Swidden Agriculture in Developing Countries: An Ecological-Economic Analysis of the Fallow Period and its Length¹

by

Amitrajeet A. Batabyal,²

and

Hamid Beladi³

1

The idea for this paper arose from a conversation between Charles Perrings and the first author in June 2001 in Southampton, UK. Batabyal acknowledges financial support from the Gosnell endowment at RIT. The usual disclaimer applies.

2

Department of Economics, Rochester Institute of Technology, 92 Lomb Memorial Drive, Rochester, NY 14623-5604, USA. Internet aabgsh@rit.edu

3

Department of Economics and Finance, University of Dayton, 300 College Park, Dayton, OH 45469-2251, USA. Internet beladi@udayton.edu

Swidden Agriculture in Developing Countries: An Ecological-Economic Analysis of the Fallow Period and its Length

Abstract

Small farmers in many tropical developing countries practice swidden agriculture. A key aspect of swidden agriculture is the time period during which the land is left fallow. This paper uses a new ecological-economic approach to study the fallow period and to determine the optimal length of this period in swidden agriculture. We first construct a theoretical model of a parcel of forest land that has been cleared for swidden agriculture. We then show how the dynamic and the stochastic properties of this cleared land can be used to derive two objective functions for a small farmer that are ecologically meaningful. Finally, using these two objectives, we discuss a probabilistic approach to the determination of the optimal length of the fallow period. In this approach, the focus of the small farmer is on maintaining the ecological and the economic sustainability of swidden agriculture on the cleared parcel of forest land (CPFL).

Keywords: Cleared Parcel of Forest Land, Developing Country, Fallow Period, Semi-Markov Process, Swidden Agriculture

JEL Classification: O13, Q15, D81

Swidden Agriculture in Developing Countries: An Ecological-Economic Analysis of the Fallow Period and its Length

1. Introduction

Small farmers in most tropical developing countries practice swidden agriculture.⁴ There are five essential stages in the swidden cycle.⁵ First, large forest trees are cut down by the farmer, the debris is cleared, and the cut growth is burned. The burning of the forest vegetation clears the ground for planting and releases essential nutrients. As the burned vegetation decays, the organic levels in the soil rise and this enhances the soil's fertility. Second, before rains cause soil erosion and before the ash bed can be blown or leached away, planting commences. This typically involves the dropping of seeds into shallow holes made by dibble sticks. Third, with the onset of the rainy season, regular precipitation leads to rapid plant growth. This rapid growth is occasionally accompanied by the simultaneous growth of weeds. These weeds are regularly removed by the farmer to prevent them from taking nutrients away from the crop under cultivation. Fourth, during the harvesting season, the farmer protects the crop from pests and (s)he often uses simple implements such as finger knives to harvest the grain. In the process of harvesting the grain, the farmer retains some of the best seeds for the next planting. Finally, and this is the crucial stage, the cleared parcel of forest land (hereafter CPFL) is left fallow after one or two harvests. Within a couple of years, a closed canopy of secondary forest develops. If the CPFL is left fallow for a sufficiently long period of time then nutrients will

4

Swidden agriculture is also known as slash-and-burn agriculture and as shifting cultivation. As such, in the rest of this paper, we shall use these three terms interchangeably.

5

For more on this and related issues, see Dove (1983), Peters and Neuenschwander (1988), Pearce and Warford (1993), Brown and Pearce (1994), Swinkels *et al.* (1997), and Coomes *et al.* (2000).

revert back to the soil and this will permit the above described swidden cycle to be repeated.

Despite the salience of swidden agriculture in tropical developing countries, there is some controversy about the merits of this kind of agriculture. On the one hand, researchers such as Dove, Southgate (1990), and Pearce and Warford (1993) have criticized this kind of agriculture. In particular, these researchers have pointed out that slash-and-burn agriculture is environmentally destructive because the land clearing activities of shifting cultivators is directly linked to massive and deleterious tropical forest deforestation. On the other hand, a second group of researchers including Peters and Neuenschwander (1988) and Dufour (1990) have claimed that under some circumstances, swidden agriculture based on long fallow periods can be an ecologically and an economically sustainable practice in tropical forests.

The viability of swidden agriculture in the long run depends crucially on the length of the fallow period; hence, this period must be chosen optimally. There is no dispute on this basic point and there is now a sizeable empirical and case study based literature on this point in particular and on the salience of the fallow period in general.⁶ However, beyond recognizing this basic point, researchers have not explained *theoretically* how the length of the fallow period ought to be chosen by a small farmer. In addition to this, researchers have *not* studied the ways in which the choice of the fallow period length affects the ecology and the economics of the underlying CPFL.

Given this state of affairs, our paper has three goals. First, we construct a theoretical model of a parcel of forest land that has been cleared for swidden agriculture. This model accounts for the ecological *and* the economic aspects of the fallow period length choice problem. Next, we show how

6

For a more detailed corroboration of this claim, see Gleave (1996), Hofstad (1997), Silva-Forsberg and Fearnside (1997), Swinkels *et al.* (1997), Coomes *et al.* (2000), Li *et al.* (2000), Ekeleme *et al.* (2000), and Udaeyo *et al.* (2001),

the dynamic and the stochastic properties of this CPFL can be used to derive two objectives for a small farmer that are ecologically meaningful. A distinguishing feature of our approach is that these two objectives are very different from the objectives found in traditional economic (and not ecological-economic) analyses of small farmer behavior.⁷ Specifically, the two objectives of this paper are probabilities that are derived from the dynamic and the stochastic properties of the CPFL. Finally, using these two objectives, we discuss a probabilistic approach to the determination of the optimal length of the fallow period in swidden agriculture. In this approach, the focus of a small farmer is on choosing the length of the fallow period so that slash-and-burn agriculture on the CPFL is ecologically and economically viable in the long run.

The rest of this paper is organized as follows: Section 2 presents a semi-Markov model of a CPFL and constructs two objectives for a small farmer practicing swidden agriculture. Section 3 uses these objectives and discusses two optimization problems that this small farmer might solve. Section 4 concludes and offers suggestions for future research on the fallow period and related issues in swidden agriculture.

2. A Model of a CPFL

2.1. Preliminaries

Following the recent suggestion in Perrings (1998), we use a semi-Markov⁸ model to analyze the fallow period length choice problem of this paper. To this end, consider a stochastic process with states $0, 1, 2, 3, \dots$, that is now in state i , $i \geq 0$, and that has the following two properties: First, the

7

For instance, see the analysis in de Janvry *et al.* (1991) and Fafchamps (1992).

8

Standard textbook accounts of semi-Markov processes can be found in Ross (1996, pp. 213-218; 2000, pp. 395-397). Our discussion of semi-Markov processes and this section's model are based in part on Ross (1996, pp. 213-218; 2000, pp. 395-397).

probability that it will next enter state j , $j \geq 0$, is given by the transition probability P_{ij} . Second, given that the next state entered is j , the time until the transition from state i to state j is a random variable with a general distribution function $G_{ij}(\cdot)$ where $G_{ij}^c(\cdot) = 1 - G_{ij}(\cdot)$. Now let $z(t)$ denote the state of the process at time t . Then $\{z(t): t \geq 0\}$ is a semi-Markov process.

Put differently, a semi-Markov process is a Markov chain with one appreciable difference. Whereas a Markov chain spends one unit of time in a state before making a transition to some other state, a semi-Markov process stays in a particular state for a random amount of time before making a transition to some other state. Let K_i denote the distribution function of the time that $\{z(t): t \geq 0\}$ spends in state i before making a transition to some state and let b_i denote the expectation of this time in state i . Finally, let T_{ii} be the time between successive transitions into state i and let b_{ii} be the expectation of T_{ii} . That is, $b_{ii} = E[T_{ii}]$. We are now in a position to discuss the properties of the CPFL that is the subject of this paper.

2.2. The Dynamic and Stochastic CPFL

Consider a dynamic and stochastic parcel of forest land that has been cleared for the planting of a certain crop. From an ecological standpoint, at any specific point in time, this CPFL can exist in any one of three possible states. State 1 is the healthiest state of the CPFL. This state corresponds to the condition of the CPFL at the time of planting for and during the first harvest. The forest land has just been cleared, the ash bed contains a rich array of minerals, and soil fertility is high. As such, assuming rains occur as expected, the small farmer can expect his/her crop harvest to be profit making. State 2 is an intermediate state. In this state, the condition of the CPFL in general and its soil cover and quality in particular are lower than in state 1. However, the CPFL is not endangered in either an ecological or an economic sense. The reader should think of state 2 as corresponding to the

small farmer's second harvest season on the CPFL under study. State 3 corresponds to the fallow period of the CPFL. In our modeling setup, the ecological condition of the CPFL in this state is delicate. In other words, if our CPFL is not left fallow after two harvest seasons then the subsequent growing of crops on this land will not be a viable prospect.⁹

Let us now formalize these remarks. As a result of the small farmer's activities (planting, weeding, harvesting) and unpredictable ecological/environmental factors (droughts, lack of plant nutrients, unusually low soil moisture), our CPFL stays in state 1 for a mean length of time b_1 and then makes a transition either to state 2 with transition probability P_{12} , or to state 3 with transition probability P_{13} .¹⁰ When the CPFL is in state 2, once again because of the previously mentioned reasons, this land will stay in state 2 for a mean length of time b_2 and then move to state 3 with transition probability P_{23} . When in state 3, all crop growing, weeding, and harvesting activities are terminated and the CPFL is left fallow. As a result of this fallowing, the CPFL vegetation gradually recovers and, depending on the length of the fallow period, the CPFL may grow back into a secondary forest. It is important to note that the rate of recovery in the fallow state depends not only on the nature of the small farmer's activities in states 1 and 2 but also on unpredictable ecological/environmental factors. What this means for our purpose is that the length of the fallow period is itself a *random* variable. Denote the mean length of the fallow period by b_3 . Leaving the

9

In our modeling setup, the fallow period occurs after two harvesting seasons. In swidden agriculture, farmers typically cultivate a plot of land "for a *few* seasons, then move onto another plot, abandoning the first to regenerate naturally over a period often measured in decades" (Barrett, 1999, p. 162, emphasis added). Although the precise number of seasons corresponding to *few* will depend on a number of factors, we're analyzing this three state model in order to keep the subsequent mathematical analysis tractable. The reader should note that at the cost of greater algebraic clutter, our analysis can be generalized to any finite number of harvesting seasons.

10

Clearly, this latter possibility arises only if the CPFL must be fallowed after a single harvesting season.

CPFL fallow for a specific time period does not guarantee that it will revert back to the ecologically healthiest state 1. Rare and unpredictable environmental events and farmer error in setting the length of the fallow period, either singly or collectively, may result in the CPFL recovering only to the intermediate state 2. To account for these features of the problem, we suppose that after the CPFL has been fallowed for a time period of mean length b_3 , it returns either to state 1 with transition probability P_{31} , or to state 2 with transition probability P_{32} . We now use these dynamic and stochastic attributes of this CPFL and derive two objectives that our small farmer might optimize.

2.3. Two Small Farmer Objectives

2.3.1. The First Objective: An Unconditional Probability

To derive the first farmer objective, it will be necessary to compute the stationary probabilities for our three state CPFL. Formally, we are interested in computing $P_i = \lim_{t \rightarrow \infty} \text{Prob}\{z(t)=i/z(0)=j\}$ for any state j and for states $i=1,2,3$. In words, given that our CPFL is in state j at time $t=0$, we want to compute the limiting probability, as time approaches infinity, that the CPFL will be in state i . To perform this computation, let us denote the limiting probabilities of the embedded Markov chain of our CPFL¹¹ by δ_i , $i=1,2,3$. Now it is well known—see equation 7.23 in Ross (2000, p. 396)—that these limiting probabilities satisfy

$$\delta_j = \sum_{i=1}^{i=3} \delta_i P_{ij}, \quad \sum_{j=1}^{j=3} \delta_j = 1. \quad (1)$$

Consequently, using the transition probabilities of the CPFL and equation (1), we can calculate the

11

For additional details on the embedded Markov chain of a semi-Markov process, see the references cited in footnote 8.

required limiting probabilities. These are

$$\delta_1 = \frac{P_{31}}{1 + P_{31} + P_{12}P_{31} + P_{32}}, \delta_2 = \frac{P_{12}P_{31} + P_{32}}{1 + P_{31} + P_{12}P_{31} + P_{32}}, \delta_3 = \frac{1}{1 + P_{31} + P_{12}P_{31} + P_{32}}. \quad (2)$$

To determine the stationary probabilities (the P_i 's) of the CPFL, we now use equation 7.24 in Ross (2000, p. 396). This equation tells us that the P_i 's satisfy

$$P_i = \frac{\delta_i b_i}{\sum_{j=1}^3 \delta_j b_j}. \quad (3)$$

Equations (2) and (3) together give us the stationary probabilities that we are after. We get

$$P_1 = \frac{P_{31} b_1}{P_{31} b_1 + (P_{12}P_{31} + P_{32})b_2 + b_3}, \quad (4)$$

and

$$P_2 = \frac{(P_{12}P_{31} + P_{32})b_2}{P_{31} b_1 + (P_{12}P_{31} + P_{32})b_2 + b_3}, \quad P_3 = \frac{b_3}{P_{31} b_1 + (P_{12}P_{31} + P_{32})b_2 + b_3}. \quad (5)$$

In the context of this paper's ecological-economic approach to determining the optimal length of the fallow period, these stationary probabilities have a distinct ecological meaning. As discussed in Krebs (1985, p. 587), Perrings (1998), Batabyal (1999, 2000), and Batabyal and Beladi (1999), these probabilities measure the asymptotic *resilience* of the CPFL in each of these three states. Resilience is an ecological stability property and it refers to “the amount of disturbance that can be

sustained [by a CPFL] before a change in system control or structure occurs.” (Holling *et al.*, 1995, p. 50). This means that we can think of the resilience of a CPFL as a long run measure of its well-being. Now, if we rank the three states from this well-being perspective, then it should be clear that our CPFL’s well-being is highest in state 1 because in this state soil quality is high, minerals are plentiful, and the land is ripe for planting and subsequent harvesting. From a well-being perspective, state 2 is a middle-of-the-road state because minerals, nutrients, and soil quality in general are at an intermediate level. Finally, the CPFL is least well off in state 3 because in this state its ecological condition is delicate. This is also why the CPFL is fallowed in this state.

Recall that the small farmer leaves the CPFL fallow after two harvesting seasons. Further, the mean length of the fallow period is b_3 . With these two remarks and the previous paragraph’s discussion of the three states in mind, we can now discuss the first objective for our small farmer. Ideally, this farmer would like to choose the expected length of the fallow period b_3 to *maximize* the long run probability of being in the ecologically most desirable state 1. However, calculus and equation (4) tell us that P_1 is convex in b_3 . As such, it does not make sense to maximize P_1 over b_3 . Given this state of affairs, we suppose that our small farmer chooses b_3 to minimize P_2 , the long run probability of being in the intermediate state 2. Further, note that because these long run probabilities can also be interpreted as the long run proportion of *time* that the CPFL is in a particular state (see Ross (1996, pp. 213-218) and Ross (2000, pp. 395-397)), by minimizing the long run proportion of time the CPFL spends in state 2, our small farmer is indirectly increasing the long run proportion of time that the CPFL spends in the ecologically most desirable state 1. Finally, because the long run probability of being in state 2 is the resilience of the CPFL in state 2 (see the definition in the previous paragraph), we can think of this minimization exercise as one that involves the concurrent

minimization of the CPFL's resilience in the intermediate state.

The reader should note that minimizing resilience does *not* mean that the small farmer is minimizing disturbance or usage of the CPFL. What it does mean is that in the face of shocks from ongoing farming activities and ecological/environmental factors (droughts, lack of plant nutrients, unusually low soil moisture), the small farmer is choosing the length of the fallow period to minimize the proportion of time that the CPFL spends in the intermediate state 2. This is the ecological side of the fallow period length choice problem.

In fragile environments of the sort that we're analyzing in this paper, it is very important to choose the length of the fallow period carefully. It is clear that if the fallow period is too short, then our CPFL will not have had enough time to revert to state 1. However, this does *not* mean that the manager should err on the side of caution and, *ceteris paribus*, make the fallow period very long. With rising land and population pressures (see Southgate (1990) and Barrett (1999)), if a small farmer chooses a very long fallow period, then (s)he also foregoes the profits from growing and harvesting crops. Put differently, the ecological and the economic aspects of the farmer's choice problem pull in opposite directions. Consequently, in choosing the length of the fallow period, our small farmer will want to account for this ecology versus economics tradeoff optimally.

Let us now focus on the economic side of the fallow period length choice problem in greater detail. Note that swidden agriculture gives rise to economic profits to our small farmer where profits equal the difference between total revenues and costs. First consider the revenue aspect. A well managed CPFL will provide our small farmer with a flow of consumptive (crops that (s)he consumes himself/herself) and monetary (crops that (s)he sells) benefits over time. On the cost side, it is necessary to account for the opportunity cost of the farmer's labor and other costs pertaining to the

growing, weeding, and harvesting of crops. Consequently, in determining the length of the fallow period, our small farmer will pay attention to the economic profits from crop growing activities. We suppose that in order to survive, the small farmer cannot let the economic profits associated with swidden agriculture fall below a certain minimum threshold. Denote this threshold by $\tilde{D}$. This tells us that the economic side of the small farmer's choice problem is given by a constraint on the economic profits to this farmer from the practice of swidden agriculture. This constraint is $D(b_3) \geq \tilde{D}$, where $D'(b_3) \leq 0$. In words, the constraint or profit function is decreasing in the length of the fallow period b_3 .

To see why this profit function is decreasing in the length of the fallow period, recall that this function measures the economic profit to our farmer from crop growing on the CPFL. Now, when this land is in the fallow state, it is recovering from two harvesting seasons. Consequently, during this time period, the CPFL is not being used for agriculture. This means that from a use perspective, the longer the fallow period, the lower the economic profits. This is why the profit function $D(\cdot)$ is decreasing in the length of the fallow period b_3 . This completes the derivation of the first small farmer objective and our discussion of this farmer's minimization problem.

2.3.2. The Second Objective: A Conditional Probability

The second farmer objective also involves working with a probability, but now the focus of the small farmer is a little different. As in section 2.3.1, once again we shall take a long run view of the CPFL. In particular, suppose that at time t the CPFL is in the fallow state 3. By choosing the length of the fallow period b_3 , the small farmer can affect the state into which the CPFL will next make a transition. Ideally, the farmer would like this next state to be the ecologically healthiest state, i.e., state 1. To this end, if we let $S(t)$ be the state entered at the first transition after time t , then we

can determine the long run conditional probability that the next state visited after t is 1, given that at time t the CPFL is in state 3 and that the mean length of the fallow period is b_3 . In other words, ideally, we would like to compute $\lim_{t \rightarrow \infty} \text{Prob}\{S(t)=1/z(t)=3\}$ and maximize this long run probability. However, it does not make much sense to maximize this probability because it can be shown that this probability too is convex in the length of the fallow period b_3 . Consequently, we suppose that our small farmer minimizes $\lim_{t \rightarrow \infty} \text{Prob}\{S(t)=2/z(t)=3\}$ over b_3 .

There are two additional things to note here. First, the farmer's principal concern now is to *minimize* the likelihood of going to state 2, given that the CPFL is currently in the fallow state 3. The reader will note that given the long run proportion of *time* interpretation of these stationary probabilities, once again, our small farmer is attempting to indirectly increase the amount of time spent in the ecologically healthiest state 1. Second, unlike the probability derived in the previous subsection, $\lim_{t \rightarrow \infty} \text{Prob}\{S(t)=2/z(t)=3\}$ is a *conditional* probability. We now compute this stationary conditional probability. Elementary probability theory tells us that

$$\lim_{t \rightarrow \infty} \text{Prob}\{S(t)=2/z(t)=3\} = \lim_{t \rightarrow \infty} \frac{\text{Prob}\{S(t)=2, z(t)=3\}}{\text{Prob}\{z(t)=3\}}. \quad (6)$$

The joint probability in the numerator of the right hand side (RHS) of this equation can be simplified with the aid of Theorem 4.8.4 in Ross (1996, p. 217). The probability in the denominator of the RHS of equation (7) is simply P_3 , the stationary probability (see equation (5)) of finding the CPFL in state 3. With these simplifications, we get

$$\lim_{t \rightarrow \infty} \text{Prob}\{S(t)=2/z(t)=3\} = P_{32} \bullet \frac{\int_0^{\infty} G_{32}^c(w) dw}{P_3 b_{33}}. \quad (7)$$

Proposition 4.8.1 in Ross (1996, p. 214) can be used to further simplify the denominator on the RHS of equation (7). This gives

$$\lim_{t \rightarrow \infty} Prob\{S(t)=2/z(t)=3\} = P_{32} \bullet \frac{\int_0^{\infty} G_{32}^c(w)dw}{b_3}. \quad (8)$$

The RHS of equation (8) is the product of two terms. The first term is the probability of making a transition from state 3 to 2. The second term is the ratio of the integral of the tail distribution of the amount of time the CPFL spends in state 3 before making a transition to state 2 to the mean length of the fallow period in state 3. Following Perrings (1998), we can now give an ecological interpretation to this first term. This term is the transient or the short run resilience of the CPFL in the fallow state 3.

The small farmer's objective now is to choose b_3 to minimize the long run conditional probability in equation (8). This is the ecological side of the fallow period length choice problem. The economic side is similar to that in the previous sub-section. In order to survive, our farmer cannot let the economic profits from swidden agriculture fall below a certain minimum threshold. Denote this threshold by $\tilde{D}$. Then, as in the previous sub-section, the economic side of the farmer's problem is given by a constraint on the minimum acceptable level of profits from swidden agriculture. This constraint is $\mathcal{D}(b_3) \geq \tilde{D}$, where $\mathcal{D}'(b_3) \leq 0$. This completes the derivation of the second farmer objective and our discussion of the small farmer's optimization problem. We now analyze these optimization problems and then draw inferences for the fallow period length choice problem that is the subject of this paper.

3. The Small Farmer's Choice Problem With Ecological-Economic Criteria

3.1. Minimizing the Unconditional Probability

Recall from the discussion in section 2.3.1 that the first problem faced by our small farmer involves the minimization of an ecological criterion subject to an economic constraint. The ecological criterion is the resilience of the CPFL in the intermediate state 2 and the economic constraint says that the profits from swidden agriculture must not fall below a certain minimum threshold. Formally, our farmer solves

$$\min_{\{b_3 \geq 0\}} \frac{(P_{12}P_{31} + P_{32})b_2}{P_{31}b_1 + (P_{12}P_{31} + P_{32})b_2 + b_3}, \quad (9)$$

subject to

$$\mathfrak{D}(b_3) \geq \tilde{\mathfrak{D}}. \quad (10)$$

Now, without loss of generality, suppose that the solution to problem (9)-(10) yields an interior minimum at which the constraint binds. Then, omitting the complementary slackness conditions, the Kuhn-Tucker conditions for a minimum are

$$\frac{-(P_{12}P_{31} + P_{32})b_2}{\{P_{31}b_1 + (P_{12}P_{31} + P_{32})b_2 + b_3\}^2} = \tilde{\mathfrak{n}}\mathfrak{D}'(b_3), \quad (11)$$

where $\tilde{\mathfrak{n}}$ is the multiplier on the profit constraint, and

$$\mathbb{D}(b_3) = \tilde{\mathbb{D}}. \quad (12)$$

On solving equations (11) and (12) simultaneously, we get the optimal length of the fallow period (b_3^*) and the shadow value of the profit constraint ($\tilde{\pi}^*$). The key condition here is equation (11). This first order necessary condition tells us that in choosing the length of the fallow period optimally, the small farmer will balance ecological and economic considerations. Specifically, b_3^* will be chosen so that the marginal impact of the length of the fallow period on the probability of the CPFL being in state 2 (the LHS) is set equal to the product of the shadow value of the profit constraint and the marginal profit from choosing the fallow period length optimally (the RHS).

If the fallow period length is chosen in this way, then we can be fairly sure that the CPFL will be healthy in the long run. From an ecological perspective, this means that the resilience of the CPFL in the intermediate state 2 will be low. In economic terms, this means that the CPFL will provide our small farmer with a flow of profits or a flow of consumptive and non-consumptive net benefits in the long run.

3.2. *Minimizing the Conditional Probability*

Recall from section 2.3.2 that in this version of the fallow period length choice problem, the small farmer's principal goal is to choose the length of the fallow period so that the amount of time the CPFL spends in state 2 is small, given that this land is currently in the fallow state 3. Formally, the farmer solves

$$\min_{\{b_3 \geq 0\}} P_{32} \bullet \frac{\int_0^\infty G_{32}^c(w) dw}{b_3}, \quad (13)$$

subject to equation (10).

As stated, this minimization problem is unwieldy. Therefore, to demonstrate our approach, we suppose that the amount of time that the CPFL spends in state 3 before making a transition to state 2 is exponentially distributed. Then, integrating the tail distribution function for an exponentially distributed random variable—see Jeffrey (1995, p. 248)—and then evaluating this integral between the upper and the lower limits, we get

$$\int_0^{\infty} G_{32}^c(w)dw = \frac{1}{\hat{c}}, \quad (14)$$

where $\hat{c} > 0$ is the parameter of the exponential distribution function. Using equation (14), our small farmer's minimization problem becomes

$$\min_{\{b_3 \geq 0\}} P_{32} \bullet \frac{1}{\hat{c}b_3} \quad (15)$$

subject to equation (10). Now, as in the previous sub-section, suppose that the solution to problem (15)-(10) yields an interior minimum at which the constraint binds. Then, omitting the complementary slackness conditions, the Kuhn-Tucker conditions for a minimum are

$$\frac{-P_{32}}{\hat{c}(b_3)^2} = \tilde{n}\hat{D}'(b_3), \quad (16)$$

equation (12), and $\tilde{n}$ is the multiplier on the profit constraint.

On solving equations (12) and (16) simultaneously, we obtain the optimal values of the fallow

period length (b_3^*) and the shadow value of the profit constraint ($\tilde{n}^*$). The “ecological-economic” optimality condition is equation (16). This equation tells us that when the small farmer’s main concern is to *minimize* the long run likelihood of moving to the intermediate state 2 from the fallow state, (s)he will choose the length of the fallow period so that the marginal impact of the fallow period length on the long run conditional probability of being in state 3 and then making a transition to state 2 (the LHS) is equal to the product of the shadow value of the profit constraint and the marginal profit from choosing the fallow period length optimally (the RHS).

If b_3^* is chosen in this way, then one can be fairly sure that our CPFL will be sustainable in the long run. Once again, it is important to stress that in the context of this paper, sustainability has a dual meaning. From an ecological standpoint, sustainable means that in the long run, the CPFL will not be resilient in the intermediate state 2. From an economic standpoint, sustainable means that the CPFL will provide our small farmer with a flow of profits in the long run. We now discuss the salience and the policy implications of this paper’s research in the next section.

4. Conclusions

We addressed three issues in this paper that, to the best of our knowledge, have *not* been addressed previously in the literature on swidden agriculture in developing countries. First, in section 2, we used the theory of semi-Markov processes to provide an ecological-economic characterization of a CPFL on which crops are grown and then the land is fallowed. Next, we used the dynamic and the stochastic properties of this CPFL to derive two objectives for a small farmer that are ecologically meaningful. Finally, in section 3, we used these two objectives to analyze two fallow period length choice problems from an ecological-economic perspective. In this perspective, the focus of our small farmer is on choosing the length of the fallow period so that the CPFL recovers to the ecologically

healthiest state 1 and profits from agriculture do not fall below a minimum threshold.

Five specific policy implications follow from this paper's research. First, unlike many economics papers on the subject of swidden agriculture, our paper shows that the practice of successful slash-and-burn agriculture involves paying attention to both the ecology *and* the economics of the CPFL under consideration. Second, we have shown that by optimizing the *long run* objective functions of this paper, a small farmer will also be simultaneously optimizing the resilience of the appropriate states of the CPFL. Third, this paper has shown how a small farmer might choose the length of the fallow period optimally in an ecological-economic context. Fourth, from a practical perspective, this paper sheds light on the transition probabilities that will need to be estimated in order to set up the objective functions described in equations (9) and (15). In addition to this, the minimization exercises of sections 3.1 and 3.2 provide the small farmer with two different ways of selecting the length of the fallow period optimally. Finally, our research shows that the ecological and the economic aspects of swidden agriculture can be in *conflict*. This is particularly relevant in developing countries such as Brazil and Indonesia where the practice of swidden agriculture has often been blamed for causing massive tropical deforestation (see Myers (1994) and Rudel and Roper (1997)).

The analysis contained in this paper can be extended in a number of different directions. In what follows, we suggest three avenues for empirical research on the subject of swidden agriculture. First, it would be useful to ascertain whether extant econometric techniques can be used to estimate the transition probabilities of the CPFL under study. Second, given a specific swidden system, knowledge of the amount of time a CPFL spends in a particular state would be helpful in setting up the objective functions discussed in this paper. Finally, our analysis of the two minimization problems

in section 3 is based on the assumption that the small farmer's profit function is decreasing in the length of the fallow period. Although this seems reasonable from a theoretical standpoint, it would be useful to conduct empirical research to determine whether this assumption is justified. Studies of the fallow period that incorporate these aspects of the problem into the analysis will provide additional insights into the nexuses between the length of the fallow period and the successful practice of swidden agriculture.

References

- Barrett, C.B. 1999. Stochastic Food Prices and Slash-and-Burn Agriculture, *Environment and Development Economics*, 4, 161-176.
- Batabyal, A.A. 1999. Species Substitutability, Resilience, and the Optimal Management of Ecological-Economic Systems, *Mathematical and Computer Modelling*, 29, 35-43.
- Batabyal, A.A. 2000. Quantifying the Transient Response of Ecological-Economic Systems to Perturbations, *Environmental Impact Assessment Review*, 20, 125-133.
- Batabyal, A.A., and Beladi, H. 1999. The Stability of Stochastic Systems: The Case of Persistence and Resilience, *Mathematical and Computer Modelling*, 30, 27-34.
- Brown, K., and Pearce, D.W., Eds. 1994. *The Causes of Tropical Deforestation*. University of British Columbia Press, Vancouver, British Columbia.
- Coomes, O.T., Grimard, F., and Burt, G.J. 2000. Tropical Forests and Shifting Cultivation: Secondary Forest Fallow Dynamics Among Traditional Farmers of the Peruvian Amazon, *Ecological Economics*, 32, 109-124.
- de Janvry, A., Fafchamps, M., and Sadoulet, E. 1991. Peasant Household Behavior With Missing Markets: Some Paradoxes Explained, *Economic Journal*, 101, 1400-1417.
- Dove, M.R. 1983. Theories of Swidden Agriculture and the Political Economy of Ignorance, *Agroforestry Systems*, 1, 85-99.
- Dufour, D.L. 1990. Use of Tropical Rainforests by Native Amazonians, *BioScience*, 40, 652-659.
- Ekeleme, F., Akobundu, I.O., Isichei, A.O., and Chikoye, D. 2000. Influence of Fallow Type and Land-Use Intensity on Weed Seed Rain in a Forest/Savanna Transition Zone, *Weed Science*, 48, 604-612.

- Fafchamps, M. 1992. Cash Crop Production, Food Price Volatility, and Rural Market Integration in the Third World, *American Journal of Agricultural Economics*, 74, 90-99.
- Gleave, M.B. 1996. The Length of the Fallow Period in Tropical Fallow Farming Systems: A Discussion With Evidence from Sierra Leone, *Geographical Journal*, 162, 14-24.
- Holling, C.S. Schindler, D.W., Walker, B., and Roughgarden, J. 1995. Biodiversity in the Functioning of Ecosystems: An Ecological Synthesis, in C. Perrings, K.G. Maler, C. Folke, C.S. Holling, and B.O. Jansson, (Eds.), *Biodiversity Loss*. Cambridge University Press, Cambridge, UK.
- Hofstad, O. 1997. Degradation Processes in Tanzanian Woodlands, *Forum for Development Studies*, 0, 95-115.
- Jeffrey, A. 1995. *Handbook of Mathematical Formulas and Integrals*. Academic Press, San Diego, California.
- Krebs, C.J. 1985. *Ecology*, 3rd edition. Harper and Row, New York, New York.
- Li, F., Zhao, S., and Geballe, G.T. 2000. Water Use Patterns and Agronomic Performance for Some Cropping Systems With and Without Fallow Crops in a Semi-Arid Environment of Northwest China, *Agriculture, Ecosystems, and Environment*, 79, 129-142.
- Myers, N. 1994. Tropical Deforestation: Rates and Patterns, in K. Brown and D.W. Pearce, (eds.), *The Causes of Tropical Deforestation*, University of British Columbia Press, Vancouver, British Columbia.
- Pearce, D.W., and Warford, J.J. 1993. *World Without End: Economics, Environment, and Sustainable Development*. Oxford University Press, Oxford, UK.
- Perrings, C. 1998. Resilience in the Dynamics of Economy-Environment Systems, *Environmental*

- and Resource Economics*, 11, 503-520.
- Peters, W.J., and Neuenschwander, L.F. 1988. *Slash and Burn: Farming in the Third World Forest*. University of Idaho Press, Moscow, Idaho.
- Ross, S.M. 1996. *Stochastic Processes*, 2nd edition. Wiley, New York, New York.
- Ross, S.M. 2000. *Introduction to Probability Models*, 7th edition. Academic Press, San Diego, California.
- Rudel, T., and Roper, J. 1997. The Paths to Rainforest Destruction: Crossnational Patterns of Tropical Deforestation 1975-90, *World Development*, 25, 53-65.
- Silva-Forsberg, M.C., and Fearnside, P.M. 1997. Brazilian Amazonian Caboclo Agriculture: Effect of Fallow Period on Maize Yield, *Forest Ecology and Management*, 97, 283-291.
- Southgate, D. 1990. The Causes of Land Degradation along Spontaneously Expanding Agricultural Frontiers in the Third World, *Land Economics*, 66, 93-101.
- Swinkels, R.A., Franzel, S., Shepherd, K.D., Ohlsson, E., and Ndufa, J.K. 1997. The Economics of Short Rotation Improved Fallows: Evidence From Areas of High Population Density in Western Kenya, *Agricultural Systems*, 55, 99-121.
- Udaeyo, N.U., Umoh, G.S., and Ekpe, E.O. 2001. Farming Systems in Southeastern Nigeria: Implications for Sustainable Agricultural Production, *Journal of Sustainable Agriculture*, 17, 75-89.