June 1993
draft 4

Secure Tenure and the Optimal Level of Deforestation: Theory, Empirical Observations, and Policy Implications

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The exploitation of global, and especially tropical, forests threatens the earth's long-term climate patterns, its reserve of genetic resources, and the more immediate life support of dependent local human communities. Deforestation is a recent concern, by and large, that now occurs at a rate exceeding three percent in some developing countries and at a global rate of almost one percent. It annually disturbs global land cover over an area equal to the size of Great Britain. The widespread public concern for tropical deforestation focuses on global values like carbon sequestration and biodiversity, and on commercial forest exploitation. Yet forest conversion for agricultural use, both for permanent crop and livestock production and for shifting cultivation, is generally considered the primary source of deforestation.

The object of this paper is to assess the optimal rate of deforestation when the forest serves domestic and commercial forest uses and also provides land for agricultural conversion. We anticipate a difference between socially and privately optimal rates of forest conversion because agricultural values are well-represented in markets and also in the implicit utility functions of subsistence households, while a few of the many values originating in the forests (fuelwood, forage, fodder, fruits and nuts, latex, carbon sequestration, and biodiversity, as well as timber) are less well-represented, and also because secure property rights are more difficult to establish for forests than for agricultural land uses. Indeed, many observations of overexploited open access forest resources support this contention.

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Our paper begins with the common explanation of the optimal forest conversion problem, an explanation that can be made explicit with a variation of Howe's (1979) control model explaining natural resource scarcity. In the simple case, the natural forest resource stock supports two outputs, marketed agricultural products from converted forest land and non-marketed environmental services from the forest itself. The Hamiltonian for this model explains optimal forest conversion to agriculture. Nevertheless, this model is incomplete because it overlooks the costs of forest land conversion and ignores consumer and investor responses to the increasing scarcity of forest-based goods and environmental services. The latter are particularly important. In two most diverse cases among many, we observe US lumber prices rising at 1.8 percent annually for over a century (Barnett and Morse 196) and fuelwood prices in Malawi rising at greater than five percent annually for the last decade (Hyde and Seve 1993). In both the US and Malawi, relative agricultural prices are constant or declining and we observe that shifts in land use reflect investor responses to relative scarcity in both the agricultural and forestry sectors.

We can extend this common model by adding new information about the expanding establishment of property rights to the forest as the physical forest stock declines and the goods and services originating in the forest become dearer. This leads to a new formulation of the Hamiltonian and to new definitions of the social and private optima. It improves the reliability of our anticipations about what it takes for secure property rights to the forest and its environmental services to arise naturally and how the new geographic configuration of land uses differs from the old. In fact, forest-based goods and environmental services will eventually compete well with some agricultural land uses and the divergence between social and private optima will eventually recede (but not disappear). Empirical evidence from various prior economic analyses for both developed and developing countries support our new conclusions regarding a) forest conversion to agriculture and b) the importance and difficulty of securing property rights to the forest.

This revised theory and these empirical results suggest a revised forest policy concentration on specific features of forest land tenure, environmental investments in forests lands and forest-based resources, and agricultural policies impacting the agriculture-forest land use margin. The very important remaining questions associated with deforestation have to do with three implicit results of our analysis: the increased competition for the scarce inputs of very poor people, the level of deterioration of the natural environment that occurs before secure property rights arise naturally, and the new mix of environmental services (and remaining environmental problems).

The Basic Model

Expanding populations and world food demands, along with government policies encouraging agriculture, generate increasing commercial demands for agricultural land. They also push populations of shifting cultivators further into the forested interior where soils are often thinner and the shifting cultivators must either move and clear the forest more frequently or manage an increasingly degraded environment. Except for the difficulty of clearing the trees, little deters these agricultural expansions because the adjacent forest is either unclaimed public domain, the legally unrecognized possession of some indigenous human population, or the relatively unmanaged and unenforced responsibility of a state agency such as the Forest Ministry.

More formally, and closely following Howe (1979), agricultural production Q at time t can be expressed as

$$Q(t) = \alpha\,[L(t),S(t),t] \tag{1}$$

where L is a composite labor-capital input to agricultural production and S is the stock of forest land which is converted for use in agricultural production.[2]

The combination of market and subsistence household demands for agricultural production is

$$p(t) = D[Q(t),t] \tag{2}$$

where p is the farmgate price of agricultural products set in an aggregate market.

If E[S(t)] is the cumulative value of all (non-marketed) goods and environmental services provided by the forest at time t, and w is the unit opportunity cost of the composite labor-capital input for agriculture, then the aggregate social welfare W_1 obtained from the stock of forest land is

$$W_1[L(t)] = \int_0^{Q(t)} D[\eta(t),t]d\eta - wL + E[S(t)] \tag{3}$$

where η is a variable of integration related to agricultural output at each moment in time.[3]

The optimization problem for forest land use becomes:

$$\begin{aligned} \max_{L(t)} \quad & \int_0^{\infty} \{ \int_0^{Q(t)} D[\eta(t),t]d\eta - wL + E[S(t)] \} e^{-rt} dt \\ s.t. \quad & S(t) = S(0) - a\int_0^{t} Q(t)\,dt \\ & S(t) \geq 0 \qquad \forall \; t \end{aligned} \tag{4}$$

where r is the social discount rate, and a is a positive constant reflecting the level of agricultural production from converted forest land. The rate of change in the stock of forest land is

$$\dot{S}(t) = -aQ(t) \tag{5}$$

The current value Hamiltonian depicting social welfare at time t is

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[2] The usual underlying assumptions prevail: $\partial Q/\partial t > 0$, $\partial^2 Q/\partial t^2 < 0$; $\partial Q/\partial S > 0$, $\partial^2 Q/\partial S^2 < 0$; and $\partial Q/\partial L > 0$, $\partial^2 Q/\partial L^2 < 0$.

[3] $\partial E/\partial S > 0$.

$$H = \int_{0}^{Q(t)} D[\eta(t),t]\,d\eta - wL(t) + E[S(t)] - a\mu_1(t)Q(t) \qquad (6)$$

The current value Lagrangian multiplier $\mu_1(t)=\lambda e^{rt}$ corresponds to constraint eq. (5). The first three terms in eq. (6) are the rates of agricultural net benefits and benefits from environmental services, both originating from the initial stock of forest land. The final term is the future sacrifice imposed by current deforestation for conversion to agricultural production.

Differentiating the Hamiltonian with respect to L(t), and setting the derivative equal to zero, provides the first basic condition on prices, costs, and rents:

$$p(t) = \frac{w}{\partial Q(t)/\partial L(t)} - \frac{dE}{dS(t)}\frac{dS(t)}{dQ(t)} + a\mu_1(t) \qquad (7)$$

Or, the value of an additional unit of agricultural production in any time period equals the marginal unit cost of agricultural production plus the loss in forgone forest-based goods and environmental services plus the user cost for forest stocks depleted in this time period. This condition explains the socially optimal rate for converting to agricultural production and, therefore, the optimal level of periodic deforestation.

Differentiating such that $\dot{\mu}_1 = r\mu_1 - \partial H/\partial S$ provides the second basic condition:

$$r\mu_1(t) = \dot{\mu}_1(t) + [p(t) - a\mu_1(t)]\frac{\partial Q(t)}{\partial S(t)} + \frac{dE}{dS(t)} \qquad (8)$$

Or, the return from maintaining a unit of forest stock equals the increase in its own value plus the net loss in agricultural production and the value of the increment in forest-based goods and environmental services. This second condition identifies the socially optimal stock of forest land.

A policy problem arises because the social optima described by the two basic conditions depart from the private optima. Private agricultural producers, whether active in the market economy or subsistence farmers, perceive the forest as an open access resource and consider forest-based goods and environmental services as free goods. They also perceive that the forest is sufficiently plentiful that they can overlook all stock effects. Therefore, the terms in E and $a\mu_1$ drop out of eqs. (7) and (8). The privately optimal rate of agricultural production is greater and the privately optimal forest stock is smaller than the socially optimal levels. In sum, private incentives create a socially excessive level of deforestation. This reasoning focuses the general policy discussion of deforestation on socially optimal prices and on extracting public rents for consumption of the residual forest resource, and also on regulating the (open access) forest commons (e.g., Repetto and Gillis 198 , Sharma 1993, Vincent 1991, Hyde and Sedjo 1992).

A More Complete Model

This model and the policy discussions arising from it overlook several costs of forest land conversion, as well as local responses to increasing scarcity in forest-based goods and environmental services. Table 1 summarizes our additional information about prices and costs, but it begins with a refinement in our definition of the forest stock. There are now two potential forest stocks. The first is the open access natural forest S^1 explicit in eqs. (1)-(8). The second is a managed forest S^2 that may be introduced on land with secure property rights once the price incentives are great enough. The two forests are equivalent. Both provide timber, fruit, nuts, fuelwood, watershed protection, carbon sequestration, etc., both market and non-market valued goods and services.

The farmgate price of agricultural goods p is stationary in the aggregate market. The delivered price of forest-based goods and environmental services p_e increases as the aggregate forest stock S declines and as the access and harvest costs for the natural forest increase. This price is never zero--except in the previous simplistic model. For the final unit of harvest in any time period, all rents for open access forest resources S^1 are dissipated in access and harvest costs, and the *in situ* price for open

Table 1: Definitions

$S^1(t)$ = stock of natural forest (on open access forestland); $S^1(0)$ is known, $S^1(t) > 0$ for all t if $c_r + c_m < \infty$
$S^2(t)$ = stock of forest on land with secure property rights, $S^2(0) = 0$
$S(t)$ = $S^1(t) + S^2(t)$; $S(T)$ is undetermined

T = period identifying the end of all natural forest conversion, an unidentified known value

p = farmgate price of agricultural goods
$p_e[S(t)]$ = price of forest-based goods and environmental services delivered to the farmgate equivalent, the local market or farm homestead (e.g., logs, not stumpage), $\partial p_e/\partial S < 0$ for all $p_e < c_r + c_m$, $p_e = c_r + c_m$ at T

$c_a[S^1(t)]$ = access and harvest costs, $\partial c_a/\partial S^1 < 0$
c_m = cost of forest growth and management (e.g, planting seedlings), a constant

c_e = cost of converting forest land to agriculture (e.g., stump removal), a constant
c_{r1} = cost of initially establishing secure property rights to the land, a constant
$c_r[S^2(t)]$ = differential cost of protecting the tree crop (relative to agricultural crops) from trespass, $\partial c_r/\partial S^2 > 0$
c_o = $c_{r1} + c_e$

w = opportunity cost of composite labor-capital input to agricultural production

$L(t)$ = composite labor-capital input to agricultural production
$Q(t)$ = measure of agricultural output

access forest resources is zero. Private loggers and collectors of other forest-based goods and services have no reason to extend their open access harvests beyond the point where the *in situ* price is zero, nor to halt their harvests before this point. The delivered price of forest-based goods and services continues rising over time, and the natural forest stock S^1 continues to decline, until the delivered price (which equals the access and harvest costs) reaches the backstop created by the opportunity to actively plant and grow forests S^2 on land with secure property rights.

Converting natural forests to agricultural production requires a one-time direct conversion cost c_e for making the land suitable for agriculture. It also requires a one-time cost for establishing secure rights c_{r1}, whether registering a legal claim or establishing a customary right, plus a periodic cost for protecting the new crop against trespass and theft. The two one-time costs can be combined as c_o in order to simplify our mathematical exposition. The periodic protection cost is greater for forests than for agricultural crops and it increases with the size of the protected stock (S^2) because the incentives for and the ease of removal are generally greater for a unit of mature forest than for a comparable measure of some subsistence crop. This explains why subsistence farmers tend to plant trees near their homesteads but not at the far boundaries of their personal property.

The true backstop price is the sum of the tree planting and growing cost c_m and the differential forest-agricultural protection cost c_r. The period for mining and converting the original forest stock to agricultural production comes to an end at time $t=T$, or once the price of forest-based goods and services rises to the level of the backstop. All future harvests will originate either from managed forests on land with established and secure rights, or from occasional 'pulse' harvests of naturally regenerated forests on open access land. We expect that some natural forest, that beyond the boundary set by access and harvest costs equal to the backstop price, is never fully depleted, let alone converted to agricultural production--unless the backstop price is infinitely high.

The new social welfare function is

$$W[L(t),b(t)] = \int_0^{Q(t)} [D(\eta,t) - c_0]\,d\eta - wL + [p_e(S) - c_a(S^1)]\,E(S^1) + \int_0^{Q(t)} [p_e(S) - c_r(S^2) - c_m]\,E(S^2)\,d\eta \qquad (9)$$

Arguments in t are dropped where they should be obvious. The first two terms are the net value of agricultural production on converted forest land, the third term is the value of forest-based production of goods and services from the natural stock, the final term is the value of production from the newly managed forest stock, all during the period of forest conversion. It is positive only when access and harvest costs equal the backstop and both managed and open access harvests exist simultaneously.

The new optimization problem is

$$\begin{aligned} &\max_{L(t),b(t)} \int_0^T W[L(t),b(t)]\, e^{-rt}\,dt + \psi[S(T),T] \\ &s.t. \quad S(t) = S^1(t) + S^2(t) \\ &\qquad S(t) = S(0) - a\int_0^t Q(t) + \int_0^t b(t)Q(t) \\ &\qquad \dot{S}^1(t) = \dot{S}(t) - b(t)Q(t) \\ &\qquad \dot{S}^2 = b(t)Q(t) \\ &\qquad \dot{S}(t) = -aQ(t) + S^2(t) \\ &\qquad T \text{ is known}, \quad S(T) \text{ is free}, \quad S(0) \text{ is given} \end{aligned} \qquad (10)$$

where b is the proportion of agricultural land that is reconverted to managed forest. The second term is a salvage term. It explains agricultural and forest-based production in the period after all forest conversion has occurred. Eq. (10) is a free endpoint control problem with two controls and one state variable. The state is total forest stock S(t). S(t), along with Q(t) and b(t), it uniquely determines the two component forest stocks, S^1 and S^2.

Public concern with deforestation focuses on behavior during the period of deforestation and on the final forest stock, rather than the length of the period of deforestation. Therefore, we can accept T as known by assumption, but allow it to remain unspecified. The remainder of this paper will examine the steady flows as we seek to describe deforestation, or forest conversion behavior, and the final stock and its distribution after deforestation and conversion are complete. We can subsequently extend our analysis to incorporate growth in the stock itself. The final term in eq. (11) will become important in this extension.

Completing the Proposed Paper

The next two sections of the paper will solve the deforestation behavior and final stock problems mathematically--using the current value Hamiltonian from eq. (11) and the definitions from table 1. We might speculate on what they will show.

It should be clear that depletion of the forest base causes the price of forest-based goods and services to rise. Eventually the price increase is sufficient to induce some reforestation and protection of the reforested land. Total deforestation of the original stock will never occur because total deforestation requires an infinite price. The forthcoming section on deforestation behavior will derive the marginal conditions for a) deforestation of natural stock, b) pulse harvests, c) agricultural land conversion, and d) management of the new plantation forest stock.

The final allocation of the natural forest stock will be divided among land satisfying these four uses. It should be clear that the remaining natural stock will be too costly to harvest. Pulse harvests originate from a natural forest of positive value but of value insufficient to overcome the costs of land clearing and establishing secure rights. Agricultural land has sufficient value to overcome these thresholds, but some agricultural land is insufficient in value to compete with the new forest plantations.

We can produce simulations that reflect this deforestation behavior and final land allocation. It is clear from a wide range of the analytical economic literature, however, that these are general and very real cases--historically and cross-sectionally, for developed and developing countries, in temperate and tropical regions.

For example, Berck (197) and Libecap and Johnson (198) have shown the economic rationality of the draw down of the initial forest stock in the US West and Lake States occurring since the last century. Amacher, Hyde and Joshee (1993) compare households in adjacent districts of Nepal and find open access deforestation in one district, yet private reforestation in the other. The comparison follows the economic rules for open access forest inventories, prices, and competitive thresholds with agricultural production. Hyde and Seve (1993) observe and anticipate similar patterns in southern and central Malawi. Templeton (1992) reports similar observations, including private reforestation, in the uplands of Luzon. Rice (1993) observes similar patterns for commercial reforestation in Costa Rica.

In sum, the observations of price-induced reforestation are scattered, but they come from most every environment conceivable. They are scattered only because the prices of forest-based goods and services are generally not high enough worldwide to provide the incentives for the full shift to the steady state in a large number of cases. It should be clear, however, that the worst fears for deforestation are unfounded in any case.

It should also be clear that some of our policy foci are ill-conceived. In particular, extracting the maximum rents and establishing secure property rights for the economically harvestable forest inventory may both receive undue attention. The economically harvestable inventory must originate from one of three sources: a) managed forest land which already has secure property rights and associated appropriate rents, b) the area of pulse harvests, and c) the fringe of natural forest.

The area of pulse harvest is an open access resource without secure rights but the costs of establishing these rights are greater that the value of the rights. Of course, different institutional arrangements might permit lower establishment costs. In this case, thoughtful policy might search for an improved institutional arrangement.

The forest resource values can only be marginal on the fringe of the natural forest stock. The costs of establishing secure rights or administering precisely accurate royalties must be greater than the resource value in most cases--perhaps in all cases except those exposed to an external shock like a new road built by an outside agent. The road would alter access costs and, therefore, the location of the natural forest margin. Of course, the new forest rents in this case should be attributed to the roadbuilding effort, and not to the forest.

These observations--or anticipated observations, at this point--may seem optimistic. They suggest that the market works--even for a problem like global deforestation. We should be careful not to overstate our case, however, and we should be careful to examine our results closely.

We should not overstate our case because our analysis may not incorporate all forest-based environmental values. One that comes to mind is biodiversity. Biodiversity may be lost in any drawdown of the open access natural forest, and not regained in reforestation on private land. Furthermore, the market includes administered prices that send socially sub-optimal signals. This was the case with implicit livestock subsidies in some Central and South American countries. The implicit subsidies altered the net value of rangeland and induced a socially excessive rate of deforestation.

Finally, for many poor developing countries the market may work well for subsistence farmers. The social responses to forest resource prices and the rate of deforestation on private land may be great and the eventual net effect may be little change in the total forest stock of today. This is the Hyde and Seve (1993) observation for Malawi. This adjustment may only occur, however, along with a 200 percent fuelwood price increase in ten years--and for a population that already may spend up to twenty percent of its cash income for fuel! Thus, the market may adjust and deforestation may not be a problem. Nevertheless, as the market does adjust, it may severely tax the scarce resources of the poorest people. It takes from their small cash reserves and from their scarce supplies of productive agricultural land. This is a serious problem, a serious result of the processes associated with the decline in the world's stock of natural forest.

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Conversion Behavior

Using the current value Hamiltonian and the definitions from table 1, the optimality condition for the labor-capital input becomes:

$$
\begin{aligned}
p &= c_o + \frac{w}{\partial Q/\partial L} + a\mu \\
&\quad - \frac{\partial S}{\partial Q}\left[E\left(\frac{\partial p_e}{\partial S} - \frac{\partial c_a}{\partial S}\right) + \frac{\partial E}{\partial S}(p_e - c_a)\right]
\end{aligned}
\tag{10}
$$

where μ is the revised user cost and the t's are implicit. Eq. (10) states that the marginal benefit from forest conversion equals the marginal cost of conversion and agricultural production (including the direct user costs) plus the marginal loss in forest-based goods and services. It varies from its more naive version in eq. (7) by the addition of forest conversion c_o and the more complex final term for forest-based losses. This final RHS term, the marginal forest-based loss, is composed of the change in value of the inframarginal stock (scarcity value) plus the forgone benefit from the physical change in the marginal stock (depleted forest-based goods and services).

The necessary condition for the co-state variable becomes

$$
r\mu = \dot{\mu} + (p - a\mu)\frac{\partial Q}{\partial S} - E(S)\left(\frac{\partial p_e}{\partial S} - \frac{\partial c_a}{\partial S}\right) + \frac{\partial E}{\partial S}(p_e - c_a)
\tag{11}
$$

Eq. (11) varies from the naive version of eq. (8) by its more complex term explaining the incremental value of forest-based goods and services, a term similar to the final term in eq. (10).

Eqs. (10) and (11), taken together, describe deforestation, or conversion behavior until the time T when access and harvest costs equal the backstop price. Rearranging terms in eq. (11):

$$
\frac{\dot{\mu}}{\mu} = r - \left(\frac{p}{\mu} - a\right)\frac{\partial Q}{\partial S} - \frac{E(S)}{\mu}\left(\frac{\partial p_e}{\partial S} - \frac{\partial c_a}{\partial S}\right) - \frac{\partial E}{\partial S}\left(\frac{p_e - c_a}{\mu}\right)
\tag{12}
$$

Hotelling's result for exhaustible resource extraction is now modified to account for both i) conversion value measured by the relative value of forest-to-agricultural services (p/μ), the conversion rate (a), and the importance of forest stock converted to agricultural productivity (∂Q/∂S), and ii) forest-based stock effects of conversion [the terms in E(S)].

Final Stock, S(T)

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