Modelling land degradation in low-input agriculture:
The ‘Population Pressure Hypothesis’ revised

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ABSTRACT

This paper provides a theoretical framework to analyse land quality and labour allocation decisions by poor rural households in the context of increased population densities in slash-and-burn (shifting cultivation) agro-ecosystems. A bio-economic optimal control model is presented and its results calibrated with data from two farming communities from Yucatán (Mexico). The ecological-economic model restates the validity of the neo-Malthusian ‘Population Pressure Hypothesis’ (PPH) as a major factor of land degradation. It is pointed out that ‘fallow crises’ may be overcome when the production elasticity of total farm labour is sufficiently high compared to the elasticity of substitution between farm labour and soil quality. Calibration of the model also suggests that the strategy by poor households is to allocate more labour to clearing forestland when population densities increase, hence adding to `population pressure’ on the forest commons.

JEL: D1, I3, Q1, Q2

KEYWORDS: Population pressure, deforestation, soil degradation, rural poverty, Yucatan, Mexico.

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1 INTRODUCTION

The rising trend of rural poverty in rural areas of developing countries and the unprecedented high rates of land degradation on which peasants' livelihood depend are indisputable phenomena. The linkage between poverty and land degradation is gaining much attention and numerous theoretical and empirical analyses are being carried out to explain the different economic determinants of the problem. One causation link has gained much attention focuses on high rates of population growth. However, there is little agreement on the relationship between population and land degradation, not only on the magnitude but also on the directional link. Two main perspectives have attempted to explain the causes and consequences of the rural poverty-land degradation link through the role of population growth. At one extreme of the debate we find the land degradation-poverty 'vicious circle' approach which is Neo-Malthusian in inspiration (Dasgupta, 1992; Myers 1992; Ehrlich and Daily, 1996). In the other extreme of the debate we can find the Boserupian idea that in response to greater population density and declining yields, shifting cultivator farmers intensify land use by reducing natural fallow periods towards continuous cropping (aided by the application of artificial capital accessible in the marketplace) to maintain/increase crop yields. This puts less pressure on the extensive and often fragile land resource (Boserup, 1965). There is a growing realisation that 'cumulative effects' associated with the institutional fabric at the meso-economy level need to be put at the forefront of the population-land degradation debate. For instance, it may be crucial to address the effects of alternative land tenure regimes (Larson and Bromley, 1990), or the role of uncertainty and risk in rural economies (Ardila and Innes, 1993; Grepperud, 1997) to shed additional light into how peasants' land conservation strategies are shaped.[1]

The empirical evidence shows that both neo-Malthusian and Boserupian hypotheses of land degradation are likely to be valid depending on the institutional (including the market) fabric of the agro-ecosystem under scrutiny. Nevertheless, the policy arena is still very much biased towards the neo-Malthusian approach, therefore implicitly arguing that the core of the land degradation problem begins and ends with the land-users themselves. This idea of the *Population Pressure Hypothesis* (PPH) in the case of soil degradation in traditional farming systems, is summarised by Grepperud (1996): "*only when population is greater than the carrying capacity of land is a more rapid degradation of land identified and 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*'' (Grepperud, 1996) [pp. 31].

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[1] Panayotou (2000) offers a comprehensive review of the different historical perspectives underpinning the population-environmental degradation debate.

This paper analyses the usefulness of the PPH in the context of slash-and-burn (shifting cultivation agriculture) systems. But rather than looking at the PPH from an agroecological perspective (Bandy et al, 1993; Kleinman et al. 1995), the focus here is on the inter-connectedness between peasant households' level of welfare and wealth and their economic behaviour as regards the allocation of their three most basic assets: labour, available land and its quality when population-land ratios change.[2] [3]

Despite the scope and importance of slash-and-burn (SAB) in the tropics, this agro-ecological system has, rather surprisingly, attracted relatively low academic and policy interest than other forms of cropping systems throughout the developing world. While tropical SAB is based on the exploitation of forest land, the diversity of shifting cultivation agriculture can be found at many levels and ecosystems ranging from forests to grassland, savannas and mountain environments. An often cited estimate is that there are around 300-500 million shifting cultivators in the tropics (Sánchez, 1996). Bandy et al (1993) estimated that about 30% of the arable soils of the world are thought to be involved in some sort of shifting cultivation. This accounts for a total of around 240 and 170 million hectares of closed and open forests respectively. In essence, SAB consists of clearing patches of primary or secondary-growth forest, by cutting down the bush-tree biomass and burning as much of it as possible. Crops are then planted among the charred stumps. The cleared land is usually free from weeds and the soil has a reserve of plant nutrients in addition to those contained in the ash of the burned woody material. After one or more years of cultivation, the farmer may leave the plot in fallow and allow secondary forest to return in order to replenish soil nutrient capital. After some time, the forest fallow is cut and the cycle begins again.

Traditionally SAB systems have been regarded as a wasteful system that cannot allow for sufficiently long forest regrowth intervals to replenish the nutrient stores. This effect, commonly known as the fallow crisis, implies a vicious circle of declining crop yields and the need to clear additional forest-land area to achieve a minimum crop output. This idea is Neo-Malthusian in inspiration and is popular in the agro-ecologic literature (Sánchez, 1996). However, there have been few attempts to include a peasant behavioral component and market constraints to shed additional light on the fallow-crisis problem (Dvorak, 1992; Albers and Goldbach, 2000; Pascual, 2002).

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[2] A restrictive concept of quality as reflecting agricultural productive potential is employed throughout the paper, but no attempt is made to supply a concrete definition of the 'soil quality' concept, thereby skipping the longstanding debate on its meaning.

[3] Others (e.g. Dasgupta, 1992) present their arguments about land degradation and population dynamics focusing on the Vicious Cycle Model that brings into the picture important aspects such as illiteracy of the households that prevents switching to better environmental technologies (e.g. alternative cooking fuel sources) and the gender dimension specifically the stagnation of education levels by young girls.

The literature about modelling the economics of SAB systems under population pressure is a relatively new one.[4] Salehi-Isfahani (1988) first formalised the Boserupian labour intensification path in SAB agriculture and Krautkraemer (1994) used this framework to predict that as population growth induces increases in output prices (via increases in the demand of food), land management is expected to evolve towards continuous cropping at the steady state, hence once rationalising the Boserupian hypothesis. In a similar context of an indivisible farm plot under SAB, Barrett's (1991) shows that under initial low levels of soil fertility, the duration of fallow is expected to exceed that of each succeeding fallow. But, if soil fertility is high, households will tend to intensify land use by cultivating immediately and increasing the duration of cropping period. Holden's (1993) linear programming model points out that despite high population densities, farmers' risk aversion to yield failure is the main reason why shifting cultivation is still practiced under increasing input market integration in Northern Zambia. Similarly, Barrett (1999) argues that risk aversion to output price volatility explains why price liberalisation policies lead to a reallocation of time from leisure to cultivation by (staple) net-buyer shifting cultivating households. Others have applied econometric analyses about the effect of population pressure on land degradation in SAB systems. Place and Otsuka (2001) have recently suggested that Boserupian induced responses may be at work in Malawi and Tachibana et al. (2001) have claimed that even with high population growth, land extensification through SAB in the forest margins of Vietnam can be deterred by strengthening land use rights. Lastly, Coomes et al's (2000) duration model for fallow systems in the Peruvian Amazon point out that additional farm labour access from female members and communal labour can be associated with longer natural fallow periods.

The remainder of the paper unfolds as follows: The next section outlines a control model of a typical shifting cultivator household, which focuses on optimal labour and soil use, to derive a PPH condition specific to SAB. Section 3 provides background information about the study area (comprising two communities from Yucatan, Mexico) and the PPH obtained in the model is calibrated. Finally, the last section concludes the paper.[5]

2. A MODEL OF OPTIMAL LAND USE IN SLASH-AND-BURN

This section sets up a dynamic bio-economic model that represents key factors behind the economics of land degradation in SAB agriculture. The model considers the quality of cultivable land as being a function of the state of the soil-forest vegetation complex. This is considered to be farmers' productive

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[4] Since early attempts to model optimal soil use decisions by farmers, (McConnel 1983; Shortle and Miranowski, 1987) models of optimal soil capital depletion in developing economies have also found their niche (Perrings, 1989; Barbier, 1990; Larson and Bromley 1990; Grepperud, 1997).

[5] This paper develops from Pascual and Barbier (2001) in which a more detailed model than the one sketched here can be accessed.

asset, which in turn evolves simultaneously together with farmers labour extensification decisions. The SAB model presented here is close in inspiration to the models by López (1997, 1998). López, points out that the community costs incurred by SAB households, due to the negative effect that clearing village-land has on the rest of the farmers should also be taken into account. His point is that depreciation of village level forest vegetation biomass might contribute to higher yields for any given farmer in the short run, but not in the longer run. The model also follows Angelsen (1999), by considering the competitiveness in the main markets, i.e. food and labour market, implying that output and input prices are exogenously determined. As regards the labour market, the model assumes that peasant households are well integrated to the off-farm labour market. Hence, the opportunity cost of time can be equated to the off-farm wage rate, under negligible transaction costs, and, the value of the non marketed maize output can be considered to be subsistence cash value to the peasant.[6]

The representative shifting cultivator household's utility function assumed to depend on staple consumption (*m*), i.e. $U = U(m)$, where $U'(m)>0$ and $U''(m)<0$. Leisure time is not included explicitly in the utility function since it is assumed that households in the tropics are usually bound by a strict climatic calendar in each crop cycle, thus taking leisure time practically predetermined at the beginning of each agricultural cycle. Given the dynamic nature of land degradation, it is assumed that households aim at maximising the household's inter-temporal utility level, It is also assumed that in every time period (*t*), the key constraints faced by the household conform to the budget and ecological state of land for agricultural purposes. The budget constraint depends, in turn, on the crop production function. Total output, $Z_i(t)$, and income, $Y_i(t)$, are described in the following equations:

$$Z_i (t)=f_i [g\, Li(t)/b_i,\ (1-g_i)L(t),\ Q_i (t)] \qquad (1)$$

$$m_i (t)= Z_i (t) + c[T_i- L_i (t)] + E_i \qquad (2)$$

where, $f_J>0$, $f_{JJ}< 0$ and $f_{jk}=f_{kj}>0$, *i* identifies the household and *j* identifies the argument in the crop production function. $Z(t)$ is total crop output expressed through a transformation function of three factors: the area of new cleared land at period *t*, $gL(t)/b$, labour used in crop production on this land, $(1-g)L(t)$, and soil quality $Q(t)$. Note that $Q(t)$ is included in the production function since, by contrast to areas where land is homogeneous and in abundant supply, it is expected to be associated with a positive marginal value. New cleared land is in turn a function of (i) total labour allocated on-farm, $L(t)$, (ii) the proportion of that labour devoted to clearing new forest land, *g,* and (iii) a measure of

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[6] Anglesen (1999) and Bluffstone (1995) model the effects of ill functioning labour markets on deforestation. Note that as in these models we are dealing with a partial equilibrium model. The general equilibrium effects of changes in population density through price effects have been treated elsewhere (Salehi-Isfahani, 1988; Krautkraemer, 1994).

labour intensity in forest land clearing, i.e. the amount of on-farm labour needed to clear a unit of forest land, *b*. The second argument in the production function (1) is `cropping labour'; that is, the proportion, (*1-g)*, of farm labour allocated to tasks other than forest clearing, such as sowing and weeding. As regards (2), $c[T_i - L_i(t)]$ is the real wage revenue obtained in the off-farm labour market, c being the real wage rate (*w/P*) and *T* the discretionary labour time diversified between the on- and off-farm labour markets. If $T_i - L_i < 0$, then it represents hire-in labour costs. *E(t)* represent real exogenous income that would include government or inter-household cash and in-kind transfers, etc.

New cleared land is parametrically linked to *L(t)*, through *b* in (1), implying that there are very limited options for an intensive management of shifting cultivation (Boserup, 1965). Thus, 'cropping labour' also is assumed to be allocated in fixed proportion to the amount of newly converted forest-land, and therefore without much loss of generality, *g* becomes exogenous.[7] Thus, *g* and *b* provide a link between total labour applied on the land and forest area cleared.

The fundamental natural asset in shifting cultivation is the above-ground tree biomass. However, it is not forest-land *per se* that shifting cultivators exploit, but the vegetation-soil complex that has developed on the land. Hence, any indicator of the soil quality of land cleared for cultivation ought to reflect the state of the key components determining the vegetation-soil complex. Soil fertility at period *t* is proxied by *N(t)*, i.e, the nitrogen content in the topsoil at period *t*. More specifically, *Q(t)* is given by the relative dynamic nitrogen content that is pumped, at rate *v,* by the fallowed forest biomass onto the soil, i.e $Q(t) = N(t)/N_{max}(t)$, where N_{max} is the maximum level of natural nitrogen deposits in the topsoil. In SAB where soil fertility is maintained through fallowing and usually does not involve any further input use (such as mulch, dung or crop residues), *Q(t)*, can be modelled as an standard renewable resource which evolves as a by-product of forest dynamics (Nye and Greenland, 1960). This means that the recuperative potential of *Q(t)* in a recently cleared forest plot greatly depends upon two related elements: (i) tree biomass during forest fallow prior to clearing (Trenbath, 1984), and (ii) the species composition of the tree biomass in fallow (Kleinman et al., 1995). In addition, in early fallows the rate of accumulation of soil nutrients is at a maximum, resembling an asymptotic approach to high levels of soil fertility under longer forest fallows (Nye and Greenland, 1960; Trenbath, 1984). It is thus convenient to represent this relationship for the *N(t)* of the cleared plot in the following way:

$$N(t) = v \ln[B(t)] + s \tag{3}$$

where, *B(t)* represents the tree biomass existing in the forest plot prior to clearing, *v* is the rate at which nitrogen is pumped from the tree biomass to the soil and *s* stands for a scaling intercept, that reflects

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[7] This hypothesis has been tested by Pascual (2002) with data from the Yucatan and could not be rejected.

tree species composition since different species are able to fix nitrogen at different rates. It follows that the change in *Q(t)* from one period to the next is given by $\dot{Q} = v\frac{\dot{B}}{B(t)}$. Thus, if the household left the land fallow for a period of time longer, any resulting growth in biomass would also increase soil quality of that land.

Under common property forest land we assume that the biomass on a plot of forest-land depends on the remaining area of fallow land available to the whole village (Lopez, 1997, 1998; Place and Otsuka, 2001). It follows that the yearly evolution of the fallow biomass on the average SAB plot to be converted for cultivation is expressed as follows (and suppressing the time index) (López, 1997):

$$\dot{B} = \gamma - \frac{\sum_{i=1}^{n} \frac{L_i}{a_i}}{A} B \tag{4}$$

where *n* represents the number of households in the village converting fallow land; $a_i=b_i/g_i$, is the labour intensity of slash and burning per unit area by household *i*, and *A* stands for the total land area both fallowed and converted under the community's control. The annual net growth of tree biomass on fallow land is determined by the constant intrinsic growth of the secondary vegetation, γ , less the depreciation of the biomass stock, through conversion of forested to cultivated land by each household *(L_i/a_i)*. For simplicity, is we assume that all households are identical, by substitution we obtain:

$$\dot{Q} = \lambda\left(\gamma e^{1/B(t)} - \Phi\frac{L}{a}\right) \equiv \lambda\left(\gamma e^{-q(t)} - \Phi\frac{L}{a}\right) \tag{5}$$

where $\lambda = v/N_{\max}$ is the coefficient that translates the nutrient stock pumped from the biomass to a notion of land quality prior to be converted; $\Phi \equiv \frac{n}{A}$ represents the ratio of number of households practising SAB to the total available forest area for annual conversion to agriculture, and $\exp[q(t)] \equiv \exp\left[\frac{Q(t)}{\lambda} - \frac{s}{v}\right]$ for shorter notation.[8]

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[8] $\gamma \exp[-q(t)] = -\lambda\frac{\partial \dot{Q}}{\partial Q}$ is the natural own rate of soil nutrient depreciation.. The net marginal cost of waiting for biomass to grow in order to improve the soil condition, or net interest rate of soil capital is therefore endogenous to the state of *Q*: $r + i \equiv r + \gamma \exp[-q(t)]$ (see equation A1.c in the appendix).

The periodic evolution of soil quality is given in (5). The problem of the shifting cultivator household is to choose the optimal amount of farm labour, *L(t),* in every period or agricultural season that maximises its welfare over time. *L(t)* is therefore the choice, control, variable. The problem of the household can be formally stated using an autonomous dynamic model. Under a long run scenario, and using a positive discount rate, *r*, the maximum value function (V^*) is represented by (6):

$$V^* = \max_L \int_{t_0}^{t\to\infty} e^{-rt} U[m(t)]dt \tag{6}$$

subject to constraints (1), (2) and (5). The current value Hamiltonian is in turn given by (7):

$$\widetilde{H}\left[Q(t),L(t),\mu(t)\right] = U[m(t)] + \mu(t)\left[\gamma e^{-q(t)} - \Phi\frac{L(t)}{a}\right] \tag{7}$$

where, $\mu(t)$ is the costate variable or shadow value of soil fertility in period *t.* By approximating the problem using continuous time and solving for the maximum principle, and invoking the steady state condition for the control, state and costate and control variables, $\dot{L} = \dot{Q} = \dot{\mu} = 0$, the farm labour and soil quality isoclines, $\dot{L} = 0$ and $\dot{Q} = 0$, respectively, and the optimal long run shadow value of soil quality are obtained (Appendix):

$$\dot{L} = 0: \qquad \lambda\Phi f_Q = a(r+i)(f_L - c) \tag{8.a}$$

$$\dot{Q} = 0:^9 \qquad \gamma\exp(-q) = \Phi\frac{L^*}{a} \tag{8.b}$$

$$\dot{\mu} = 0: \qquad \mu^* = \frac{U'(m)f_3}{r+i} \tag{8.c}$$

where f_Q and $f_L \equiv f_1/a+(1-g)f_2$ are the marginal product of soil quality and farm labour, with f_1 and f_2 as the marginal products associated with the first and second arguments in (1); Equations (8a-8b) illustrate that the representative household is always allocating soil quality among two competing uses. The choice is about making use of it immediately as a variable factor of crop production, or alternatively, delaying clearing and cultivating, allowing further tree biomass growth on fallow land and thus, improving soil quality for future higher yields.

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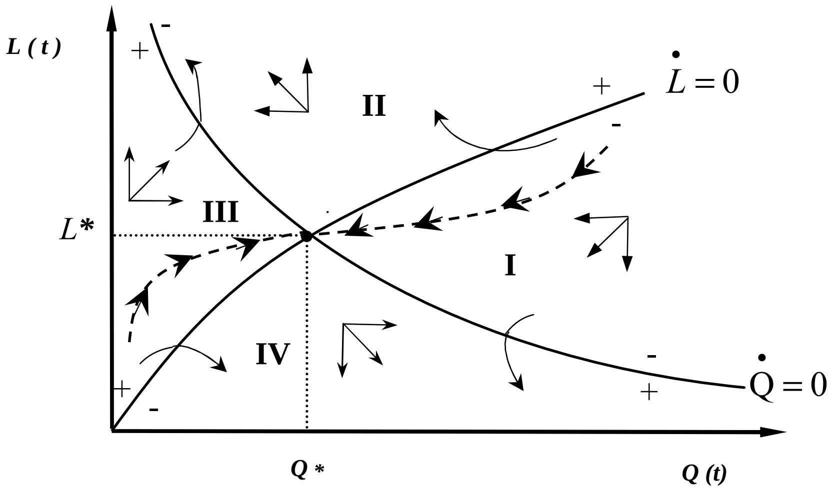
[9] See footnote 8 for interpretation of $\gamma\exp(-q) \equiv i$.

Figure 1 shows that at any time, *t*, the optimal allocation of labour in slash-and-burn depends on soil fertility levels in the fallowed area prior to the land being cleared. If the household clears and cultivates land that initially has a high level of soil fertility ($Q_0>Q^*$), then in order to be on a stable path, the household should also allocate a large amount of its time to on-farm labour. 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 fertility and labour allocated to on-farm activities will fall, until the long-run equilibrium is reached. Alternatively, if the household initially has access to land with relatively low soil fertility ($Q_0<Q^*$), 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 fertility to recover ($\dot{Q} > 0$). Consequently, along this saddle path, the household is able to increase its allocation of labour for clearing and cultivation as the soil fertility of the land gradually improves, until the stable equilibrium is reached. As the sketching of the phase paths suggests, farm labour and soil fertility are complementary inputs along the optimal paths in shifting cultivation. How much labour a household can devote to farm activities is conditional on soil fertility. For example, as Figure 1 shows, if the land available to a household has low soil fertility initially but the household allocates too much labour on-farm then eventually soil fertility may deteriorate rapidly $Q \to 0$. The result is likely to be collapse of the natural subsystem as documented in the literature (Trenbath, 1984; Dvorak, 1992; López 1997; Albers and Goldbach, 2000).

Figure 1: Phase-plane diagram of the SAB control problem.
Steady state equilibrium as "saddle point".



It is widely postulated by agro-ecologists that a crucial element explaining the breakdown of the ecological sustainability in fallow systems, is due to excessive exaction rates on the fertility of the soil

from the natural subsystem driven by high population densities, i.e., the so called `fallow crisis'. In addition to the average labour applied in shifting cultivation (which through g determines the amount of land cleared by each household), the 'social scale' of soil fertility exaction describes the degree of pressure upon the soil-vegetation complex. This can be proxied by the population-area ratio, Φ.
Applying Cramer's rule to the system of equations (8a-8b), the following long run comparative static result is obtained as regards the effect of Φ on the long run optimal level of L^* and Q^*.[10]

$$\frac{dL^*}{d\Phi} \geq 0 \Leftrightarrow a(f_L - c) \geq F \tag{9a}$$

where

$$F = \lambda \left[\frac{(r+i) f_{LQ} - \lambda \Phi f_{QQ}}{i} + \frac{f_Q}{L^* / a} \right] > 0$$

is the marginal opportunity cost of using soil quality today and not leave it to grow to obtain higher output tomorrow. Condition (9a) states the obvious. In equilibrium, farm labour by the representative shifting cultivator will increase, when population density increases, only when the net marginal returns to farm labour, $a(f_L - c)$ outweigh the marginal cost of exploiting soil quality through converting communal forest-land into cultivated land, *F.* The marginal cost assessed by the household includes the reciprocal externalities on the rest of the community are fully internalised. Thus, if condition (9a) does not hold, then it is possible for farmers to allocate less farm labour under higher population densities. On aggregate this could cause a rebound effect by which the effect on forest biomass of a decrease in labour use to clear additional forestland by each household outweighs the effect of increased population density in the area. Thus, the effect on average soil quality in shifting cultivation is necessarily ambiguous. The net effect is given in (9b):

$$\frac{dQ^*}{d\Phi} \leq 0 \Leftrightarrow \Phi \geq \Omega \tag{9b}$$

where

$$\Omega = \frac{(r+i)}{\lambda} \left(\frac{f_{LL}}{f_{LQ} - {}^{f_Q}\!/_{L}} \right)$$

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[10] See Pascual and Barbier (2001) for the derivation of the sign of the Jacobian determinant in the application of Cramer's rule.

Equation (9b) is a reformulation of the PPH, where Ω now is the population density threshold beyond which soil quality is expected to decrease. Note that this is not 'bad' because households causing soil deterioration are assumed to be fully conscious of it and fully absorb its costs. Note that since $f_{LL}<0$, $f_{LQ}>0$ and $f_Q>0$, then

$$L^* > \frac{f_L}{f_{LQ}} \Rightarrow \frac{dQ^*}{d\Phi} < 0 \qquad (9b')$$

Furthermore, assuming a linear homogeneous production function, (9b') can be restated as a sufficient condition for the PPH to hold:

$$\varepsilon_L > \sigma_{LQ} \Rightarrow \frac{dQ^*}{d\Phi} < 0 \qquad (9b')$$

where ε_L is the output elasticity of L^* and σ_{LQ} is the elasticity of substitution between optimal levels of L^* and Q^*. Thus, the model restates the PPH by taking into account the state of the technology in SAB. That is, the PPH holds in SAB low input systems when the output elasticity of labour outweighs the elasticity of substitution between labour and soil quality, once inputs are allocated optimally. In this case shifting cultivation households will disinvest soil quality regardless whether each farm household applies more or less labour to farming after the change in population density has occurred. This analysis also calls for due caution when invoking the PPH. Together conditions (9a) and (9b) point out that soil capital in SAB would not necessarily decline through decreases in fallow periods, due to an increase in population density. The reason ought to be found in farmers' strategies to convert less communal land and apply more labour off-farm. Once the PPH is restated in the context of SAB, conditions (9a-9b) can be evaluated with household and ecological data.

3. DATA AND CALIBRATION OF THE PPH

The case study is based on two traditional slash-and-burn communities from Yucatan, Mexico: Hocaba and Sahcaba. Both belong to the municipality of Hocaba, that owes his name to the municipality seat. This municipality is one of the 106 municipalities of the State of Yucatan, which is located in the Northeastern part of the Yucatán peninsula in the Southeast of Mexico (figure 2).

Figure 2: Location of case study in the Yucatan (Mexico)

The municipality is within an inter-tropical area under a climate described as the driest among the warm sub-tropical classes. At an ecosystem scale, this climate has largely determined the structure of the forest vegetation. The composition of the typical secondary vegetation in fallow is characteristic of 8% of forests cover in Mexico. It consists of an ecotone of low (i.e., trees of 5--8 m) to medium (8--12 m) height tropical dry deciduous forest. These agro-ecological characteristics have determined the farming practices of the Yucatec Maya to what is referred locally as milpa *SAB* (nearly 95% of agricultural land area in Yucatán is cultivated under this shifting cultivation system). Maize is, by far, the most important crop grown on SAB fields, usually for home consumption. This however, is not due to absence of a reliable market for maize, but due to the general lack of maize surpluses from fields in the region. Interestingly, SAB is mostly practised in common property land, known as *ejido* land. The ejido in the municipality is well established besides the land liberalisation reform that started a decade ago.[11] Regarding population levels, in 1998 there were 4,275 persons (approximately 820 households) living in Hocaba and 1,740 dwellers (approximately 215 households) in Sahcaba. From these households, about 60% were engaged in the SAB, implying that the SAB population density in the area is about 6 households (34 persons) per square km (Pascual, 2002). This is thought to be far greater than what is thought to be sustainable in this area (Mizrahi et al 1995).

Regarding income levels in the area, around 21% of households are below the most extreme poverty line, determined as the expenditure level to achieve a minimum nutritional requirement (around US$

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[11] The reform is based on the amendment to Article 27 of the constitution that had served, since the end of the Mexican Revolution in 1917, as the embodiment of the government's commitment to the rural poor by redistributing land.

258 *per capita per annum*). Further, according to the most conservative poverty line (US$ 587 pcpa), around 70% of households can be deemed poor (Pascual, 2002).[12] Maize yield ranges between 500-600 kg/ha, which is substantially less than the average of 2.3 tons/ha in Mexico in 1998 and a minuscule figure if compared to capital intensive maize farming in neighbouring US (i.e. 8.5 tons/ha) (FAO, 2002).

With a sample of 74 SAB households, the production elasticity estimates appear in Table 1. These have been obtained estimating a Cob-Douglass Stochastic Production Frontier with the same arguments as in Eq. (1), which called for estimating a soil quality index based on the relative content of nitrogen in each farmer's plot, and the effects in the distribution of total labour on the farm between slashing the tree cover and applying labour for cropping.

Table 1: Cobb-Douglas Stochastic Production Frontier elasticity estimates

	ln(Constant)	***Coeff ln(L/a)***	***Coeff ln[(1-g)L]***	***Coeff ln(Q)***
Municipality	5.33*	0.98*	0.25*	0.56^{+}
Poor	4.88*	2.03*	-0.14	0.30
Non-poor	3.41*	0.33*	0.27*	1.28*

All models pass the Likelihood Ratio Test (Pascual, 2002).

** and $^{+}$ indicate P<1% and P<10% respectively..*

Table 2. Parameter estimates used for model calibration

		Municipality	***Poorest***	***Non-poor***
Income per capita/year (1998 Mex. $)	Y	*4,329*	*1,338*	*7,933*
Production of maize (kg)	Z	*580*	*515*	*660*
Total labour hours/yr applied in SAB	L	*638*	*780*	*615*
% of labour time in SAB for cutting trees	g	*60*	*66*	*54*
Hours/ha to clear forest land	b	*441*	*563*	*418*
Total cleared land area in SAB (ha)	L/a	*1.0*	*1.1*	*0.9*
Tree biomass used in SAB plot (tons/ha)	B	*40.7*	*47.0*	*44.9*
Soil quality used (% relative fertility)	Q	*44*	*42*	*44*
Natural growth of Biomass/soil	γ	*0.17*	*0.18*	*0.17*
Price of maize ($/kg)	P	*1.5*	*1.5*	*1.5*
Population density (households/ha)	n/A	*0.06*	*0.06*	*0.06*

Source: Fieldwork (Pascual, 2002).

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[12] The poverty estimates have been adjusted using Rothbarth adult equivalency index.

Table 2 provides descriptive data on the economic structure of the communities under study. These data are used for the calibration of the model. The data is shown for the community as a whole, and also stratified by income levels: (i) the poorest sub-sample of households (21%) characterised by having income below the most extreme poverty line, and (ii) those above the most moderate poverty line, that we call the 'non-poor'.

Equation (9b) has predicted that when the elasticity of production for the labour input is greater than the elasticity of substitution between labour and the quality of the resource base (soil), then the fallow crisis is inevitable (soil quality will decrease as population densities increase). It can be shown that this result also holds when changing the world labour for new cleared land (Pascual, 2002). Table 1 indicates that the production elasticity for *L/a* (new cleared land) is greater than 1 for the poor and less than one for the rich.[13] It implies that necessarily, in the area under study, soil quality will decrease when income levels are low. However, this may not be the case when income levels increase sufficiently. We turn to a Cartesian analysis to ascertain the direction of changes of L^* and Q* after a change in population density. The calibration of the comparative static analysis around the steady state requires to (i) calculate an endogenous real wage rate, *c,* determined at when observed L equals L^* as per (8a), and (ii) the calibration of the intercept and slope values of the isoclines (8a, 8b) before and after an exogenous change in Φ occurs.

These steps allow the Cartesian analysis to show the relative position of the new steady state equilibrium point under linearised $\dot{L} = 0$ and $\dot{Q} = 0$ isoclines. This, in turn, can be compared with the position of the original steady state equilibrium. The calibration of the steady state analysis is presented in Figure 3 and Figure 4 associated to the effect of an increase in population density on the poorest and least poor farm households. The original steady state equilibrium point (Q^*, L^*) can be recognised as point A since it is determined by the intersection of the soil and labour isoclines before the change in population density. After the exogenous change in *n/A*, the new equilibrium becomes point B. Thus the focus is on the relative location of B relative to A in the linearised (Q, L) phase-space.

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[13] The elasticity of substitution between new cleared land area and soil quality with a Cob-Douglass production function is always 1.

Figure 3: Phase diagram: Effect of changing population density on the poorest households

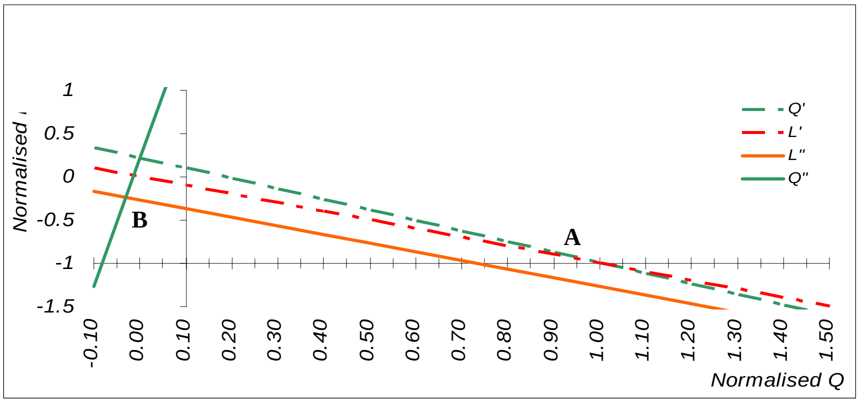
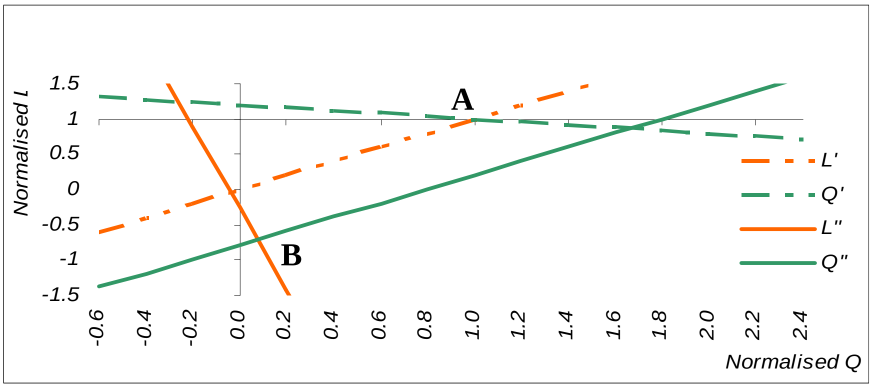


Figure 4: Phase diagram: Effect of changing population density on least poor households



Figures 3 and 4 indicate that regardless of income level the PPH will occur in the area under study. But interestingly, the effect on the optimal allocation of farm labour is different between the poorest and the least poor households. While the former find it optimal to supply more labour on-farm, the rich will substitute off-farm labour for SAB labour, and thus clear less forest-land per household. This is an important finding. It implies that although the PPH does not necessarily need to happen, and it will depend on the technology at hand (relative values of the elasticities of production), labour supply patterns may differ substantially for households with different income, given an exogenous change in population densities. The numerical exercise corroborates the theoretical expectation. Besides supporting the Population Pressure Hypothesis, the results state that the effect on soil quality depends upon the crop production technology. More concretely, the theoretical model and the numerical calibration suggests that the PPH or ‘fallow crisis’ is consistent in SAB systems, the phenomenon can be more complicated if households’ labour supply patterns associated with their income levels are taken into account.

4. CONCLUSION

The findings presented in this paper are based on a theoretical approach and a numerical calibration of the long-run results of a bio-economic control model. Primary data from the field study has been applied to shed additional light on the possible impacts of increased population densities in traditional slash-and-burn systems, similar to the ones found in Yucatán (Mexico). The model has shown the possibility for households' adaptation to increased population density by changing on-farm labour supply. Normally this effect is overlooked in the literature on SAB. Indeed, when households can adapt to changing population density conditions by reallocating labour from the farm to the off-farm sector, higher population density does not necessarily imply higher population pressure on the agro-ecosystem (Pascual, 2002). The insights from the Cartesian analysis are that, in the longer run, higher population density in the studied area will make soil quality deteriorate. However, the effect is due to different reasons when households with different income levels are taken into account. The poorest households may find it optimal to increase their allocation of SAB labour, and the least poor under fixed leisure time, would prefer to substitute off-farm labour for SAB labour. In the case of the least poor although on average less labour-induced soil degradation will occur by each household, the result of the lower soil quality is due to more households clearing the fixed community area of forest-land. The analysis thus shows that behavioural responses to changes in population densities in traditional agro-ecosystems may be structurally linked to farmers' income level. Therefore poverty and the PPH are related in that the former acts as a behavioural constraint to exogenous changes. We argue therefore that PPH as a cause of land degradation in tropical agriculture should be evaluated given that the technological and socio-economic fabric of the community under analysis is also controlled for.

The theoretical results rely on the assumption that households' leisure time is fixed. While this assumption may be suitable for the poor given their highly inelastic labour supply in the area under study (Pascual, 2002), the assumption may be more problematic for the least poor. This is because of the latter having a higher amount of discretionary time for pure leisure. Hence, we argue that this analysis is better suited for rural areas where poverty is prevalent, as most slash-and-burn systems are. In terms of the policy implications of this analysis, poverty makes it optimal to increase allocation of labour to extensive shifting cultivation. This would undoubtedly put higher pressure on the remaining common property land and soil quality would decline as a result. This may well be the reason why the communities studied here, have repeatedly refused to join the land titling program aimed at liberalising the land market in rural Mexico. Poor farmers' rejection to the liberalisation plan may therefore make economic sense and can be interpreted as such, and not only as a cultural attachment to their ancestral communal forest land resource.

APPENDIX

The First Order Conditions for an optimal path, along with the transversality and boundary conditions are (A1.a – A1.e):

$$U'(m)\left[\frac{f_1}{a}+(1-g)f_2-c\right]=\frac{\mu\Phi\lambda}{a} \tag{A1.a}$$

$$\frac{\dot{\mu}}{\mu}+\frac{U'(m)f_3}{\mu}=r+\gamma e^{-q}(\equiv r+i) \tag{A1.b}$$

$$\dot{Q}=\lambda\left[\gamma e^{-q}-\Phi\frac{L}{a}\right] \tag{A1.c}$$

$$\lim_{t\to\infty}\mu(t)Q(t)=0 \tag{A1.d}$$

$$Q(0)=Q_0 \tag{A1.e}$$

The interpretation of the maximum principle can be obtained in Pascual and Barbier (2001). The system (8a-8c) can be reduced to a two-equation system in a (*Q,L*) dimension. The total farm labour, *L*, allocation path and its steady state solution is derived by totally differentiating (A1.a) with respect to time, and substituting for $\dot{Q}=0$ and $\dot{\mu}$, derived by amalgamating (A1.a) and (A1.b). The optimal path for *L* is given by:

$$\dot{L}=\frac{\lambda\Phi f_Q-\left(r+e^{-q^*}\right)af_L}{\theta a(f_L-c)^2-f_{LL}} \tag{A.2}$$

where θ is the marginal elasticity of staple consumption and measures the global concavity of the utility function. Since at the steady state $\dot{L}=0,$ if follows from (A.2) that the implicit farm labour allocation rule evaluated at equilibrium is (8.a). In addition, the long run (current) shadow value of soil quality is obtained by setting $\dot{u}=0$ in (A1.c). The stability and sufficiency conditions for optimality can be seen in the appendix to Pascual and Barbier (2001).

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