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Economic Models of Shifting Cultivation: A Review

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1. Introduction

Shifting cultivation is a dominant agricultural system in tropical forests. Shifting cultivators transform nutrients stored in standing forests to soils by slashing, felling, and burning forests (i.e., slash-and-burn); they regularly shift crop lands by replacing depleted plots with cleared forest lands (Denevan & Padoch, 1987; Kleinman et al., 1995; Ruthenberg, 1980). Approximately 300–500 million people practice slash-and-burn agriculture on almost one third of the planet's 1,500 million ha of arable land (Giaradina et al., 2000; Goldammer, 1993). Shifting cultivation is central to the poverty-environment nexus in the tropics. On one hand, shifting cultivation is a dominant livelihood activity among small-scale tropical farmers with various cultural, ethnic, and social backgrounds, and thus it is tightly linked with poverty and development (Angelsen & Wunder, 2003; Byron & Arnold, 1999; Reardon & Vosti, 1995; Sunderlin et al., 2005; Wunder, 2001). On the other hand, not only is shifting cultivation one of the major causes of tropical deforestation, but also, the associated forest-cover change leads to multiple environmental problems, such as soil degradation, biodiversity loss, and reduced carbon sequestration (e.g., Chazdon et al., 2009; Dent & Wright, 2009; Kleinman et al., 1995; Lawrence et al., 2005; Myers, 1992). As such, shifting cultivation can conflict with various conservation efforts, such as maintaining protected areas, engaging in community-based conservation, sustaining integrated conservation-development programs (ICDPs), making payments for environmental services (PES), and reducing emissions from deforestation and forest degradation (REDD) (e.g., Angelsen, 2008; Wilshusen et al., 2002; Wunder, 2006). A win-win goal of poverty alleviation and rainforest conservation in shifting cultivation systems is a global challenge of the first order. To design an effective policy mix, it is crucial to develop a better understanding of shifting cultivators' decision making; to that end, economic modeling is a powerful tool.

This chapter reviews economic models of shifting cultivation and those of deforestation and soil conservation related to shifting cultivation developed by economists over the last two decades. My goal is not to offer a comprehensive review, but to highlight key modeling approaches (what is modeled and what is not, and with what assumptions), clarify how they are useful and incomplete in efforts to examine shifting cultivators' behaviors, and point to promising directions for future modeling. I encourage readers to

see other reviews on economic models, such as Kaimowitz and Angelsen (1998) and Barbier and Burgess (2001) for deforestation and Barbier (1997) for land degradation in developing countries. As far as I know, no other reviews on economic models of shifting cultivation are available.

I focus on farm-level models that characterize individual farmers' behaviors (endogenous variables) under certain environmental and institutional conditions, such as resource stock, markets, and property rights (Binswanger & McIntire, 1987).¹ Farm models allow modelers to examine how farmers' behaviors are affected by policy parameters (exogenous variables). Modelers usually focus on individual farmers' key decisions that directly or indirectly determine environmental outcomes of interest (e.g., forest clearing in deforestation models). Although no models fully capture the complexity of the real world, economic models highlight key aspects of the reality to better understand causal mechanisms.

1.1 Modeling approach

Three important choices in modeling approaches require attention: static vs. dynamic modeling, market conditions, and policies. Economic models are generally classified into static or dynamic models; whereas static models capture economic agents' decisions at a point in time, dynamic models consider the potentially changing path of their behaviors. The choice depends on whether agents' decisions at a point in time affect their future decisions. This dynamic linkage is described by state equations, i.e., the law of motion of state variables, which can be the outcome of interest. Although static models characterize agents' optimal decisions at a given point in time, dynamic models characterize the over-time path of their optimal decisions (control variables) and corresponding state variables. For example, in a soil-conservation model, the state variable can be soil stock (or fertility) and the control variables can be farmers' choices that affect soil fertility, such as cultivation intensity and soil conservation input. The simplest dynamic model is a two-period model, although most dynamic models discussed below consider an infinite time horizon, while in this chapter, models are considered to be static when agents make current decisions based only on the present value of the net benefit/cost stream.

Although perfect markets enable an efficient allocation of resources, market imperfection is the norm in developing countries, where most tropical forests are situated. Better understanding market imperfection and non-market institutions has been a central theme of development economics over the last three decades (Bardhan & Udry, 1999; Ray, 1998). Although many shifting cultivation, deforestation, and soil conservation models in the literature assume perfect markets to examine price policies, such as those related to taxes and subsidies, some models consider imperfect factor markets. In particular, although with a perfect labor market a market price (wage) supports a separation of farm households' consumption (labor supply) and production (labor demand) decisions, market imperfection can break this separation (Singh et al., 1986); here wage represents the opportunity cost of

¹ Kaimowitz and Angelsen (1998) review deforestation models other than farm-level models, such as regional-level models and national and macro-level models, including general equilibrium models (see also Angelsen & Kaimowitz, 1999). Although tropical forests are often common property, soils are individual farmers' private property; most soil conservation models are farm-level models.

labor in the form of returns to any non-farm activities (Benjamin, 1992). Not surprisingly, market imperfection commonly gives rise to ambiguous policy impacts. In contrast, some models employ a framework that does not involve any factor markets (e.g., models focusing on fallow-cultivation cycle).

Most models examine farm output price (mostly food price) and wage (opportunity cost of labor), which can be altered by various macroeconomic policies; some models also examine input price other than wage, technological progress, and property rights.² Many dynamic models highlight the role of the discount rate, which can be altered by credit policies. Some models that consider farmers' decisions with uncertainty – especially in production and price – focus on the roles of risk and risk aversion. Most deforestation models show that promoting farming through price and technology leads to greater forest clearing as the farmers augment farm production; in contrast, promoting non-farm activities discourages forest clearing. Most dynamic models reveal that a lower discount rate encourages investment not only in soils (soil conservation), but also in land holdings (forest clearing). Other policy impacts are generally mixed, depending on modeling specification (assumption). Specific theoretical predictions of each model are not reviewed in this chapter.

1.2 Organization of the chapter

The remainder of the chapter is organized as follows. Sections 2, 3, and 4 review deforestation, soil conservation, and shifting cultivation models, respectively. The main papers cited in these sections are listed in chronological order in Tables 1, 2, and 3, respectively, which summarize decision variables, outcome variables, policy parameters, modeling frameworks (static vs. dynamic), and factor markets (perfect vs. imperfect vs. not modeled).

The tables also report whether the modeling work is accompanied with a substantial empirical analysis; an empirical analysis can be a case study, a descriptive analysis of micro data, simulation work based on micro data, or a regression analysis (to test theoretical hypotheses). Whereas some models – especially those accompanied with an empirical analysis – consider specific empirical contexts (e.g., colonists in Amazonia), others are developed in general contexts. Although this distinction is not always clear, it is clarified when needed. In some models I show mathematical equations to highlight their key features in a concrete way; when I do so, I change original notations (and functions in some cases) to uniform notations for clarity and clear comparisons across models.

Based on these reviews, Section 5 discusses major lacunae in extant shifting cultivation models and promising avenues for future modeling. Section 6 concludes.

2. Deforestation models

Most farm-level deforestation models examine forest-clearing labor as a key decision variable. Assuming a simple function of forest clearing with labor as a unique input (which is valid among small-scale farmers who do not use chainsaws), cleared forest is directly captured by forest-clearing labor.

²Welfare-augmenting policies are usually considered. It is a straightforward process to examine welfare impacts of specific policies in dynamic models by applying the procedure developed by Caputo (1990) (see Takasaki, 2006 for an example).

	Main decision variables	Main outcome variables	Main policy parameters	Static vs. dynamic	Factor markets	Empirics
Southgate (1990)	Forest-clearing labor, soil conservation labor	Forest-clearing labor, soil conservation labor	Output price, wage, interest rate	Static	Perfect	None
Larson (1991)	Forest-clearing labor, soil conservation labor	Forest-clearing labor, soil conservation labor	Output price, wage, interest rate, technological progress	Static	Perfect	None
DeShazo and DeShazo (1995)	On-farm labor	Forest clearing (land value)	Output price, input price, wage, cost of land clearing	Static	Perfect	None
Bluffstone (1995)	Labor for firewood collection	Firewood collection, forest stock	Wage	Dynamic	Perfect, imperfect	Nepal (simulation)
Angelsen (1999)	Cleared forest (distance)	Cleared forest (distance)	Output price, wage, transport cost, discount rate, population	Static	None, perfect	None
Barrett (1999)	Forest-clearing labor	Forest-clearing labor	Output price - mean and standard deviation	Static	Perfect	Madagascar (case study)
Barbier (2000)	Forest-clearing labor	Cultivated land	Output price, wage	Dynamic	Perfect	Mexico, Ghana (case study)
Pendleton and Howe (2002)	Forest-clearing labor	Cleared forest	Market integration (generated from price and wage), technological progress	Dynamic (2 periods)	Perfect	Bolivia (regression)
van Soest et al. (2002)	Forest-clearing labor	Cleared forest	Technological progress, output price	Static	Perfect, imperfect	None
Takasaki (2007)	Forest-clearing labor	Cleared forest	Output price, wage, land price, discount rate	Dynamic (2 periods)	Perfect, imperfect	None
Delacote (2007)	Proportion of land cultivated	Proportion of land cultivated	Risk, risk aversion, population, forest profitability	Static	Not modeled	None

Table 1. Deforestation models

	Main decision variables	Main outcome variables	Main policy parameters	Static vs. dynamic	Factor markets	Empirics
McConnell (1983)	Soil loss, non-soil input	Soil depth	Tenure	Dynamic	Perfect	None
Barbier (1990)	Soil-degrading input, soil-conserving input	Soil depth	Output price, input price	Dynamic	Perfect	Indonesia (descriptive)
Barrett (1991)	Soil loss, non-soil input	Soil depth	Output price	Dynamic	Perfect	None
Clarke (1992)	Farm input, soil investment	Soil quality	Output price, input price, discount rate	Dynamic	Perfect	None
LaFrance (1992)	Cultivation input, soil-conservation input	Soil stock	Output price	Dynamic	Perfect	None
Krautkraemer (1994)	Soil loss	Soil fertility	Population	Dynamic	Perfect	None
Barrett (1996)	Soil loss, soil-conservation input	Soil depth	Output price, discount rate	Dynamic	Perfect	None
Grepperud (1997a)	Farming labor, soil-conservation labor	Farming labor, soil-conservation labor	Farming support, soil-conservation support, off-farm support	Static	Perfect	None
Grepperud (1997b)	Farm input, investment in soil-conservation structure	Soil stock	Output price, discount rate	Dynamic	Perfect	None
Bulte and van Soest (1999)	Soil loss, farming labor	Soil depth	Output price	Dynamic	Perfect, imperfect	None
Grepperud (2000)	Farming intensity (soil depleting/conserving)	Soil fertility	Risk aversion	Dynamic	Perfect	None
Lichtenberg (2006)	Soil loss, farming labor	Soil depth	Output price	Dynamic	Perfect	None
Graff-Zivin and Lipper (2008)	Soil carbon-sequestration investment	Soil carbon-sequestration investment	Sequestration cost, output price, discount rate, risk aversion	Dynamic	Perfect	None

Table 2. Soil-conservation models

	Main decision variables	Main outcome variables	Main policy parameters	Static vs. dynamic	Factor markets	Empirics
Barrett (1991)	Cultivation length, fallow length	Fallow-cultivation cycle	Output price	Dynamic	Not modeled	None
Jones and O'Neill (1993)	Proportion of land cultivated	Fallow length	Output price, wage, discount rate, population	Static	Perfect	None
López (1997)	Cleared forest	Cleared forest	Output price	Dynamic	Perfect	Ghana (regression)
Tachibana et al. (2001)	Proportion of upland land cultivated, upland forest cleared	Proportion of upland cultivated, shifting cultivation area, upland forest cleared	Lowland technological progress, lowland farm area, output price, forest-clearing cost, tenure security	Dynamic	Perfect	Vietnam (regression)
Batabyal and Lee (2003)	Fallow length	Fallow length	Return to fallow, discount rate	Dynamic	Not modeled	None
Sylwester (2004)	Proportion of land cultivated	Land quality	Income transfer, output price, population	Dynamic	Not modeled	None
Willassen (2004)	Fallow-cultivation cycle	Fallow-cultivation cycle, soil fertility (present value of gross output)	Output price	Dynamic	Not modeled	None
Takasaki (2006)	Proportion of land cleared	Proportion of land cleared	Output price, wage, discount rate, soil-regeneration rate, soil erosivity	Dynamic	Perfect	None
Pascual and Barbier (2006)	Farming labor (clearing and on-farm labor with a fixed proportion)	Fallow soil fertility, forest clearing	Population	Dynamic	Perfect	Mexico (simulation)
Pascual and Barbier (2007)	Farming labor (clearing and on-farm labor with a fixed proportion)	Fallow soil fertility, forest clearing	Output price	Dynamic	Perfect	Mexico (simulation)
Balsdon (2007)	Cultivation length	Cultivation length	Output price, non-farm income	Dynamic	Not modeled	None
Brown (2008)	Proportion of land cultivated	Proportion of land cultivated	Preference, spatial dependency	Dynamic	Perfect	Cameroon (regression, simulation)

Table 3. Shifting cultivation models

2.1 Static deforestation models

Early deforestation models are static. Southgate (1990), which is elaborated by Larson (1991), considers not only forest-clearing labor, but also soil-conservation labor among colonists in the forest frontier;³ these two labors separately determine the present value of agricultural production (cropping and livestock) and soil conservation. DeShazo and DeShazo (1995) apply an agricultural household model (Singh et al., 1986) to forest clearing with a perfect labor market, though they capture forest clearing through the value of land (rent), not forest clearing itself. van Soest et al. (2002) directly extend the agricultural household model to forest clearing, comparing effects of farm technological progress on forest clearing under perfect and no labor-market conditions.

Barrett (1999) and Delacote (2007), respectively, examine influences of price and production risk in farming on forest clearing in their static models; Delacote (2007) also addresses effects of risk aversion and returns to standing forest in the form of non-timber forest products (NTFPs).⁴

2.2 Discrete dynamic deforestation models

Static deforestation models effectively treat cleared land as a variable input (produced by labor) for farming. This setup is valid if tropical farmers replace their old infertile plots with newly cleared forest lands every agricultural season or do not consider future production on their cleared lands because of insecure tenure. This is not a common practice among shifting cultivators, because (1) forest clearing is very costly to them (especially with no use of chainsaws), (2) they can employ a variety of traditional soil management techniques (in particular fallowing), and (3) forest clearing and cultivation often give them some claims to the land (Takasaki, 2007). Instead, shifting cultivators crop their cleared lands for more than one agricultural season over time.

Takasaki (2007) treats forest clearing as both an input for current production and an investment in future production in his two-period model. Quality-adjusted land for cultivation at period t is given by:

$$A_1 = a(L_1) \quad (1.1)$$

$$A_2 = (1 - \rho)A_1 + a(L_2) \quad (1.2)$$

where L_t is labor allocated to clear forest at period t , a is forest-clearing function, and ρ captures fertility decline through cultivation (depreciation rate). van Soest et al. (2002) use the same forest-clearing function as in equation (1.1); equation (1.2) is a state equation of

³Although conflicts over property rights are central issues among colonists in the forest frontier (e.g., Alston et al., 2000; Anderson & Hill, 1990; Hotte, 2001; Mueller, 1997), related theoretical modeling is not reviewed in this chapter.

⁴The potential role of NTFPs for sustainable development and poverty alleviation in the tropics is often emphasized (e.g., Arnold & Perez, 2001; Coomes et al., 2004; Wunder, 2001); at the same time, overexploitation of forest resources as local commons among poor populations has been a major concern (i.e., poverty-environment trap) (Barbier, 2010; Dasgupta, 1993, 2001; Jodha, 1986). In particular, firewood collection and associated forest degradation have received much attention. Bluffstone (1995), for example, examines firewood/fodder collection and forest biomass evolution.

crop land. Takasaki (2007) considers not only labor-market conditions, but also land-market conditions, comparing four distinct market institutions (Latin America vs. Sub-Saharan Africa), including the effects of land price.

Some static models, such as Southgate (1990), Larson (1991), and Angelsen (1999), jointly address input and investment aspects of forest clearing by considering the benefit/cost stream over time generated by current forest clearing; such models capture neither farmers' behaviors over time nor the evolution of land assets.⁵

Pendleton and Howe (2002) develop a two-period model for Amerindians in Bolivia, capturing forest clearing in the dry season (period 1) for production in the wet season (period 2). Distinct from other modeling works, Pendleton and Howe (2002) distinguish between primary and secondary forests; they also construct a measure of market integration from market prices.

2.3 Continuous dynamic deforestation models

Following a standard capital model, dynamic farm-level deforestation models consider forest clearing as a pure investment in land capital for future production. This modeling is commonly used to examine a society's optimal deforestation – i.e., exploitation of tropical forests as the commons – in the literature (e.g., Barbier & Burgess, 1997; Ehui et al., 1990; López, 1994; López & Niklitschek, 1991); most models employ control theory in a continuous time framework (e.g., Kamien & Schwartz, 1991; Seietstad & Sydsaeter, 1987).

Assuming that a fixed proportion of arable land (δ) is fallowed in each time period, Barbier (2000) considers the following state equation:

$$\dot{A} = a(L) - \delta A \quad (2)$$

where time index is suppressed and $\dot{A} = dA/dt$. The depreciation rate δ is effectively the same as ρ in equation (1) in the discrete-time framework.

3. Soil-conservation models

Soil-management measures are classified into two groups based on their costs: one with reduced current output levels, such as less intensified cultivation, forest fallowing, and perennial systems, and the other with input use, which can take various forms, such as mulching, composting, terracing, and creating hedgerows, depending on agroecological conditions in specific locales. Although fertilizer is an essential input in other agricultural systems, fertilizer use is very limited in shifting cultivation that relies heavily on forest-based measures (forest clearing and fallowing) (Nicholaides et al., 1983; Sanchez et al., 1982). Grepperud (1997a) examines how programs supporting farming, soil conservation, and non-farm activities affect labor allocations for these three activities in his static model, in the same spirit as Southgate (1990) and Larson (1991).

⁵The key decision variable in Angelsen's model (1999) is the distance to forest cleared. Such spatial modeling, which is common among geographers, is not reviewed in this chapter (other examples of spatial farm-level deforestation models developed by economists include Angelsen, 1994; Chomitz & Gray, 1996; Mendelsohn, 1994). Angelsen (1999) compares four models under distinct modeling assumptions and property rights, not market conditions, in a unified framework.

All soil conservation models developed in the literature examine continuous cultivation with fixed land size.

3.1 Canonical soil dynamics

McConnell (1983) models the dynamics of soil depth x as follows:

$$\dot{x} = \alpha - s \quad (3)$$

where α is natural soil regeneration and s is soil loss associated with cultivation; farm output is a function of soil loss, soil depth (fertility), and non-soil inputs (evaluated at factor price).⁶ This model captures only the adjustment of cultivation intensity among soil-management measures.

3.2 Input-based soil-conservation models

Economists have extended McConnell's (1983) dynamic model by incorporating input-based soil-conservation measures in various ways. Clarke (1992) adds soil investment as a choice variable to equation (3); Barbier (1990) and LaFrance (1992) consider inputs for (soil degrading) cultivation and soil conservation separately; Barrett (1996) adds a soil-conservation measure as a function of conservation input to equation (3); and Grepperud (1997b) considers an investment in soil-conservation structure, such as terraces, modeling the joint evolution of soil stock and conservation structure.

Bulte and van Soest (1999) examine the soil dynamics with no labor market, using the following state equation:

$$\dot{x} = \alpha(l) - s \quad (4)$$

where l is labor for soil conservation. Equation (4) captures labor-intensive soil conservation.⁷

Grepperud (2000) examines how risk aversion influences soil conservation with production and price uncertainty. Graff-Zivin and Lipper (2008) examine the farmer's decision on investment in soil carbon sequestration by explicitly modeling soil carbon as well as soil fertility with production risk; they examine effects of sequestration cost and risk aversion, as well as output price and discount rate.

3.3 Continuous vs. cyclical farming

Assuming stock-dependent soil regeneration (cf. equations 3 and 4),

$$\dot{x} = \alpha(x) - s \quad (5)$$

Krautkraemer (1994) shows that in the presence of nonconvexity in the net benefit function, a non-continuous farming strategy – periodic cycles of cultivation and fallow – can be an

⁶Barrett (1991) compares McConnell's (1983) models with and without non-soil inputs.

⁷Using equation (4), Bulte and van Soest (2001) examine an environmental Kuznets curve for land degradation with no labor market. Lichtenberg (2006) demonstrates that ambiguous impacts of output price found by Bulte and van Soest (1999) is not attributable to labor-market failure, but can occur depending on the labor supply's wage elasticity.

equilibrium (Lewis & Schmalensee, 1977, 1979) and that population growth leads to a shift from cyclical cultivation to continuous cultivation (*sensu* Boserup, 1965).

4. Shifting cultivation models

Shifting cultivation models in the economics literature can be classified into four: the fallow-cultivation cycle model, the forest-fallow model, the cultivation-intensity model, and the land-replacement model.⁸ Almost all models are dynamic; all models except for Tachibana et al. (2001) assume a fixed land size.

4.1 Fallow-cultivation cycle models

Fallow-cultivation cycle models focus on fallow and/or cultivation length as decision variables, ignoring all other decisions, such as labor allocation. Barrett (1991) extends the optimal forest-rotation problem (Faustmann, 1995) to fallow-cultivation cycles by treating both fallow and cultivation lengths as choice variables. This rotation problem does not explicitly capture soil dynamics. In contrast, Willassen (2004) models the cyclical evolution of soil fertility in the cultivation and fallow phases; the farmer chooses only the phase – binary choice $q = 0$ (fallow) or 1 (cultivation) – over time, and distinct from soil conservation models (e.g., equation 3), soil dynamics under cultivation as well as fallow are assumed to be determined by soil fertility level x only.

In these cyclical models, the farmer does no cultivation in the fallow phase. This simplification is for analytical tractability. Of course, in practice, shifting cultivators mix different stages of cultivation and fallow across plots.

Assuming fixed fallow length and on-farm soil dynamics characterized by equation (5), Balsdon (2007) focuses on cultivation length as a choice variable; distinct from other cyclical models, the termination of the cultivation phase in one plot is instantly followed by cultivation on the next plot. Batabyal and Lee (2003), in contrast, focus on the choice of fallow length.

4.2 Cultivation-intensity models

Cultivation-intensity models capture soil degradation resulting from shortened fallow through the cultivation-intensity measure without explicitly modeling fallow dynamics. Although cultivation-intensity models differ depending on their focus, their common feature is to capture cultivation intensity through the proportion of land cultivated (b). For a given land size, $1 - b$ is the proportion of fallow land and $1/b$ represents fallow length. For example, for $b = .1$, fallow length is 10 (years).

4.2.1 Early cultivation-intensity models

Larson and Bromley (1990) develop a dynamic model with a fixed cultivation intensity. Jones and O'Neill (1993) develop a static model using cultivation intensity b as a key decision variable.⁹

⁸Batabyal and Beladi (2004) and Batabyal and Nijkamp (2009) apply stochastic modeling to shifting cultivation, which is not reviewed in this chapter.

⁹Jones and O'Neill (1993) extend their model to a spatial model.

4.2.2 Cultivation-intensity models with soil dynamics

In Sylwester's (2004) model, the soil dynamics under cultivation follows equation (5), with soil loss s replaced with a function of cultivation intensity b ; distinct from other cultivation-intensity models, Sylwester does not model factor markets as in fallow-cultivation cycle models.

Whereas Brown (2008) considers a binary choice between cultivation and fallow – on each plot over time – as in fallow-cultivation cycle models, he solves the dynamic problem by treating this binary variable q as continuous; that is, he effectively uses cultivation intensity b as a choice variable. His focus is to examine the roles of preference (measured by the revealed preference approach) and spatial dependency in farmers' forest clearing using simulation (see also Brown, 2006).

4.2.3 Cultivation-intensity models with land dynamics

Tachibana et al. (2001) develop a cultivation-intensity model that endogenizes the evolution of upland holdings (T) among Vietnamese farmers who combine upland shifting cultivation and lowland paddy cultivation:

$$\dot{T} = a - \delta(b)bT \quad (6)$$

where a is (upland) forest cleared and endogenized depreciation rate $\delta(b)$ (cf. equation 2) captures soil degradation through shortened fallow (higher b captures depriving intensification). Note that distinct from equation (2), T is total land holdings, consisting of cultivated land $bT (=A)$ and fallow land $(1-b)T (=T - A)$. Furthermore, fallow land is under the risk of being grabbed by neighbors. Tachibana et al. (2001) examine how the proportion of cultivated upland land (inverse of fallow length), shifting cultivation area, and upland forest clearing are affected by a rich set of policies, such as lowland technological progress, lowland farm area, forest clearing cost, and upland tenure security, as well as output price.

4.3 Forest-fallow models

4.3.1 Forest-fallow models with communal fallow forest

Forest-fallow models endogenize the dynamics of biomass accumulation in fallow forest as a soil builder. Fallow forest is explicitly or implicitly assumed to be communally owned by villagers. López (1997) introduces the following dynamics of fallow biomass density η :

$$\dot{\eta} = \gamma - \frac{\sum_i a_i}{Q} \eta \quad (7)$$

where γ is the intrinsic growth of secondary vegetation, a_i is cleared forest by household i , and Q is total land area under both cultivation and fallow – of the village. Equation (7) assumes that fallow biomass density is determined by the proportion of cleared forest land for cultivation, i.e., village-level cultivation intensity.¹⁰

Assuming equation (7) and a simple conversion of biomass to soil fertility on cleared fallow forest, Pascual and Barbier (2006; 2007) derive the dynamics of soil fertility on cleared forest (Pascual & Barbier, 2006, equation 5). They assume that in each period of time the farmer

¹⁰In the forest-fallow model, adding NTFPs collected from secondary fallow forest as an additional benefit of fallowing is a straightforward extension.

cultivates only the cleared land; then, on-farm soil conservation is irrelevant. In Pascual and Barbier (2006; 2007), the only decision variable is farm labor, which is assumed to be allocated between forest clearing and cultivation with a fixed proportion. Pascual and Barbier (2006; 2007) examine impacts of population density (n/Q , where n is the number of households in the village) and output price on forest clearing and fallow soil fertility.

4.3.2 Forest-fallow models with private fallow forest

Shifting cultivators commonly have usufruct of not only the cultivated land they have cleared, but also their fallow land; customary tenure of fallow land tends to be insecure, however, and this tenure insecurity influences their forest clearing and fallowing decisions (Otsuka & Place, 2001; Place & Otsuka, 2001; Tachibana et al., 2001). It is straightforward to revise equation (7) to characterize such an alternative customary tenure setting; then, soil fertility of cleared fallow forest is effectively determined by fallow length or the inverse of cultivation intensity, $1/b$. In this way, the fallow-forest model with private fallow forest directly corresponds to the cultivation-intensity model; a key difference is that the former focuses on fallow dynamics and the latter highlights other dynamics, such as on-farm soil or land holdings.

4.4 Land-replacement models

Fallow-cultivation cycle models assume a cyclical switch of the whole land between cultivation and fallow; fallow-forest models assume that the farmer cultivates cleared forest land only in each period of time. In practice, shifting cultivators replace some depleted plots with cleared forest land each time, while continuing to cultivate the remaining plots; replacing all plots simultaneously is a polar case.

This aspect is explicitly captured in the land-replacement model (with fixed land size) introduced by Takasaki (2006). The key choice variable is the proportion of cultivated land, not total land, replaced with cleared forest land (c). This modeling approach highlights the tension between replaced (cleared) and non-replaced (remaining) plots – the former is more fertile but clearing is costly. It also directly captures new soils on cleared forest land added to soils on remaining plots. Specifically, the dynamics of on-farm soil stock is obtained by extending equation (3):

$$\dot{x} = \varphi c + \alpha(1 - c) - s \quad (8)$$

where φ is soil stock (per unit of land) of cleared forest (see Takasaki, 2006, Figure 1 for derivation). Note that for $c = 0$ (continuous cultivation), equation (8) is the same as (3); for $c = 1$ (complete replacement), equation (8) corresponds to forest-fallow models, though fallow dynamics is not modeled (φ is not endogenized). Takasaki (2006) examines effects on forest clearing (measured by c) of soil-regeneration rate α and soil erosivity altered by soil conservation programs, as well as output price, wage, and discount rate.

5. Discussion

5.1 Primary vs. secondary forests

The review in the last section indicates two significant lacunae in the extant shifting cultivation models. The first lacuna is that the extant models do not distinguish between

primary and secondary forests.¹¹ This distinction is critically important for both environmental and economic reasons. First, in general, protecting primary forest with greater biodiversity needs to be given a higher priority than secondary forest protection. At the same time, as primary forest becomes scarce in the tropics, researchers and practitioners pay greater attention to secondary fallow forest (Coomes et al., 2000). In particular, short fallow results in less matured secondary forest with limited biomass accumulation and poor protection of erodible soils, as well as low biodiversity, weak carbon sequestration, and limited timber and NTFPs (Brown & Lugo, 1990; Chazdon et al., 2009; Dalle & de Bois, 2006; Dent & Wright, 2009; Lawrence et al., 2005). Shifting cultivation models need to jointly address cleared primary forest and fallow length of secondary forest as key environmental outcomes.

Second, the choice between primary and secondary forest is determined by farmers' decisions under specific environmental and economic conditions: In particular, secondary forest is less fertile but easier to clear than primary forest (Scatena et al., 1996), and this comparison depends on fallow length (farmer's decision) (Dvořák, 1992) and the availability of primary forest (determined by population growth, etc.). This choice also has a direct implication for asset accumulation: Although clearing secondary forest does not alter total land holdings (only the plot phase changes from fallow to cultivation), clearing new primary forest augments land holdings. That is, although secondary forest brings fertile soil, primary forest brings both more fertile soil and new land itself. Shifting cultivation models need to capture these key differences.

Pendleton and Howe (2002) address the choice between primary and secondary forests as a pure forest-clearing problem; they neither model the role of secondary fallow forest as a soil builder nor consider soil addition through primary forest clearing. No other deforestation models distinguish or specify the type of cleared forest; this is also true in dynamic deforestation models, which necessarily involve land accumulation (Barbier, 2000; Takasaki, 2007). Not only all soil conservation models but also most shifting cultivation models assume fixed land holdings, and thus implicitly focus on secondary forest; Tachibana et al. (2001) do not distinguish or specify the type of cleared forest, either.

This lacuna in the theoretical literature is in contrast to the considerable number of empirical studies on primary and secondary forests. Smith et al. (1999), for example, show that the relative importance of secondary forest to primary forest increases over time among Amazonian colonists; Coomes et al. (2000; 2011) also find this pattern over a longer time span among Amazonian peasants (in their study village in Peru, primary forest has virtually disappeared).

5.2 On-farm soil conservation in shifting cultivation

Supporting non-farm activities discourages farming, thereby releasing pressure on forests. This policy option becomes available and significant only after non-agricultural sectors sufficiently develop, often following massive deforestation and forest degradation. What policies can slow down this trend along the development path?

¹¹ Primary forest "has had little or no anthropogenic intervention" and secondary forest is "woody successional vegetation that regenerates after the original forest cover has been removed for agriculture or cattle ranching" (Smith et al., 1999, p.86).

The second lacuna not only in the extant theoretical works on shifting cultivation, but also in related empirical works is the investigation into potential roles of on-farm soil conservation. Among poor shifting cultivators, forest-based soil-management options (forest clearing and fallowing) outweighs on-farm soil conservation (Barbier, 1997); when degraded land can be easily replaced, farmers have little incentive to adopt expensive input-based soil-conservation measures. Then, the question is whether policy makers can alter shifting cultivators' benefit-cost calculations by introducing effective soil-conservation programs, as discussed by Takasaki (2006) (see also Grepperud, 1997a).

Although developing locally adoptable, effective soil-conservation measures in tropical forests has been a daunting task (Lal, 1995), soil scientists' recent growing interest in biochar in Amazonia may lead to significant improvement in soil fertility and soil carbon sequestration in shifting cultivation systems (Glaser, 2007; Marris, 2006; Steiner et al., 2004). Biochar, also known as black carbon, is the residue of organic matter that has been pyrolyzed (partially combusted in a low-oxygen environment). Research indicates that Amazonian black carbon (*terra preta*) has, on average, three times more soil organic matter (SOM) content, higher nutrient levels, and a better nutrient retention capacity than surrounding infertile soils (Glaser, 2007). How the labor-intensive alternative "slash-and-char" system, combined with sustainable charcoal production, can be promoted among poor shifting cultivators is still an open question, however (Swami et al., 2009) (see Coomes & Burt, 2001 for charcoal production among Amazonian peasants).

Soil-conservation models extensively developed in the literature can well capture various input-based soil-conservation measures; in particular, equation (4) or its variant can be applied to labor-intensive conservation like biochar.

5.3 Shifting cultivation regimes

It is very useful to differentiate two regimes of shifting cultivation. In regime 1, where primary forest is available, farmers choose to clear primary or secondary forest. Although the extant deforestation and shifting cultivation models effectively capture primary forest clearing and secondary fallow forest clearing (cyclical cultivation), respectively, neither of them addresses the choice of these two. As primary forest becomes scarce (deforestation), cultivation shifts to regime 2, in which only secondary forest is cleared; in another words, primary forest has been so degraded that clearing primary forest is too costly or simply not an available option. Policies effectively protecting primary forest (in particular, protected areas with compliance) can also make this regime shift.¹² Although the extant shifting

¹² Migration can also significantly affect the regime shift. Coomes et al. (2011) find that urban migration plays an important role in lowering pressure on diminishing forest land among shifting cultivators in their study village. The extensive migration option in the forest frontier, however, may allow farmers to clear forest – both primary and secondary – without employing fallowing practices; this is possible among colonists in land-abundant areas in Latin America, especially in locales where selling cleared lands is an additional motive for forest clearing (Barbier, 2004; Binswanger, 1991; Takasaki, 2007). Conceptually, further regime shifts following regime 2 can be considered. Once shifting cultivators start to employ continuous cultivation on some plots, regime 3 emerges; in this new regime, in addition to forest fallow management, farmers make a key choice between shifting and continuous. Lastly, regime 3 is followed by the complete shift to continuous cultivation, i.e., abandonment of shifting cultivation (Krautkraemer, 1994).

cultivation models essentially focus on regime 2, protecting remaining primary forest and promoting sustainable secondary forest management (long fallow) in regime 1 should be given a higher priority for conservation and development in shifting cultivation systems.

5.4 Future modeling

It is now clear that a promising avenue for future modeling of shifting cultivation is to extend extant models for secondary fallow forest in regime 2 by adding primary forest clearing to capture regime 1 and by endogenizing on-farm soil conservation to examine its effects on forest outcomes. That is, a unified farm model of primary forest clearing, forest fallowing, and on-farm soil conservation is needed to examine effective policies for protecting primary forest and maintaining sustainable long fallow.

Two extensions toward such a unified model are suggested. The first is to augment a cultivation-intensity model so that it captures the dynamics of both on-farm soil and land holdings (through primary forest clearing). Such an augmented model could explicitly capture the mechanism of depriving intensification embedded in $\delta(b)$ in equation (6).

The second extension is to augment Takasaki's (2006) land-replacement model by endogenizing cultivation intensity and capturing acquisition of new land and soil through primary forest clearing. The proportion of total land, not cultivated land, replaced with fallow forest is bc , and fallow length $1/bc$ determines the soil stock of cleared fallow forest φ in equation (8).

5.5 Hypothetical effects of on-farm soil conservation

How does better on-farm soil conservation affect forest outcomes? On one hand, in regime 2 with no primary forest clearing, it is expected that shifting cultivators intensify on-farm soil conservation and rely less on fallow soils (less frequent clearing), resulting in longer fallow. On the other hand, in regime 1, better on-farm soil conservation encourages shifting cultivators to clear more primary forest with increased returns to farming; at the same time, primary forest clearing (land accumulation) is balanced with secondary forest clearing (fallow management). A well-designed soil conservation program might result in longer fallow at the cost of primary forest; then, it becomes crucial to combine the soil program with other measures to protect primary forest, such as protected areas.

The unified farm model proposed above can dissect shifting cultivators' benefit-cost calculations, shedding light on an effective policy mix for conservation and development and pointing to promising avenues for empirical research.

6. Conclusion

This chapter reviewed farm-level economic models of shifting cultivation, as well as those of deforestation and soil conservation related to shifting cultivation. Although economists have made significant progress in modeling shifting cultivation over the last two decades, extant economic models neither clearly distinguish between primary and secondary forests nor address potential roles of on-farm soil conservation in shifting cultivation. Developing a unified farm model of primary forest clearing, forest fallowing, and on-farm soil conservation is needed to examine effective policies for protecting primary forest and maintaining sustainable secondary fallow forest. The chapter pointed to promising avenues for future modeling.

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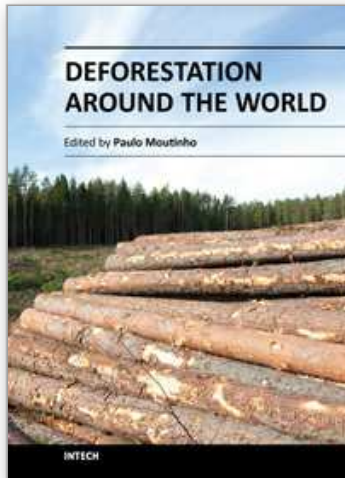
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Deforestation Around the World

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Deforestation and forest degradation represent a significant fraction of the annual worldwide human-induced emission of greenhouse gases to the atmosphere, the main source of biodiversity losses and the destruction of millions of people's homes. Despite local/regional causes, its consequences are global. This book provides a general view about deforestation dynamics around the world, incorporating analyses of its causes, impacts and actions to prevent it. Its 17 Chapters, organized in three sections, refer to deforestation impacts on climate, soil, biodiversity and human population, but also describe several initiatives to prevent it. A special emphasis is given to different remote-sensing and mapping techniques that could be used as a source for decision-makers and society to promote forest conservation and control deforestation.

How to reference

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