Preliminary Draft –
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Deforestation and asset accumulation among small scale farmers

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May 12, 2000

Prepared for the American Agricultural Economics Association Annual Meeting,
Tampa, Florida, July 31-August 2, 2000

Basic ideas for this paper are a result of my fieldwork experience in the Peruvian Amazon. I wish to thank my field team – Carlos Rengifo, Doris Diaz and Jaime Salazar – for their advice, enthusiasm and Herculean effort that made this project possible. Special thanks are owed also to the ribereños of the region who so willingly participated in the long interviews on repeat visits to their homes. I owe a particularly large debt of gratitude to my collaborators – Brad Barham and Oliver Coomes – for their continuing advice, support and encouragement at every step of this project. Finally, I gratefully acknowledge the generous financial support of this project by the following organizations: The Nature Conservancy, Ford Foundation, AVINA/North-South Center of the University of Miami, Foundation for Advanced Studies on International Development (FASID), The Institute for the Study of World Politics, The Mellon Foundation, The Graduate School of the University of Wisconsin-Madison, McGill University, the Social Sciences and Humanities Research Council of Canada and the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche. Any errors of interpretation are solely the responsibility of the author.

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Abstract

This paper explores deforestation and asset accumulation among small scale farmers in tropical forests. In a two-state variable control model, forest clearing is an investment in land holdings and the productivity of forest clearing is a function of non-land assets like chainsaws. Comparative static analyses demonstrate that: (1) the addition of non-land asset accumulation options may or may not change the impacts of policy measures on deforestation, depending on labor market conditions; and (2) discount rate decreases (through for example credit subsidies) offer the prospect of a win-win scenario – forest protection and asset accumulation – only when an active labor market exits.

JEL classification: Q12; O13.

Key words: Deforestation; Accumulation.

1. Introduction

Deforestation is one of the major environmental issues in tropical forests. The majority of forest dwellers are small scale farmers who take part in traditional shifting cultivation (Myers, 1992). These farmers are usually very poor by any standard. With limited non-agricultural opportunities and non-land assets, farmers necessarily rely on rich environmental assets, common property forests, for their livelihoods. This poverty-environment link is a crucial ingredient to characterize economic-ecological landscapes in tropical forests.

In a sustainable development scheme, researchers and practitioners often explore a possibility of a win-win scenario – economic development and environmental conservation. The win-win scenario in the context of shifting cultivation implies the combination of poverty alleviation and forest protection. Poverty alleviation usually consists of an increase of income and any associated asset accumulation. A special feature of agricultural expansion by small scale farmers is that their primary force of forest clearing is often an investment in land holdings (Angelsen, 1999), which in turn generally comprise the majority share of their asset portfolios. As far as land accumulation is a favorable investment strategy for these farmers with limited opportunities for non-land asset investments, poverty alleviation necessarily involves further deforestation. Thus, in this context, a win-win scenario is likely to require a portfolio shift among these farmers from land to non-land assets, as they pursue further wealth accumulation. As the Boserupian hypothesis suggests, increasing scarcity of forest land may facilitate intensified land use among farmers (Boserup, 1965). This paper does not consider this type of intensification strategy; rather, it focuses on frontier

areas with relatively abundant forests like Amazonia, where the scale of deforestation is much larger than other areas with relatively scarce forests.

In tropical forests farmers hold a variety of non-land assets, including capital for agricultural production like chainsaws, capital for resource extraction like shotgun and fishing nets, livestock, consumer durables, and shops (Takasaki, et al., forthcoming). Obviously, chainsaw holdings are directly related to deforestation since they significantly increase the productivity of forest clearing (Reardon and Vosti, 1995). Indeed, a variety of non-land assets other than chainsaws can indirectly affect the productivity of forest clearing through labor market or reciprocal communal labor schemes. For example, renting or sharing of extractive capital may allow farmers to build social capital which increases the productivity of hired or communal labor for clearing forests. Similar effects can be observed among other types of assets. With no or limited credit or insurance markets, relatively rich farmers with higher asset holdings are likely to offer informal credits and/or insurance substitutes to poor farmers within a patron-client relationship, allowing the rich to accumulate social capital which positively affects the productivity of their forest clearing efforts. Thus, in general, it is expected that non-land asset accumulation will directly or indirectly increase the productivity of forest clearing. However, this does not necessarily mean that non-land asset accumulation results in further deforestation since forest clearing also depends on farmers' labor allocation. Based on economic modeling, this paper explores the possibility of a win-win scenario among small scale farmers in tropical forests – forest protection and asset accumulation.

Economists have modeled deforestation both as a social problem of optimal forest stock use (e.g., Barbier and Burgess, 1997, Ehui, et al., 1990) and as a private problem of

forest clearing for land accumulation (see Kaimowitz and Angelsen, 1998 for a review).[1] This paper takes the latter approach, but the model developed here can be easily extended to the social problem as shown by Takasaki (2000).[2] Here, we develop a two-state variable control model which integrates land and non-land asset accumulation options. Forest clearing is modeled as an investment in land holdings. The productivity of forest clearing becomes a function of non-land asset holdings. As far as the author knows, no previous work explicitly links non-land asset accumulation to deforestation in a dynamic framework. When non-land asset holdings are fixed and thus clearing productivity is fixed, this integrated model becomes a constrained model which is comparable to the deforestation models in the literature using one state variable.

One common policy approach to environmental problems is to shape farmers' investment decisions and thus deforestation outcomes by altering the economic conditions or incentives they face. The unique modeling approach of this paper allows us to explore two important questions associated with this kind of policy approach. First, does the presence of interlinked asset accumulation options change the predicted effect of policies? Second, are there policies which can mitigate deforestation while facilitating asset accumulation?

The organization of this paper follows. Section 2 develops a portfolio model of integrated land and non-land asset accumulation decisions and characterizes a steady state equilibrium. Section 3 conducts comparative static analyses to evaluate policy impacts on these two types of accumulation. Section 4 concludes.

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[1] Private deforestation models include Anderson and Hill (1990), Mendelsohn (1994), Bluffstone (1995), DeShazo and DeShazo (1995), Angelsen (1999), and Barrett (1999), all of which are static. Mueller (1997) develops a dynamic private deforestation model.

2. Model

Consider agricultural expansion by a small scale farmer in open-access tropical forests, the type which can be normally seen at the forest edge (e.g., Angelsen, 1999). Given that the farmer allocates labor l to forest clearing, the rate of deforestation is given by $G(Z)l$, where G is a forest area cleared per unit of labor which is a function of non-land assets, Z, such as chainsaws, such that $G(0) = 0$, $G' > 0$, and $G'' < 0$.[3] Cleared land is privately used with tenure or usufruct. However, tenure security is not perfect due to squatting which is common at the forest frontier (Mendelsohn, 1994, Mueller, 1997). It is assumed that due to insecure tenure the farmer loses a fixed proportion of land, β ($0 \leq \beta < 1$).[4] The evolution of farmer's total land holdings, A, follows:

$$\dot{A} = G(Z)l - \beta A, \qquad 0 \leq A(0) = A_0 . \tag{1}$$

This is a simple law of motion of capital accumulation with depreciation. We assume relatively abundant forest stock such that forest is not exhausted. The case where forest is exhausted is discussed by Takasaki (2000).

The farmer produces one crop using a concave production function $F(A, m)$, where m is labor allocated to farming, $F_1, F_2, F_{12} > 0$, and $F_{11}, F_{22} < 0$.[5] The farmer accumulates non-land assets by adjusting his consumption, c. Non-land assets can earn a

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[2] By developing comparable social and private deforestation models, Takasaki (2000) shows that policy impacts are common between these two approaches except for those affecting discount rates.

[3] While it may be more realistic to assume a concave clearing function with respect to clearing labor, this extension will not change our results. The forest clearing productivity may decrease as the remaining forest stock diminishes and thus as the land holdings increase. Such a extension will not change our results.

[4] Tenure insecurity can be also modeled by adjusting a discount rate (Angelsen, 1994, Mendelsohn, 1994).

[5] Non-land assets may include farming equipment which affects farming productivity. To focus on assets' impacts on forest clearing, we ignore this factor. In tropical forests, forest clearing is much more labor intensive than farming. Thus, farmers tend to invest in chainsaws first because of its higher marginal return than other farming equipment.

fixed return, k (≥ 0). We assume that $r > k$ to guarantee stability (see Equation 13). Assuming a perfect labor market, the evolution of non-land asset holdings follow:

$$\dot{Z} = pF(A,m) + w(L - l - m) + kZ - c, \qquad 0 \leq Z(0) = Z_0 \,, \tag{2}$$

where p is output price, w is wage rate, and L is labor endowment, all of which are fixed and exogenously given.

The problem facing the farmer would be to choose optimal consumption, forest clearing labor, and farming labor paths. Using a concave utility function such that $U' > 0$ and $U'' < 0$, the farmer's problem can be written as:

$$\max_{c,l,m} \int_0^\infty U(c)e^{-rt}dt \tag{A}$$

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

$$0 \leq Z, \tag{3}$$

where r is a discount rate. The non-negativity constraint on Z implies that there is no borrowing under credit constraints. The model (A) combines land and non-land asset accumulations. If we assume a fixed Z, the model (A) becomes a one-state variable deforestation model which is common in the literature (see Kaimowitz and Angelsen, 1998 for a review). A complete analysis of this constrained model is given in Appendix A. While the model (A) assumes an active labor market, this may not be true at some forest margins. With absent labor markets, forest clearing is commonly done using reciprocal communal labor (Chibnik and de Jong, 1989). The broad indirect impacts of non-land asset holdings on forest clearing discussed above still hold in this communal labor scheme. For simplicity, it is assumed that the household works for others just as much as the help the household receives (i.e., balanced reciprocity). Then, forest clearing

labor l can include all communal and domestic labor allocated to forest clearing. The integrated model (A) and its constrained version in Appendix A (model B) can be extended to the models with no labor markets by simply assuming that $m = L - l$. Complete analyses of the unconstrained and constrained models with no labor markets are given in Appendixes B and C, respectively.

Because of the constraints on the state variables, the current-value Hamiltonian of the model (A) is given by:

$$H = U(c) + m\left[G(Z)l - \beta A\right] + \lambda\left[pF(A,m) + w(L - l - m) + kZ - c\right] + \eta Z\,, \qquad (4)$$

where m and λ are the current-value costate variables for land holdings and non-land assets, respectively, and η is a multiplier function with Equation (6). Assuming an interior solution, the first order necessary conditions are (1) and (2) plus the following:

$$\partial H/\partial c = U' - \lambda = 0\,, \qquad (5)$$

$$\partial H/\partial l = Gm - w\lambda = 0\,, \qquad (6)$$

$$\partial H/\partial m = \left(pF_2 - w\right)\lambda = 0\,, \qquad (7)$$

$$\dot{m} = rm - \partial H/\partial A = \left(r + \beta\right)m - pF_1\lambda\,, \qquad (8)$$

$$\dot{\lambda} = r\lambda - \partial H/\partial x = (r - k)\lambda - G'lm - \eta\,, \qquad (9)$$

$$\eta \geq 0, \qquad \eta Z = 0\,. \qquad (10)$$

Equation (5) indicates that $\lambda > 0$. Then, (6) implies that $m > 0$, and (7) becomes:

$$pF_2 - w = 0\,. \qquad (7')$$

Equation (5) is the standard condition that the marginal utility of consumption equals the shadow value of foregone assets, λ. Equation (6) indicates that labor is allocated to forest clearing up to the point where the marginal benefit equals the marginal cost in terms of

non-land asset depletion, $w\boldsymbol{l}$. Equation (7') is the standard condition that the farmer equates the marginal product of farming labor to wage. Equation (8) indicates that the shadow value of land, $\boldsymbol{m}$, must grow at the discount rate plus the land depreciation rate less the marginal product of land holdings in terms of asset accumulation. Similarly, Equation (9) indicates that the shadow value of assets must grow at the discount rate minus the rate of return of non-land assets less the marginal benefit of asset holdings in terms of land accumulation. Because of the concavity of U, F and G the necessary conditions are also sufficient for optimality, since then the Hamiltonian is jointly concave in the state and control variables.

Consider the steady-state equilibrium for the problem (A). From the first order conditions, the long run steady state will occur when $\dot{A} = \dot{Z} = \dot{m} = \dot{\boldsymbol{l}} = 0$, and the system of equations depicting this equilibrium is given by:

$$0 = G\left(Z^*\right)l^* - \boldsymbol{b}A^*, \qquad \dot{A} = 0, \tag{11}$$

$$0 = pF\left(A^*, m^*\right) + w\left(L - l^* - m^*\right) + kZ^* - c^*, \qquad \dot{Z} = 0, \tag{12}$$

$$0 = \left(r + \boldsymbol{b}\right)m^* - pF_1\left(A^*, m^*\right)\boldsymbol{l}^*, \qquad \dot{m} = 0, \tag{13}$$

$$0 = \left(r - k\right)\boldsymbol{l}^* - G'\left(Z^*\right)l^* m^* - \boldsymbol{h}^*, \qquad \dot{\boldsymbol{l}} = 0. \tag{14}$$

We assume that $A^* > 0$ since otherwise deforestation would not be relevant at the steady state. Then, Equation (11) indicates $Z^* > 0$, and thus $\boldsymbol{h}^* = 0$ from (10). Thus, the farmer holds positive land and non-land assets at the steady state. Equations (6), (11) and (14) yield:

$$A^* = \frac{\left(r - k\right)G^2\left(Z^*\right)}{\boldsymbol{b}wG'\left(Z^*\right)}, \tag{15}$$

and thus,

$$A' = dA^* / dZ^* = \frac{r-k}{\boldsymbol{b}w} G\left(2 - \frac{G''}{G'^2} G\right) > 0 . \tag{16}$$

Equations (6), (7') and (13) yield:

$$0 = (r + \boldsymbol{b}) \frac{w}{p} - G(Z^*) F_1\left(A^*(Z^*), m^*\left(A^*(Z^*)\right)\right) \equiv Q(Z^*) . \tag{17}$$

Once the steady state value of Z^* is known, A^* is given recursively by (15). Once the steady state values for Z^* and A^* are known, l^* and m^*, respectively, are given recursively by (11) and (7'), and thus c^* is given recursively by (12). Thus, the above long-run equilibrium can be fully represented by (17). Using (7'), (17) yields:

$$Q' = \frac{dQ}{dZ} = -G' F_1 - \frac{r-k}{\boldsymbol{b}w} G^2 \left(2 - \frac{G''}{G'^2} G\right) \frac{F_{11}F_{22} - F_{12}^2}{F_{22}} . \tag{18}$$

In general, the sign of Q' is uncertain, while for $r = +\infty$ or $\boldsymbol{b} \gg 0$, $Q' > 0$. We assume that r is large and/or $\boldsymbol{b}$ is small enough to make Q' positive. This assumption is reasonable for poor small scale farmers who use higher discount rates. When $Q' > 0$, (17) gives a unique equilibrium.

3. Policy analysis

We evaluate long-run policy impacts on land accumulation (and thus deforestation) and non-land asset accumulation. Four different policies considered are: (1) discount rate decreases through credit subsidies ($dr < 0$); (2) tenure security improvement through land tenure programs ($d\boldsymbol{b} < 0$); (3) output price increases through price subsidies ($dp > 0$); and (4) wage increases through non-agricultural employment

promotion ($dw > 0$).[6] Our unique modeling approach allows us to answer the following questions: (1) Does the addition of non-land asset accumulation options change the impacts of policy measures on deforestation?; and (2) Which policies give rise to a win-win scenario – forest protection and asset expansion? Table 1 reports the comparative static results for both the unconstrained model (A) and constrained model (B) (which is developed in Appendix A) with a labor market. In Table 1, Q', A', and $Q^c{}'$ are defined by Equations (18), (16), and (A7), respectively, and they are all positive. Table 2 summarizes the policy impacts based on these results. Table 2 also summarizes the policy impacts based on the unconstrained model (A') and constrained model (B') with no labor markets analyzed in Appendix B and C, respectively. These results are discussed later.

Without the option of non-land asset accumulation, lower discount rates, improved tenure, and higher output prices will increase land accumulation and thus deforestation, while higher wages will decrease deforestation. All of these results are consistent with the theoretical and empirical findings in the literature (see Angelsen, 1999, also see Kaimowitz and Angelsen, 1998 for a review). With lower discount rates, the farmer makes more investment in land holdings. This negative impact on deforestation of lower discount rates in an open-access setting is distinct from the opposite impact observed in a planning model (Takasaki, 2000). With improved tenure, land becomes a securer investment option for the farmer, resulting in more forest clearing. With higher prices, the farmer expands agricultural production by clearing

[6] Discount rate decreases and price increases are welfare enhancing in the sense that policy impacts on the maximized value of the total net benefits are positive as shown by Takasaki (2000) using comparative dynamic framework. Wage increases are also welfare enhancing with an assumption that farmers work partially as a wage labor. Similarly, it can be shown that tenure improvement is also welfare enhancing.

more forests and allocating more labor to farming. The impact of higher wages is totally opposite; with higher wages, the farmer lowers agricultural production by clearing less forests and allocating less labor to farming.

Now, let us consider policy impacts with the addition of the non-land asset accumulation option. Lower discount rates will increase non-land asset holdings while the impact on deforestation becomes ambiguous. With lower discount rates, the farmer makes more investment in non-land asset holdings. The ambiguity of the deforestation impacts can become clear when we look at Equations (15) and (16). Positive impacts of increased Z^* on A^* may be offset by negative impacts of decreased r itself. Distinct from the constrained problem, the asset accumulation option allows the farmer to adjust land holdings in either direction. If the farmer decreases land holdings, a win-win scenario – forest protection and non-land accumulation – is achieved. In this case, forest clearing labor and farming labor are also decreased (see Equations 11 and 7').

Improved tenure and higher prices will increase both land and non-land asset holdings. Thus, adding a non-land asset accumulation option does not change the impacts of these variables on deforestation. The improved security of land holdings facilitates investment in non-land asset holdings. That is, these two assets complement each other. With higher prices, the farmer earns more income and thus accumulates assets, thereby increasing the productivity of forest clearing and furthering deforestation. What differs from the constrained problem without the non-land asset accumulation option is the uncertainty of whether the farmer allocates more labor to forest clearing (see Equation 11). That is, increased deforestation may be caused by the increased productivity of forest clearing with lower labor input. Meanwhile, with more land

holdings, farming labor is unambiguously increased as in the constrained model (see Equation 7'). As a result, tenure improvement and price increases always promote both deforestation and non-land asset accumulation. For example, Coomes (1996) describes how agricultural credits, price subsidies, and land titling facilitated both deforestation and non-land asset accumulation (like chainsaws and buffalo) among peasants in the Peruvian Amazon. In this case, a win-win scenario was not realized through credit programs.

Higher wages will decrease both land and non-land asset holdings. Thus, adding a non-land asset accumulation option does not change the impacts of this variable on deforestation. This unambiguous negative impact of higher wages on non-land asset holdings may seem surprising. It would be natural to suppose that with higher wages a farmer who works partially as a wage labor earns more income and invests in more non-land assets. The reason why the impacts of wage increases are unambiguously opposite to those of tenure improvement and price increases become clear when we look at Equation (17). What differs from the constrained problem is the uncertainty of whether the farmer allocates less labor to forest clearing (see Equation 11). That is, decreased deforestation may be caused by the decreased productivity of forest clearing with higher labor input. Meanwhile, with less land holdings, farming labor is unambiguously decreased as in the constrained model (see Equation 7'). As a result, wage increases promote forest protection not non-land asset accumulation.

Compared to these results based on the models with a labor market, policy impacts based on the models with no labor markets become different in three different ways. First, discount rate decreases will unambiguously increase deforestation. This result suggests that wage labor opportunities give the farmer flexibility in his portfolio

management, making a win-win scenario possible. Second, tenure improvement has ambiguous policy impacts in the unconstrained model, while tenure improvement cannot decrease deforestation and increase non-land asset holdings simultaneously (that is, a win-win scenario is not possible). This result suggests that wage labor opportunities support the complementary relationship of land and non-land asset accumulations. Third, price has no impacts on deforestation in the constrained model. This is an artifact of the model (B') which has no other price or cost that can be compared to output price.[7] Adding non-land asset accumulation (model A') essentially introduces an investment tradeoff and has the effect of adding another. All other results are the same as those with a labor market.

4. Conclusion

This paper developed a two-state variable control model of small-scale farmer's land and non-land asset accumulation decisions in open-access tropical forests. One-state variable deforestation models in the literature are essentially a constrained model of this portfolio model with the assumption of fixed non-land assets. A crucial feature of this portfolio model is that non-land asset holdings increase the productivity of forest clearing. The paper examined the impacts of four policies on land holdings (and thus deforestation) and non-land asset holdings at a long-run steady state. It was shown that: (1) discount rate decreases will increase non-land asset holdings and the impacts on deforestation are ambiguous with labor markets, while discount rate decreases will increase both deforestation and non-land asset holdings without labor markets; (2) tenure improvement will increase both deforestation and non-land asset holdings with a labor

[7] Barrett (1991) reports a similar result in the context of land degradation; output price has no impacts on soil conservation if there is no non-soil input like fertilizer.

market, while the impacts are ambiguous with no labor markets; (3) price increases will increase both deforestation and non-land asset holdings regardless of labor market conditions; and (4) wage increases will decrease both deforestation and non-land asset holdings. Thus, whether the addition of non-land asset accumulation options changes the deforestation impacts of policy measures depends on labor conditions.

It was shown that discount rate decreases offer the prospect of a win-win scenario – forest protection and non-land asset accumulation – only with a labor market. With lower discount rates, the farmer may shift his portfolio from land to non-land assets and allocate less labor to forest clearing and farming by using wage labor opportunities. If we use a maximized value of total net benefits as a welfare measure as Takasaki (2000), our models suggest that wage increases attain both forest protection and poverty alleviation among farmers who work partially as a wage labor. Our new finding is that when we directly consider non-land asset accumulation as a measure of poverty alleviation, wage increases cannot attain a win-win possibility.

For farmers' portfolio to be shifted from land to non-land assets in a sustainable development scheme, the link of non-land assets to forest clearing among small scale farmers may need to be weakened. As far as chainsaws are concerned, this seems a daunting task unless any strict regulations are enforced. As discussed above, imperfect factor markets can make this link persistent for a variety of non-land assets. Thus, policy makers commonly face a fundamental tradeoff between forest protection and asset accumulation.

Table 1. Comparative statics

	With non-land asset accumulation		No non-land asset accumulation
r	$dZ^*/dr = -Q'^{-1}\, w/p < 0$	$dA^*/dr = -A'\,Q'^{-1}\, w/p + \dfrac{G^2}{\boldsymbol{b}wG'}$	$dA^*/dr = -Q^{c\,\prime -1}\, w/p < 0$
$\boldsymbol{b}$	$dZ^*/d\boldsymbol{b} = -Q'^{-1}\, w/p < 0$	$dA^*/d\boldsymbol{b} = -A'\,Q'^{-1}\, w/p - \dfrac{(r-k)G^2}{\boldsymbol{b}^2 wG'} < 0$	$dA^*/d\boldsymbol{b} = -Q^{c\,\prime -1}\, w/p < 0$
p	$dZ^*/dp = Q'^{-1}(r+\boldsymbol{b})w/p^2 > 0$	$dA^*/dp = A'\,Q'^{-1}(r+\boldsymbol{b})w/p^2 > 0$	$dA^*/dp = Q^{c\,\prime -1}(r+\boldsymbol{b} - GF_{12}/F_{22})w/p^2 > 0$
w	$dZ^*/dw = -Q'^{-1}(r+\boldsymbol{b})/p < 0$	$dA^*/dw = -A'\,Q'^{-1}(r+\boldsymbol{b})/p - \dfrac{(r-k)G^2}{\boldsymbol{b}w^2 G'} < 0$	$dA^*/dw = -Q^{c\,\prime -1}(r+\boldsymbol{b} - GF_{12}/F_{22})/p < 0$

Table 2. Policy impacts

↓: Decrease ↑: Increase 0: No change ?: Uncertain	**With labor market**			**No labor market**		
	With non-land asset accumulation (*Model A*)		**No non-land asset accumulation (*Model B*)**	**With non-land asset accumulation (*Model A'*)**		**No non-land asset accumulation (*Model B'*)**
	Non-land asset holdings (dZ^*)	Land holdings (Deforestation) (dA^*)		Non-land asset holdings (dZ^*)	Land holdings (Deforestation) (dA^*)	
Discount rate decreases ($dr<0$)	↑	?	↑	↑	↑	↑
Tenure security improvement ($d\boldsymbol{b}<0$)	↑	↑	↑	?[1)]	?[1)]	↑
Price increases ($dp>0$)	↑	↑	↑	↑	↑	0
Wage increases ($dw>0$)	↓	↓	↓	n.a.	n.a.	n.a.

[1)] Tenure improvement cannot increase non-land assets and decrease deforestation simultaneously.

Appendix A

The farmer's problem with no non-land asset accumulation options and with a labor market is given by:

$$\max_{l,m} \int_0^\infty U(c)e^{-rt}dt \tag{B}$$

s.t., (1), (2) with $\dot{Z} = 0$.

The current-value Hamiltonian of the problem (B) is:

$$H = U\left(pF(A,m) + w(L - l - m) + kZ\right) + m\left[G(Z)l - \beta A\right]. \tag{A1}$$

The first order necessary conditions are (1), (7'), plus the following:

$$\partial H/\partial l = Gm - wU' = 0, \tag{A2}$$

$$\dot{m} = rm - \partial H/\partial A = (r + \beta)m - pF_1U'. \tag{A3}$$

From the first order conditions, the system of equations depicting a steady state equilibrium is given by:

$$0 = Gl^* - \beta A^*, \qquad \dot{A} = 0, \tag{A4}$$

$$0 = (r + \beta)m^* - pF_1\left(A^*, m^*\right)U', \qquad \dot{m} = 0, \tag{A5}$$

Equations (A2), (A3), and (7') yields:

$$0 = (r + \beta)\frac{w}{p} - GF_1\left(A^*, m^*\left(A^*\right)\right) \equiv Q^c\left(A^*\right), \tag{A6}$$

which is equivalent to (17) in the unconstrained model with a fixed Z. Once the steady state values for A^* are known, l^* and m^*, respectively, are given recursively by (A4) and (7'). Using (7'), (A6) yields:

$$\partial Q^c/\partial A = Q^{c\prime} = -G\frac{F_{11}F_{22} - F_{12}^2}{F_{22}} > 0. \tag{A7}$$

Appendix B

The farmer's problem with non-land asset accumulation options and with no labor markets is given by:

$$\max_{c,l} \int_0^\infty U(c)e^{-rt}dt \qquad \text{(A')}$$

s.t., (1), (2) with $m = L - l$, and (3).

The current-value Hamiltonian of the problem (A') is:

$$H = U(c) + m\left[G(Z)l - bA\right] + l\left[pF(A, L-l) + kZ - c\right] + hZ\,. \qquad \text{(B1)}$$

The first order necessary conditions are (1), (2), (5), (8), (9) with $m = L - l$, plus:

$$\P L/\P l = Gm - pF_2\, l = 0\,, \qquad \text{(B2)}$$

From the first order conditions, the system of equations depicting a steady state equilibrium is given by (11)-(14) with $m = L - l$. We assume that $A^* > 0$. Equations (B2), (11) and (14) yield:

$$0 = pbG'\left(Z^*\right)A^* F_2\left(A^*, L - \frac{bA^*}{G\left(Z^*\right)}\right) - (r-k)G^2\left(Z^*\right) \equiv R(Z, A)\,. \qquad \text{(B3)}$$

Equations (B2), (11) and (13) yield:

$$0 = (r+b)F_2\left(A^*, L - \frac{bA^*}{G\left(Z^*\right)}\right) - G\left(Z^*\right)F_1\left(A^*, L - \frac{bA^*}{G\left(Z^*\right)}\right) \equiv Q(Z, A)\,. \qquad \text{(B4)}$$

Thus, the long-run equilibrium can be fully represented graphically in *Z-A* space as an intersection of the $Q(Z, A) = 0$ and $R(Z, A) = 0$ loci. The evaluation of (B3) and (B4) yields:

$$\P Q/\P Z = \left((r+b)F_{22} - GF_{12}\right)\frac{bA^*}{G^2} - G'F_1 \equiv Q_1 < 0\,,$$

$$\P Q/\P A = (r+\boldsymbol{b})\left(F_{12} - F_{22}\frac{\boldsymbol{b}}{G}\right) - G\left(F_{11} - F_{12}\frac{\boldsymbol{b}}{G}\right) \equiv Q_2 > 0\,,$$

$$\P R/\P Z = p\boldsymbol{b}A^*\left(G''F_2 + G'F_{22}\frac{\boldsymbol{b}A^*}{G^2}\right) - 2(r-k)GG' \equiv R_1 < 0\,,$$

$$\P R/\P A = p\boldsymbol{b}G'\left(F_2 + A^*F_{12} - F_{22}\frac{\boldsymbol{b}}{G}\right) \equiv R_2 > 0\,.$$

That is, both *Q(Z, A) = 0* and *R(Z, A) = 0* are upward sloping. It can be shown that for *r* = +¥ or $\boldsymbol{b} \gg 0$, the slope of *R(Z, A) = 0* becomes zero while the slope of *Q(Z, A) = 0* is positive. As in the model (A), we assume that *r* is large and/or $\boldsymbol{b}$ is small so that *Q(Z, A) = 0* is always steeper than *R(Z, A) = 0*. With this assumption, Equations (B3) and (B4) give a unique equilibrium.

Equations (B3) and (B4) give the following comparative static results.

$$dA/dr\big|_{Q=0,dZ=0} = -Q_2^{-1}F_2 < 0\,,\ dZ/dr\big|_{R=0,dA=0} = R_1^{-1}G^2 < 0$$

$$dA/d\boldsymbol{b}\big|_{Q=0,dZ=0} = -Q_2^{-1}\left(F_2 - (r+\boldsymbol{b})F_{22}A^*G^{-1}\right) < 0\,,$$

$$dZ/d\boldsymbol{b}\big|_{R=0,dA=0} = -R_1^{-1}pA^*\left(G'F_2 - \boldsymbol{b}GF_{22}A^*\right) > 0\,,$$

$$dA/dp\big|_{Q=0,dZ=0} = 0\,,\ dZ/dp\big|_{R=0,dA=0} = -R_1^{-1}\boldsymbol{b}A^*G'F_2 > 0\,.$$

By applying these results to the *Q(Z, A) = 0* and *R(Z, A) = 0* loci in *Z-A* space, it can be shown that: $dZ^*/dr < 0$, $dA^*/dr < 0$, $dZ^*/dp > 0$, $dA^*/dp > 0$, and the signs of $dZ^*/d\boldsymbol{b}$ and $dA^*/d\boldsymbol{b}$ are ambiguous while $dZ^*/d\boldsymbol{b} < 0$ and $dA^*/d\boldsymbol{b} > 0$ do not occur simultaneously.

Appendix C

The farmer's problem with no non-land asset accumulation and with no labor markets is given by:

$$\max_{l} \int_{0}^{\infty} U(c)e^{-rt}dt \qquad \text{(B')}$$

s.t., (1), (2) with $\dot{Z} = 0$ and $m = L - l$.

The current-value Hamiltonian of the problem (B') is:

$$H = U\left(pF(A, L-l) + kZ\right) + m\left[G(Z)l - bA\right]. \qquad \text{(C1)}$$

Assuming an interior solution, the first order necessary conditions are (1), (A3) plus:

$$\P H / \P l = Gm - U'\, pF_2 = 0. \qquad \text{(C2)}$$

From the first order conditions, the system of equations depicting a steady state equilibrium is given by (A4) and (A5) with $m = L - l$. Equations (C2), (A4), and (A5) yields:

$$0 = (r + b)F_2\left(A^*, L - \frac{bA^*}{G}\right) - GF_1\left(A^*, L - \frac{bA^*}{G}\right) \equiv Q^{cn}(A). \qquad \text{(C3)}$$

which is equivalent to (B4) in the unconstrained model with a fixed Z, and thus $dQ^{cn}/dA = Q^{cn\prime} > 0$. It is analogous to show that $dA^*/dr < 0$, $dA^*/dp = 0$, and $dZ^*/db < 0$.

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