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A Model of Optimal Labour and Soil Use with Shifting Cultivation

Unai Pascual* and Edward Barbier**

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*University of York
**University of Wyoming

Fondazione Eni Enrico Mattei
Corso Magenta, 63, 20123 Milano, tel. +39/02/52036934 – fax +39/02/52036946
E-mail: letter@feem.it
C.F. 97080600154

SUMMARY

This paper analyses the relationship between rural poverty and soil degradation in the context of a shifting cultivating community. A deterministic optimal control model demonstrates how a representative household's labour allocation affects the natural resource base on which its livelihood largely depends. The comparative static examination of relevant parameters and welfare effects of changes in the real wage rate are discussed. The theoretical results obtained are calibrated with data from the Yucatán, México.

JEL: Q12, Q23, D13, I3

NON TECHNICAL SUMMARY

The linkage between rural poverty, land degradation and deforestation in Latin America and the Caribbean is well documented in the literature. However, the relationships underlying this matrix are complex. Peasant households make use of land and natural resources, their own labour, formal and informal financial assets and purchased inputs including hired labour, to generate flows of product and/or cash income. The level and composition of that income determine whether households are above a certain cut-off point that would define poverty. In addition, the availability of some of these basic assets to peasant households, influences their economic behaviour, their livelihood strategies and their technological responses to environmental degradation. Thus, what is often perceived as a direct link between poverty and environmental degradation, proves under careful analysis to be a complex interrelationship between a household 's level of welfare and wealth and its economic behaviour, such as the allocation of labour and other assets. Given the widespread phenomenon of shifting cultivation (slash-and-burn agriculture) in Latin America and other tropical regions, it is surprising that so little attention has been paid to the potential linkages between poverty and the natural resource base in fallow-based slash-and-burn systems. There have been some recent attempts to model the economic behaviour determining shifting cultivation systems. However, the effect of peasant households' labour allocation decisions on rural resource degradation has only been recently tackled. The focus of this paper is on analysing socially optimal soil use as a semi-renewable resource in shifting cultivation agro-ecosystems. To do so, a stylised dynamic model of a representative shifting cultivator household operating in communal fragile or marginal land-forest complex is developed. The main interest is to draw attention at the economic behaviour of poor households as regards the optimal rates of soil exploitation: namely, the role of labour allocation decisions as a means of diversifying income sources. By presenting a model of a representative agricultural household, we aim at answering whether and to which extent labour allocation/diversification in a peasant community context affects the agricultural soil base as a production input. A salient feature of the model comes from the introduction of a dynamic soil quality index that is regarded a natural capital that is fundamental for household crop production.

To date, some analyses (mostly from the agronomic science) have been made to measure yield loss from soil degradation (mainly erosion) using

various specifications of production functions, however the studies which estimate the returns from agricultural soil quality are few. In addition, using primary data collected for a typical municipality from the Yucatán, México, during 1998/99, the paper conducts long run simulations to illustrate further the shifting cultivator 's economic motivations behind labour allocation and land degradation. The paper is organised as follows: following a brief introduction, we develop an agricultural household model based on optimal control theory. Then, we discuss the long run comparative statics and welfare effects of changes in key parameters of the system in the next section. In addition, we illustrate the results of the long run scenario applying the model to a representative community of the Yucatán (Mexico). Finally, the last section discusses the overall policy implications and conclusions of the analysis. In particular, we interpret the following theoretical results from a policy perspective: (i) agricultural labour and soil quality might be deemed as complementary inputs that are allocated towards a conditionally stable long run equilibrium; (ii) our neo-malthusian 'population pressure hypothesis' is a redefinition of an ecological-economic carrying capacity. Similarly, for the empirical results we discuss the implications of the following findings: (i) the Environmental Kuznets Curve hypothesis does not necessarily hold in traditional peasant economies where soil quality becomes a critical input in crop production; (ii) the degree of internalisation of the user cost is low in Yucatán, and further, this market failure prevails more among richer households than poorer households.

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CONTENTS

1 Introduction

The linkage between rural poverty, land degradation and deforestation in Latin America and the Caribbean is well documented (Barbier 2000, Deininger and Minten 1999, Echeverria 1998, de Janvry et al. 1997, McKinley and Alarcón 1995). However, the relationships underlying this matrix are complex. Peasant households make use of land and natural resources, their own labour, formal and informal financial assets and purchased inputs including hired labour, to generate flows of product and/or cash income. The level and composition of that income determine whether households are above a certain cut-off point that would define poverty. In addition, the availability of some of these basic assets to peasant households, influences their economic behaviour, their livelihood strategies and their technological responses to environmental degradation. Thus, what is often perceived as a direct link between poverty and environmental degradation, proves under careful analysis to be a complex interrelationship between a household's level of welfare and wealth and its economic behaviour, such as the allocation of labour and other assets (Lipton 1997, Perrings 1989, Reardon and Vosti 1995).

One key agroecological system used by many poor rural households in tropical areas is the shifting cultivation, or slash-and-burn, system. The diversity of shifting cultivation agriculture can be found at many levels and ecosystems ranging from forests to grassland, savanna and mountain environments. Sánchez et al., (1996) estimates that there are between 300 and 500 million shifting cultivators around the tropics. Further, about 30% of the arable soils of the world are thought to be involved in some sort of shifting cultivation (Bandy, Garrity, and Sanchez 1993). This accounts for a total of around 240 and 170 million hectares of closed and open forests respectively. In Latin America, forest fallow areas due to shifting cultivation are equivalent to 16% of the remaining closed forests (Brady 1996).

Given the widespread phenomenon of shifting cultivation in Latin America and other tropical regions, it is surprising that so little attention has been paid to the potential linkages between poverty and the natural resource base in fallow-based slash-and-burn systems. There have been some recent attempts to model the economic behaviour determining shifting cultivation systems (e.g., see Angelsen 1999, Dvoř̀aK 1992, Holden 1993, López 1998 and Vosti and Witcover 1996) In addition, the effect of peasant households' labour allocation decisions on rural resource degradation has only been recently tackled (e.g., see Bluffstone 1995, Bulte and Van Soest 1999 and Cooke 1998).

The aim of the following paper is to shed some additional light on the relationship between rural poverty and natural resource exploitation in the context of a shifting cultivation system. We analyse a representative peasant household's labour allocation decision as a crucial 'control' factor directing the state of land quality and by extension, the household's long run livelihood strategy. The focus is thus on ascertaining the socially optimal on-farm labour and land use decisions of the swidden household. Using data collected for a typical municipality from the Yucatán, México, the paper conducts long run simulations to illustrate further the shifting cultivator's economic motivations behind labour allocation and land degradation. The main contribution of the paper is to provide a formal analysis of how poverty affects the resource degradation decisions of shifting cultivator households through their allocation of labour. A further concern is to devise a theoretical ecological-economic carrying capacity index that can be measured with field data to know whether land in shifting cultivation is to be degraded under rising population pressure.

The paper is organised as follows: The next section develops the basic model of a representative shifting cultivator household. Section 3 discusses the long run comparative statics and welfare effects of changes in key parameters of the system. Section 4 illustrates the results applying the model to a representative community of the Yucatán. Finally, section 5 discusses the overall policy implications and conclusions of the analysis.

2 A bioeconomic model of on-farm labour and land allocation by a shifting cultivation household

The following model is based on the neoclassical 'agricultural household' modelling tradition (Singh, Squire, and Strauss 1986), which assumes that the representative shifting cultivator household makes a unified labour allocation decision[1]. Given our interest in the joint determination of the long run optimal labour and land use allocation, we take the 'open economy' case as the basic framework of the analysis. That is, output and input prices are exogenously determined under perfect functioning of the relevant markets, and by extension, on-farm family labour becomes independent from the household's demographic composition. It is also assumed even when households cannot supply any output to the food market, that the non marketed output can be considered to have a subsistence cash value to the peasant household.

The stylised utility function of the representative shifting cultivator household is assumed to be a function of an aggregate quantity of staple consumption (m) above some minimum caloric requirement. The direct utility function is expressed as: $U = U(m)$. It is assumed to be continuous, twice differentiable, non-decreasing and concave, i.e., $U'(m) > 0$ and $U''(m) < 0$. Leisure time is not an

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[1] The intrahousehold resource allocation decision is beyond the scope of this paper. As pointed by Binswanger and Rosenzweig (1986) and Fortin and Lacroix (1997), intrahousehold allocations are crucial for a better understanding of the long-term evolution of production relations, and have important implications in labour allocation within the household.

argument in the utility function since it is further assumed that any leisure time is predetermined at the beginning of each agricultural cycle[2]. It is assumed that utility is discounted at the rate, r. The constraints faced by the household conform to the budget and ecological state of land for agricultural purposes. The budget constraint is in turn based on the crop production technology. This is captured by the following equations:

$$z_i(t) = f_i\left[g\,L_i(t)/b_i, (1-g)L(t), Q_i(t)\right] \tag{1a}$$

$$Y_i(t) \equiv P.m_i(t) = P.z_i(t) + w[T_i - L_i(t)] + E_i \tag{1b}$$

where $f_j \geq 0, f_{jj} \leq 0$, and $f_{jk} = f_{kj} \geq 0$ for $k \neq j$.

where i represents the ith household, j is for the jth argument in the production function and t stands for time. In equation (1a) z is total crop output, which is a function of three variable inputs: the area of new cleared land, $g\,L/b$, labour used in crop production on this land, $(1-g)L$, and soil quality, Q. New cleared land is in turn a function of (i) total labour allocated on-farm, L, (ii) the proportion of that labour dedicated to clearing new forest land, g, and (iii) a measure of labour intensity in forest land clearing, i.e., the amount of on-farm labour needed to clear a unit of forest land, b. By extension, the second argument in the crop production function (1a), is 'cropping labour', i.e., the proportion, $1-g$, of on-farm labour allocated to tasks other than forest clearing, such as sowing and weeding.

The cross partial derivatives in the production function are assumed to be positive. This is quite plausible in a shifting cultivation context where land area, cropping labour and soil quality are all output enhancing inputs. For instance, the marginal product of an additional area-unit of cleared forest would be higher if that land is of better quality (and vice versa due to Young's theorem). Similarly cropping labour is expected be more 'productive' under higher soil quality. It can be argued that $f_{12} > 0$ (the subscripts 1 and 2 are for L_i/a_i and $L_i(1-g_i)$ respectively) because the marginal product of an additional unit of land increases if more thorough cropping labour (mostly hoe-weeding) is applied on it[3]. Equation (1b) describes the budget constraint and states that disposable income, Y, consists of non-labour income, E, any surplus crop production valued at the per unit crop output price, P, and the wage bill, $w[T_i - L_i(t)]$. The latter can be either positive or negative depending on whether the household is a net supplier or purchaser of labour,

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[2] See Bluffstone (1995) for a similar assumption concerning the direct utility function. The exclusion of leisure as a choice variable has some justification, given that shifting cultivator households in the tropics are usually bound by an strict climatic calendar in each crop cycle, thus taking leisure time practically as given for that whole agricultural cycle.

[3] One reason for declines in crop production in tropical shifting cultivation systems, is due to the effects of weed and other grass invasions on the cultivated crop. The shifting farmer needs to control the luxuriant growth of weeds under tropical conditions and hence hoe-weeding becomes a critical task in shifting cultivation. In fact, it is often pointed out that besides high soil nutrient depletion rates, farmers do abandon the cultivated plot due to excessive weed competition (Arnon 1981, Brady 1996).

respectively (i.e., if $[T_i - L(t)_i] > 0$, the household supplies labour off-farm), where T is household's predetermined endowment of labour supply (on-farm plus off-farm labour) and w is the market wage rate.

2.1 The biophysical dynamics of shifting cultivation

The land cleared by shifting cultivators for production is generally fallow forested land. 'Slash-and-burn' clearing of fallow land to maintaining the soil quality, Q, is necessary for cultivation. Thus in traditional shifting cultivation agroecosystem the fundamental economic asset is the available forest land. However as pointed by McGrath (1987), it is not the forest land *per se* that shifting cultivators exploit, but the vegetation-soil complex that has developed on the land. This suggests that any indicator of the soil quality, Q, of land cleared for cultivation should reflect the state of the key components determining the vegetation-soil complex. Hence we propose to represent Q by a weighted linear soil quality index based on the macro-nutrient nitrogen content, x, and the structural characteristics of the soil, s:

$$Q(t) = \rho\,\mathrm{x}(t) + \phi\, s \tag{2a}$$

We represent $x(t)$ by the nitrogen density of the forest-farm plot, i.e., $x(t) = (N(t) - \underline{N})/(\overline{N} - \underline{N})$, where $\underline{N}$ and $\overline{N}$ are respectively, the minimum and maximum levels of natural nitrogen deposits, N, in the agroecosystem. If we assume $\underline{N} = 0$, then $0 \leq x(t) = \frac{N(t)}{\overline{N}} \leq 1$. Finally, the index s in equation (2a) describes the static structural characteristics of the soil (e.g., shallowness of the soil, slope of land, percentage of rocky area in the farm plot) and ρ and ϕ are the relative weights attached to $x(t)$ and s in the soil quality index, Q, respectively.

The agroecology literature Kleinman et al., (1995) assumes that nitrogen stock (N) contained in the soil of recently cleared fallow land is a function of three related elements: the *'weighted'* average bush-tree biomass during forest fallow prior to clearing, the tree species composition of that biomass and a biomass–soil nitrogen transformation rate[4]. It is convenient to represent this relationship for the nitrogen stock contained in the soil of the cleared plot in the following way:

$$\mathrm{N}(t) = v \ln[\eta(t)] + \sigma \tag{2b}$$

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[4] Tree biomass acts as a 'soil builder' adding nitrogen and organic matter to the soil. 'Average' biomass is the aboveground phytomass in the forest land containing the oldest woody species that will be converted to cultivated area in t., which as López (1995) suggests, can be functionally related to the average biomass of all uncultivated land. In addition, the bush-tree species composition also determines soil quality. For instance, leguminous species fix more nitrogen in the soil relative to other species. Finally in shifting cultivation, the nitrogen contained in the tree phytomass passes into the soil by natural fixation. The transformation rate can vary depending on different environmental condition, e.g., changes in the microclimate. Here, it is assumed constant under a certain biophysical micro-environment.

The average biomass for fallow land, η has a positive but decreasing impact on nitrogen content, N. This effect is also scaled by the tree species composition of the biomass found in the plot during fallow, and the nitrogen transformation rate, v. σ is a static intercept term that reflects the structure of the forest biomassSubstituting (2b) into (2a) we obtain:

$$\mathrm{Q}(t) = \lambda \ln[\eta(t)] + \phi\, s + \sigma \tag{2c}$$

where $\lambda = \rho\, v\, \overline{N}$. As s and σ do not change over time, it follows that the rate of change in soil quality is:

$$\dot{Q}(t) = \lambda \frac{\dot{\eta}(t)}{\eta(t)} \tag{3a}$$

The rate of change in soil quality of any plot cleared for cultivation is therefore proportional to the rate of growth of the woody biomass, η, on the land if it remained fallow. In other words, if the farmer left the land to be fallow for an instant of time longer, any resulting growth in biomass would also increase the soil quality of the land. Finally, following López (1998), it can be argued that the representative shifting cultivation household selects land to clear from a 'common pool' of fallow forested land maintained by the entire village. This implies that the average biomass on a plot of land available for clearing by a shifting cultivator household is dependent on the remaining area of fallow land available to the whole village, and if households in the village clear the highest quality fallow land first, then average biomass on a plot of the remaining fallow land would decline as more fallow land is cleared by the village. Thus as López (1998) suggests, the rate of growth of biomass on the average plot in fallow is determined by:

$$\dot{\eta}(t) = \gamma - \frac{\sum_{i=1}^{n} g_i L_i(t)/b_i}{A}\eta(t) \tag{3b}$$

where n is the number of households in the village converting fallow land, and A represents the total land area both fallowed and converted under the community's control. The net change in average biomass on fallow land is determined by the constant intrinsic growth of the secondary vegetation, γ, less the depreciation of the biomass stock, $[\sum_{i=1}^{n}(L_i(t)/a_i)/A]\eta(t)$, through conversion of forested to cultivated land by peasant households.

Inverting equation (2c) to obtain η, combining the result with (3a) and (3b), and assuming that all households in the village are identical, yields the following expression for the change in soil quality:

$$\dot{Q} \;=\; \lambda\,[\gamma\, e^{(\frac{\phi s\, -\, Q}{\lambda})} - \frac{\Phi L}{a}] \equiv\; \Theta(Q,\, L) \tag{3c}$$

where $\Phi = n/A$ represents the intensity of land exploitation at the community level and $L/a = gL/b$ is the amount of land converted by the representative household. Equation (3c) indicates that the soil quality of land utilised by a shifting cultivator, increases with the intrinsic growth of secondary vegetation scaled by a density dependent exponential factor (which stands for the per unit of biomass found on the land where it is fallow, γ/η), less the proportion of village land that is cleared, $\Phi L/a$.

2.2 The household's optimal allocation of labour and soil quality

The problem of the representative household is to choose how much of its labour to allocate to on-farm activities, which through the crop production function, income and time constraint, and changes in soil quality will maximise the welfare of the household over time. An infinite time horizon (i.e., $\mathcal{T} \to \infty$) problem in continuous time can be formally stated as (suppressing the subscripts for the time notation (t) and i)[5]:

$$J = \max_{L} \int_0^\infty e^{-rt} U(m)\, dt \tag{4}$$

subject to 1a, (1b) and (3c). The current value Hamiltonian for the representative household is:

$$\tilde{H} = U(m) + \mu\, \lambda\, (\gamma\, e^{(\frac{\phi\, s - Q}{\lambda})} - \frac{\Phi L}{a}) \tag{5}$$

where from the budget constraint (1b), m is simply defined as:

$$m \equiv f\left[\frac{L}{a}, (1-g)L, Q\right] + \frac{w}{P}(T - L) + \frac{E}{P}$$

Assuming an interior solution, the maximum principle yields the following necessary conditions for an optimal path, along with the transversality and boundary conditions:

$$U'(m)[f_1 + a(1-g)f_2 - ca] = \mu\Phi\, \lambda \tag{6a}$$

$$\frac{\dot{\mu}}{\mu} + \frac{U'(m)\, f_3}{\mu} = r + \gamma e^{(\frac{\phi\, s - Q}{\lambda})} \tag{6b}$$

$$\dot{Q} = \lambda \left[\gamma\, e^{(\frac{\phi s - Q}{\lambda})} - \frac{\Phi L}{a}\right] \tag{6c}$$

$$\lim_{\mathcal{T} \to \infty} \mu(\mathcal{T}) Q(\mathcal{T}) = 0 \tag{6d}$$

$$Q(0) = Q_0 \tag{6e}$$

where $c = w/P$, the real wage rate, and μ is the current shadow value of soil quality, which is positive. Condition (6a) indicates that the household uses on-farm labour until the gain in utility by clearing additional forest land and utilising the remaining labour for 'cropping' equals the full opportunity cost of on-farm labour allocation. The latter cost consists of the marginal real wage cost plus the loss in valuable soil quality incurred by depreciating the communal natural capital asset of soil quality through forest land conversion.

Equation (6b) is the 'non-arbitrage condition', or optimal allocation rule, for maintaining soil quality. No gain in utility can be achieved by a change in soil quality when its current marginal

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[5] An infinite planning horizon is as it is commonly done in the soil resource modelling literature where the main focus in on the steady state (see Barbier 1990, Barrett 1991, Krautkraemer 1994 and Grepperud 1997). It is used to avoid specifying a terminal value for the soil fertility level.

return equals its cost. The latter includes the discount rate, r, or the cost of holding on to soil as an economic asset, plus the additional cost of waiting for biomass to grow to improve soil quality, γ/η. The returns to holding on to soil involves any current appreciation in its value, $\frac{\dot{\mu}}{\mu}$, plus the increase in utility of additional soil quality through current crop production, $\frac{U_1 f_3}{\mu}$. The state equation (6c) simply describes the evolution of soil quality, and finally, the transversality condition (6d) serves to ensure that the household would optimally mine soil quality by the end of the time frame, since the returns to soil quality would tend to zero as time approaches infinity.

The above conditions illustrate that the household is always allocating labour and soil among two competing uses, both in the long run as well as along any possible optimal path towards a steady-state equilibrium. With regard to labour, the choice is between on-farm and off-farm work. As for soil quality, the choice is about making use of it immediately as an input in crop production, or alternatively, delaying clearing and cultivation, allowing further biomass growth on fallow land and thus, improving soil quality for future higher agricultural yields.

The long run steady state for the household occurs when the rate of change in the state, costate and control variables are zero, i.e., $\dot{Q} = \dot{\mu} = \dot{L} = 0$. We can therefore solve for the steady-state equilibrium values of the three unknowns, Q, L, μ within the three equation system (6a) – (6c), which through substitution, can be reduced to a two-equation system (Q, L)[6]. For example, depicting steady state values with an asterisk, the optimal long run shadow value of soil quality is:

$$\mu^* = \frac{U_1 f_3}{r + \gamma e^{(\frac{\phi s - Q^*}{\lambda})}} \tag{7}$$

Substituting (7) into (6a) yields the resulting two-equation system depicting the long run equilibrium for the household:

$$\Theta(Q^*, L^*) \equiv \gamma e^{(\frac{\phi s - Q^*}{\lambda})} = \Phi \frac{L^*}{a} \tag{8a}$$

$$\Psi(Q^*, L^*) \equiv [f_1 + a(1-g) f_2 - ca] \left[r + \gamma e^{(\frac{\phi s - Q^*}{\lambda})} \right] = \Phi \lambda f_3 \tag{8b}$$

The optimal trajectories converging to such an equilibrium can be determined qualitatively in (Q, L) state-control space, based on the behaviour of the two stationary loci given by $\Psi(Q^*, L^*) = 0$ and

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[6] It can be demonstrated that including leisure both in the direct utility function and in the full-income constraint does not alter the steady state results significantly, and that the solution retains the standard separability result from agricultural household models. Note however, that separability would not hold in any trajectory to steady state, which would preclude inferring any conclusion about the stability of any possible equilibrium. Along this factor, the usual assumptions pertaining to the open economy case are still assumed to hold, i.e., (i) No difference exists in terms of utility by either engaging in farm or non-farm labour, (ii) farm and hired labour in farm production are perfect substitutes, and (iii) crop production is not ruled by any stochastic element.

$\Theta(Q^*, L^*) = 0$ in the above system (8a)-(8b). Since the slope $\Theta(Q^*, L^*) = 0$ is negative and that of $\Psi(Q^*, L^*) = 0$ is positive a single intersection point will be assured. The kind of dynamics that will take place around the equilibrium is likely to render the steady state equilibrium as conditionally stable saddle point. The necessary conditions for a unique equilibrium that is also a saddlepoint are shown in the appendix to this paper. These conditions are summarised by the following proposition:

Proposition 1a. *The necessary conditions for a unique equilibrium to exist is that the net marginal productivity of on-farm labour allocated by the household shows diminishing returns, and that it must exceed the relative capital gains from soil quality utilisation by that household net of any external costs of lowering the marginal productivity of the soil on the common land.*

Proposition 1b. *Under shifting cultivating conditions, where virtually all labour is allocated to clearing land ($g \rightarrow 1$), then the unique equilibrium is likely to be a saddlepoint.*

Figure 1 illustrates the optimal trajectories and saddle point equilibrium implied by proposition one. The two possible saddle paths to the equilibrium (Q^*, L^*) are shown. If the extremely poor household clears and cultivates land that initially has a high level of soil quality $(Q_0 > Q^*)$, then in order to be on a stable path, the household should also allocate a large amount of its time to on-farm labour, L. As most of this labour is for land clearing, the result will be declining soil fertility $(\dot{Q} < 0)$. Thus, along this saddle path, both soil quality and labour allocated to on-farm activities will fall, until the long run equilibrium is reached. Alternatively, if the poor household initially has access to land with relatively low soil quality $(Q_0 < Q^*)$, then to attain a stable path, the household must allocate less of its time to on-farm activities. Less land conversion takes place, and increased fallowing allows soil quality to recover $(\dot{Q} > 0)$. Consequently, along this saddle path, the poor household is able to increase its allocation of labour for clearing and cultivation as the soil quality of the land gradually improves, until the stable equilibrium (Q^*, L^*) is reached.

[Figure 1 about here.]

The implication of this analysis is that on-farm labour and soil quality are complementary inputs in the dynamics of shifting cultivation systems operated by extremely poor households that must allocate substantial labour inputs to land clearing. How much labour a household can devote to on-farm activities is conditional on soil quality. For example, as Figure 1 shows, if the land available to a poor household has low soil quality initially but the household allocates too much labour on-farm, then eventually soil quality will deteriorate rapidly. The result is likely to be collapse and abandonment of the shifting cultivation system.

This analysis also illustrates, at least implicitly, the importance of off-farm employment as a 'safety valve' for poor shifting cultivators. As pointed out by Reardon and Vosti (1995), poor rural households in developing countries are generally not net buyers of labour, i.e., for these households $[T_i - L(t)_i] \geq 0$. As we have seen, if these households have access only to poor quality land initially, then their optimal choice should be to allocate less of their available time to on-farm labour. This in turn implies that they will devote more time to off-farm work. However, if there are insufficient off-farm employment opportunities, then poor households may allocate too much labour to on-farm activities. The outcome may once again be too much land clearing, declining soil quality, and eventual ecological collapse of the shifting cultivation system.

3 Comparative static analysis

The long run allocation of labour and soil quality by the poor shifting cultivator will clearly be affected by changes in the key parameters of the model. In the following section, we employ comparative static analysis to examine some of these effects. They include standard market impacts, such as changes in the real wage rate, as well as other exogenous shocks, such as changes in the discount rate, r, and the scale of land use, Φ. We apply Cramer's rule to derive these steady-state comparative static effects. The results depend on the sign of the determinant of the Jacobian of the two-equation system depicting the long run equilibrium of the household, i.e., equations (8a) and (8b). As shown in the appendix, this determinant is negative when Proposition 1 holds.

The effects of a change in the discount rate, r, for the household are unambiguous:

$$\frac{dL^*}{dr} = \frac{-P[f_1 + a(1-g)f_2 - ca]\gamma e^{(\frac{\phi s - Q^*}{\lambda})}}{|J|} > 0 \tag{9a}$$

$$\frac{dQ^*}{dr} = \frac{\frac{P\lambda\Phi}{a}[f_1 + a(1-g)f_2 - ca]}{|J|} < 0 \tag{9b}$$

The result is consistent with standard resource depletion theory, and is summarised by the following proposition:

Proposition 2. *An increase in the discount rate will both increase the shifting cultivating household's use of on-farm labour and lead to more mining of soil fertility.*

Increased depletion of soil fertility arises through two effects. First, there is the well-known result from resource depletion theory that a rise in the discount rate increases the opportunity cost of ‘holding on’ to a natural resource asset, which in our model is the amount of soil fertility available for exploitation through shifting cultivation. The second effect is more unique to our model. As equilibrium condition (8a) defining the $\partial Q/\partial t = 0$ isoquant suggests, provided that $g \neq 0$ any decline in long-run soil fertility necessarily results from an increase in on-farm labour use. From Proposition 1, we have identified a unique saddlepoint equilibrium for a shifting cultivating household as a situation whereby the household allocates nearly all of its on-farm labour to land clearing. That is, with $g \to 1$, then the amount of land converted by the representative household is $L/a = gL/b \approx L/b$, where b is simply the amount of labour needed to clear a unit of forestland. It is therefore unlikely that the stable long-run equilibrium of the shifting cultivation household will be characterised by an on-farm labour allocation whereby $g \neq 0$. If this is the case, then any long-run increase in the household’s use of on-farm labour must unambiguously cause a decline in the stock of soil fertility available for farming.

The long run effect of a change in real wage rate, w/P, has the expected effect on the use of on-farm labour, given that transaction costs in the labour market are negligible. Again, our model would also predict a corresponding unambiguous impact on long-run soil fertility:

$$\frac{dL^*}{d(w/P)} = \frac{a\,(r + \gamma\, e^{(\frac{-Q+\phi\, s}{\lambda})})\, \gamma\, e^{(\frac{-Q+\phi\, s}{\lambda})}}{|J|} < 0 \tag{10a}$$

$$\frac{dQ^*}{d(w/P)} = \frac{-(r + \gamma\, e^{(\frac{\phi\, s - Q}{\lambda})})\, \lambda\, \Phi}{|J|} > 0 \tag{10b}$$

Thus the following proposition holds

Proposition 3. *A rise in the real wage causes the shifting cultivating household’s use of on-farm labour to decrease. As this will result in a decline in the amount of common forestland area converted to agriculture, and thus increased fallowing, then soil quality will improve.*

The effects of a change in the real wage on the long run welfare of the shifting cultivating household can also be determined. Differentiating equation (1b′) and invoking the assumption that $U'(\cdot) > 0$, a change in w/P has the following impact on household utility:

$$\frac{dU}{dw/P} > 0 \Longleftrightarrow c\frac{(T-L)}{L} > |\xi_{L,c}|\, \mathcal{A} \tag{11}$$

where $c = w/P$ is our short-hand expression for the real wage rate, $\mathcal{A} \equiv f_1 + a(1-g)f_2 - ca > 0$ is the net value marginal product of on-farm labour, and $\xi_{L,c}$ is the elasticity of on-farm labour with respect to the real wage. Note that it is fairly straightforward to demonstrate that $\mathcal{A}$ can serve as a proxy as the degree of poverty of the household, with $\mathcal{A} \to 0$ representing a situation of extreme poverty.[7] This supposition helps clarify the welfare effects of a change in the real wage, for the general case and extremely poor household, which are summarised in Propositions 4 and 5, respectively:

Proposition 4. *If the household devotes all of its available labour to shifting cultivation, an increase in the real wage has a negative impact on the household's welfare, given that* $L \geq T$ *and* $\mathcal{A} > 0$. *If the household engages in off-farm work,* $L \leq T$, *then the welfare effect would depend on the relative magnitude of the real wage, the net value marginal product of on-farm labour and the elasticity of on-farm labour with respect to the real wage.*

Proposition 5. *For an extremely poor shifting cultivating household,* $\mathcal{A} \to 0$, *the welfare impact of a change in the real wage is unambiguously negative if the household devotes all its labour to farming and is unambiguously positive if the household engages in off-farm work.*

These propositions conform with available empirical evidence on the effects of off-farm labour markets on the welfare of rural households in Mexico and developing countries generally (Bluffstone 1995; Brady 1996; Reardon and Vosti 1995; Taylor et al., 1999). Households that devote all their available labour to farming do not benefit from a rise in the real wage as this represents an increase in the opportunity cost of this labour. In contrast, extremely poor households that out of necessity supplement their agricultural income with off-farm work will generally gain from any increase in the real wage rates in labour markets. This latter welfare effect is necessarily unambiguous in our model, where we associate extreme poverty with a negligible net value marginal product of on-farm labour.

It is widely postulated that high population densities explain the breakdown of the ecological sustainability of fallow systems. The reason is that when, every thing else is kept constant, higher population densities creates an excessive exaction rate of soil fertility from the natural subsystem due to the need of shortening the fallow period. This phenomenon is known as the 'fallow crisis' or more generally, the Population Pressure Hypothesis (PPH) (Grepperud 1996)[8]. The intensity

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[7] Suppose that we have two households, i and j. Both households are cultivating land with the same level of soil quality, Q, and thus the shadow value of an additional unit of soil fertility, μ, is also the same for both households. However, suppose that household i is relatively poorer then j in terms of income, m. It follows that $U'(m_i) > U(m_j)$. From (6a), and assuming that the parameters Φ and λ are the same for the two households, then a higher marginal utility of income for the poorer household i also implies a lower net value marginal product for on-farm labour, i.e., $\mathcal{A}_i < \mathcal{A}_j$. Thus, *ceteris paribus,* $\mathcal{A}$ *can be viewed as a proxy index for the degree of relative poverty across households. Extreme poverty would be the case were* $\mathcal{A} \to 0$. *This also accords with recent empirical evidence, which suggests that poor households in rural environments in developing countries with only land and unskilled labour as their productive assets often exhibit very low levels of labour productivity (Reardon and Vosti 1995)*

of land use or the degree of pressure upon the soil-vegetation complex in shifting cultivation is related to population density and thus reflected by $\Phi = n/A$. We can gain further insight about the PPH by examining the comparative static effect of a change in population density on the long run equilibrium level of soil quality, Q^*, available to the shifting cultivating household:

$$\begin{aligned} \frac{dQ^*}{d\Phi} &< 0 \Longleftrightarrow \Omega < \left(\frac{n}{A}\right)^* \\ \Omega &\equiv \frac{r+\gamma/\eta}{\lambda} \cdot \left[\frac{f_{11} + 2a(1-g)f_{12} + [a(1-g)]^2 f_{22}}{f_{13} + a(1-g)f_{23} - \frac{\lambda f_3}{L/a}}\right] \end{aligned} \tag{12a}$$

The above condition is essentially a reformulation of the PPH characterised by Grepperud (1996) in terms of a long run critical population density threshold, $\left(\frac{n}{A}\right)^*$. If population densities are already very high, then increased population pressure on communal lands is likely to result in a decline in long run soil fertility. Equation (12a) can also be further simplified. Recall from Proposition 1 that a unique saddlepoint equilibrium may exist if the shifting cultivating household devotes nearly all of its labour to clearing forestland, i.e., $g \rightarrow 1$. If this is the case, then the total amount of labour allocated to shifting cultivation becomes critical to signing (12a). This result can be summarised in the following proposition:

Proposition 6. *If a shifting cultivating household allocates virtually all its on-farm labour to clearing land, i.e., $g \rightarrow 1$, then an increase in population density will undermine the ecological sustainability of the shifting cultivation system if the amount of on-farm labour used by the household exceeds the marginal productivity of soil quality, i.e., $L > \lambda \frac{f_3}{f_{13}/a}$.*

Proposition 6 is likely to hold when, due to population pressure, the shifting cultivating household is forced to clear very marginal forestland, i.e., land that has very poor soil quality characteristics. As population densities increase on a fixed area of communal forestland, it is inevitable that poorer quality land will be brought into production, and the ecological sustainability of shifting cultivation systems will be undermined. This phenomenon has been observed for many such systems in the developing world (Ahuja 1998; Bandy et al., 1993; Brady 1996; DvoráK 1992; López 1998; Mizrahi et al., 1995; Vosti and Witcover 1996).

An increase in population density will also affect on-farm labour use by a shifting cultivating

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[8] Grepperud (1996) points out that *"(...) only when population is greater than the carrying capacity of land is a more rapid degradation of land identified"* and that *"As long as population (...) is far below the supporting capacity of the region, a growing population and increasing population-land ratios are not expected to cause a rise in soil erosion"*.

household:

$$\frac{dL^*}{d\Phi} > 0 \Longleftrightarrow \Lambda < \mathcal{A}$$

$$\Lambda \equiv \underbrace{\frac{(r+\gamma/\eta)}{\gamma/\eta}\cdot[f_{13}+a(1-g)f_{23}]}_{\Lambda_1} + \lambda\left(\underbrace{\frac{f_3}{L/a}}_{\Lambda_2} - \underbrace{\frac{\Phi f_{33}}{\gamma/\eta}}_{\Lambda_3}\right) > 0 \tag{12b}$$

On-farm labour use will increase with rising population pressure provided that the net value marginal product of this labour exceeds the marginal cost of exploiting the soil-vegetation complex through converting and using communal forestland in shifting cultivation. The latter cost comprises the net opportunity cost of soil as capital (Λ_1), the user cost for the representative household (Λ_2) and that for the rest of the community (Λ_3).

However, if the marginal cost of exploiting the soil-vegetation complex exceeds the net value marginal product of on-farm labour in shifting cultivation, then an increase in population density will cause a fall in the use of on-farm labour by the shifting cultivating household. This result can be stated as:

Proposition 7 *An increase in population density will lead to a rise in on-farm labour use by the shifting cultivating household provided that the net value marginal product of this labour is greater than the marginal cost of shifting cultivation. If the latter cost exceeds $\mathcal{A}$, then increasing population pressure will lead to a fall in on-farm labour use by the household.*

Together, Propositions 6 and 7 offer interesting insights into the PPH with respect to shifting cultivating households. First, when population densities increase beyond a critical threshold on a fixed area of communal forestland, poorer quality land will be brought into production, and the ecological sustainability of shifting cultivation systems will be undermined. Second, the shifting cultivating household will nevertheless continue to increase on-farm labour use, and thus clearing additional communal forestland, provided that the net value marginal product of this labour is greater than the marginal cost of further shifting cultivation. A critical component of this cost is that the household takes into account the external cost imposed on the rest of the community of its decision to convert and use communal forestland, Λ_3. However, as noted by Ahuja (1998) and López (1998), under a breakdown of common property rules governing use of this forestland, an individual household would no longer take into account the full negative externality of forest conversion on all the members of the community; i.e., Λ_3 would need to be scaled by a factor i/N, where $1 < i < N$. Population pressure has been observed as a major factor in causing the breakdown in the common-property rules in traditional shifting cultivation systems (Bandy et al., 1993; Brady 1996; Reardon and Vosti 1995). Under such conditions, additional increases in population density are likely to encourage a shifting cultivating household to increase land clearing, thus further undermining the sustainability of the shifting cultivation system.

There is also a distributional implication to these impacts. Recall that for extremely poor households $\mathcal{A} \rightarrow 0$. As population pressure increases, and possibly communal institutions break down, condition (12b) suggests that it is more likely that poorer households will reduce their use of on-farm labour. These households will therefore convert less communal forestland. In contrast, richer households with a high net value marginal product of labour are likely to increase their conversion of communal land, particularly if the breakdown of the community institutions and increased population densities mean that Λ_3 is negligible. The resulting distribution of remaining communal land will increase the holdings of the rich at the expense of the poor. Throughout Latin America, there are many examples in rural areas where richer households are better able than poorer household to take advantage of open access conditions to secure greater access to land and other resources (Barbier 2000).

4 A case study application from the Yucatán

To explore further the possible poverty, labour allocation and land degradation effects of shifting cultivation, we conduct a simulation of our model based on empirical data obtained over1998-9 from a municipality in the Yucatán State, Mexico. First, we use these data to simulate the steady-state conditions of our model. We then derive and compare the optimal real wage-labour allocations by households from different income groups as predicted by our steady-state conditions and compare these with the actual labour allocations by these households in response to the real wage rates they face. This allows us to determine the extent to which households from different income groups are allocating too much labour to on-farm activities, including clearing more communal land. Second, we also estimate the shadow value of soil quality, and observe how it varies across shifting cultivating households with different income levels. This enables us to determine whether or not there is an environmental Kuznets curve (EKC) relationship between soil quality and income levels. Finally, we explore further the population pressure hypothesis (PPH) by numerically simulating the effects of a change in population density on the steady-state values for soil quality and on-farm labour use. This analysis reveals whether the shifting cultivating communities in our case study are still ecologically sustainable, and therefore if future increases in population density will lead to declining soil quality. We also disaggregate the analysis to examine the effects for different income groups.

4.1 Case study area: Hocaba Municipality, the Yucatán

The Municipality of Hocaba (MH) is named after the municipal seat, the Hocaba ejido community. MH also contains the Sahcaba ejido. The Hocaba ejido contains approximately 5,000 households and occupies a total land area of 5,920 hectares (ha). The Sahcaba ejido comprises 1,500 households and 1,381 ha of land. Both communities are well connected by road to the State capital, Mérida, which is 55 kilometres (km) to the north.

There are several reasons why the Yucatán, and the Municipality of Hocaba in particular, is a good case study site for application of our model. First, the Yucatán is considered to be within one of three main focal areas of deforestation in Mexico (Deininger and Minten 1999).

Second, traditional shifting cultivation based on the traditional staple maize crop (referred to locally as milpa) is the prevalent farming practice in the ejido communities of MH. In fact, throughout the state of Yucatán, virtually all of the 180,000 ha of agricultural land are farmed using shifting cultivation (Bautista and Jiménez-Osornio 1999). Third, the common property land ownership, or ejido, system is the prevalent land tenure system in the Yucatán. Ownership by ejidos accounts for 56land area in the state (Thompson and Wilson 1994). As noted above, MH consists of two ejido communities, Hocaba and Sahcaba. Fourth, rural poverty is widespread in the Yucatán. An estimated 41.6% of the rural population is considered to be below the official minimum income poverty line (INEGI 1990, SEDESOL 1999). Fifth, in the MH case study site, many shifting cultivating households depend on off-farm employment to supplement their income and as a survival strategy. Finally, there is evidence that many milpa-based shifting cultivation systems in the Yucatán are close to ecological collapse, given current levels of population density in the state (Mizrahi et al., 1995).

Shifting cultivating households from both the Hocaba and Sahcaba ejidos of MH were surveyed over 1998-9. The field data suggest that around 65% of the surveyed households were unable to supply any marketable surplus of the main crop, maize, due to the very low yields from shifting cultivation. At best, milpa appears to be a secondary source of income for households in MH. However, shifting cultivation is important to each household's food security strategy and overall economic livelihood, as well as having an important influence on the social and cultural fabric of the local community. The survey also reveals that almost 20% of households are below the official poverty line based on the minimum income threshold of 2,376 $ per capita annually (adjusted for Rothbarth's adult equivalency). As is typical of the rural poor throughout the developing world (Dasgupta 1993), these households supplement their income through non-marketed and natural resource-based extractive activities. For example, if the value of home garden products (e.g., fruits, vegetables, wood and livestock products) were taken into account, then only 14.5% of households would fall below the 2,376 $ poverty line (Ortiz 1999). Monetary income per capita appears to be fairly evenly distributed across the MH households surveyed. The Gini coefficient for these households is 0.31, which is the same as the Gini coefficient estimated across the rural poor in Mexico (McKinley and Alarcón 1995).

[Table 1 about here.]

Estimation of the relative share of the monetary income sources are shown in table 1 for different subsamples according to whether they are above or below the three official Mexican poverty lines. While the off-farm income share falls as total income decreases, on-farm shares increase[9]. Thus, agriculture, and not just off-farm income, is key for the poor, whereas wage income, not just agriculture, is key for the non-poor. Another relevant feature is that the non-labour income share, mainly made up by kinship and government transfers, increases with rising poverty levels, and is the second most important income source for all groups, except for the poorest households.

Concerning the agroecological context, the MH is under a warm and sub-humid climatic influence with a dry season from October to May and an average annual precipitation of 978 mm (Mizrahi et al. 1995). The implication is that the natural vegetation is mainly made up of a low and medium tropical dry deciduous forest. The extensive traditional milpa has configured the landscape as a complex mosaic of patches of fallow vegetation fields at different succession stages that are cleared for cultivation. The data suggests that the average forest fallow is around 14 and 16 years in Sahcaba and Hocaba ejidos, respectively.

4.2 Data and model calibration

A calibrated model has been developed in order to ascertain how population pressure is affecting soil quality and labour allocation. The model calibration is also carried out to impute the optimum scarcity value of soil quality and the shadow wage rate of shifting cultivators. To do this, a functional form for the crop production and direct utility function have been postulated.

The data were collected through surveys in Sahcaba and Hocaba ejidos at the household level (74 households, 15% of all peasant households), and agronomic field surveying techniques. The agronomic data for each households milpa plots correspond to η, σ and $\overline{N}$ in order to obtain the constructed Q index through equations (2a)–(2c)[10]. Household-plot specific biological maize yields were also recorded applying a crop cutting field sampling method (Casley and Lury 1987). In addition the households were distinguished by relative income. We use the three poverty lines (PL) that are often employed in Mexico: The lowest poverty line of 2,376 \$/year (258 US\$) per capita (PL1 henceforth), the adjusted poverty line of 2,976 \$ (324 US\$) (PL2) and the most conservative

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[9] The average off-farm share (66%) is higher than that reported by De Janvry et al., (1997) for rural Mexico as a whole (55%). The imputed share of crop production, coincides with that reported by Taylor et al., (1999) for the state of Michoacán.

[10] For simplicity, the variable Q recovers the dynamic nature of soil quality and does not account for the structural characteristic (i.e., $\rho = 1$, $\phi = 0$ in equation (2c)).

one of 5,400 $ (587 US$) (or PL3, henceforth). The symbol "$" stands for Mexican pesos, unless otherwise explicitly stated. The average values of the variables entering the model are shown in table 2.[11]

[Table 2 about here.]

A Cobb-Douglas functional form with the same arguments as in equation (1a) has been estimated to estimate crop production elasticities[12]. Table 3 shows the descriptive statistic values of the input and output values for all income subgroups. Table 4 presents the estimated parameters of the crop production function allowing for an stochastic technical efficiency error. The results indicate that new cleared forest-land area becomes the most important input in production, followed by soil quality and then by cropping labour. While new cleared land area and cropping labour are highly significant at most times, soil quality becomes significant for the whole sample at the 92% confidence level and demonstrates that biomass plays an important role in production. It is also worth noting the difference in elasticity estimates and significance levels between income groups stratified according to the three poverty lines defined above. It seems that richer households exploit land quality better than the poor and that the poor exploit the new cleared forest area better than the rich. One plausible hypothesis is that the poor, who do not get enough off-farm income, have more available labour time to allocate in clearing additional units of forest land (irrespective of its quality). In contrast, the richer households allocate more labour off-farm and have less available time to clear forest land, and therefore need to substitute land quality for quantity.

[Table 3 about here.]

[Table 4 about here.]

The soil quality and labour allocation isocline system [8a, 8b] can be solved numerically by parameterisation. One difficulty, however, lies on the highly non-linear nature of the system. Following Lopez (1998), the empirical analysis is carried out under the assumption that the main biophysical and economic characteristics of the agroecosystem correspond to the steady state. Calibration of the long run equilibrium, has been carried out as follows: first, the optimum value for Q^* is obtained numerically recalling equation (2c). Then my This value is then substituted back into the labour isocline using a Cobb-Douglas production function, obtaining a modified isocline:

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[11] Table notations in the paper is as follows: PL1$^-$, PL2$^-$, PL3$^-$, PL1$^+$, PL2$^+$ and PL3$^+$ stand for the six income groups used throughout, i.e., $I < 2,376$ $, $I < 2,976$$,$I < 5,400$ $, $I > 2,376$ $, $I > 2,976$$ and $I > 5,400$ $, respectively. I stands for average income *p. cap p. annum*, adjusted for Rothbarth's adult equivalency.

[12] 74 observations are used although 24 households do not clear forest land in the ejido. A test on whether the CPF is not structurally different between ejido and private property users cannot be rejected (P=0.88). In addition, all other parameters outside the production function are based on 'ejido'-based households only.

$$c^* = \frac{(\hat{\alpha_1} + \hat{\alpha_2})\, z^*}{L^*} - \frac{\hat{\alpha_3} \Phi\, \lambda\, z^*}{a\, Q^*\, (r + \Phi\, L^*/a)} \tag{8b$'$}$$

[Table 5 about here.]

Irrespective of any which the three poverty lines are used, the poor are supplying significantly more labour to shifting cultivation than richer households. Our interest lies in ascertaining whether there is any evidence in the deviation from the socially optimum labour allocation behaviour between the poor and the rich. If the steady state situation was not significatively different from the current situation, any marked divergence between actual hours supplied on-farm (reported by the household-survey) and the optimum hours supply (determined by calibrating the model) would imply that peasants are not allocating labour according to optimal household behaviour. That is to say, households would not be fully considering the user cost of their labour allocation decisions and hence would not be internalising the negative externality on the rest of the community when deciding upon labour allocation. Table 6 shows the degree of the private on-farm labour oversupply by households at different income strata. Apparently, according to the PL1 poverty line, on average, the households below (PL1$^-$) and above (PL1$^+$) the extreme poverty line appear to deviate from the optimal on-farm labour supply by 69%. This shows that the privately labour allocation decision is highly suboptimal from a social point of view. Interestingly, when households are stratified as regards the adjusted poverty line (PL2) and moderate poverty line (PL3), the data suggests that for those households above the poverty line (PL2$^+$, PL3$^+$), the degree of divergence form the socially optimum labour allocation in shifting cultivation is higher than for those below the poverty line (PL2$^-$, PL3$^-$). This is depicted in figure 2. Thus, although the degree of internalisation of the user cost is low in the area of study, this market failure prevails more among richer households.

[Table 6 about here.]

[Figure 2 about here.]

Households are clearly supplying an excess amount of labour on-farm, and hence clearing more forest land than the socially optimal level. For example, given the average intensity of labour invested in clearing land per surveyed household, (738 labour hours/ha) our calibration model suggests that it would have been socially optimal not to clear 0.32 ha. of forest land. However, on average each household clears 0.91 ha. Thus 35% forested land is being overused. Although clearing more land brings about higher crop output, there is a negative impact on output due to lowering the quality of agricultural soil, given shorter fallow periods. In fact, while actual forest fallow periods in the municipality average 17 years, under an optimal allocation of labour and land area, the fallow period would be up to 50 years. Following an agroecological case study analysis by Pascual (2000) (relating fallow years and the nitrogen stock in the soils of the area, an additional 33 years of fallowing would have increased the soil quality index. The actual average soil quality index for the study area was 0.44. [13] From the soil quality elasticity estimate from the crop function (see table 4), such an increase in soil quality would have implied an average increase in output across all farms of 178 kg. However, due to farmers having to give up 35% of forestland for cultivation on average, they would incur in an output loss of 525 kg. (425 kg plus 100 kg. from reducing L/a and $(1-g)L$, respectively. Hence, households would need to produce 347 kg (525 − 178) less of maize to be optimal. This implies that optimal output level would be 288 kg.

Therefore, under perfectly functioning labour markets, peasants' welfare is not being maximised. While an output loss would follow from optimal behaviour, on-farm labour could be saved and supplied to the off-farm market at the prevailing wage rate. If on-farm labour allocation equals the socially optimal level, the average household would be supplying 400 more hours/year to the off-farm sector and given the prevailing wage rate and current maize prices, would be able to consume 1,092 kg more of maize. Thus, the net real gain of reducing shifting cultivation labour (by clearing less forest land and reducing 'cropping' labour) thus would be an increase in consumption of maize of 745 kg. This is equivalent to an increase in average monetary income of US$ 121 per household, i.e., US $ 25 per capita using Rothbarth's adult equivalency method.

An approximation of the relationship between socially optimal shadow real wages (c^*) and income levels is also reported in table 6[14]. It can be seen that the shadow wage rates are higher for the poorer households. This is true when the PL2 and PL3 poverty lines are considered, although the evidence is more doubtful with respect to PL1 where the shadow wages for the poorest households and those above PL1 are almost identical. Our evidence suggests that in theory the poor would have a lower propensity to participate in the off-farm labour market given their higher shadow wages (Huffman 1991).

It is generally postulated that poor peasants in Latin America suffer to a disproportionate degree from land degradation (e.g., deforestation, soil erosion and fuelwood shortage) compared to richer farm households (Barbier 2000). Usually, this assertion is based on the fact that poor people's reliance on the natural resource base is essential to secure their livelihood. Richer households are generally associated with higher market participation, and a wider choice set of income sources. However, labour 'diversification' between farm and off-farm, is increasingly being considered to be

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[13] Recall that the soil quality index (Q) is the ratio of the average potentially mineralisable nitrogen in the soil found in each farm to the maximum mineralizable nitrogen stock found in the soils of the study area. Pascual (2000) found that for any increase in one year of fallow of the secondary vegetation, the potentially mineralizable nitrogen stock increases by 0.25 mg/g. Given the actual 16.40 mg/g of mineralizable nitrogen in the soil, 33 additional years of fallow would have enhanced the nitrogen stock by 8.25 mg/g.

[14] The shadow wage is that equilibrium wage rate under which the current labour allocation would be described as optimal.

an important characteristic of the poor (Reardon and Vosti 1995, de Janvry and Sadoulet 2001). The present analysis helps to illustrate some of the relationships between poverty and resource degradation by quantifying the cost of a decline in soil quality for households at different levels of income.

In order to approximate the relationship between the optimal long run shadow value of defined in equation (7), and income levels, a stylised functional form representing the preference ordering of the representative household is needed. A standard way of thinking about such a preference ordering is to assume that the poorer the household is, the sharper the curvature of the utility function becomes. That is to say, an additional *kg.* of a utility-yielding staple food will increase (for a poorer household) utility more than for a less poor household. We can incorporate this approach in our analytical model, by assuming that utility function depends upon the per capita food consumption, m, and that all *per capita* income, y is spent on an aggregate staple commodity, where $y/P = m$[15]. It follows that a general logarithmic function, $U(m) = \ln(y/P)$, yields the desired preference ordering.

The marginal utility of income and the marginal product of soil quality (composed by α_3, Q and average total output, $\hat{z}$) can now be substituted into equation (7), thus obtaining:

$$\mu^* = \frac{P\alpha_3\,\hat{z}}{y^*\,Q^*\left[r + \gamma\, e^{\left(\frac{\phi\, s - Q^*}{\lambda}\right)}\right]} \tag{7'}$$

which is a measure in terms of *kg.* of maize. Equation (7′) can be used to compare the optimal current value of soil quality in the long run between the poor and the non poor relative to the three poverty lines (PL1, PL2 and PL3)

The resulting values from parameterisation of equation (7′) are presented in table 7 (using the mean values for all the necessary variables in table 2).

[Table 7 about here.]

[Figure 3 about here.]

For a representative household associated to the $\mathrm{PL1}^-$ and $\mathrm{PL3}^+$ income groups we find that they have a shadow value of soil of 3.73 and 3.33, respectively. It is harder to obtain such a measure for an average household between these two income groups. Given that for $\mathrm{PL1}^+$ the value is 1.53 and for $\mathrm{PL3}^+$ is 3.33, an average household falling into the two categories ($\mathrm{PL1}^+$ and $\mathrm{PL3}^+$)

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[15] It is implicitly assumed that all members of the household have equal access to the food resource. Per capita income (y) is derived by dividing total disposable income of the household (Y) by the number of members in the household corrected for Rothbarth's adult equivalency.

would have a value for soil quality between 1.53 and 3.33.[16] This implies that we are dealing with an inverted-U shape curve linking households' 'subjective' perception of soil quality scarcity and income levels. Therefore, the Environmental Kuznets Curve (EKC) hypothesis, commonly interpreted as the inverted U-shaped curve between income levels and environmental degradation is not found in our case. On the contrary, an anti-EKC pattern is obtained.[17]. The reason for refuting the EKC-type relationship is clear: on the one hand, as shown in table 4, the marginal product of soil quality (f_3) is higher for the least poor given the higher elasticity of soil quality and total output, under 'objective' similar soil quality values[18]. On the other hand, the poor face high values of soil quality because the utility function is set up in a way to reflect a high curvature at low income levels. In essence, the U-shape curve for the shadow value of soil quality is the product of (i) low income levels make households to value an income generating asset (such as soil quality) more, given the specified utility function, and (ii) richer households seem to be making a better use of natural capital, thus facing a high marginal product of soil quality, which is also translated into a higher valuation of this asset. One main reason for this phenomenon ought to be found in the higher off-farm hours supply (in detriment of milpa labour supply) by richer households and a lower proportion of time spent clearing forest biomass out of total milpa labour (see variables L and g respectively in table 2). This would imply that richer households face a higher opportunity cost of milpa-labour time and therefore prefer exploiting better quality land plots and hence substitute land quality for quantity. This might well be the reason behind the higher valuation of soil quality for the richest households.

We now turn to discuss the effects of a population density change in MH. The long run effect on soil degradation and labour allocation under an increase in population density is numerically estimated for Sahcaba, Hocaba and the whole MH through parameterisation of equations (12a) and (12b). The numerical analysis indicates whether the communities have surpassed the ecological carrying capacity, and therefore if under future population density increases, soil quality will diminish. By parameterising the model, it can be proved that for households at all income levels except for the richest group, there exists a stable local equilibrium in the steady state[19]. Also, table 8 (see

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[16] Note that while households within the two income groups at the extreme sides of the income axis (PL1$^-$ and PL3$^+$) do not overlap among them, there is some degree of overlapping in the rest of the income-poverty groups. Thus, it is the trends in the middle income groups (between PL1$^-$ and PL3$^+$) which reinforces the hypothesis of a U-shape relationship between income levels and the shadow value of soil quality.

[17] See Stern et al., (1996) for a general discussion of the EKC and (Koop and Tole 1999) for a recent review of the EKC hypothesis concerning deforestation, in which the authors reject the existence of an EKC relationship at the country level.

[18] The Cobb-Douglas functional form implies a higher marginal product values for richer households, under similar Q values, higher elasticities and higher output levels.

[19] Table 9 in the appendix shows that the necessary-and-sufficient condition for dynamic stability is met across all income groups in the form of a saddle point, except for the richest (PL3$^+$) and households from Hocaba for whom the equilibrium is described as an stable node.

appendix) shows that the algebraic sign of the Jacobian determinant $|J|$ needed for application of Cramer's rule is positive across income and location subsamples, as well as for the municipality (MH) as a whole.[20]

Referring back to the PPH condition, calibration of equation (12a) suggests for the whole municipality, the effect of increasing population pressure is for a decline in soil quality. Parameterising eq. (12a) we obtain that $[\Omega_{MH} > (n/A)_{MH}]$ (with $|J_{MH}| > 0$). If the two communities are studied separately, the data shows that in the Sahcaba ejido (SAH) an increase in population density would negatively affect soil quality: $[\Omega_{SAH} > (n/A)_{SAH}]$ (with $|J_{SAH}| > 0$). In the Hocaba ejido (HOC), instead, $[\Omega_{HOC} < (n/A)_{HOC}]$ (and $|J_{HOC}| > 0$), which suggests that higher population densities in Hocaba would not necessarily undermine the ecological sustainability of the agroecosystem in the longer run.

Further, average labour allocation to shifting cultivation would tend to increase in the whole municipality. This effect is the same for Sahcaba and Hocaba and when the entire municipality is considered, since calibration of equation (12b) suggests that $[\Lambda_{SAH} - \mathcal{A}_{SAH}] > 0$ ($|J_{SAH}| > 0$), $[\Lambda_{HOC} - \mathcal{A}_{HOC}] > 0$ ($|J_{HOC}| > 0$) and $[\Lambda_{MH} - \mathcal{A}_{MH}] > 0$ ($|J_E| > 0$). The calibrated results suggest that higher population densities are predicted to cause an increase in the on-farm labour supply by shifting cultivating households, i.e., L^* will increase. This in turn implies that a larger forestland area will be converted to agriculture (directly due to more households practicing traditional shifting cultivation and indirectly because on average each household would be clearing additional units of forestland).

Although converted forestland is assumed to increase in the longer run due to higher population pressure, the calibrated results suggest that on average, higher population density rates do not necessarily mean increased depletion of soil fertility in the agroecosystem. This finding directly contradicts the standard argument found in the agroecology literature: more shifting cultivating households creates a shortage of forestland which produces a shortening of fallow periods and inevitable 'fallow crisis'. However, our analysis suggests that this view needs to take into account an important behavioural component at the household level, which is seldom included in the agroecological debate. This critical behaviour to do with the potential labour allocation strategies of the shifting cultivating household. These households adapt to changing socio-economic conditions, including increasing number of fellow shifting cultivating households, reallocating their available time between farm and off-farm activities. For example if in response to greater population pressure on the land shifting cultivating households choose to decrease their on-farm labour supply, it is likely that the net effect on soil quality of increased population density will be ambiguous.

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[20] This is due to (i) $\mathcal{A}$ being nonpositive across all defined subsamples, (ii) the production function for most subsamples showing elasticities above unity, thus implying non diminishing marginal returns to some inputs, and (iii) g being moderately far from unity, therefore describing a somewhat different technology from the one assumed in the theoretical construct.

The effects of income levels in the area of study on the optimum labour strategy by shifting cultivating households is clear following parameterisation of equation (12b). All households except for the wealthiest (PL3+), i.e., those above the 5,400 \$ *per capita* poverty line, have the incentive to increase their on-farm labour allocation when population density increases. This result is in line with the finding from our model suggesting that the poor have higher shadow wage rates compared to the rich, which prevent the former from reallocating their available time out of farm labour as much as the rich actually do.

5 Conclusion

The main purpose of this paper has been to illustrate how labour allocation decisions by poor farm households in a context of shifting cultivation agriculture are related to the dynamics of the state of the natural resource base (i.e., soil/biomass complex). The paper has provided a dynamic framework to analyse the connection between changes in soil quality levels and labour allocative behaviour by poor peasant households in low productivity tropical regions.

An important finding from the model is that it is plausible that agricultural labour and soil quality are inputs allocated complementarily towards a conditionally stable long run equilibrium. This has direct consequences for policy making since the amount of labour a household can devote to shifting cultivation activities is conditional on soil quality. The analysis predicts that if households have access only to poor quality land initially, then their optimal strategy would be to substitute off-farm labour time for on-farm labour allocation. Under insufficient off-farm employment opportunities or high transaction costs in the labour market, then peasant households may allocate an excess of labour to shifting cultivation. The effect being too much land clearing, which in turn implies declining soil quality, and eventual ecological collapse of the shifting cultivation system.

It is widely postulated, that high rates of population growth do pose a threat on the environment. The steady state comparative results derived from the optimal control model has formally addressed the neo-malthusian population pressure hypothesis pointed out by Grepperud (1996). The model is able to specify whether peasants would dissave (in soil quality) in order to maintain consumption under increasing population pressure. The key point is to know whether a critical bio-economic threshold has been already surpassed or not. Such information can prove helpful for rural development policies targeting peasants through labour allocation incentives and at the same time aiming at conserving the natural resource base. Our point is that the ratio of the existing peasant population to all available land as often used to predict the future productive state of that land, might supply insufficient information if only biophysical elements are considered. Our model suggests that the labour behavioural component together with peasants' effective use of the technology should be taken into account to design sound rural development policies in rural areas of developing countries where traditional shifting cultivation is maintained.

Several direct policy implications can be derived from the case study analysis of Yucatán, which is a prototype of traditional rainfed agro-ecosystems in Mexico. Since the article 27 of the Mexican constitution was changed in 1992, favouring a land market development through privatisation of ex-ejido titled parcels, there still remains a high degree of uncertainty concerning its impacts on the economic fabric and land use patterns in rainfed agro-ecosystems. It is likely that wealthier households would take advantage of the land market liberalisation by purchasing more land from distressed poor households in need of cash. Following the Brazilian Amazonian example, this newly privatised land in turn is likely to be put into a more profitable use than shifting cultivation with low labour requirements (e.g., cattle raising). This in turn, might imply less available forest-land area for the rest, i.e., the majority of poor households, and hence higher population density in the commons. How the new land market policy will affect households labour allocation will depend on the technological as well as biophysical structure of the community under scrutiny. In addition, on average, poorer communities would respond to a higher population density by allocating more on-farm labour on average. This possibly implies an scenario where shifting cultivation becomes 'locked up' as an economic activity for the poor.

Further, market signals changes through the real wage rate appear to have an unambiguous effects on soil quality and labour allocation. This effects ought to be taken into account for policy decision making in an ever increasing integration between traditional cropping systems and the markets in rural areas of the tropics. As for the case of Yucatán, it appears that households would face a backward bending supply curve.[21] An increase in the off-farm market real wage is expected to decrease off-farm labour participation by households in order to invest their available labour time in shifting cultivation. This, we believe, can have deleterious effects on soil quality in the longer run. and would affect households' welfare due to changes in the real wage rates. This is so because their welfare level has been shown to depend on poverty levels, the degree of labour diversification between on and off-farm and the own price elasticity of agricultural labour demand.

The calibration of the bio-economic model also suggests that the Environmental Kuznets Curve hypothesis does not necessarily hold in traditional peasant economies where soil quality becomes a critical input in crop production. We suggest that in addition to the generally accepted idea that the poor put high values on the natural capital because it becomes indispensable to secure their livelihood, also the rich, in virtue of their high opportunity cost of shifting cultivation labour time, tend to put high values on soil quality. This implies that targeting the moderately poor to increase their income levels can have substantial benefits regarding agricultural soil quality conservation. This can be done by designing incentives for the moderately poor to further engage in off-farm

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[21] This is in virtue to the calibrated positive sign of the Jacobian determinant used to derive long run comparative static analysis.

activities thus increasing their income levels and as a consequence putting a higher shadow value on the natural resource base. Therefore, further engagement in off-farm activities can prove to be useful to break the vicious circle between moderate poverty and resource degradation in traditional agricultural systems. In addition, the empirical finding that wealthier households oversupply farm labour to a higher extent than the poorer households, supports the view that policies should also be focused on wealthier households by giving them the incentives to reallocate their available labour time toward the off-farm sector and out of agriculture. This in turn, might allow poorer households, that are associated with a lower reliance in off-farm activities, to increase their agricultural yields through an increase in soil quality given lower population pressure.

The insights of the model therefore are in accordance with the general view, that provision for peasants of greater opportunities to participate in the off-farm labour market, might imply a 'win-win' scenario; on the one hand, off-farm labour being a clear alternative to low-profit agriculture on 'low potential' lands would provide additional cash, thereby increasing income levels, and in addition it would directly prevent peasant communities from exerting excessive pressure on the fragile soil/biomass resource. We see this as a potential way to break the vicious circle of poverty and soil degradation.

6 Appendix

6.1. The derivation of the optimal labour demand solution

The on-farm optimal labour allocation path and its steady state solution is derived by total differentiation of the control equation (6a) with respect to time and substituting for $\dot{Q} = 0$ and $\dot{\mu}$ which is derived amalgamating equations (6a) and (6b):

$$\dot{L} = \frac{\lambda\Phi\, f_3 \;-\; [r + \gamma\, e^{(\frac{\phi\, s - Q}{\lambda})}]\, [f_1 + a(1-g)\, f_2 - ca]}{\frac{\mathcal{R}(m)}{a}\, [f_1 + a(1-g) f_2 - ca]^2 \;-\; [a\,(1-g)^2\, f_{22} + 2(1-g) f_{12} + f_{11}/a]} \tag{A1}$$

where $\mathcal{R}(m) \equiv \frac{-U_{11}}{U_1}$. Given the assumption of strict concavity of $U(m)$, we have postulated risk aversion on the part of the representative household[22]. $\mathcal{R}(m)$ measures the global concavity of the utility function and is naturally interpreted as the Arrow-Pratt index of absolute risk aversion. It follows an implicit total on-farm labour demand function at the steady state, $\Psi(Q, L)$:

$$\Psi(Q^*, L^*) \;\equiv [f_1 + a(1-g) f_2 - ca] \left[r + \gamma\, e^{(\frac{\phi\, s - Q^*}{\lambda})}\right] \;=\; \Phi\lambda f_3 \tag{A2}$$

6.2. The signs of the slopes of the isoclines

The signs of the slopes of the isoclines are obtained by applying the implicit function rule to equations (8a) and (8b) therefore obtaining:

$$\begin{array}{ll} \frac{dL}{dQ} = -\frac{a\mathcal{E}}{\Phi} < 0 & \Theta(Q, L) = 0 \\ \frac{dL}{dQ} = -\frac{\mathcal{DB} - \mathcal{AE} - \mathcal{F}}{\mathcal{G} - \mathcal{CB}} > 0 & \Psi(Q, L) = 0 \end{array} \tag{A3}$$

For the labour isocline to be positive two sufficient conditions must hold:

$$\frac{\partial \mathcal{A}}{\partial L} \equiv \mathcal{C} < 0 \tag{A4.a}$$

$$\mathcal{A} > \frac{\mathcal{BD} - \mathcal{F}}{\mathcal{E}} \tag{A4.b}$$

---

[22] In addition, it has been assumed that $U'''(m) = 0$, therefore imposing constant absolute risk aversion (CARA). A next step would be to assume DARA (decreasing absolute risk aversion) and compare the results from both models (with CARA and DARA).

$$
\begin{aligned}
\mathcal{A} &\equiv f_1 + a(1-g)f_2 - ca > 0 \\
\mathcal{B} &\equiv r + e^{(\frac{\phi\, s - Q^*}{\lambda})} > 0 \\
\mathcal{C} &\equiv f_{11}/a \;+\; 2(1-g)f_{12} + a(1-g)^2 f_{22} \\
\mathcal{D} &\equiv f_{13} + a(1-g)f_{23} > 0 \\
\mathcal{E} &\equiv e^{(\frac{\phi\, s - Q^*}{\lambda})} \cdot \gamma/\lambda > 0 \\
\mathcal{F} &\equiv \Phi\lambda\, f_{33} < 0 \\
\mathcal{G} &\equiv \Phi\lambda[f_{13}/a \;+\; (1-g)f_{23}] > 0
\end{aligned}
$$

These joint sufficient conditions, can be interpreted focusing on both the net marginal returns to on-farm labour in (A4.a), and the marginal productivities of agricultural labour in (A4.b). Condition (A4.a) says that the ratio between (i) the net capital gains from soil quality utilisation ($\mathcal{BD}$) minus the external cost of lowering the soil's marginal productivity in the commons ($\mathcal{F}$) and (ii) the foregone own appreciation of soil quality ($\mathcal{E}$), should not outweigh the long run net marginal value product of on-farm labour, $\mathcal{A}$. Condition (A4.b) simply states that the private net marginal product of on-farm labour should show diminishing returns.

Given that the soil isocline is downward sloping, and the labour isocline is upward sloping, a unique intersection point between the two isoclines is assured.

6.3 Derivation of the jacobian determinant $|J|$ for the comparative static analysis

The jacobian determinant used to apply Crammer's rule can be signed by conditions (A4.a - A4.b):

$$
|\mathbf{J}| = \begin{vmatrix} \underset{(+)}{h_{11}} & \underset{(-)}{h_{12}} \\ \underset{(-)}{h_{21}} & \underset{(-)}{h_{22}} \end{vmatrix} < 0 \tag{A5}
$$

where

$$
\begin{aligned}
h_{11} &\equiv \frac{d\Psi(Q,L)}{dL} = \mathcal{G} - \mathcal{CB} \\
h_{12} &\equiv \frac{d\Psi(Q,L)}{dQ} = \mathcal{DB} - \mathcal{AE} - \mathcal{F} \\
h_{21} &\equiv \frac{d\Theta(Q,L)}{dL} = -\frac{\Phi}{a} \\
h_{22} &\equiv \frac{d\Theta(Q,L)}{dQ} = -\mathcal{E}
\end{aligned}
$$

6.4 Derivation of the directionals of the soil quality and on-farm labour isoclines

The two isocline curves in figure 1, intersecting at the long run equilibrium point, divide the phase space into four isosectors, labelled I through IV. At any point, but the intertemporal equilibrium of the system at (Q^*, L^*), either Q or L (or both) would be changing over time. The directions of such changes are derived next:

The arrow phase directionals associated with $\frac{d\dot{Q}}{dQ}$ can be ascertained by differentiating equation (3c) with respect to Q, yielding:

$$\frac{d\dot{Q}}{dQ} = -\mathcal{E} < 0 \tag{A6}$$

implying that as Q increases, $\dot{Q}$ undergoes a steady decrease. Hence moving continually from west to east in the phase space, the sign of $\dot{Q}$ pases through the following three stages, $+, 0, -$. The directional arrows are drawn according to the derived signs, therefore with a direction from east to west in isosectors I and II, and a direction from west to east in isosectors III and IV. These arrows then, indicate the intertemporal movement of Q. Analogously, we can derive the signs of the $\Psi(Q, L) = 0$ isocline:

$$\frac{d\dot{L}}{dL} = \frac{\left(\mathcal{B}\mathcal{C} + \mathcal{G}\right)\mathcal{K} - \left[\frac{U''(m)\mathcal{A}}{U'(m)a}\left(2\mathcal{C} - \frac{U''(m)\mathcal{A}^2}{U'(m)a}\right)\right]\mathcal{N}}{\mathcal{K}^2} \tag{A7.a}$$

where $\mathcal{N}$ and $\mathcal{K}$ stand for the numerator and denominator of the labour path in expression (A1) respectively. The sign of expression (A7.a) is indeterminate. However, under a fairly extensive shifting cultivation technology (i.e., $g \to 1$), it is likely that the labour isocline to be upward sloping. This is true when the following two conditions hold:

$$\left|\frac{f_{13}}{f_{11}}\right| > \frac{\mathcal{B}'}{\lambda\Phi} \tag{A7.b}$$

and

$$\mathcal{R}(m) > 2\frac{|f_{11}|}{\mathcal{A}'} \tag{A7.c}$$

where, due to $g \to 1$, $\mathcal{A}$ now becomes $\mathcal{A}' \approx\ f_1 - ca > 0$

Equation (A7.b) says that the ratio between the cross marginal productivity of labour and soil quality and labour productivity should outweigh the marginal cost of soil quality use. Equation (A7.c), suggests that the absolute risk aversion of the representative household should be high enough.

These two conditions suffice for $\dot{L}$ to undergo the following three stages: $-, 0, +$ from south to north (as L increases), therefore determining the direction of the arrows associated with the intertemporal movement of L.

6.5 The local stability of the steady state equilibrium

The local stability can be studied by considering an approximation of the dynamics near the steady state (Q^*, L^*) by a first order Taylor expansion of the non-linear differential equation system given by equations (8a) and (8b):

$$\begin{pmatrix} \Psi \\ \Theta \end{pmatrix} = \begin{pmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{pmatrix} \begin{pmatrix} L - L^* \\ Q - Q^* \end{pmatrix}$$

The arguments of the Jacobian matrix being:

$$\begin{aligned} x_{11} &= \frac{d\dot{L}}{dL} \\ x_{12} &= \frac{d\dot{L}}{dQ} \\ x_{21} &= \frac{d\dot{Q}}{dL} \\ x_{22} &= \frac{d\dot{Q}}{dQ} \end{aligned}$$

which are associated with the following algebraic signs:

From the study of the directionals of the soil quality (Q) and on-farm labour (L) isoclines, we have that $x_{22} < 0$, from equation (A6) and $x_{11} > 0$, from equations (A7.a), (A7.b) and (A7.c). In addition we have that:

$$x_{21} = -\frac{\Phi}{a} < 0 \tag{A8}$$

and

$$x_{12} = \frac{[\mathcal{B}\mathcal{D} - \mathcal{A}\mathcal{E} - \mathcal{F}]\mathcal{K} - \left[\frac{U''(m)\mathcal{A}}{U'(m)a}\left(2\mathcal{D} - \frac{U''(m)\mathcal{A}f_3}{U'(m)a}\right)\right]\mathcal{N}}{\mathcal{K}^2} \tag{A9.a}$$

which under our extensive shifting cultivation setting (i.e., $g \to 1$), equation (A9.a) becomes (A9.b):

$$\frac{d\dot{L}}{dQ} = \frac{[\mathcal{B}\mathcal{D}' - \mathcal{A}'\mathcal{E} - \mathcal{F}]\mathcal{K}' + \left[\frac{\mathcal{R}(m)\mathcal{A}'}{a}\left(2\mathcal{D}' + \frac{\mathcal{R}(m)\mathcal{A}'f_3}{a}\right)\right]\mathcal{N}'}{\mathcal{K}'^2} \tag{A9.b}$$

where,

$$
\begin{aligned}
\mathcal{D}' &\approx f_{13} > 0 \\
\mathcal{N}' &\approx \lambda\Phi\, f_3 \, - \, [r + \gamma\, e^{(\frac{\phi\, s - Q}{\lambda})}]\, [f_1 - ca] \\
\mathcal{K}' &\approx \frac{\mathcal{R}(m)}{a}\, [f_1 - ca]^2 \, - \, f_{11}/a > 0
\end{aligned}
$$

If $[\mathcal{B}\mathcal{D}' - \mathcal{A}'\mathcal{E} - \mathcal{F}]$ and $\mathcal{N}'$ are negative, then equation (A9.b) is also negative. Note that for $\mathcal{N}'$ to be negative it should apply that:

$$\mathcal{A}' < \frac{\lambda\Phi f_3}{\mathcal{B}} \tag{A9.c}$$

which coupled with $[\mathcal{B}\mathcal{D}' - \mathcal{A}'\mathcal{E} - \mathcal{F}]$ that holds when condition (A4.b) applies, for the equilibrium to be depicted as a saddlepoint it is sufficient that: the farm household's net marginal value product of labour ($\mathcal{A}$) is bound as expressed in condition (A9.d) below:

$$\frac{\lambda\Phi f_3}{\mathcal{B}} > \mathcal{A}' > \frac{\mathcal{B}\mathcal{D}' - \mathcal{F}}{\mathcal{E}} \tag{A9.d}$$

Therefore, under a highly extensive shifting cultivation system ($g \rightarrow 1$), and under sufficient conditions (A7.b), (A7.c) and (A9.d), the determinant of arguments of the Jacobian matrix $\mathbf{\Gamma}$ becomes unambiguously negative:

$$|\mathbf{\Gamma}| = \begin{vmatrix} \underset{(+)}{x_{11}} & \underset{(-)}{x_{12}} \\ \underset{(-)}{x_{21}} & \underset{(-)}{x_{22}} \end{vmatrix} < 0 \tag{A10}$$

from which it is suggested that a saddlepoint equilibrium is the case in our model.

6.6 Parameterisation of $|J|$ and $|\Gamma|$

[Table 8 about here.]

[Table 9 about here.]

7 Annex

[Table 10 about here.]

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Figures

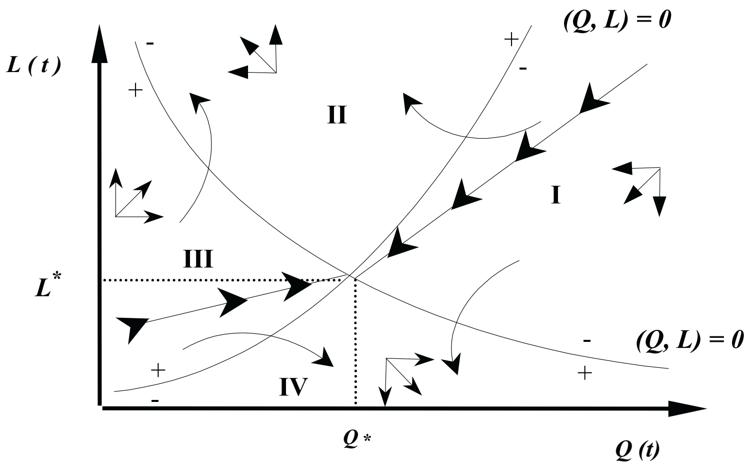

Figure 1: The (Q, L) dimension phase diagram and the steady state equilibrium depicted as a saddle point

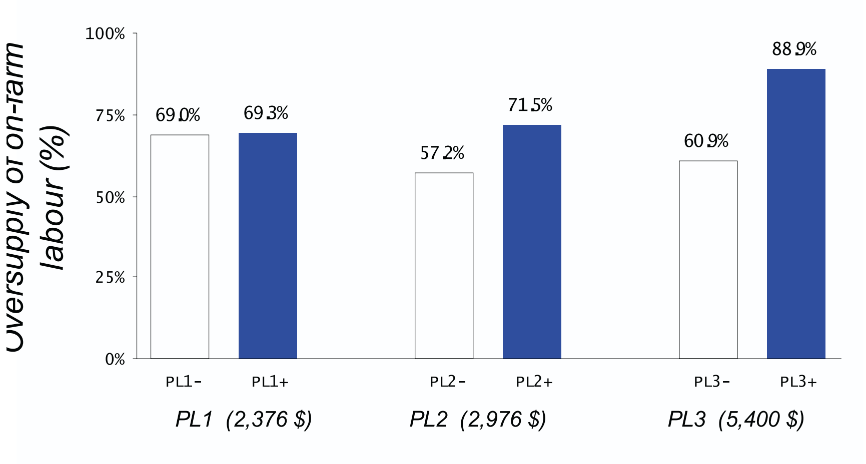

Figure 2: Oversupply of on-farm labour for the poor and rich (according to three poverty lines)

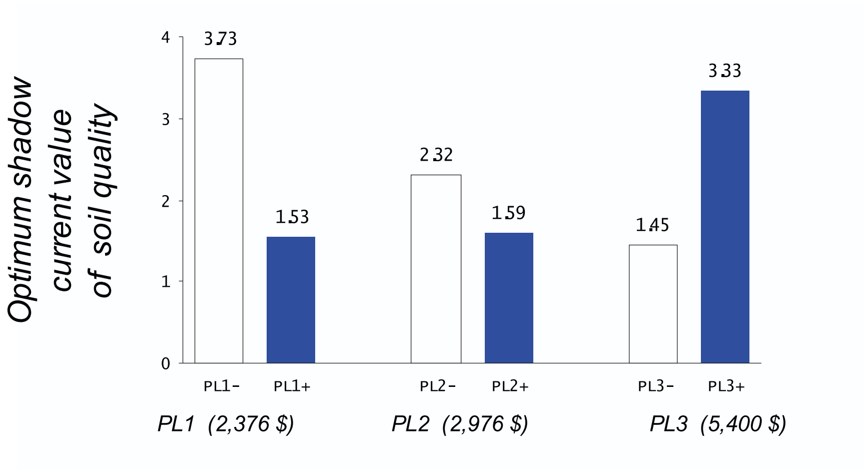

Figure 3: Optimal current soil quality values for the poor and rich (according to three poverty lines)

Tables

Table 1: Distribution of income shares (in%) across poverty groups based on 1998-99 data

	Off-farm	On-farm†	Non-labour	Crafting	Backyard animal sale	Cattle sale
PL1$^-$	28.60	17.08	42.75	9.37	2.19	1.52
	(31.13)	(17.78)	(31.86)	(20.79)	(3.70)	(6.63)
PL2$^-$	38.67	15.45	36.57	7.74	1.99	1.26
	(35.74)	(16.62)	(32.10)	(19.15)	(3.46)	(6.03)
PL3$^-$	60.75	8.86	22.29	4.72	2.69	1.77
	(33.09)	(12.21)	(26.63)	(13.43)	(6.97)	(8.92)
PL1$^+$	78.38	4.30	11.36	1.53	3.06	1.38
	(18.26)	(3.90)	(13.83)	(5.23)	(7.19)	(8.00)
PL2$^+$	77.97	4.05	11.66	1.64	3.20	1.48
	(18.70)	(3.70)	(14.14)	(5.40)	(7.42)	(8.29)
PL3$^+$	81.71	3.74	10.65	0.17	3.24	0.49
	(13.73)	(3.79)	(10.67)	(0.47)	(5.25)	(2.29)
Sahcaba	80.29	5.74	7.26	3.60	1.95	1.16
	(22.01)	(6.07)	(11.43)	(7.62)	(4.28)	(5.78)
Hocaba	60.23	8.20	24.54	3.36	3.27	1.53
	(31.80)	(12.35)	(26.06)	(13.05)	(7.32)	(8.44)
MH	66.25	7.55	19.25	3.46	2.91	1.45
	(30.60)	(10.87)	(24.04)	(11.68)	(6.58)	(7.75)

Average estimates based on field data (Standard deviations in parenthesis).

† Calculations based on maize crop alone (other inter-cropped vegetables such as beans and squash are not considered.

Table 2: Distribution of mean parameter values, across poverty groups based on 1998/99 field data

Variable	$PL1^-$	$PL2^-$	$PL3^-$	HOC	MH	SAH	$PL1^+$	$PL2^+$	$PL3^+$
I	1337.64	1429.12	2940.44	3730.70	4328.59	4898.05	5486.39	5587.09	7933.17
P	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
z	514.67	520.34	544.80	534.44	580.20	669.62	603.40	608.76	659.84
L	779.62	715.43	647.81	528.00	637.78	852.34	587.54	600.72	615.20
b	562.97	530.63	451.11	421.69	440.90	478.45	397.67	398.08	417.93
g	0.66	0.66	0.62	0.64	0.60	0.52	0.58	0.57	0.54
Q	0.42	0.44	0.44	0.45	0.44	0.43	0.45	0.45	0.44
η	40.72	47.67	47.89	52.43	46.98	36.33	49.20	46.65	44.95
λ	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Φ	0.06	0.06	0.06	0.05	0.06	0.08	0.06	0.06	0.06
γ	0.06	0.06	0.06	0.05	0.06	0.08	0.06	0.06	0.06

Calculations based on fieldwork data.

Table 3: Descriptive statistics for production function estimation

	z	L/a	$(1-g)L$	Q		z	L/a	$(1-g)L$	Q
MH									
Mean	635.51	1.01	260.18	0.450					
Std.Dev.	488.73	0.67	203.80	0.094					
Min.	23.76	0.00	18.00	0.215					
Max.	2421.73	3.00	880.00	0.631					
N	74	74	74	74					
Hocaba					**Sahcaba**				
Mean	571.98	1.01	198.44	0.459	Mean	760.01	1.01	381.19	0.434
Std.Dev.	425.06	0.72	167.15	0.086	Std.Dev.	583.77	0.58	217.75	0.107
Min.	23.76	0.00	18.00	0.215	Min.	142.58	0.00	79.10	0.234
Max.	2265.84	3.00	720.00	0.631	Max.	2421.73	2.12	880.00	0.615
N	49	49	49	49	N	25	25	25	25
$PL1^-$					$PL1^+$				
Mean	514.67	1.10	252.71	0.423	Mean	671.55	0.98	262.41	0.459
Std.Dev.	330.99	0.73	194.89	0.094	Std.Dev.	523.75	0.66	208.01	0.093
Min.	23.76	0.20	36.00	0.215	Min.	34.95	0.00	18.00	0.234
Max.	1207.72	3.00	720.00	0.580	Max.	2421.73	3.00	880.00	0.631
N	17	17	17	17	N	57	57	57	57
$PL2^-$					$PL2^+$				
Mean	520.34	1.04	237.52	0.435	Mean	681.14	1.00	269.16	0.456
Std.Dev.	351.46	0.68	195.08	0.095	Std.Dev.	529.46	0.67	208.28	0.093
Min.	23.76	0.20	18.00	0.215	Min.	34.95	0.00	28.00	0.234
Max.	1207.72	3.00	720.00	0.615	Max.	2421.73	3.00	880.00	0.631
N	21	21	21	21	N	53	53	53	53
$PL3^-$					$PL3^+$				
Mean	597.74	1.05	249.72	0.447	Mean	724.77	0.92	284.91	0.458
Std.Dev.	470.18	0.67	201.04	0.091	Std.Dev.	530.60	0.69	212.85	0.101
Min.	23.76	0.00	18.00	0.215	Min.	139.78	0.00	72.00	0.278
Max.	2421.73	3.00	744.00	0.615	Max.	2265.84	2.52	880.00	0.631
N	52	52	52	52	N	22	22	22	22

z: total maize output (Kg.); L/a: New cleared forest land (ha.);
$(1-g)L$: 'cropping' (non-clearing) labour (hours man/year); Q: Soil quality index $(0,1)$.

Table 4: Crop production function estimates

Sample	$\ln E$	α_1	α_2	α_3	n
Whole sample†	5.33^{***} (8.55)	0.98^{***} (3.55)	0.25^{***} (2.79)	0.56^{*} (1.73)	74
PL1$^{-\ \dagger}$	4.88^{***} (3.65)	2.03^{***} (2.98)	-0.14 (1.02)	0.30 (1.22)	17
PL1^{+}	4.49^{***} (7.50)	0.97^{***} (2.73)	0.28^{***} (3.22)	0.45 (1.39)	57
PL2^{-}	3.72^{***} (4.09)	1.89^{***} (3.06)	0.22^{**} (1.64)	0.20 (0.47)	21
PL2^{+}	4.77^{***} (6.79)	0.98^{***} (2.71)	0.23^{***} (2.31)	0.47 (1.41)	53
PL3^{-}	4.03^{***} (6.43)	1.42^{***} (3.47)	0.25^{***} (2.38)	0.26 (0.81)	52
PL3$^{+\dagger}$	3.41^{***} (2.29)	0.33^{***} (9.94)	0.27^{***} (7.74)	1.28^{***} (9.53)	22
Hocaba†	1.23 (0.82)	0.29^{*} (1.67)	0.18 (0.83)	1.25^{*} (1.83)	25
Sahcaba	5.17^{***} (4.81)	1.41^{***} (3.31)	0.13 (0.89)	0.56 (1.16)	49

White's asymptotic t-statistics in parentheses. $^{*}p < 10\%$; $^{**}p < 5\%$ $^{***}p < 1\%$.

α_1, α_2 and α_3 are the elasticities of L/a, $(1-g)L$ and Q respectively; $\ln E$: intercept.

$\dagger$: An stochastic production function is used allowing for random inefficiency effects. Inefficiency effects cannot be rejected at 15% sig. level (mixed $\chi^2(2)$:2.67) for MH, and 2.5% for PL1^{-} and PL3^{+} with ixed $\chi^2(2)$ equal to 7.22 and 7.9 respectively.

Table 5: Observed average rural and urban wages (Mexican $/hour)

Type of job	RURAL	URBAN	Average
In agriculture	5.14	n.a.	5.14
In building sector	n.a.	6.88	6.88
Other non-farm jobs	5.11	7.74	6.67
Other non-farm (b)	n.a.	4.02	4.02
Self employment	4.44	n.a.	4.44
Hired labourers' average wage			3.17
Average off-farm household wage			6.12

(b): Mostly women cleaning houses in Mérida
n.a: no observed.

Table 6: Optimum and current on-farm labour supply across income groups

Variable	PL1^{-}	PL1^{+}	PL2^{-}	PL2^{+}	PL3^{-}	PL3^{+}	HOC	SAH	MH
c	4.00	4.25	3.57	5.23	3.59	5.20	4.40	4.13	4.08
c^{*}	1.22	1.23	1.52	1.17	1.39	0.42	0.35	1.18	1.08
L	779.62	587.54	715.43	600.72	647.81	615.20	528.00	852.34	637.78
L^{*}	241.80	180.36	306.14	171.14	253.34	68.75	55.55	291.00	236.47
$(L-L^{*})/L$	0.69	0.69	0.57	0.72	0.61	0.89	0.89	0.66	0.63

Calculations of current c and L are based on fieldwork data.

Table 7: Optimum current soil quality values across poverty groups

	PL1$^-$	PL1$^+$	PL2$^-$	PL2$^+$	PL3$^-$	PL3$^+$	HOC	SAH	MH
μ^*	3.73	1.53	2.32	1.59	1.45	3.33	5.63	2.39	1.63

PL1$^-$, PL2$^-$, PL3$^-$, PL1$^+$, PL2$^+$ and PL3$^+$ stand for the six income groups as in table 6 $I < 5,400$ \$, $I > 2,376$ \$, $I > 2,976$\$ and $I > 5,400$ \$, respectively.
HOC: Hocaba, SAH: Sahcaba, MH: whole municipality.

Table 8: Calibration of $|J|$ across poverty groups and location

	MH	**HOC**	**SAH**
h_{11}	0.029	-0.053	0.081
h_{12}	269.338	236.070	439.102
h_{21}	-8.454E-05	-8.286E-05	-9.012E-05
h_{21}	-0.056	-0.046	-0.076
$\|J\|$	0.021	0.022	0.033
	PL1$^-$	**PL2$^-$**	**PL3$^-$**
h_{11}	0.118	0.212	0.133
h_{12}	271.326	180.545	177.458
h_{21}	-7.273E-05	-7.743E-05	-8.604E-05
h_{21}	-0.066	-0.057	-0.055
$\|J\|$	0.012	0.002	0.008
	PL1$^+$	**PL2$^+$**	**PL3$^+$**
h_{11}	0.043	0.034	-0.065
h_{12}	239.953	259.850	408.693
h_{21}	-9.039E-05	-8.895E-05	-8.045E-05
h_{21}	-0.052	-0.055	-0.057
$\|J\|$	0.019	0.021	0.037

Table 9: Type of equilibrium by income and location groups

	MH	**HOC**	**SAH**
x_{11}	16.462	-4.259	44.312
x_{12}	120.236	-2.636	194.495
x_{21}	-1.232E-05	-1.207E-05	-1.313E-05
x_{21}	-0.008	-0.007	-0.011
$\|\Gamma\|^a$	-0.132	0.029	-0.486
$Trace^b$	16.454	-4.266	44.301
$RootTest^c$	271.262	18.084	1964.483
Equilibrium	SADDLE POINT	STABLE NODE	SADDLE POINT

	PL1$^-$	**PL2**$^-$	**PL3**$^-$
x_{11}	10.708	45.164	119.392
x_{12}	-9.459	93.747	1600.478
x_{21}	-1.060E-05	-1.128E-05	-1.254E-05
x_{21}	-0.010	-0.008	-0.008
$\|\Gamma\|$	-0.103	-0.373	-0.937
$Trace$	10.699	45.156	119.384
$RootTest$	114.877	2040.520	14256.338
Equilibrium	SADDLE POINT	SADDLE POINT	SADDLE POINT

	PL1$^+$	**PL2**$^+$	**PL3**$^+$
x_{11}	30.905	22.486	-7.157
x_{12}	290.352	152.063	-9.982
x_{21}	-1.317E-05	-1.296E-05	-1.172E-05
x_{21}	-0.008	-0.008	-0.008
$\|\Gamma\|$	-0.232	-0.179	0.060
$Trace$	30.898	22.478	-7.165
$RootTest$	955.594	505.955	51.103
Equilibrium	SADDLE POINT	SADDLE POINT	STABLE NODE

[a]: Determinant of Γ at equilibrium values.

[b]: Trace of the Γ.

[c]: Root Test for Γ.

Table 10: Variable definitions

A	Total available common property land for shifting cultivation.
b	Amount of time needed to clear a unit of forest land (hours/ha).
E	External income from exogenous transfers.
g	Ratio of labour time clearing forest to labour time cropping.
I	Income per capita.
L	Household labour in shifting cultivation (hours).
m	Staple consumption (kg). Is equal to I/P.
N	Nitrogen (mineralizable) stock in the soil.
n	Number of households clearing forest land for cultivation.
P	Nominal Price of maize (per Kg.).
Q	Soil quality index (lies between 0 and 1).
r	Discount rate.
s	index of structural suitability of soil for agriculture.
T	Total disposable time for the household.
v	Transformation rate between biomass and nitrogen in the soil.
w	Off-farm wage rate.
x	Soil nitrogen index: ratio of nitrogen content (N) to nitrogen carrying capacity ($\bar{N}$).
Y	Household disposable income.
z	Output of maize (in Kg).
η	Above-ground phytomass (tons/ha).
γ	Intrinsic growth rate of biomass.
λ	$\rho \times v/\bar{N}$.
$\mathcal{A}$	Proxy for poverty.
$\mathcal{H}$	Current value Hamiltonian.
μ	Current value costate.
Ω	Soil isocline.
Ψ	Labour isocline.
Φ	population density: n/A.
ρ, ϕ	Linear weights of x and s, respectively in Q.
σ	Intercept Vector for the effects of forest structure ($D_!$) and cropping cycle (D_2) on N.

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