Deforestation, forest fallowing, and soil conservation in shifting cultivation

by

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Abstract
To design effective policies for rainforest conservation in shifting cultivation systems, it is crucial to have a better understanding of shifting cultivators' decision making. This paper develops a unified dynamic farm model of shifting cultivation, addressing two lacunae in extant theoretical works: taking into account differences between primary and secondary forests and potential roles of on-farm soil conservation. The model unifies shifting cultivator's decisions about primary-forest clearing, forest fallowing, and on-farm soil conservation by incorporating new soils acquired from cleared primary/secondary forest land into on-farm soil dynamics. I examine how three distinct policies – forest protection (e.g., protected areas), fallow management (e.g., improved fallow), and on-farm soil management (e.g., biochar in Amazonia) – alter primary-forest clearing (deforestation) and fallow length. The analysis reveals that although all three policies reduce deforestation, only on-farm soil management leads to longer fallow, i.e., sustainable secondary fallow forest.

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) [1, 2]. Not only is shifting cultivation one of the major causes of deforestation and forest degradation, but also, the associated forest-cover change results in other environmental problems, such as soil degradation, biodiversity loss, and reduced carbon sequestration [e.g., 1, 3-6]. To design effective policies for rainforest conservation in shifting cultivation systems, having a better understanding of shifting cultivators' decision making is crucial. This paper develops a new shifting-cultivation model to address two major lacunae in the literature [see 7 for an extensive review].

First, extant theoretical works do not distinguish between primary and secondary forests.[1,2] 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.[3] In particular, short fallow results in less matured secondary

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[1] 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" [8, p.86].
[2] As an exception, Pendleton and Howe [9] address making 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.
[3] Smith et al. [8] show that the relative importance of secondary forest to primary forest increased over time among Amazonian colonists. Coomes, Grimard and Burt [10] and

forest with limited biomass accumulation and poor protection of erodible soils, as well as low biodiversity, weak carbon sequestration, and limited timber and non-timber forest products [4-6, 12, 13].

The second lacuna is the investigation into potential roles of on-farm soil conservation. Among poor shifting cultivators, forest-based soil-management options – forest clearing and fallowing – outweigh on-farm soil conservation [14]. This is because when degraded land can be easily replaced, farmers have little incentive to adopt expensive, input-based soil-conservation measures. Although developing locally adoptable, effective on-farm soil-conservation measures in tropical forests has been a daunting task [15], soil scientists' recent growing interest in biochar in Amazonia may lead to a significant improvement in soil fertility and soil carbon sequestration in shifting cultivation systems [16-19].[4] At the same time, various management measures to improve fallows by planting species that replenish soil nutrient stocks faster than plants in natural succession are available and have been practiced across the tropics [e.g., 20, 21, 22].[5]

To fill these two lacunae, the paper unifies shifting cultivator's decisions about primary-forest clearing, forest fallowing, and on-farm soil conservation. I do so by extending the land-replacement-modeling approach, which explicitly captures shifting cultivators' motive for clearing forests: to acquire new fertile soils [7, 27]. As labor is a key scarce factor among shifting cultivators in land-abundant tropical environments [28], the model highlights the tradeoff in labor allocations associated with primary/secondary-forest clearing and on-farm soil management; cleared primary forest is more fertile than secondary forest land, but the former clearing is more labor intensive, and the alternative "slash-and-char" system is also labor intensive [29]. In particular, the model incorporates new soils acquired from cleared primary/secondary forest land into on-farm soil dynamics. Although my model best reflects shifting cultivation practices among Amazonian peasants [e.g., 10, 11], the modeling framework can be widely applied to other shifting cultivation systems in the tropics.

This unified model allows me to examine how policies can alter shifting cultivators' decisions about primary-forest clearing and fallow length, which determine the two key outcomes of rainforest conservation: protecting primary forest and maintaining sustainable secondary fallow forest [they are a key for reducing emissions

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Coomes, Takasaki and Rhemtulla [11] also find this pattern over a longer time span among Amazonian peasants (in their study village in Peru, primary forest has virtually disappeared).

[4] 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 content, higher nutrient levels, and a better nutrient retention capacity than surrounding infertile soils [17].

[5] Enriched fallows, which involve planting tree species with economic benefits (e.g., fruits, medicines) [e.g., 23, 24], may also enhance nutrient recovery, as shown by Unruh [25] in the Peruvian Amazon. An alternative approach to speed up soil regeneration under fallow is to accelerate secondary forest regrowth, for example, by canopy removal [e.g., 26].

from deforestation and forest degradation (REDD), e.g., 30]. I compare three policies –
soil management interventions for fallow and cultivated land, respectively, as discussed
above, and forest-protection measures [e.g., protected area, 31].[6] Although many
empirical studies show that protected areas can significantly reduce tropical deforestation
[e.g., 32, 33-35], systematic empirical works on the roles of fallow and on-farm soil
management for rainforest conservation in shifting cultivation systems are lacking. The
comparative static analyses reveal that although not only forest protection but also fallow
and on-farm soil management reduces deforestation in the long run, only on-farm soil
management increases fallow length.

As is any theoretical model, my unified model is built on various assumptions
(detailed below). In particular, a fixed land size is assumed. This assumption is
restrictive, because cleared primary forest usually adds to land holdings [as emphasized
by 7]. Then, it is possible that better on-farm soil management encourages shifting
cultivators to clear more primary forest to expand land holdings in response to increased
returns to farming. The theoretical literature, however, has not yet fully integrated
shifting-cultivation practices and land accumulation [see, for example, 11 for such an
empirical work].[7] The paper is a first attempt to model shifting cultivation in a way that
addresses the two major lacunae in the literature discussed above; developing a more
comprehensive model, especially one endogenizing land accumulation, is an important
agenda for future research.

The rest of the paper is organized as follows. Section 2 develops the dynamic
farm model, derives the optimal path of labor allocations, and characterizes the steady-
state equilibrium. Section 3 conducts comparative static analyses on policy impacts. The
last section concludes.

2. The model

Let us consider a representative farmer who cultivates agricultural land with the
size of 1. Let a and b ($0 < a, b < 1, a + b < 1$) denote the land that is replaced with newly
cleared primary and secondary fallow forest lands, respectively. Cleared forests bring
new soils. Secondary forest is less fertile but easier to clear than primary forest [37].
Primary forest land is homogeneous in terms of soil fertility, and the soil stock per unit
forest land is assumed to be 1, with no loss of generality. Contrarily, the fertility of
secondary forest land is determined by fallow length [e.g., 38]. Following Larson and
Bromley [39], I assume a fixed land allocation between swidden and fallow. Then, the
size of fallow forest land is written as $\theta(1 - a)$, where θ is the fixed ratio of fallow land to
swidden land $1 - a$. Fallow length N is given by θn, where $n = (1 - a)/b$, i.e., the ratio of
swidden land to the land switched between swidden and fallow ($n > 1$, because $a + b <$
1).[8] Thus, fallow length is determined by both primary- and secondary-forest clearings: If

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[6] Although protecting primary forest as the common often faces enforcement problems in
practice, such problems are much smaller in the incentive-compatible measures affecting
shifting-cultivators' management of soils as their private asset.
[7] Although Tachibana, Nguyen and Otsuka [36] endogenize the evolution of upland
holdings among Vietnamese farmers who combine upland shifting cultivation and
lowland paddy cultivation, they do not distinguish or specify the type of cleared forest.
[8] For example, if $\theta = 5$, $a = 1/4$, and $b = 1/3$, then $n = 3$ and $N = 15$.

both clearings diminish, fallow becomes longer; if the diminished and augmented clearings coexist, their net effect on fallow length is generally ambiguous. With a fixed θ, the fertility of fallow land is determined only by n: The fallow-land fertility per unit of land is $\eta k(n)$, where $k' > 0$, $k'' < 0$, and η is a fixed productivity parameter of soil regeneration under natural fallow. $\eta k'$ measures the rate of soil regeneration per unit of fallow length. Secondary fallow forest land never becomes more fertile than primary forest land, i.e., $\eta k(\infty) < 1$.

The farmer's soil regeneration technology on the cultivated land uses labor as an unique input [as modeled by 40, 41]. Letting m denote the labor per unit land allocated to on-farm soil management, the total regenerated soil is a concave function of non-replaced land $1 - a - b$ and labor input on the non-replaced land $m(1 - a - b)$. With a constant-returns-to-scale regeneration function, the total regenerated soil is written as $\alpha h(m)(1 - a - b)$, where $\alpha h(m)$ is the regenerated soil per unit land, such that $h' > 0$, $h'' < 0$, and α is a fixed productivity parameter of on-farm soil regeneration. The regenerated soil on the non-replaced land never becomes more fertile than primary forest land, i.e., $\alpha h(\infty) < 1$. The farmer's cultivation intensity also affects soil dynamics; the more labor-intensive the cultivation, the more soil is lost. Total soil loss is given by βl, where l is labor allocated to cultivation and β is constant soil loss per unit of cultivation labor.

An example of the fertility profile across plots (for given a and b) is depicted by the solid line ABCDEF in Figure 1, where each plot is displayed in the decreasing order of fertility. The total soil stock x, the area below ABCDEF, consists of a on the newly cleared primary forest land OG, $\eta k b$ on the cleared secondary forest land GH, and the soil on the remaining plots HK. The fertility profile after cultivation and the replacement and abandonment of the infertile plots IJ and JK, respectively, is depicted by the broken line LM.[9] The area between ABCDEF and LMIK is total soil loss resulting from cultivation βl. The revised fertility profile of OI after regeneration is given by the dotted line NP (LM has shifted upward by αh). In the next cultivation, NP becomes old plots and shifts rightward by $a + b$ (at a steady state, NP and EF are the same). Hence, the evolution of soil stock x on the farm land is written as:[10]

$$\dot{x} = a + \eta k\left(\frac{1-a}{b}\right)b + \alpha h(m)(1-a-b) - \beta l, \qquad 0 < x(0) = x_0 . \tag{1}$$

The farmer acquires new soil a and loses regenerated soils on the abandoned plots $\alpha h(m)a$. Thus, $1 - \alpha h(m)$, which is positive, represents the net soil addition per unit crop land through primary-forest clearing. Similarly, $\eta k(n) - \alpha h(m)$ captures the net soil addition through secondary-forest clearing, which is also shown to be positive below.

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[9] The remaining soils on the replaced and abandoned plots (which are not specified in Figure 1) do not affect the soil dynamics on the farm land. In particular, it is assumed that 1) the former soil stock does not affect the fertility of fallow forest, or the soil on the former land is used up before replacement, and 2) the latter plot is not added to fallow land (i.e., θ is unaltered).

[10] A perfect substitutability between regenerated soils through fallow and on-farm management is assumed; in particular, the nutrient accumulation process in these two is assumed not to be substantially different from each other. This assumption is consistent with biochar in Amazonia [17-19].

The following three assumptions are made. First, primary forest is locally abundant, open-access, and unmanaged. Thus, forest stock is exogenous to the private farmer. This institutional setup, which is common in the deforestation literature [e.g., 7, 42, 43], applies to many tropical areas, especially those where rapid deforestation is an emergency problem, as in Amazonia. Second, all cleared lands, both farm land and fallow land, are secure under customary tenure (usufruct). This institutional setup applies to peasants and indigenous populations in Amazonia.[11] Third, the farmer earns no income from standing primary and secondary forests in the form of non-timber forest products. Because to add such earning options would augment the benefit of maintaining standing forests, the present model ignoring them is considered to be 'conservative' in the study of forest clearing.[12]

With the fixed amount of primary forest land, more forest clearing requires longer travel for clearing. Labor required to clear a primary forest land is given by $\pi s(a)$, where $s(0) = 0$, s', $s'' > 0$, and a fixed parameter π increases as the per-capita stock of primary forest declines (e.g., through the establishment of protected areas). A linear clearing function is assumed for secondary fallow forest with the proximity to the farmer's plots: The farmer allocates τb labor to clear b secondary forest, where τ is a fixed marginal labor cost, which is always smaller than that of primary-forest clearing, i.e., $\tau < \pi s'(0)$.[13]

The farmer's crop output is a function of soil stock and cultivation labor, $f(x,l)$, where $f(0, l) = f(x, 0) = 0$, $f_x, f_l > 0$, $f_{xx}, f_{ll} < 0$, and $f_{xl} \geq 0$ (the subscripts represent derivatives in a standard manner). Concavity is guaranteed by the non-negativity of the determinant of the Hessian matrix of f, i.e., $d = f_{xx}f_{ll} - f_{xl}^2 \geq 0$. The farmer hires labor l^h at a fixed wage w in a perfect labor market, and alternatively, the negative l^h means that he/she sells labor.[14] The farmer's labor time constraint is

$$l + m(1 - a - b) + \tau b + \pi s(a) = L + l^h , \tag{2}$$

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[11] In practice, however, the customary tenure of fallow land can be insecure, and this tenure insecurity influences shifting cultivators' forest clearing and fallowing decisions [36, 44, 45]. Conflicts over property rights are common among colonists in the forest frontier [e.g., 46, 47-49].

[12] Among Amazonian colonists, Smith et al. [8, p.95] find that secondary forest management is determined primarily by soil regeneration considerations and is unaffected by such forest products; farmers regard those products as "a bonus obtained during the fallow period."

[13] The more matured the secondary fallow forest, the more labor is needed for clearing. Assuming that τ is positively related to fallow length does not alter the main results.

[14] Wage represents the opportunity cost of labor in the form of returns to any non-farm activities [50]. Although with a perfect labor market a market price (wage) supports a separation of a farm household's consumption (labor supply) and production (labor demand) decisions, market imperfection can break this separation [51], often giving rise to ambiguous policy impacts on its decisions [as shown by 52, 53 for forest clearing]. In contrast, examining Amazonian peasants' forest clearing in Peru, Takasaki et al. [28] find that not only is their labor allocation efficient, as hired labor is combined with labor sharing, but also, family, hired, and shared labor are perfect substitutes for each other. This buttresses the assumption of labor-market perfection, which is common in extant theoretical works [7].

where L is his/her time endowment. With a perfect labor market, the farmer's utility maximization is recursive: The farmer maximizes the profit first [51].

The farmer chooses cultivation labor, soil conservation labor, and secondary- and primary-forest clearing over time to maximize his/her discounted total profits:

$$\max_{l,m,b,a} \int_0^\infty e^{-rt}\left[pf\left(l,x\right)-wl^h\right]dt$$

s.t., (1), (2),

where p is a fixed crop price and r is a fixed discount rate (risk is ignored). The current-value Hamiltonian is given by

$$H \equiv pf\left(x,l\right)-w\left[l+m\left(1-a-b\right)+\pi s\left(a\right)+\tau b-L\right]$$
$$+\lambda\left[a+\eta k\left(\frac{1-a}{b}\right)b+\alpha h\left(m\right)\left(1-a-b\right)-\beta l\right] \quad,$$

where λ is the current-value costate variable for soil stock.

Given an internal solution, the first-order necessary conditions for optimality are (1) plus the following:

$$H_l = 0 \Rightarrow pf_l = w+\lambda\beta, \tag{3}$$

$$H_m = 0 \Rightarrow \lambda\alpha h' = w, \tag{4}$$

$$H_b = 0 \Rightarrow \lambda\left(\eta k-\alpha h\right)+wm = w\tau+\lambda\eta k'\frac{1-a}{b}, \tag{5}$$

$$H_a = 0 \Rightarrow \lambda\left(1-\alpha h\right)+wm = w\pi s'+\lambda\eta k', \tag{6}$$

$$\dot{\lambda} = r\lambda-H_x = r\lambda-pf_x, \tag{7}$$

$$\lim_{t\to\infty} e^{-rt}\lambda x = 0, \; \lim_{t\to\infty} e^{-rt}\lambda \geq 0. \tag{8}$$

Equation (3) indicates that farming labor is chosen to the point where the value of the marginal product of labor equals wage, plus the marginal value of soil loss resulting from cultivation. Equation (4) suggests that soil conservation labor is chosen to the extent that the value of the marginal product of on-farm soil regeneration equals forgone wage. In equation (5), secondary fallow forest is cleared to the extent that the value of net soil addition, plus the saved wage through a reduction in soil conservation labor (more intensive secondary-forest clearing involves more land replacement), equals the forgone wage through clearing, plus the value of the forgone marginal soil regeneration on the fallow land through shortened fallow. The interpretation of equation (6) with respect to primary-forest clearing is analogous. Equation (7) is the standard costate condition, giving the optimal evolution of the shadow value of soil stock. Transversality conditions are given by equation (8). Because the Hamiltonian is jointly concave in the state and control variables, these necessary conditions are sufficient for optimality.[15]

The steady-state equilibrium, the existence of which is assumed, is shown to be unique and stable, as follows. The steady-state equilibrium (x^*, λ^*) is given by $\dot{x} = \dot{\lambda} = 0$ in equations (1) and (7), and once the steady-state values for x^* and λ^* are known, those for l^*, m^*, b^*, and a^* are obtained recursively from (3)-(6). Substituting l, m, b, and a from

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[15] Considering corner solutions is a straightforward extension. In particular, if $a = 0$, i.e., no primary-forest clearing, for example, in highly deforested areas, equation (6) is irrelevant.

equations (3)-(6), the canonical system is expressed by (1) and (7). Linearising the system at the steady state yields the following Jacobian matrix:

$$J = \begin{pmatrix} \dfrac{\beta f_{xl}}{f_{ll}} & -\dfrac{\beta^2}{pf_{ll}} - \dfrac{\alpha h'^2 \gamma}{\lambda h''} + \dfrac{e^2}{\lambda \eta k'' \dfrac{n^2}{b}} + \dfrac{\varphi^2}{w \pi s''} \\[4mm] -\dfrac{pd}{f_{ll}} & r - \dfrac{\beta f_{xl}}{f_{ll}} \end{pmatrix},$$

where $\gamma = 1 - a - b > 0$; $e = \eta k - \alpha h - \eta k' n$; $\varphi = 1 - \alpha h - (k - \alpha h)n^{-1} > 0$; $J_{11} < 0$, J_{12}, $J_{22} > 0$, and $J_{21} \geq 0$, where J_{mn} is the (m, n) factor of matrix J. Because the $\dot{x} = 0$ and $\dot{\lambda} = 0$ loci, respectively, are upward and downward sloping in the λ-x space, the equilibrium (x^*, λ^*), which is determined as their intersection, is unique. Because $|J| = J_{11}J_{22} - J_{12}J_{21} < 0$ and $(J_{11} - J_{22})^2 + 4J_{12}J_{21} > 0$, both characteristic roots are real and have opposite signs, and thus the equilibrium is stable as a saddle point [54, p.253].

3. Policy analysis

The comparative statics of l^*, m^*, b^*, a^*, and x^* with respect to exogenous variables can be obtained from equations (3), (5), (6), (1), and (7) with the substitution of λ from (4). The determinant of the Hessian matrix of the system of these five equations is given by:

$$D = p^2 d \left[\pi s'' \left(\dfrac{h''}{\alpha h'^2} e^2 + \eta k'' \dfrac{n^2}{b} \gamma \right) + \dfrac{h''}{\alpha^2 h'^3} \eta k'' \dfrac{n^2}{b} \varphi^2 \right] - \beta \dfrac{1}{\alpha h'} \eta k'' \dfrac{n^2}{b} \pi s'' \Phi < 0,$$

where $\Phi = \dfrac{pwh''}{\alpha h'^2}(-\beta f_{xx} + r f_{xl}) < 0$. Secondary-forest-clearing labor is assumed to be greater than soil-conservation labor, i.e., $\tau > m$; then, $e > 0$ (see equation 5).

I consider three policies: 1) forest protection (higher π); 2) improved fallow to augment soil regeneration under fallow (higher η); and 3) on-farm soil management to augment soil regeneration on non-replaced cultivated land (higher α). Key outcome measures are primary-forest clearing a^* and fallow length N^* in the long run (the asterisks represent the steady-state equilibrium). With a fixed θ, effects on N^* are qualitatively the same as those on $n^* = (1 - a^*)/b^*$. To facilitate interpretations, soil conservation labor m^* is also examined.

The comparative statics are reported in Table 1. Many results of the two soil management measures, but not forest protection, depend on farming technology: Many results are ambiguous when $d > 0$, but most ambiguities vanish when $d = 0$. This is because for the latter technologies, all adjustments in equations (3) and (7) are determined by the shadow value of soil stock, which unambiguously increases with augmented soil conservation labor (see equation 4), because adjustments in cultivation labor and soil stock cancel each other out (note that no other endogenous variables appear in equations 3 and 7). With $d > 0$, this neutrality of farming technology vanishes because of the adjustments in crop production. Many empirical works that estimate the production functions of shifting cultivation employ a Cobb-Douglas technology, for which $d = 0$ [e.g., 55, 56, 57]. The summary of the comparative static results in Table 2 is based on

those with $d = 0$ for soil-management measures; those for forest protection do not depend on the sign of d.

First, forest protection always reduces and increases primary- and secondary-forest clearing, respectively. As the former becomes more costly than the latter, this shift is an obvious result of substitution. Although these two impacts counteract each other in determining fallow length, the secondary-forest effect always outweighs the primary-forest effect, resulting in shorter fallow. Thus, protecting primary forest involves less sustainable secondary forest as a tradeoff. In contrast, soil-conservation labor input is always augmented. This is because the farmer offsets a decrease in the acquisition of fertile soil from primary forest land, which is greater in magnitude than an increase in the acquisition of less fertile soil (as a result of shortened fallow) from secondary forest land.

Second, the results for improved fallow are qualitatively the same as those for forest protection. Secondary forest is substituted for primary forest in the farmer's soil management portfolio, as follows. On one hand, primary-forest clearing is reduced, because with higher η, its marginal cost $\eta k'$ – reduced soil regeneration under fallow – increases more than its benefit (see equation 6). On the other hand, secondary-forest clearing is augmented, because higher η increases fallow soil minus the forgone marginal soil regeneration on the fallow land, $\eta k - \eta k'n$ ($\equiv g > 0$ because $e > 0$) (see equation 5). As the latter effect unambiguously outweighs the former, fallow always becomes shorter. To offset the balance of these two forest-based soil managements, on-farm soil management is intensified. Shortened fallow is not surprising at all, because this policy speeds up the soil regeneration. The question is whether or not the fertility of fallow land $\eta k(n)$ is improved. Although $d(\eta k(n))/d\eta = k(n) + \eta k'(n)dn/d\eta$ is generally unsigned even if $d = 0$, this comparative statics is likely to be positive, unless fallow length n becomes very short. Whether and how much this policy mitigates adverse ecological impacts of short fallow discussed above are empirical questions, the answers to which depend on specific fallow-management measures. As such, although improved fallow protects primary forest, it may do so at the cost of unsustainable secondary-fallow forest.

Third, enhanced on-farm soil regeneration always leads to the intensification of on-farm soil management and thus more fertile soil on the cultivated land $\alpha h(m)$. It also unambiguously reduces primary-forest clearing, because the net soil addition on crop land through primary-forest clearing $(1 - \alpha h)$ decreases. In contrast, the impacts on secondary-forest clearing are indeterminate even if $d = 0$, because the net soil addition through secondary-forest clearing $(\eta k - \alpha h)$ is ambiguously altered, depending on fallow length. Fallow unambiguously becomes longer, because the former primary-forest effect always outweighs the latter secondary-forest effect. An important difference of this policy from the other two policies is that although the latter two directly affect either one of the two forest-based soil management options – primary- or secondary-forest clearing –, the former alters the benefit-cost comparisons of the on-farm option with both of them.[16]

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[16] I also examine impacts of output price and wage, which can be altered by a variety of macroeconomic policies, such as price subsidies, exchange-rate policies, and trade policies; alternatively, a higher p captures Hicks neutral technological progress in farming. Standard results are obtained: Regardless of the sign on d, promoting non-agricultural activities (higher w) always reduces primary-forest clearing and soil-

4. Conclusion

This paper developed a unified dynamic farm model of primary-forest clearing, forest fallowing, and on-farm soil conservation in shifting cultivation by incorporating new soils acquired from cleared primary/secondary forest land into on-farm soil dynamics. The comparative static analysis revealed that although forest protection (e.g., protected areas), fallow management (e.g., improved fallow), and on-farm soil management (e.g., biochar in Amazonia) all reduce primary-forest clearing (deforestation) in the long run, only on-farm soil management increases fallow length. A caveat is that the model ignores land accumulation; with an additional motive for clearing primary forest – land expansion – better on-farm soil management instead may lead to augmented deforestation. Then, to attain the win-win goal of protecting primary forest and maintaining sustainable secondary fallow forest (longer fallow), an effective policy mix is needed. These promising findings of the paper call for new empirical studies on the roles of fallow and on-farm soil management for rainforest conservation in shifting cultivation systems.

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conservation labor (and thus on-farm soil regeneration) and increases fallow length, as they discourage farming itself (the impact on secondary-forest clearing is ambiguous); the converse holds true for promoting agriculture (higher p).

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Table 1. Comparative statics

Forest protection:

$$\frac{da^*}{d\pi} = -\frac{1}{D}s'\left[p^2 d\left(\frac{h''}{\alpha h'^2}e^2 + \eta k''\frac{n^2}{b}\gamma\right) - \beta\Phi\frac{1}{\alpha h'}\eta k''\frac{n^2}{b}\right] < 0$$

$$\frac{db^*}{d\pi} = \frac{1}{D}s'\left[p^2 d\left(\frac{h''}{\alpha h'^2}eq + \eta k''\frac{n}{b}\gamma\right) - \beta\Phi\frac{1}{\alpha h'}\eta k''\frac{n}{b}\right] > 0$$

$$\frac{dn^*}{d\pi} = -\frac{1}{D}\cdot\frac{n}{b}s'p^2 d\frac{h''}{\alpha h'^2}\varphi e < 0$$

$$\frac{dm^*}{d\pi} = \frac{1}{D}s'p^2 d\frac{n^2}{b}\cdot\frac{1}{\alpha h'}\eta k''\varphi > 0$$

Fallow regeneration:

$$\frac{da^*}{d\eta} = \frac{1}{D}\left[p^2 d\left(e\Theta + \frac{1}{\alpha h'}\eta k''\frac{n^2}{b}\Omega\right) + \beta\Phi\frac{1}{\alpha^2 h'^2}\eta k''\frac{n}{b}k\right] < 0$$

$$\frac{db^*}{d\eta} = \frac{1}{D}\left[p^2 d\left(\pi s''\Psi + q\Theta + \frac{1}{\alpha h'}\eta k''\frac{n}{b}\Omega\right) - \beta\Phi\frac{1}{\alpha h'}\left(-g\pi s'' + \frac{1}{\alpha h'}\eta k''\frac{k}{b}\right)\right]$$

$$\frac{dn^*}{d\eta} = -\frac{1}{D}\cdot\frac{n}{b}\left[p^2 d\left(\pi s''\Psi + \varphi\Theta\right) + \beta\Phi\frac{1}{\alpha h'}g\pi s''\right]$$

$$\frac{dm^*}{d\eta} = \frac{1}{D}\cdot\frac{1}{\alpha h'}\left[p^2 d\left(\pi s''\left(ge - \eta k''n^2 k\right) + \varphi\frac{1}{\alpha^2 h'^2}\eta k''\frac{n}{b}k\right) - \beta\Phi\eta k''\frac{n^2}{b}\pi s''\right]$$

On-farm soil regeneration:

$$\frac{da^*}{d\alpha} = \frac{1}{D}\left[-p^2 d\left(e\Gamma + \frac{1}{\alpha h'}\eta k''\frac{n^2}{b}\Lambda\right) + \beta\Phi\frac{1}{\alpha^2 h'^2}\eta k''\frac{n^2}{b}\cdot\frac{\gamma}{1-a}\right]$$

$$\frac{db^*}{d\alpha} = \frac{1}{D}\left[p^2 d\left(\pi s''\Pi + q\Gamma + \frac{1}{\alpha h'}\eta k''\frac{n}{b}\Lambda\right) - \beta\Phi\frac{1}{\alpha h'}\left(h\pi s'' + \frac{1}{\alpha h'}\eta k''\frac{n}{b}\cdot\frac{\gamma}{1-a}\right)\right]$$

$$\frac{dn^*}{d\alpha} = -\frac{1}{D}\cdot\frac{n}{b}\left[p^2 d\left(\pi s''\Pi + \varphi\Gamma\right) - \beta\Phi\frac{h}{\alpha h'}\pi s''\right]$$

$$\frac{dm^*}{d\alpha} = \frac{1}{D}\cdot\frac{1}{\alpha h'}\left\{-p^2 d\left[\pi s''\frac{1}{\alpha}eg + \eta k''\frac{n^2}{b}\left(h\gamma - \varphi\frac{1}{\alpha^2 h'}\left(1 - k\frac{b}{1-a}\right)\right)\right] - \beta\Phi\eta k''\frac{n^2}{b}\pi s''\right\}$$

Note: $\chi = -h + \dfrac{h'^2}{h''} < 0$, $q = 1 - \alpha h - \eta k' > 0$ (because $q > e > 0$),

$$\Gamma = \frac{h''}{\alpha^2 h'^3}\left(e\frac{\gamma}{1-a} - \varphi\right), \quad \Lambda = \left(\frac{h''}{\alpha h'^2}\varphi\chi + h\frac{\gamma}{1-a}\right)\gamma > 0, \quad \Pi = \left(\frac{h''}{\alpha h'^2}e\chi + h\right)\gamma > 0,$$

$$\Theta = \frac{h''}{\alpha^2 h'^3}\left(e\frac{k}{n} + gq\right) < 0, \quad \Omega = \left(-\frac{h''}{\alpha h'^2}qb + \frac{\gamma}{n}\right)k > 0, \quad \Psi = -\pi s''\frac{h''}{\alpha h'^2}ekb + g\gamma > 0.$$

Table 2. Summary of comparative static results.

		Primary forest clearing a^*	Secondary forest clearing b^*	Fallow length n^*	On-farm soil conservation labor m^*
Forest protection	π	-	+	-	+
Fallow regeneration	η	-	+	-	+
On-farm soil regeneration	α	-	?	+	+

Note: Results for π do not depend on the sign of d; with respect to η and α, results with $d = 0$ are shown.

Figure 1. Soil fertility profile across plots.