Shifting Cultivation Expansion and Intensity of Production: The Open Economy Case

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Summary:
This paper studies decision making in shifting cultivation, in particular labour inputs, length of rotation or fallow period (intensity of production), and the agricultural frontier (expansion). Analytical models are developed, combining forest rotation and spatial approaches in resource economics. The small, open economy assumption is used, that is, all prices, including the wage rate, are fixed in the models. This is crucial for the effects of various policies. Three different property rights regimes are discussed: Social planner's solution with secure rights to all forestland, open access, and homesteading, where property rights are established through forest clearance.

Sammendrag:
Dette arbeidsnotatet analyserer beslutninger i svedjebruk, spesielt arbeidsinnsats, rotasjonslengde og ekspansjon. Analytiske modeller utvikles ved bruk av to ulike innfallsvinkler i ressursøkonomi for skogsrotasjon og lokalisering. En bruker forutsetningen om en liten, åpen økonomi, dvs. at alle priser, inkludert lønn, er gitt i modellene. Dette er en kritisk forutsetning for effekten av ulike typer politikk. Tre ulike regimer for eiendomsretter diskuteres: En sentral samfunnsplanlegger med sikre rettigheter til all skog, en situasjon med fri adgang ("open access"), og en situasjon hvor nyrydding av skog gir bonden eiendomsrettigheter.

Indexing terms:
Shifting cultivation
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Contents

Tables:

Figures:

1 Introduction and overview[1]

1.1 The importance of shifting cultivation

Shifting cultivation is an agricultural practice at an early stage in the evolution of agricultural systems (Boserup, 1965; Ruthenberg, 1980). The system is characterized by abundant land, whereas labour is considered the constraining factor. A system with effortless self-fertilization of the soil through a long fallow period, and burning of the vegetation before one or a few years of cropping, is therefore a rational response from the farmers side to the relative scarcity of inputs. In this situation, the shifting cultivation system may yield higher output per unit labour input than sedentary systems (Boserup, 1965; World Bank, 1990).

Most studies of shifting cultivation are either within the anthropological sphere, typically focusing on how the production system is integrated in a wider cultural and social structure, or the soil science sphere, focusing on issues like erosion and nutrient cycling (see Robinson and McKean, 1992, for an extensive bibliography). There are relatively few *economic* studies and models of shifting cultivators' behaviour and decision-making. Exceptions include Dvorak (1992), who develops a simple model with no costs of expanding land use and a subsistence requirement; Holden (1993) uses a Chayanov (1966) approach and develops linear programming models to study of shifting cultivation in northern Zambia; Nghiep (1986) similarly uses a LP model to study conditions for agricultural transformation in Brazil; whereas López and Niklitschek (1991) develop a more general dual (two sector) model. This paper presents an alternative economic approach to the study of shifting cultivation, which focuses on two particular characteristics of the shifting cultivation system, that is its *spatial* dimension, and the *forest rotation* aspect. These issues are not treated satisfactory in the above models.

There is a number of good reasons as to why shifting cultivation deserves further economic analysis and modelling. The deficiency of economics modelling provides an argument in itself, as the nature of economic decision-making and farmers' response to exogenous changes need to be better understood in order to design effective policy instruments. Policy makers may want to influence the development of shifting cultivation for both environmental, social, economic, and political reasons. The problems of deforestation and soil erosion related to expansion of shifting cultivation are well established. Shifting cultivation is commonly being held responsible for about half of tropical deforestation (see, however, Angelsen, 1994, for a critical discussion of this estimate, and of the different environmental effects of various forestland uses). Some governments focus on the extensive nature of the practice, considering it an inefficient use of forestland (high opportunity costs).

[1] I would like to thank Röngvaldur Hanneson, Stein Holden, Karl Pedersen, Ussif Rashid Sumaila, and Arne Wiig for comments on draft versions of this paper. Remaining errors and omissions are my responsibility.

On the political side, governments may also want to "develop" shifting cultivation into more permanent settlements which may be easier to control politically, or due to the economics of scale in the supply of public services. Others argue that the "primitive" nature of shifting cultivation may not correspond to the image of progress that governments want to present (Dove, 1983). Whereas our sympathy for such arguments are limited, the fact that there exist important negative external (environmental) effects, provides a sufficient rationale for the study of shifting cultivation.

Moreover, the often low incomes among shifting cultivators make increasing agricultural income an important element in the combat against poverty. The key challenge is how to enhance the output from the system, while maintaining its long term productivity (e.g., soil erosion), and avoid losses in other environmental functions (e.g., expansion into virgin forest which reduce the biodiversity). In other words, how to achieve a *sustainable intensification* of the system. There is no easy answer to this end, and it may even entail important trade-offs in some situations: The concern for the system's long term productivity indicates longer fallow periods, whereas the goal of limiting its expansion may call for an intensification through shorter fallow periods. Thus, we may have conflicts between short and long term productivity, and between production and environmental conservation objectives.[2]

This paper will focus on how three key variables in the shifting cultivation production system are determined and affected by changes in various exogenous parameters. The endogenous variables are (1) the agricultural frontier or maximum distance of cultivation from a village centre, which then determine total agricultural land and deforestation; (2) the length of the fallow period (that is, the inverse of the intensity of production); and (3) labour inputs.

1.2 The von Thünen approach

The models in this paper make use of and integrate two different approaches in agricultural and resource economics: *Spatial* models in the von Thünen (1826) tradition, and *forest rotation* models in the Faustman (1849) tradition.

In the von Thünen models transport costs and accessibility play a crucial role in determining the land rent and the agricultural frontier, and thereby land area under cultivation. In this approach, land is assumed to be homogenous, and differs only by the location as measured by distance from a centre (village). This is contrasted with the Ricardo approach, where distance costs are neglected, but land differs in quality (soil fertility). Including differences in fertility would add another dimension to the problem, but not change any of the main results presented in this paper (see Randall and Castle, 1985, for a comparison).

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[2] This is elaborated in Angelsen (1993).

In the von Thünen model land is assumed to be physically infinite.[3] There is, however, scarcity of *good* land, that is land close to the centre (land with low distance costs). The land frontier or the border between cultivation and virgin forest will be determined endogenously. A basic premise in the model here is that all forestland which yield a positive land rent will be converted to agricultural use. All land rent will be captured. The frontier is defined as where the rent is zero.

A large body of studies in the von Thünen tradition focuses on how different activities are located in zones of different distance from the centre, depending on their transport costs, e.g., value/weight ratio for agricultural products (Randall and Castle, 1985). We ignore this aspect, and consider only the choice between one activity, that is shifting cultivation, and virgin forest. Further, we only deal with one homogenous agricultural crop, and do not discuss the choice between different crops, in particular between annuals and perennials. These choices could be solved by using the usual "brute force" methods, i.e., to compare the maximum value of the objective function for different land uses or crops. Implicitly, we assume that these choices already have been made, and we consider the most profitable (mix of) agricultural product.

This paper is within the branch of spatial models which takes the centre as given, and a transport network already in place, i.e., a *partial equilibrium approach* (Starret, 1974). Thus we do not address some important issues, including endogenous changes in the transport system, formation of new villages or centres, and expansion of existing ones. This could be an acceptable simplification if the costs of establishing new centres are very high, and the transport system is a result of exogenous decisions. The latter is clearly the case in my study area in Seberida, Sumatra as well as many other areas in Southeast Asia, where road construction and other infrastructure developments have been closely connected to government sponsored projects like large-scale logging, plantations, and transmigration.

1.3 The Faustman approach

In the Faustman (1849) forest rotation models the optimal age of the forest at the time of cutting is discussed under various assumptions (discount rate, relative prices, costs, technology, risk, environmental effects, etc.). Most models developed in this tradition, like the one presented in this paper, assume all important parameters to be constant over time, and then discuss changes in the steady-state from one-time changes in exogenous variables. Thus, the models deal with different long-term bio-economic equilibria; there is, for example, no land degradation over time (the production function remains constant). The model does

[3] Or in the words of von Thünen himself: "Imagine a very large city in the midst of a fertile plain not traversed by any navigable river. The plain's soil is of uniform quality and capable of cultivation everywhere. At a great distance from the city the plain turns into an uncultivated wilderness separating this state from the rest of the world. The question is this: under these conditions what kind of agriculture will develop and how will the distance to the city affect the use of land if this is chosen with the utmost rationality?" (Quoted in Beckman, 1972: 1.)

not either deal with possible irreversibilities involved. These are crucial assumptions, which simplify the analytics tremendously, as a dynamic problem is reduced to a static optimization problem. To include land degradation over time calls for more truly dynamic methods like dynamic programming.

The obvious similarity between timber production and shifting cultivation is the *rotation* aspect and the cyclical harvesting of a renewable resource. However, applying models of timber production to shifting cultivation requires several modifications. First, the benefits and costs involved are different, e.g., costs of planting trees are normally not present in shifting cultivation, whereas the clearing of forest is the start of a production cycle that involves labour inputs for planting, weeding, pest control, harvesting, etc. This paper explores how forest rotation models could be reformulated to the shifting cultivation setting.

More important, timber economics models normally assume private or government operated forests with well defined and secure property rights, and competitive input (including labour) and output markets. This may not always be the case in a shifting cultivation setting. This and a companion paper intend to carry out a *structural sensitivity analysis,* that is to see how the outcome and effect of various policies depend on the economic structures, here defined as different assumptions about the labour market and the property regime (see below).

The application of the von Thünen and the Faustman approaches separately or in combination to economic models of shifting cultivation has been very limited so far (no attempts are known to the author). Models which combine these two approaches when it comes to forest used for timber production exist, for example in Ledyard and Moses (1976). By combining these two approaches, it is possible to make a more realistic description of shifting cultivation systems, and at the same time draw on the large literature that exists, particularly in the Faustman tradition. Thus, a contribution of this paper is partly to integrate these two approaches in general, and to apply them to a number of different settings for shifting cultivation in particular.

1.4 Labour market assumptions

Economic models for the study of agricultural decision-making can be categorized along a number of axes, in particular the behavioural and market assumptions (of which the labour, product, and credit markets are the most important). We focus on the labour market assumptions, for several reasons: They are closely connected with the behavioural assumptions that can be made (see below); they are crucial for the formulation and structure of the model; and differences in how labour markets function are a very distinct empirical feature. Four important and somewhat stylized categories of economic models for the study of agricultural decision making, which especially relate to the labour market assumptions and how the wage rate is determined in the model, are:[4]

1. *Small, open economy models*: Markets exist, and all prices (including the wage rate) are taken as parametrically given. An intuitive interpretation is that the shifting cultivation sector is small compared to the rest of the economy. In addition to the simplification made by exogenous prices, a further simplification is due to the recursive property of such models: If labour can be sold or hired at a constant wage, the production decisions by a *utility* maximizing household can be studied as income or *profit* maximizing production behaviour (Singh et al., 1986).[5]
2. *General equilibrium models:* Models where markets exist, and prices are determined endogenously, would in most cases provide a more realistic description than subsistence or open economy models, but a price is paid in terms of complexity. Coxhead and Jayasuriya (1994) provide one of the very few applications of this approach to environmental degradation in developing countries.
3. *Closed economy models:* No off-farm employment is available, and family labour is the only input in addition to land.[6] Product markets may or may not exist. In the latter case farmers produce only for their own consumption. We distinguish between two important versions of the closed economy model, based on differences in the behavioural assumptions:
   a. A common version is the *subsistence or "full belly" model*[7], e.g., Dvorak (1992). Farmers' objective is to meet a basic subsistence requirement, and they do so by minimizing their labour efforts (maximizing leisure).
   b. The *Chayanov (1966) model* is a more general formulation. The household acts as if maximizing a utility function, with consumption and leisure as the arguments. They reach a subjective equilibrium with a shadow wage rate reflecting the rate of substitution between consumption and leisure. In this way the Chayanov model resembles the general equilibrium model; a shadow wage is determined endogenously within the household (not in the market, as in 2.). Holden (1993) compares the "full belly" and Chayanov formulation in a study of shifting cultivation in Zambia.

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4 This list of different categories of models is not exhaustive.

5 The wage rate in the small, open economy model could well be the *expected* wage rate in the urban sector in a Harris-Todaro (1970) model.

6 A situation when a fixed amount of off-farm employment becomes available is equivalent to a population change in the closed economy model.

7 The term "full belly" is due to Fisk (1962).

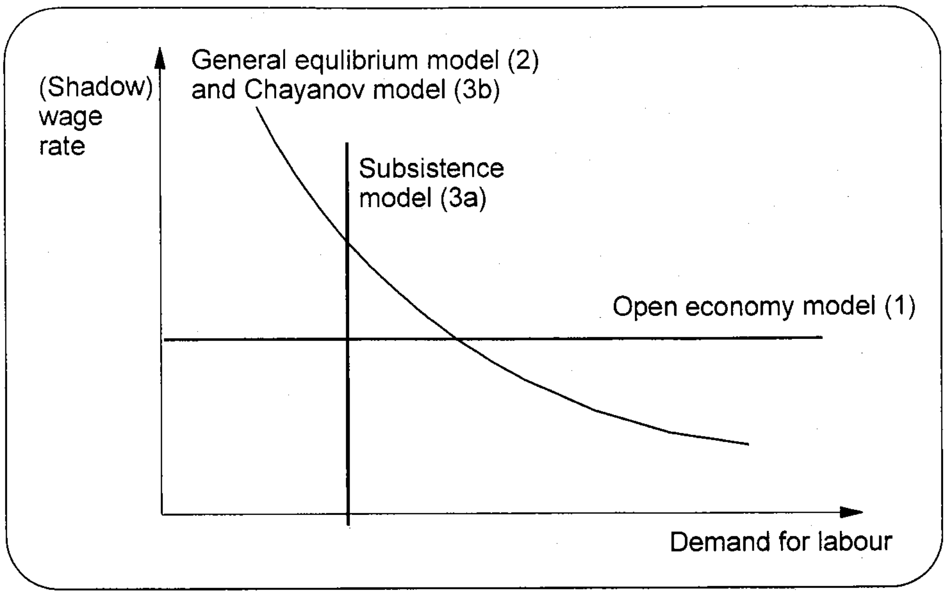

Figure 1. Labour market assumptions in four stylized economic models.

The difference between the various model categories with respect to the labour demand assumptions is illustrated in Figure 1.[8] This paper deals with the simplest case where the wage is fixed (small, open economy model). A companion paper deals with the closed economy model. Though the models in *2* and *3b* are more realistic formulations, and *1* and *3a* can be viewed as special cases of these two, they are analytically more complex. Moreover, as visualized by Figure 1, the assumptions in *1* and *3a* represent the two extreme cases, and therefore give the range of possible adaptations and responses to changes in exogenous factors.

When it comes to the output market, we assume output prices to be exogenously given (small, open economy). The credit market only enters the discussion implicitly. The recursive property of open economy models allows us to neglect the consumption side when analyzing production decisions. Thus the use of credit to, for example, smoothen consumption is not included. Neither are there any capital investments in the production, as labour and land are the only inputs. Moreover, we mainly confine the discussion to long-run steady states, where consumption equals income. To the extent a credit market is needed, the implicit assumption is that it works perfect; farmers can borrow and save as much as they want at a fixed interest rate (e.g., in the Faustman model). Though this may be unrealistic, we consider it to be of minor importance for the main arguments of the paper.

Which model gives the most realistic description of farmers' adaptation and responses to exogenous changes? It is commonly argued that the subsistence model may be the most appropriate for traditional societies, whereas the open economy models give a better description of a modernized society, e.g., Stryker, 1976.

[8] Note that the demand for labour in the figure is *total* demand (farm and off-farm).

Whereas Stryker and others focus on the behavioural assumptions, we argue that the labour market assumptions are equally, or even more important.

The appropriateness of the different models also depends on the time perspective. As an example, the open economy model, which assumes a migration equilibrium based on real wages in different sectors, is a more realistic description of the long term adaptation than of the short run. Another dimension necessary to consider is the unit or area studied; assuming prices to be fixed and determined exogenously may be more realistic for micro studies of individual decision-makers than for macro studies of a region or country. Definite tests of the subsistence versus the open economy hypothesis are difficult to formulate, and are rarely undertaken in empirical work (López, 1992). Moreover, one should keep in mind that these models are stylized descriptions, and empirical analysis may need to draw on elements from several approaches.

1.5 Property rights regimes

It is widely recognized that the property rights regime is a crucial factor in determining resource allocation in tropical agriculture in general, and in frontier systems, like shifting cultivation, in particular (see, for example, Bromley, 1991). The property regime is crucial in determining which costs and benefits that are to be included in the decision makers' optimizing problem. We can identify at least five different regimes or solutions to the model:

1. *Global social planner:* All externalities are included in the optimization problem.
2. *Communal management (local social planner):* Local, but not national or global, externalities are included.
3. *Private property:* No externalities are included, but discounted future private benefits and costs are included in the optimization problem.
4. *Open access:* Neither externalities nor any future benefits and costs are included.
5. *Homesteading:* This could be regarded as a special kind of open access, where forest clearing gives private property rights to the cleared land. Under this regime land is transferred from an open access resource (regime 4) to a private property resource (regime 3).

The global social planner's solution is employed to define the socially optimal solution, and acts as a yardstick to measure the outcome under other regimes. Each of the four other property regimes have empirical relevance, and will be discussed. State property is sometimes referred to as a separate property regime (e.g., Bromley, 1991). We have not included it as we could regard it as a special case of private property, where the owner is not a person, a household, or a firm but the state.[9] Parts of economic theory have traditionally not distinguished between state property and the social planner's solution, but little knowledge about tropical resource management is needed to realize the lack of realism in this assumption. One may hope, however, that state management would include at least *some* of the elements included in the social planner's problem. Generally, however, the state (or powerful groups within the state) may have strong financial interests in *certain* productive (as opposed to protective) uses of the forest, for example in logging or plantations.

Much of the debate on tropical deforestation and shifting cultivation is focused on environmental externalities like the carbon storage of tropical forest, and the preservation of biodiversity. We shall *not* pay too much attention to these issues (except some under the social planner's solution), not because they are unimportant, but because the model here will not add much to the standard approaches in environmental economics. Under all the four property regimes above (2.-5.), there will be no incentives to include (global) externalities, and the rate of deforestation will be too high. We do not make any attempt to answer the question of how much deforestation is optimal, that is how different uses of the forest should be balanced. Instead, a major aim of the paper is to explore which factors determine the expansion of shifting cultivation (extent of deforestation), and thereby identify policy handles which can be used to influence shifting cultivators decision-making.

The outline of the rest of the paper is as follows. In section 2 the main components of the model are developed. Section 3 discusses the simplest version of the social planner's solution, that is the single rotation (Fisher) model without discounting. Section 4 deals with the more complete multi-rotation (Faustman) problem, where discounting and the value of land after clearing are included. Section 5 very briefly compares the Faustman solution with the communal and private management outcomes. The open access case is discussed in section 6. Section 7 deals with a special case of open access, namely when forest clearing gives property rights to the farmers (homesteading). Section 8 compares the solution of the different models, and the effects of changes in exogenous variable. Section 9 provides some concluding remarks.

[9] Communal property could indeed also be considered a special case of private property, where the owner is a group of individuals, e.g., a community. The main distinction is between situations *with* property rights (where the agent with the rights is either the almighty, fully informed, and welfare maximizing social planner; the community; the state; or an individual/household), and situations where *no one* has property rights (open access). Real life situations will be a continuum along this axis, depending on how *secure* the rights (claims) are. Another complication of this categorization is the fact that the agent may not be well defined, for example, individual households may use land in a particular way after consultations with the leaders of the community. Property rights are a bundle of rights, which are always constrained to various degrees, for example, households may not be allowed to sell the land (to outsiders). Finally, a resource (land) may have different regimes governing different uses, for example, agricultural use resembles a private property regime, whereas collection of forest products from the same land is governed by communal management.

The present, theoretically oriented paper is complementary to Angelsen (1994). The latter gives a non-technical analysis of the main factors behind shifting cultivation expansion, and a presentation and analysis of recent changes in the shifting cultivation system of the Seberida district, Sumatra.

2 Basic model

2.1 Fallow period and intensity of production

A crucial variable in a shifting cultivation system is the length of the fallow period, or to be more precise: The relationship between the fallow period and the cropping (tillage) period. Let H be cropping land, A total agricultural land (cropping and fallow land), C the length of the cropping cycle, and F the length of the fallow period. Then we have the following relationship;

$$(1) \qquad A = \frac{H}{\frac{C}{C+F}} = Hm \quad \Leftrightarrow \quad \frac{H}{A} = \frac{1}{m}$$

Here $\frac{C*100}{C+F} = R$ is Ruthenberg's (1980) R-value, i.e., the percentage of land that is under cultivation. $m = \frac{C+F}{C}$ is Boserup's (1965) land use intensity factor, which will be the key variable in our model. The inverse of m gives the share of land under cultivation, and can be used as a measure of intensity of production; lower m implies an intensification. Indeed, agricultural systems are commonly classified on the basis of these factors, as done by Boserup (1981: 19): Forest fallow (R = 0 - 10); bush fallow (R = 10 - 40); short fallow (R = 40 - 80); annual cropping (R = 80 - 100); and multicropping (R = 200 - 300).[10] Ruthenberg (1980: 16), on the other hand, distinguishes between shifting systems ($R < 33$); fallow systems ($33 < R < 66$); and permanent cultivation systems ($R > 66$).

If we set the cropping period (C) to unity, $m = (1 + F)$. In the following we shall for simplicity (to make the language easier) refer to m as the fallow period, but keeping in mind that m is actually the length between the beginning (or the end) of two cropping cycles.

2.2 Production function

The yield or output per ha of cleared land or land currently in production (x) is dependent on the length of the fallow period (m), the labour inputs for weeding, pest control, etc. (l), and the technology level (a).[11] Labour for clearing is determined by the fallow period (see below), and is not a choice variable and has no yield effect in the model.

[10] A more general definition of R is to multiply in the above definition by the number of harvests per year, thus the R-value exceeds 100 if there is more than one harvest per year.

[11] The formulation partly follows the function used by Dvorak (1992): $x = f(C,F,l)$, where F is the fallow period, and C the cropping period (number of years crops are grown between fallow).

(2) $x = af(m,l); \quad f_m \geq 0, f_{mm} \leq 0, f_l \geq 0, f_{ll} \leq 0, f_{ml} = f_{lm} \leq 0; a > 0$

Yield is an increasing function of the length of fallow, as longer fallow increases the biomass and thereby the fertilization of the soil through burning. Also, increasing m implies less weed and pest problems. The marginal increase in x is declining as m increases and eventually reaches a maximum ($f(\,)$ is concave). Similarly, the yield effect of increasing labour input is positive, but decreasing. The crossderivatives are assumed to be negative, i.e., the marginal productivity of labour decreases as the fallow increases, as, for example, weeds become less of a problem. This is in line with Dvorak (1992), whereas López and Niklitschek (1991) assume a *positive* crossderivative. An argument for a positive sign is the fact that increased fallow period means more fertile land, and this *could* increase the marginal return on labour. A third possibility is that the sign depends on the level of m, for example in the way that the crossderivative is *positive* for small values of m, whereas it is *negative* for large values of m. The empirical evidence to determine the sign is weak. In any event, one should try to avoid letting the sign of the crossderivative drive any major conclusions in the model. As the later analysis will show, none of the main conclusions on how m is affected by changes in exogenous variables depend on this assumption.

Technical change is represented in this model by the parameter a in a manner implying Hicks neutral technical progress. The main argument of Boserup (1965) and others is that most of the technical change in shifting cultivation system is *endogenous*, depending on particularly the fallow period, which in turn is determined by factors like the population pressure. The models presented in this paper, like most models for agricultural decision-making, do *not* include endogenous technical change. Technical progress included in a in our model could be for example better yielding crop varieties.[12]

Finally, this formulation of the production function implies that the elasticity for total production (X) with respect to land is one (cf. the assumption of homogenous land). $X = Haf(m,l)$, where H is the cropping area (land currently in production).

2.3 Labour costs

We include three types of cost in the model.[13] The first type of labour input is weeding, pest control, etc. described above. Second, labour for clearing and preparation of the field (g), which depends on the fallow period, $g = g(m)$, in that longer fallow requires more work to clear the field (larger trees to cut and burn).

[12] Even though the high yielding varieties (HYV) associated with the Green Revolution in intensive, irrigated agriculture is not very relevant to shifting cultivators, some intermediates between traditional crop varieties and HYV may be.

[13] Ruthenberg (1980: 50-51) separates the labour operations in shifting cultivation as follows: (1) Clearance of wild vegetation; (2) land preparation and planting; (3) weeding; and (4) harvest, transport of harvest, and processing. A slightly different categorization is used in this paper, which is more appropriate to the models developed.

The function *g()* reaches its maximum when the forest reaches its climax vegetation;

$$g = g(m), g_m \geq 0, g_{mm} \leq 0$$

Third, there are costs related to the location of the field, as measured by the distance from the village (*b*). These may be thought of as time (*c*) spent on walking between the fields and the village. A number of alternative formulations of the distance cost function is possible. We have chosen a specification which is both simple and have some intuitive appeal. It assumes *c* to be proportional to both distance and time working on the field per unit land $(l + g)$;

$$c = qb[l + g(m)]$$

q is the time spent on walking per km for one day of work on the field. Our formulation implies multiplicative distance costs, both in distance and in on-the-field labour inputs $(l + g)$. Thus, increased distance has exactly the same effect as a real wage increase in the model, which turns out to be a neat simplification. In reality there are both additive and multiplicative elements related to distance. If we have made distance costs only additive, an implication later would be that fallow length and labour inputs are independent of distance. This is clearly an unrealistic description which does not correspond to empirical observations. We have chosen to include only the multiplicative elements as these are the most important. Additive costs would only have implications for the determination of the agricultural frontier, whereas multiplicative costs are important for all three endogenous variables (labour, fallow, and agricultural frontier). Thus, adding an additive component does not give any new insight or change the main results.[14]

This formulation of distance costs also implies that there is no optimization of transport costs, for example, in the way that farmers would work more per trip on the distant fields. This is an argument for the costs being to be concave in distance. On the other hand, one may argue that time spent on walking per km should be convex in distance, e.g., one may need to take a rest on longer trips. All in all, the linearity assumption may mot be a perfect representation, but its simplicity and the lack of convincing arguments for a particular alternative make it acceptable.

Summarizing the three types of labour costs, we get;

$$(3) \qquad l + g(m) + qb[l + g(m)] = (1 + qb)[l + g(m)]$$

[14] Additive costs would behave like a kind of sunk costs in the model: They would be important to the decision of whether or not to open a swidden at a given distance, but afterwards they would *not* influence the decisions regarding fallow period and labour input.

2.4 Land rent

In a static model, the land rent (r) or profit from one single clearing of a plot at a given distance from the village, as measured in units of the agricultural product (numéraire), is given by;[15]

(4) $$r[m,l;a,w(1+qb)] = af(m,l) - w(1+qb)[l+g(m)]$$

w is the real wage rate, defined as nominal wage divided by the agricultural output price (i.e., the price of the agricultural output acts as a price deflator). Note that with our formulation of distance cost, these are equivalent to the more common formulation where the net output price is declining with distance due to costs of transportation of output.

The maximum (undiscounted) profit from a single clearing is found by setting $r_m = r_l = 0$ (FOC);

(5) $$\frac{f_m(m^*,l^*)}{g_m(m^*)} = f_l(m^*,l^*) = \frac{w}{a}(1+qb) = z$$

(5') $$m^* = m^*(z); l^* = l^*(z)$$

The second order condition, which ensures that (5) is a maximum point, is given by the assumption that $r(.)$ is concave in m and l: $r_{mm} < 0$, $r_{ll} < 0$, $r_{mm} r_{ll} - r_{ml} r_{lm} > 0$.

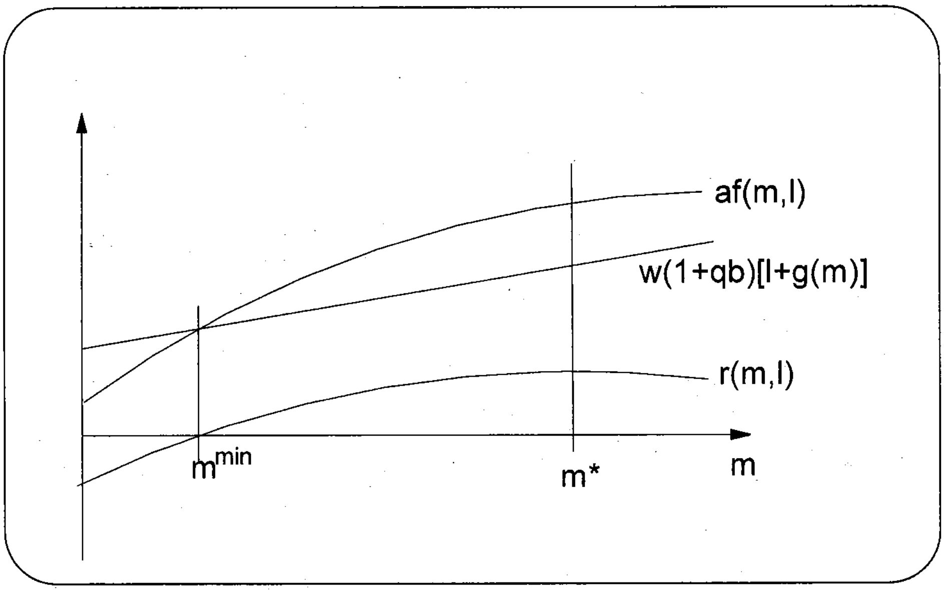

Figure 2. The optimal fallow period (m).[16]

[15] This model gives the maximum land rent from one clearing. It does not, *inter alia,* take into account discounting or the value of land after clearing, which is considered later.

[16] l would in general vary with m; higher m implies lower l because $f_{ml} < 0$. In drawing the figure

The optimal choice of m is illustrated in Figure 2. The assumption of $r_{mm} < 0$ implies that as m increases, the decline in marginal productivity (f_m) is larger than the decline in marginal costs (g_m). This would be true if there, for example, is a strictly concave relationship between yield and biomass whereas clearing costs are proportional to the biomass. The shape of $r(\ )$ is discussed in more details in section 7.5.

We note that all the exogenous factors can be summarized into one variable, $z = \frac{w}{a}(1+qb)$, which may be interpreted as the *effective real wage*, taking into account both the technological level and the distance costs. The effects of changes in z are explored later. The highest possible land rent and the effect of exogenous changes are then given by;

(6) $$r = af(m^*, l^*) - w(1+qb)[l^* + g(m^*)]; \quad r = \tilde{r}(a, w(1+bq))$$

(6') $$\frac{dr}{d[w(1+qb)]}\Big|_{da=0} = -[l^* + g(m^*)] < 0; \quad \frac{dr}{da}\Big|_{d[w(1+qb)]=0} = f(m^*, l^*) > 0$$

The results in (6') follow by applying Hotelling's lemma.

2.5 *Minimum fallow*

We define m^{min} as the minimum fallow period which gives a non-negative profit, as illustrated in Figure 2. We assume that this occurs for $m > 0$, which corresponds to the definition of a shifting cultivation system (often defined as $m > 2\text{-}3$, see Ruthenberg, 1980).

(7) $$f(m^{\min}, l^{**}) - z[l^{**} + g(m^{\min})] = 0; \quad m^{\min} = m^{\min}(z)$$

(7') $$\frac{dm^{\min}}{dz} = \frac{l^{**} + g(m^{\min})}{f_m(m^{\min}) - zg_m(m^{\min})} > 0; \quad b \in [0, b^{\max})$$

It follows from the definition of m^{min} that labour inputs must be chosen optimally according to $f_l = z$, and we have labelled the optimal labour input for the minimum fallow period l^{**} to distinguish it from the optimal labour input given in the problem in (5). One should note that the denominator in (7') is positive. Even though this resembles the first order condition in (5), here the expression is evaluated at $m = m^{min}$.

(7') shows that the minimum fallow is an increasing function of z, that is, increasing in distance (b), real wage (w), and travel efficiency (q), and decreasing in the technology level (a).

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we have neglected this feature, which is of less importance to illustrate the basic relationship.

2.6 *Agricultural frontier*

Finally, we define the agricultural frontier (margin of cultivation) or maximum distance (b^{max}) at which the land rent would still be non-negative, cf. Figure 3 below. Obviously, this will occur when the fallow period and labour inputs are optimally chosen according to (5).

$$(8) \qquad f(m^*,l^*) - \tfrac{w}{a}(1+qb^{\max})[l^* + g(m^*)] = 0$$

$$\Leftrightarrow b^{\max} = \frac{f(m^*,l^*)}{\frac{w}{a}q[l+g(m^*)]} - \frac{1}{q}; \quad b^{\max} = \tilde{b}(\tfrac{w}{a}, q)$$

$$(8') \qquad \frac{db^{\max}}{d\frac{w}{a}}\Big|_{dq=0} = -\frac{1+qb^{\max}}{q\frac{w}{a}} < 0; \quad \frac{db^{\max}}{dq}\Big|_{d\frac{w}{a}=0} = -\frac{b^{\max}}{q} < 0$$

The maximum distance at which shifting cultivation will take place is negatively related to the real wage (w), positively to the technical level (a), and negatively to the travel efficiency factor (q). We note that the minimum fallow equals the optimal fallow for plots located at the agricultural margin ($m^* = m^{min}$ *at* b^{max}.)[17]

Figure 3 illustrates the determination of the agricultural frontier. The variables *m* and *l* are in general functions of *b*, and, for example, the *af(m,l)* - curve will in general not be horizontal. We have neglected this when drawing the figure as the sign of the relationship between *m* and *b* is different in the single and multi-rotation problem, as seen below.

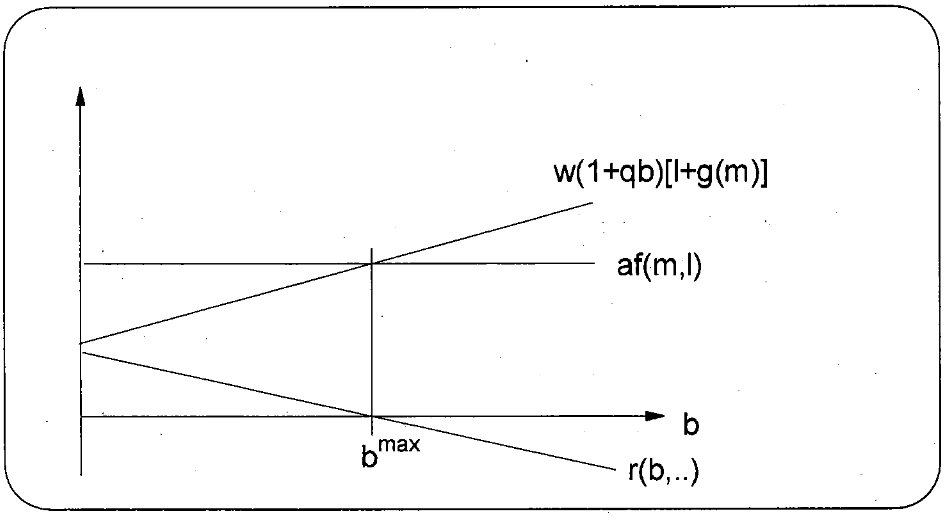

Figure 3. The determination of the agricultural frontier (b^{max}).

[17] One should note that there is no effect on b^{max} from the effect a change in z has on m and l (the envelope theorem).