced), continue whereas others are (at least partially) reversed. The mechanism that continues is that if land invasion occurs, the area of land lying fallow is decreased in order to reduce the area of land vulnerable to land invasion in the future. However, this corrective mechanism is more important in the first periods than in the later periods: the fall in land area reduces the fallow area but less so in the later periods as the sign of the coefficient of A_t is negative in equation (4.28): fallowing becomes increasingly more important as a means to secure sufficient food production. Furthermore, in order to keep the fall in food production limited, the initial increase in land area under cash crops is at least partly reversed: as land productivity falls in response to land loss, the share of land allocated to cash crop *decreases* in favour of food crop production (see also figure 4.1). Furthermore, given these developments in land allocation over time, the first-order conditions (4.26) and (4.27) indicate that the initial increase in the number of hours worked is (at least partially) reversed: as less land is available, labour productivity falls and it becomes more efficient to increase consumption of leisure.

4.4.3 Conclusions

This section presents an analysis of a utility maximising peasant household's response to land uncertainty in the case of perfect access to all markets and in the case that certain markets fail to exist. As the household's response is reasonably easy to predict if it is able to trade at all markets, the focus is on the decision-making process of a household that is assumed not to be able to hire additional labour and, more importantly, that is assumed to be self-sufficient in food production. In such case, the main decision problem the household is faced with is that on the one hand a longer fallow cycle results in increased land productivity for annual crops (mainly food crops) whereas on the other hand a larger area of (old) fallow results in a larger expected area of land lost to migrants.

The model shows that a distinction must be made between the peasant household's response to land uncertainty and its response to actual land invasion. Faced with emerging land right insecurity, the peasant household aims to reduce actual land loss by allocating more land to crop production and by reducing the land area lying fallow. Because decreasing the fallow cycle results in a decline in soil productivity of land under food crops, the land area allocated to cash crop production increases more than the land area allocated to food crop production. Furthermore, the number of hours worked is increased: more labour is applied in cash crop production because an increase in the area of land under cash crops implies that marginal labour productivity is increased; the fall in land productivity in food crop production is such that more labour is dedicated to food crop production in order to limit the fall in food crop production (and hence food consumption). Furthermore, the fact that the labour market is assumed to be missing affects the peasant household's decisions: if additional labour could be hired, the increase in the area of land cultivated would induce an even stronger increase in labour input in both cash crop and food crop production as the peasant household would still be able to consume somewhat more leisure by hiring extra labour. So far, the peasant household's response is similar to the situation with food markets do exist, albeit that the magnitude of the shifts in allocation of both land and labour time to cash crop production is reduced as compared to the case in which labour and food markets do exist, whereas the decrease in the length of the fallow cycle and the increase in labour input in food production are higher.

The response to *actual* land loss is noticeably different under the assumption of failing markets as compared to the complete markets case. Assuming a missing food market, the main result is that the initial shift towards cash crop production is at least partially reversed as the fall in food crop production must be compensated for by increasing the share of land under food crops compared to the share of land under cash crops. The model also predicts that the fallow cycle decreases as land invasion occurs, but less so when the land area becomes smaller and smaller. The reason is that fallowing land becomes increasingly more important as a means to keep up food production. Thus, in the case of actual land loss, the assumption of a missing food market results in an unexpected response: the initial shift towards cash crop production is (at least partially) reversed as the importance of limiting the decline food production becomes increasingly more important.

Therefore, the main conclusion is that the environmental consequences of land uncertainty are more serious if the peasant household is not able to supplement its own food production by buying extra food. Faced with the possibility of land loss, the shift of production from food production to cash crop production is reasonably small, whereas the reduction in the size of land lying fallow is considerable. When actual land loss occurs, additional adaptations are even more damaging in terms of soil exhaustion: the production of cash crops is even reduced in favour of food production.

These results are to a large extent driven by the fact that food markets are assumed to be missing. Apart from these assumptions which are based on the actual practice of shifting cultivation, there are several other strong assumptions that are needed to be able to solve the model. First, it is assumed that land lying fallow contributes to agricultural productivity currently rather than in the future. Of course, it would be more realistic to let future productivity depend on current fallow. However, the investment characteristic is maintained by letting fallow land be vulnerable to land invasion. In general, it is not likely that a modification of this assumption will result in an important change in results.

A second (implicit) assumption is that land under cash crops becomes productive as soon as land is allocated to that use. In practice, many cash crops need at least some years before they become productive; therefore, in reality the shift to cash crops takes time. However, the model predicts that this consideration is only important in the initial situation when the peasant household reallocates its land from the optimal allocation under certainty to the optimal allocation given the degree of uncertainty it is confronted with. As land take-over occurs, the area of land under cash crops is decreased rather than increased.

4.5 Concluding remarks

In this chapter, a general description is given of the behaviour of peasant households involved in small-scale agriculture. Shifting cultivation is the agricultural technique that is most often applied in rainforest areas. The reason is that soil productivity drops substantially over the cultivation period: although productivity can be high in the first year of cultivation, the soil becomes exhausted fairly quickly as the fertile topsoil is usually shallow. Because shifting cultivators very often do not have easy access to inputs such as fertilisers, fallowing is very important as a means of restoring soil fertility.

One of the main characteristics of the setting in which peasant households take their decisions is that peasant households do not generally trade on all markets: missing markets are a widespread phenomenon. The relevance of taking into account that peasant households may not be trading at all markets is analysed with respect to two phenomena. First, the effects of output price changes on the soil depth are addressed. In general, a price increase is likely to stimulate investments in soil conservation as the marginal productivity of labour-intensive soil regeneration will be increased. However, if the peasant household is not able to hire additional labour, the effect of increasing the price of agricultural products may be perverse: the income effect may be such that more leisure will be consumed, resulting in reduced investments in soil conservation. Second, the effects of uncertain land rights on the behaviour of peasant households are analysed. In the literature, land uncertainty is widely recognised as one of the major causes of unsustainable land use: the threat of losing land to others induces peasant households to increase the area cropped at the expense of the size of the fallow land. The reason for this is that land claims on cultivated land are easier to defend than those on fallow land. Thus, the intensity of land use is increased, which may result in soil depletion and possibly in deforestation. However, not all crops are dependent on fallow cycles in order to maintain agricultural productivity: cash crops are very often perennial crops that establish their own nutrient cycle. Therefore, the response of a peasant household that is able to buy food at the regional markets, is to increase the area of land dedicated to cash crop production at the expense of land used in food crop production (either cultivated or fallow). However, if the peasant household does not have access to food markets, it has to produce its own food. The model based on this assumption shows that the *threat* of land invasion induces the peasant household to increase cash crop production, but that food crops are still produced. Therefore, the peasant household is not able to fully protect itself against land invasion as food crop production requires a fallow period. The consequence is that land use intensity increases substantially: the area under food crops is increased at the expense of the size of the fallow area; the household is willing to accept a strong reduction in agricultural productivity in order to reduce the size of the area vulnerable to land invasion. The situation is even worsened when the peasant household's response to *actual* land loss is analysed. Rather than increasing the area of land under cash crops, the initial shift in allocation is reversed: land allocated to cash crop is returned to food crop production, in which the fallow cycle is much shorter than would be the case in the absence of land uncertainty.

The analysis of the effects on the environmental and economic environment in rainforest areas on the behaviour of shifting cultivators reveals that the increases in prices of agricultural output and in land uncertainty may result in enhanced soil depletion, as compared to the case in which households are able to trade on all markets. In terms of the price response of peasant households confronted with missing markets, an increase in the prices of its agricultural outputs may or may not result in enhanced soil conservation whereas under the assumption of a complete set of markets the response is unambiguously positive. This suggests either that pricing polices should be introduced with care or that the peasant households' access to markets should be improved. In terms of the negative environmental consequences of land uncertainty, missing markets (especially if the food market is missing) are found to induce only a small shift towards the production of perennial crops (which do not result in soil depletion) whereas actual land loss even reverses the shift. This implies that increasing tenure security should be even higher on the agenda of policy measures to combat deforestation, at least if the access to markets cannot be improved.

Appendix 4.1: Comparative statics analysis in the case of a complete set of markets

In case in which the peasant household has access to all markets, the system of equations describing equilibrium can be represented as follows[13]:

$$\begin{bmatrix} 0 & Pq_{LL} & 0 & 0 & 0 \\ (\omega^2 U_{GG}+U_{LL}) & -(U_{LL}+PU_G q_{LL}+P^2 q_L^2 U_{GG}) & -U_{LL} & -P^2 q_R q_L U_{GG} & -P^2 q_L q_S U_{GG} \\ 0 & -q_{LL} & q_R Z_{LL} & Z_L q_{RR} & 0 \\ 0 & 0 & Z_L & -1 & 0 \\ 0 & 0 & 0 & rq_{RR} & -q_{SS} \end{bmatrix} \begin{bmatrix} dL_H \\ dL_D \\ dL_I \\ dR \\ dS \end{bmatrix} = \begin{bmatrix} -q_L \\ q_L(U_G+PqU_{GG}) \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} dP \end{bmatrix} \quad \text{(A4.1)}$$

To derive the impact of a change in price P on the equilibrium soil depth, Cramer's rule is applied (see for example Chiang, 1984, pp. 107-110). This means that the determinant of the system (A4.1) must be determined:

$$D_C = -Pq_{LL}q_{SS}[\omega^2 U_{GG}+U_{LL}][Z_L^2 q_{RR}+q_R Z_{LL}] < 0 \quad \text{(A4.2)}$$

Because all first derivatives are positive whereas all second derivatives are negative, the determinant D_C is strictly negative.

Furthermore, it must be established whether the equilibrium is stable. Stability can be determined by analysing the dynamic system consisting of the differential equations of the state and control variables (Hanley *et al.*,

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[13] Note that all cross second derivatives are set equal to zero. That is, $U_{GL}=U_{LG}=0$ and $q_{RS}=q_{SR}=0$. Although this assumption is not unusual for the utility function (the function is then said to be additionally separable), it is not common for production functions. We have applied the assumption for expositional reasons, as it facilitates the mathematics without changing the results qualitatively.

1997, pp. 193-196). Stability is indicated by the eigenvalues of this (linearised) system's Jacobian (*i.e.* the matrix of partial derivatives), evaluated in the steady state solution. Given the fact that there are four control variables and one state variable, a fifth degree polynomial must be solved. Because it is not possible to derive an analytical solution, the problem of determining the stability of the steady state will be ignored for the moment; in chapter 6 this problem will be readdressed.

Appendix 4.2: Comparative statics analysis in the case of a missing labour market

Equilibrium in the case in which a labour market does not exist, is described by the following system:

$$\begin{bmatrix} -(U_{LL}+PU_G q_{LL}+P^2 q_L^2 U_{GG}) & -U_{LL} & -P^2 q_L q_R U_{GG} & -P^2 q_L q_S U_{GG} \\ -q_{LL} & q_R Z_{LL} & Z_L q_{RR} & 0 \\ 0 & Z_L & -1 & 0 \\ 0 & 0 & r q_{RR} & -q_{SS} \end{bmatrix} \begin{bmatrix} dL_D \\ dL_I \\ dR \\ dS \end{bmatrix} = \begin{bmatrix} q_L(U_G+c_G U_{GG}) \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} dP \end{bmatrix} \tag{A4.3}$$

The determinant of this system is:

$$\begin{aligned} D_F = {} & -q_{LL} q_{SS} U_{LL} - q_{LL} Z_L P^2 q_L U_{GG}[q_R q_{SS}+r q_S q_{RR}] \\ & -q_{SS}[U_{LL}+PU_G q_{LL}+P^2 q_L^2 U_{GG}][q_R Z_{LL}+Z_L^2 q_{RR}] > 0 \end{aligned} \tag{A4.4}$$

The determinant of this system is strictly positive as all first derivatives are positive and all second derivatives are negative.

Appendix 4.3: The parameterisation procedure

Due to the nonlinearity, time interdependency and uncertainty in the model, land allocation and allocation of time cannot be solved analytically. Therefore, the model results are approximated by parameterising the first-order conditions with a polynomial that contains known variables at time *t* that are expected to affect the peasant household's decision-making process concerning the allocation of land at time *t*. The procedure used has been developed by Den Haan and Marcet (1990).

In this application, not the *actual* land areas allocated to each type of land use are parameterised but the land *ratios* B_t / A_{Ft} and A_{Ft} / A_{Ct}. The reason for this is simply that it facilitates convergence of the parameterisation functions to the first-order equations. These equations are parameterised as follows:

$$\left(\frac{B_t}{A_{Ft}} \right) = \xi \left(D^i A_t, D^i dA_t \; ; \; \delta, \, e_t^{\xi} \right) \qquad i = 0,1,2,... \qquad \text{(A4.5)}$$

$$\left(\frac{A_{Ft}}{A_{Ct}} \right) = \psi \left(D^i A_t, \, D^i dA_t \; ; \; \phi, \, e_t^{\psi} \right) \qquad i = 0,1,2,... \qquad \text{(A4.6)}$$

In the parameterisation equations, D^i is the lag operator of the juxtaposed variable, *i* indicating the number of lags used; dA_t is the change in land area between periods *t* and *t-1*; δ and ϕ represent the parameter vectors and the *e*-terms are the error terms of the regression equations. The elements of δ and ϕ are denoted by δ_j, j=1,2,...,m and ϕ_k, k=1,2,...,n where *m* and *n* are the numbers of explanatory variables in the functions ξ and ψ. The successive steps of the parameterisation procedure are as follows.

1. A series is drawn for the stochastic μ-term. As has been explained in section 4.4.1, μ_t is determined as follows: parameter μ_t is unequal to zero with a certain probability (*P*) whereas the magnitude of the jump equals $\tilde{\mu}$.
2. Initial values are chosen for land and time allocation (A_{F0}, A_{C0}, B_0, L_{F0}, L_{C0}, c_{L0}) and for the parameterisation functions' coefficient vectors (δ^0 and ϕ^0).

3. Given the values of the parameter vectors δ and ϕ, the quantity of land available (A_t), the quantity of time available ($\bar{L}$) and the μ series, land allocation and time allocation series are calculated by using the parameterisation functions.
4. The series generated in step 3 are used to generate series with the model's first-order conditions for land allocation (4.24) and (4.25). The series from the parameterisation functions are used for the expected variables on the RHS of the first-order conditions; thus the model values of A_F, A_C, B, L_F, L_C, and c_L can be calculated in each period.
5. The series generated by the first-order conditions are in turn used in a regression to find new coefficient values for the parameterisation functions ($\hat{\delta}$ and $\hat{\phi}$). If the sum of the absolute differences between the vector elements δ and ϕ and the estimated coefficients ($\hat{\delta}$ and $\hat{\phi}$) in an iteration is less than a certain (very small) value (implying that the parameter vectors have almost fully converged), the procedure is ended. Otherwise the procedure continues with step 6.
6. New parameter vectors for the parameterisation functions are calculated by choosing values between the old values and the newly estimated values:

$$\delta_j^i = (1-\lambda)\delta_j^{i-1} + \lambda\hat{\delta}_j^{i-1} \qquad i=1,2,\ldots; \quad j=1,2,\ldots,m; \quad \lambda \in (0,1] \tag{A4.7}$$

$$\phi_k^i = (1-\lambda)\phi_k^{i-1} + \lambda\hat{\phi}_k^{i-1} \qquad i=1,2,\ldots; \quad k=1,2,\ldots,n; \quad \lambda \in (0,1] \tag{A4.8}$$

   where δ_j and ϕ_j are the j^{th} element of the parameter vectors δ and ϕ, $\hat{\delta}^i$ and $\hat{\phi}^i$ are the estimated parameter vectors from the regression of iteration i, and λ is the adaptation parameter. Then the procedure returns to step 3.

Note that the labour/leisure allocation is not parameterised: as there is neither uncertainty nor time interdependency, the optimal allocation of the time endowment can be calculated given the land allocation in each period. Once land allocation has been determined by the parameterisation functions, the values for L_F, L_C, and c_L follow automatically given the level of $\bar{L}$ via the first-order conditions (4.24) and (4.25).

Various specifications of the parameterisation functions have been tested. For example, the level of the total land area, the percentage change in land area, and the realisations of the jump variable (μ) have all been used as explanatory variables, taking both current and lagged values. In general, the resulting reaction paths are comparable. Therefore, we have chosen the specification using percentage changes in total land area, both current and lagged. Furthermore, several functional forms of the parameterisation functions ξ and ψ have been tested; the exponential form turned out to have the best fit. The explicit specifications of the parameterisation functions (A4.5) and (A4.6) are as follows:

$$\ln\left(\frac{B_t}{A_{Ft}}\right) = \delta_1 + \delta_2 \ln(1-dA_t) + \delta_3 \ln(1-dA_{t-1}) + \delta_4 \ln(A_t) + e_t^{\xi} \qquad \text{(A4.8)}$$

$$\ln\left(\frac{A_{Ft}}{A_{Ct}}\right) = \phi_1 + \phi_2 \ln(1-dA_t) + \phi_3 \ln(1-dA_{t-1}) + \phi_4 \ln(A_t) + e_t^{\psi} \qquad \text{(A4.9)}$$