THE WORLD BANK ECONOMIC REVIEW, VOL. 12, NO. 1: 105-31

The Tragedy of the Commons in Côte d'Ivoire Agriculture: Empirical Evidence and Implications for Evaluating Trade Policies

Ramón López

Expansion of cultivated land diminishes the extent of forestlands or reduces the length of fallow periods and, hence, reduces the amount of natural vegetation. The increase in land under cultivation has a direct output-increasing effect at the cost of reducing natural capital and agricultural productivity. The evidence for western Côte d'Ivoire *is consistent with, and provides an explanation for, the declining agricultural productivity observed in Sub-Saharan Africa during the past few decades.*

This article uses a theoretical model to determine the level of land cultivation that maximizes village income, using data from Côte d'Ivoire for 1985–87. An important part of the land is under common property, usually at the village level. The results show that farmers do not internalize even a small fraction of the external cost of biomass in their land allocation decisions. The lack of internalization of the social cost of the biomass resource leads to large income losses at the village level—as much as 14 percent of village income. These losses are many times larger than the usual estimates for conventional distortions.

Natural vegetation represents an important factor of production in the context of traditional shifting cultivation. Overexploitation of this factor may cause significant loss of income among rural communities. Farmers in an area of western Côte d'Ivoire have overexploited the natural resources (forests and natural vegetation in fallows) through excessive cultivation of communal lands and, hence, the reduction of fallows and forest areas (López 1993). Individual cultivators considered at most 30 percent—and, more likely, a negligible fraction—of the social cost of natural vegetation or biomass when deciding how much land to clear for cultivation. These social costs include the negative effects that the clearing of land by one farmer has on other farmers, through soil degradation, flooding, and sliding, the reduction of fallow and forest areas as well as the decline in natural soil fertility caused by a reduction in the fallow part of the cultivation cycle.

Ramón López is with the Department of Agricultural and Resource Economics at the University of Maryland. Financial support for this research was provided by the World Bank Research Committee, RPO 675-33. Research assistance was provided by Claudia Sepúlveda. The author would like to thank three anonymous referees for their helpful comments.

Rural communities have apparently failed to maintain a system of incentives and controls over individual cultivators that would induce a socially optimal allocation of land among forest, fallow, and cultivation and thus avoid the "tragedy of the commons." These results give support to authors who have questioned the effectiveness of indigenous forms of property in achieving a socially efficient allocation of natural resources (Perrings 1989; Sinn 1988; López and Niklitschek 1991; Glantz 1977; and Allen 1985). In contrast, anthropologists, other social scientists, and several economists, most prominently Dasgupta and Mäler (1990) and Larson and Bromley (1990), are of the opinion that communities are able to develop controls on the use of common property resources to allow for their efficient exploitation.

The evidence for western Côte d'Ivoire is consistent with and provides an explanation for the declining agricultural productivity observed in Sub-Saharan Africa over the past few decades (FAO 1986 and ADB, ECA, and OAU 1984). Several studies have illustrated the connection between declining agricultural productivity and agricultural intensification, which, in turn, is associated with population growth and the fall in biomass. A process that Geertz (1963) calls "agriculture involution" is documented, for example, by Jones and Egli (1984) in areas of fast population growth in Burundi, Rwanda, and Zaire; by Ludwig (1968) for the Ukare Island in Lake Victoria; and by Lagemann (1977) for eastern Nigeria. Niklitschek (1990) provides ample evidence of the close connection between rural population growth, expansion of area cultivated, reduction of fallows, and declining agricultural productivity in Sub-Saharan Africa.

Do the results for western Côte d'Ivoire hold for other tropical areas where farmers practice traditional agriculture in the context of communal lands with restricted access? Using data for all regions of Côte d'Ivoire, this article provides further evidence on the efficiency of exploitation of common lands. Apart from providing results that are more representative for the country, this expanded data set also provides the degrees of freedom required for a substantially more disaggregated analysis. In particular, the analysis considers three agricultural outputs: tree crops (a capital-intensive output), cereals (land-intensive), and tubers and vegetables (labor-intensive). Using three outputs permits a much richer analysis of the effects of agricultural prices as well as certain economywide policies than using an aggregate output.

The article also evaluates agricultural price and trade policies in Côte d'Ivoire. In particular, it looks at how price and trade liberalization affect agriculture, taking into account their effects on both natural resources (fallow reduction and deforestation) and conventional factors of production (labor, purchased inputs). Agricultural price and trade policies do not represent first-best solutions to eventual overexploitation of natural biomass. However, institutional and sociopolitical limitations make it unlikely that poor developing countries will be able to implement such policies effectively in the near future. Hence, in devising further price and trade policy reforms, analysts should verify whether such policies impose additional tradeoffs by magnifying the overexploitation of natural resources.

Section I provides background information regarding the role of natural vegetation or biomass in agricultural production in tropical areas. Section II presents the theoretical framework used in the analysis, while section III presents details about the empirical method. Section IV discusses the data and estimation techniques, and section V presents the results. Section VI discusses the implications of agricultural price and other economywide policies. Section VII concludes.

I. NATURAL VEGETATION AS A FACTOR OF AGRICULTURAL PRODUCTION

A system of relatively long rotation between crop cultivation and fallows (shifting cultivation) is a dominant practice in Côte d'Ivoire as well as in most other countries in Sub-Saharan Africa where population levels are not yet too large. The fallow period plays the important role of replenishing the fertility of the land by allowing natural vegetation to grow. The natural vegetation is incorporated into the soil as natural fertility (usually as ashes after burning) at the time of cultivation. Fallow periods that are too short lead to insufficient growth of natural vegetation and consequently to low soil fertility, soil instability because the vegetation does not have a sufficiently strong root system to protect it at the time of cultivation, and cultivated areas that are not protected against flooding and sliding. Thus, the vegetation that is allowed to grow in the fallow period is a form of capital that accumulates and is eventually used at the time of cultivation. The closed forest areas (that is, those areas not yet disturbed by cultivation) also play important roles not only as a reserve of land for eventual use but also as protection against soil erosion, watershed destruction, and flooding.

Expansion of the cultivated land diminishes the forestlands or reduces the length of the fallow periods and, hence, reduces the natural vegetation. The tradeoff between cultivated land and forest/fallow is clear: an increase in land under cultivation has a direct output-increasing effect at the cost of reducing the natural capital, thus reducing agricultural productivity. An optimal fraction of the land should be cultivated in order to maximize social income. If the level of land cultivated is above or below the optimum, income is reduced. The land is under common property (farmers have exclusive rights on the land usually for as long as they cultivate it), usually at the village level (that typically encompasses hundreds of families). In the absence of communal controls, individual cultivators are likely to overexploit the natural resource by cultivating too much. In deciding how much land to cultivate, farmers in this case likely consider only the private costs, ignoring contemporary and intertemporal effects on other cultivators. If communal controls are adequate, individuals would behave as if they fully accounted for both the private and social costs of clearing land. The empirical model tries to elucidate whether this happens.

There are of course substitutes for natural vegetation as a factor of production. The use of fertilizers could replenish the fertility lost as a result of shorter fallow periods. The construction of drainage and other infrastructure could replace part of the protective role of natural vegetation. These substitutes, however, are likely to be imperfect particularly in humid tropical soils where the benefits of fertilizers and other chemicals are much reduced (Sánchez 1976). Thus, the availability of substitutes may allow for a reduction in natural vegetation, but elimination of the natural vegetation is unlikely to be optimal. Further, in the absence of community controls on the use of natural resources, individual cultivators will not be prone to use usually expensive substitute inputs for natural vegetation (and thus increase land productivity) as long as forest or fallow communal lands are available for clearing. Consistent with this is the fact that only a very small fraction of the farmers located in areas where fallow lands and forest still exist use chemical fertilizers.

II. THE THEORETICAL MODEL

Equation 1 defines the net revenue function for farmer j who is assumed to take the stock of natural vegetation as given,

$$(1) \qquad \tilde{R}^j(\tilde{w}, x^j, \theta, \tilde{p}, k^j) \equiv \max_{y^j, L^j} [\tilde{p}y^j - \tilde{w}L^j : F(y^j, L^j, \theta, k^j, x^j) = 0]$$

where $\tilde{p}$ is a vector of output prices; $\tilde{w}$ is a vector of input prices other than biomass, land, and capital; x^j is land cultivated by farmer j; θ is the stock of village-level biomass per hectare; k^j is capital; y^j is a vector of output quantities produced by farmer j; L^j is labor used by farmer j; and $F(\cdot)$ is the set of production possibilities. The function $\tilde{R}^j(\cdot)$ satisfies all the conditions of a variable profit function in p and w (Diewert 1973) and is assumed to be increasing and concave in θ, x^j, and k^j.

The stock of biomass θ per hectare can be defined as

$$(2) \qquad \theta \equiv \eta(1 - x/\bar{x})$$

where η is the (average) density of biomass per acre in the land that is not cultivated, $\bar{x}$ is the total land available, and $x = \sum_{j=1}^{N} x^j$ is the total land under cultivation by the community or village (N is the number of cultivators in the village).

López (1993) has shown that the rate of extraction of biomass under shifting cultivation is proportional to the rate of land cultivation $x/\bar{x}$. Thus, if γ is the natural increase of biomass in the areas not under cultivation, change in biomass density in the uncultivated land is

$$(3) \qquad \dot{\eta} = \gamma - \eta \sum x^j / \bar{x}.$$

The level of land cultivation that maximizes the income of the village (rather than the income of individual cultivators independently) is obtained by

$$(4)\qquad \max_{x^j} \int_0^{\infty} \left\{ \sum_{j=1}^{N} \tilde{R}^j(\tilde{w}; x^j, \eta(1 - \sum_{i=1}^{N} x^i/\bar{x}), \tilde{p}, k^j) - cx^j \right\} e^{-rt} \mathrm{d}t$$

subject to

$$\dot{\eta} = \gamma - \eta \sum_{i=1}^{N} x^i/\bar{x}$$

$$\eta(0) = \eta_0,$$

$$\sum x^j \le \bar{x}.$$

where c is the private cost of land clearing per unit of land, r is the discount rate, t is time, and a dot over the variable name reflects a change over time.

The optimization (expression 4) is a benchmark for comparing actual allocations. The solution of expression 4 defines the allocation that is socially optimal from the community or village point of view. It maximizes the wealth of the community. The model does not assume this optimization; expression 4 is provided only for the purpose of comparing its solution with the observed allocations. The actual decentralized allocations by individual cultivators may not be consistent with expression 4, depending on the institutional conditions prevailing, the level of monitoring, and transaction costs. See, for example, Baland and Platteau (1996) for the nature of the games that could lead to efficient allocation of common resources through collective action and other forms of cooperation.

In the steady state, the first-order conditions of expression 4 imply that

$$(5)\qquad \tilde{R}_2^j(\cdot) = c + \frac{\eta}{\bar{x}} \sum_{i=1}^{N} \tilde{R}_3^i(\cdot) + \eta u/\bar{x}, \qquad j = 1, \ldots, N$$

where $\tilde{R}_2^j \equiv \dfrac{\partial \tilde{R}}{\partial x^j}$ and $u = (1 - x/\bar{x}) \sum_{i=1}^{N} \dfrac{\tilde{R}_3^i(\cdot)}{r + x/\bar{x}}$ is the shadow value of biomass desity η. Equation 5 is the key benchmark for deriving the empirical methodology. It says that if cultivators choose socially optimal levels of land cultivation, the marginal revenue of the last unit of land cleared for cultivation should equal the private cost of land clearing (c) plus the marginal revenues forgone by all cultivators that one additional unit of land cleared causes now $\left(\eta \sum_{i=1}^{N} \tilde{R}_3^i\right)$ and in the future ($\eta(u/\bar{x})$) due to the fall in η that increasing x^j causes. The second right-hand term in equation 5 measures the forgone marginal income for all cultivators caused by reducing the area covered with natural vegetation given a level of biomass density (η) per acre of noncultivated land. The third right-hand term in equation 5 captures the present value of all future forgone incomes due to the fall in η that will occur in the future as the rotation period is reduced as a consequence of increasing x^j.

Using the definition of u, the last two right-hand terms in equation 5 can be combined, and thus equation 5 can be rewritten as

$$(6) \qquad \tilde{R}_2^j(\cdot) = c + \eta / \bar{x}\frac{1+r}{r+z}\sum_{i+1}^{N}\tilde{R}_3^i(\cdot), \qquad j = 1, \ldots, N$$

where $z = \sum_{i=1}^{N} x^i / \bar{x}$ is the (endogenous) rate of depreciation of the stock of biomass density η. If individual cultivators make decisions completely independently and face no constraint from their communities, they would only consider 1/Nth of the external effects (of the second right-hand term in equation 6) as part of the cost of increasing x^j. In this case, a Nash equilibrium would arise as the solution of the N equations:

$$(7) \qquad \tilde{R}_2^j(\cdot) = c + \frac{\eta}{N\bar{x}}\frac{1+r}{r+z}\sum_{i=1}^{N}\tilde{R}_3^i(\cdot), \qquad j = 1, \ldots, N$$

Depending on the effectiveness of the village controls on individual cultivators' decisions, the equilibrium vector of $x = (x^1, x^2, \ldots, x^N)$ will be given by equation 6, or by equation 7, or an intermediate solution if controls exist but are imperfect.

To model these intermediate outcomes empirically, I postulate a more general specification for equation 6 or equation 7:

$$(8) \qquad \tilde{R}_2^j(\cdot) = c + \frac{\lambda\eta}{\bar{x}}\frac{1+r}{r+z}\sum_{i=1}^{N}\tilde{R}_3^i(\cdot), \qquad j = 1, \ldots, N$$

where λ is an efficiency parameter that could fluctuate between 1/N and 1, depending on the efficiency of the village controls. The closer to 1 is parameter λ, the more efficient are the land allocation decisions.

The specification of the model assumes a fixed stock of physical capital, k^j. It may be argued that this is inconsistent with the dynamic nature of the model and, therefore, that a mechanism of capital accumulation needs to be incorporated explicitly into the theoretical model. There are several ways of doing this. One possibility is to assume the extreme opposite of the assumption made so far, that capital is instantaneously adjusted to optimal levels instead of being fixed. In this case, it should be clear that the land allocation equation (equation 7 or 8) remains intact, except that the revenue function $R^j(\cdot)$ would include the rental price of capital instead of the stock of capital.

A less extreme possibility is that capital is neither fixed nor fully variable, but quasi-fixed. That is, a gradual process of capital accumulation takes place through time. To model this, there are several avenues depending on what source prevents an instantaneous adjustment of the capital stock. Appendix A presents a growth model that explicitly incorporates the two state variables, the stock of biomass and the stock of capital. Except for the addition of the biomass state variable, the model is a conventional neoclassical growth model. That is, it assumes that the main reason for slow capital adjustment is the existence of a utility function that is strictly concave in consumption and that capital accumulation is financed entirely through the savings of the individuals. Appendix A shows that in the steady state the land allocation decision is still ruled by a specification analogous to equation 7. That is, at least in the steady state, the specification used is in a sense quite robust to the assumption used regarding fixity, quasi-fixity, or full variability of the capital variable.

The empirical model is based on the assumption of a steady state. Dropping this assumption would change the specification of the land equation. The right-hand side of the land equation would be the same except that a new term involving the change in biomass, $\dot{\theta}$, would have to be added (López 1993). If $\dot{\theta} < 0$, the true shadow value of biomass is underestimated in a steady-state specification; if $\dot{\theta} > 0$, the model would overestimate the shadow value of biomass (López 1993). Because biomass decreases through time, the steady-state specification underestimates the social value of biomass. That is, the social cost of expanding x exceeds the value assumed in equation 6. This implies that the steady-state assumption will provide a value for λ that is larger than the true value of λ. So the estimated λ will be an upper bound of the true λ if biomass declines through time.

A potential limitation of the model is that it assumes that producers are risk neutral. Poor farmers tend to be risk averse and, hence, if cultivated land is risk-decreasing, farmers may behave as if the true marginal cost of cultivated land were less than the right-hand side of equation 8. It may be argued, then, that the model might estimate a λ value below unity because a misspecification is associated with ignoring risk rather than because institutions fail to assign land efficiently. However, two aspects considerably weaken this objection. First, the specific variable that dictates the value of λ is the shadow value of biomass for the community. If the omitted variable, risk level, causes a downward bias in λ, the level of risk and the shadow value of biomass would be positively correlated. It is hardly plausible, however, to argue that the shadow value of biomass for a community is correlated with the level of risk or uncertainty prevailing in the community. Second, the empirical model in section III does not use actual values for the private costs of cultivating land, c. Instead it uses an estimate of the private cost coefficient that can change across villages (these are the village fixed effects). So, if the level of risk or uncertainty faced by the farmers varies more across villages (due to climatic and agroecological differences or to proximity to markets) than through time, as might be expected, its effect would be captured by the village fixed effects without biasing the estimates of λ.

Another potential problem of the model is that it ignores the existence of credit market imperfections. Some analysts have argued that imperfect capital markets and low incomes drive farmers to behave myopically. One way of considering capital market imperfections is through the interest rate. Basu (1989), for example, argues that most farmers in developing countries have access to the informal credit market, where the main mechanism of allocation is (usually high) interest rates rather than credit rationing. If farmers face credit constraints in the formal capital market, they have to rely on informal credit sources, where interest rates are much higher than interest rates in the formal market. Although the model obviously ignores credit market imperfections, it does not rely on the existence of perfect credit markets. In fact, it explicitly allows the discount rate to assume various values in the empirical estimation, within a wide range. The analysis does not use market interest rates as a proxy for r, but rather experiments with a broad range of values for r and considers the sensitivity of the estimates of λ to changes in r.

There is still a potential problem if the levels of r vary across farmers rather than being constant, as implicitly assumed in equation 8. The problem in this case could be that the omitted variable r_j is correlated with the level of the shadow value of biomass, which is the variable that determines λ. However, the shadow value of biomass is village-specific, not farmer-specific. Hence, village fixed effects will control for the effect of the possible intervillage variations in the interest rate. The only remaining problem would be if the interest rate varies systematically through time.

III. The Empirical Model

The empirical model requires the specification of the normalized net revenue function, which is assumed to be identical for all farmers. The revenue function is normalized by the farm price of tree crops. Equation 9 is a normalized quadratic functional form for the revenue function:

$$
\begin{aligned}
(9)\quad R^j = {} & A_0 + A_1 w + A_2 x^j + A_3 \theta + A_4 k^j + A_5 p_c + A_6 p_0 \\
& + \tfrac{1}{2} A_{11} w^2 + \tfrac{1}{2} A_{22} x^{j2} + \tfrac{1}{2} A_{33} \theta^2 + \tfrac{1}{2} A_{44} k^{j2} + \tfrac{1}{2} A_{55} p_c^2 + \tfrac{1}{2} A_{66} p_0^2 \\
& + A_{12} w x^j + A_{13} w \theta + A_{14} w k^j + A_{15} w p_c + A_{16} w p_0 + A_{23} x^j \theta + A_{24} k^j x^j \\
& + A_{25} x^j p_c + A_{26} x^j p_0 + A_{34} \theta k^j + A_{35} \theta p_c + A_{36} \theta p_0 + A_{45} k^j p_c + A_{46} k^j p_0 \\
& + \sum_k B_k H_k^j + \sum_k \gamma_h V_h + \varepsilon_j^R
\end{aligned}
$$

where $R^j \equiv \tilde{R}^j/q$ is the net revenue normalized by the price of tree crops (q); $w \equiv \tilde{w}/q$; p_c and p_0 are the prices of cereals and other crops (tubers, vegetables), respectively, also normalized by q; H_k^j are household-specific characteristics; V_h are village characteristics; A_i, A_{ij}, B_k, and γ_h are fixed parameters; and ε_j^R is an error term assumed to be normally distributed with zero mean and finite variance. The village characteristics also interact with the prices and wage rate. These interactive terms are omitted in equation 9. The well-known symmetry or reciprocity conditions that arise from the implicit optimization assumption in the context of well-behaved production technologies are imposed on equation 9. The symmetry conditions imply that $A_{ij} = A_{ji}$ for all $i \neq j$. This considerably reduces the number of parameters to be estimated.

Using equation 8, an explicit functional representation for farmer j's demand for land to cultivate is

$$(10) \qquad x^j = \frac{c - A_2}{A_{22}} - \frac{A_{12}}{A_{22}} w - \frac{A_{23}}{A_{22}} \theta - \frac{A_{24}}{A_{22}} k^j - \frac{A_{25}}{A_{22}} p_c - \frac{A_{26}}{A_{22}} p_0$$
$$+ \frac{\lambda}{A_{22}} \eta \frac{(1+r)}{r+z} N \left[A_3 + A_{13}w + A_{23}\theta + A_{34}k^j + A_{35}p_c + A_{36}p_0\right] + \varepsilon_j^0$$

where ε_j^0 is an additive disturbance assumed to satisfy the same properties as ε_j^R, and $x \equiv \sum_i x_i$ is the total area cultivated in the village. The function R in equation 9 is assumed to satisfy the usual regularity assumptions: it is convex in p and w; it is increasing and strictly concave in x^j, θ, and k^j; and the marginal revenues of θ, k^j, and x are increasing in the level of the other factors. These conditions imply that A_{22}, A_{33}, and A_{44} are all negative and that A_{23}, A_{24}, and A_{34} are all positive. These conditions assure that cultivated land is decreasing in c and increasing in θ and k^j.

Using Hotelling's lemma, the labor demand and output supply equations implicit in equation 9 are

$$(11) \qquad \begin{aligned} -L^j &= A_1 + A_{11}w + A_{12}x^j + A_{13}\theta + A_{14}k^j + A_{15}p_c + A_{16}p_0 + \varepsilon_j^L, \\ Q_c^j &= A_5 + A_{15}w + A_{25}x^j + A_{35}\theta + A_{45}k^j + A_{55}p_c + A_{56}p_0 + \varepsilon_j^c, \\ Q_0^j &= A_6 + A_{16}w + A_{26}x^j + A_{36}\theta + A_{46}k^j + A_{56}p_c + A_{66}p_0 + \varepsilon_j^{00} \end{aligned}$$

where L^j is labor demand by farmer j, and Q_c^j and Q_0^j are the supply of cereals and other crops, respectively. Equation 11 omits the household-specific characteristic effects and the village characteristic effects. The supply of perennial crops (or tree crops) is obtained by noting that $Q_p^j = R^j - wL^j - p_cQ_c^j - p_0Q_0^j$. Thus,

$$(12) \qquad Q_p^j = A_0 + A_2x^j + A_3\theta + A_4k^j - \tfrac{1}{2}A_{11}w^2 - \tfrac{1}{2}A_{55}p_c^2 - \tfrac{1}{2}A_{66}p_0^2$$
$$+ \tfrac{1}{2}A_{22}x^{j2} + \tfrac{1}{2}A_{33}\theta^2 + \tfrac{1}{2}A_{44}k^{j2} + \sum_k B_kH_k^j + \sum_h \gamma_hV_h + \varepsilon_j^T.$$

The system of equations 10 and 11 and either equation 9 or 12 is jointly estimated using a maximum likelihood procedure. The joint estimation of the system permits the identification of all the relevant coefficients. The λ coefficient can be identified conditional on a fixed level of the discount rate r. The estimation strategy consists of estimating alternative values of λ for a plausible range of discount rates. Given the symmetry conditions (that is, $A_{ij} = A_{ji}$), the coefficients inside the square brackets in equation 10 (A_3 and A_{i3}, $i = 1, \ldots, 6$) are all identified by the rest of the system or by the linear part of equation 10 itself. Hence, as η and z are observed variables, λ can be exactly identified if r is also known. But since r is unknown, alternative fixed values are postulated for r. The value of λ will, of course, vary directly with the postulated level of r. This reflects the fact that any land allocation can be considered optimal if the discount rate is large enough. Thus values for λ are estimated within a plausible range of r. The key question is how high the discount rate r would have to be to make the observed resource allocation socially efficient.

The normalized quadratic is a flexible functional form, in the sense that it provides a second-order approximation to any functional form. This is one of the functional forms that Diewert (1973) proposes for revenue functions and has been frequently used in the literature (Binswanger and Evenson 1984 and Diewert and Morrison 1988). This form imposes little a priori restrictions on the matrix of elasticity of substitution and on the implicit production technologies. Unlike other commonly used functional forms (such as Cobb-Douglas and Constant Elasticity of Substitution), the normalized quadratic allows for different elasticities of substitution, it does not impose separability, and it allows for nonhomotheticity.[1] The function does impose the price homogeneity conditions that production theory predicts for input demand and output supply equations.[2]

IV. DATA AND ESTIMATION

The data come from three sources—the Living Standards Survey (LSS) conducted annually in Côte d'Ivoire between 1985 and 1988, remote sensing data based on satellite images of 20 villages scattered throughout the country for the years 1985 to 1988, and field visits to the villages. The total area covered by the remote sensing analysis is about 450,000 hectares. The LSS and remote sensing data sources were carefully matched for each of the villages and years considered. The LSS information allows the creation of a panel data set for a sample of 16 farm households in each of the 20 villages for the 1985–87 period. The LSS data used in this article concern information on farm production, labor hired, household member's work on the farm, land cultivated, other inputs used by each of the farm households, as well as demographic characteristics. The analysis also uses village-level information such as the number of households per village. (See appendix B for data definitions.)

The remote sensing data provided information about the total land under cultivation in the village, land under fallow per village, land under closed forests

---

[1] Some of the flexible functional forms do impose quasi-homotheticity and certain separability conditions (see López 1985).

[2] Some of the implicit input demand and output supply equations are linear in the normalized prices, and one of the output supply functions is nonlinear in prices. As Diewert (1973) shows, this feature imposes no special peculiarities on the underlying production technology.

per village, and average biomass density of the fallow land in each of the three years considered. Village biomass is estimated by multiplying the total land area under fallow by the biomass density index obtained from the remote sensing analysis. Also included is an estimate of biomass calculated in the same way for forest areas that have not been cultivated recently. Some of the regressions only use the fallow biomass, others use the sum of fallow and forest biomass, and still others use the two measures as separate variables. Preliminary regressions showed that the fallow biomass was the key to agricultural productivity and that including forest biomass added very little to the regressions. Therefore, the regressions reported in this article use only fallow biomass per hectare. The matching of the LSS household-level data and remote sensing village-level data provided a panel data set that combines individual household information with information on natural resource endowments at the village level.

Field visits to the villages provided data concerning the agricultural area that is under the sphere of influence of each village, that is, the area that is considered "property" of the village group. Moreover, the field visits provided certain essential qualitative information on issues such as land allocation decisions, the state of the communal system, and the functioning of labor markets within the communities. Three main conclusions that emerged from the field visits are important for the empirical analysis. First, shifting cultivation is the dominant practice in all the villages considered. Second, the system of land allocation for cultivation of the fallow areas is not transparent. In some villages, a village council is still quite important in determining the extent of land given to cultivation. In most villages, however, the decisions appear to be much more decentralized, with little input from the village chiefs. Additionally, in several areas an incipient and spontaneous process of privatization is taking place, and one of the mechanisms for obtaining land rights is to cultivate the fallow lands continuously. In general, the assessment of people in the field is that the traditional system of land allocation is changing mainly because of the reduced power of the village leaders and the process of gradual privatization. Third, in most cases, an active and seemingly efficient labor market operates within the villages.

Table 1 gives an overview of the land allocation information provided by the remote sensing analysis for Côte d'Ivoire as a whole. Table 1 shows, even at the aggregate country level, a significant degree of change in land allocation over the three-year period from January 1985 to January 1988. In particular, a decrease in the forest area of almost 9 percent and an increase in the area cultivated of about 2.5 percent a year are quite remarkable. At the same time the fallow area shows a less conspicuous but significant downward trend. The village-level data that are actually used in the regression analysis exhibit an even greater variability through time than the aggregate data for the country. The remote sensing data also include a measure of the average biomass density per hectare in the fallow land. In order to make intervillage comparisons of fallow meaningful (a village may have a large fallow area but very little vegetation density, and another may have a smaller area but much greater vegetation

Table 1. *Changes in Land Allocation in Côte d'Ivoire, 1985 and 1988*
(hectares)

Land area	*1985*	*1988*	*Percentage change*
Total area surveyed	447,132	447,132	0.0
Under closed forest	125,410	114,217	-8.9
Under fallow	172,391	169,585	-1.6
Cultivated	132,222	142,073	7.5

Source: EARTHSAT (1991).

cover), the fallow area of each village is weighted by its corresponding average biomass density.

Two alternative definitions of biomass are used in the empirical model. A narrow definition only includes average biomass per hectare in fallow lands. A broad definition includes all biomass in fallow lands as well as in forestlands (biomass is, in this case, normalized by the total fallow plus forest areas). The two measures turn out to be highly correlated, and the econometric results are only marginally different when either measure is used.

Equations 9, 10, and 11 are estimated jointly as a system restricting the A_i and A_{ij} coefficient across equations using FIML (full information maximum likelihood) estimators. Assuming that the variables N, w, θ, and Σx^j are not correlated with the error terms, the system is recursive (rather than simultaneous), a feature that greatly facilitates the estimation. Furthermore, a random effects model is used, allowing for a component of each error term that is common to a given year's observations corresponding to households located in the same village. That is, if ε^S_{ijt} is the total residual in equation s for household i located in village j at time t, assume that $\varepsilon^S_{ijt} = \rho^S_{jt} + \Delta^S_{ijt}$ where ρ^S_{jt} is the common-to-the-village component and Δ^S_{ijt} is the idiosyncratic component. $E(\rho_{jt}, \Delta_{ijt}) = 0$ is assumed for all k. The variance of the across-village estimated component (ρ^S_{jt}) is significantly larger than the variance of the idiosyncratic component in all three equations. This means that imposing a single residual would give inconsistent estimates of the standard errors of the regression.

Another important issue is the validity of the assumption that the residuals are uncorrelated with the exogenous variables. In particular, of most concern is the possibility that the biomass variable could be correlated with the error terms. This would, of course, lead to inconsistent estimates of the parameters. The endogenous variables (household revenue, cultivated area, labor demand, and the supply of the various crops) are explained by village-level variables as well as by household characteristics. A problem of simultaneity may arise if the village explanatory variables and the household dependent variables are correlated with important but unobserved variables. The key question concerns the source of variability of the village-level variables.

A positive correlation between farm revenues or output and biomass may arise if some villages have greater biomass than others because they have better soil and climate that allow the natural vegetation to grow faster. These better climatic and soil characteristics would lead to higher agricultural productivity in the villages that have more biomass. Thus any positive correlation between output and biomass could be spurious. In order to deal with this issue, village-specific characteristics (including soil and climate) are controlled for using village dummy variables.

Using village effects should control for unobserved variables such as climate and soil quality as well as for other village characteristics such as infrastructure and distance to markets. Thus, the use of village dummies is likely to eliminate the influence of such variables from the coefficients associated with the other explanatory variables. The use of village-specific dummies (rather than household dummies) is an adequate procedure because the biomass variable used is also defined at the village level. This procedure is possible because the analysis uses panel data for three years for all the relevant variables.

A remaining problem, however, is that the variation of biomass through time in a village may be associated with changes in weather. Agricultural productivity is also likely to be associated with fluctuations in weather, and, hence, a spurious correlation between biomass and agricultural productivity may arise. The extent of the biases induced in the coefficient of biomass will depend on the importance of the fluctuations in weather. Other estimates (not reported here) are obtained using instrumental variables for the various terms involving the biomass variable. These include average family size as well as two regional dummy variables. The results, particularly the sign and statistical significance of the coefficients, do not change with the instrumental variable procedures. These variables are not likely to be correlated with the weather variable but are good instruments, in the sense that they explain a high proportion of the changes in biomass.

There are large differences in agroecological conditions across the main regions in the country (West Forest, East Forest, and Savanna). In particular, the inland Savanna has a different pattern of production than the tropical forest belt in the west and in the east. Thus, using different village intercepts in the estimation of the revenue function may not be enough to capture all the production and ecological differences across the three regions. This would call for allowing the slope coefficients to vary across regions as well. Unfortunately, given the large number of coefficients of the revenue function, this is not feasible. However, using a more restricted approach with one aggregate output variable, López (1993) estimates a similar revenue function for the western region of Côte d'Ivoire, which has enough village observations to estimate the revenue function. The effect of biomass on gross revenues is indeed higher in the west than in the country as a whole, but the differences are not great. For the west, the estimates for the contribution of biomass are 0.18–0.20, only slightly larger than those for the country as a whole. The contribution of land to gross revenues is slightly larger in the forest region (with an elasticity of about 0.41 compared with 0.38 in the analysis for the whole country), but the contribution of labor is significantly smaller in the west (about 0.10 compared with 0.18 for the whole country).

V. THE RESULTS

Table 2 shows the FIML estimates of the system of equations 9, 10, and 11. The estimates were obtained assuming a discount rate of 0.2. Several other estimates were obtained by specifying different discount rates. In general, the results are robust to the changes in the assumed discount rate, and only the λ coefficient changes numerical values, but without altering its sign and degree of statistical significance.

In table 2 the estimates in the first and second columns, respectively, were obtained with and without using village dummies. The estimates are mostly (but not completely) consistent with the properties of the revenue function postulated by the optimization model. In particular, the revenue function estimated is monotonically increasing in land cultivated, biomass, and capital as well as in the output prices and is monotonically decreasing in the wage rate. The normalized revenue function estimated is not, however, convex in prices. Although the A_{11} and A_{66} coefficients have the expected signs, the fact that A_{55} is negative implies a violation of the convexity property (although this coefficient is not statistically significantly different from 0). The revenue function estimated is also strictly concave in land cultivated, biomass, and capital, implying that the marginal revenue functions are downward-sloping as expected.

The most important finding concerns the resource efficiency parameter λ. As can be seen in table 2, the parameter λ is positive but not statistically different from 0 in either of the estimates presented. The model was also estimated assuming even higher discount rates (up to $r = 0.6$), and the λ parameter is never statistically significant.[3]

This result implies that farmers do not internalize even a small fraction of the external cost of biomass in their land allocation decisions.[4] Thus, farmers are cultivating too much land to maximize the village income. Or, equivalently, given the tradeoffs between land cultivated and the stock of biomass, the village wealth can be increased by reducing the amount of land cultivated and, consequently, allowing for more natural biomass. Moreover, the income loss associated with this inefficiency is quite large.

Several reasons might explain why such a clear inefficiency occurs in a situation where village farmers exploit the biomass resource in an essentially

[3] In the López (1993) study, a statistically significant λ was found for the west of Côte d'Ivoire at least under certain specifications; the highest λ found was about 0.3.

[4] According to the theoretical specification, the smallest possible value of λ is $1/N$ rather than 0. Because the number of households in most villages is very large, fluctuating between 742 and 1,320 with a mean of 937, the lower bound of λ is very close to 0, at about 0.001.

Table 2. *Estimation Results for the Revenue Function, Côte d'Ivoire, 1985–87*

Variable	*Using village dummy variables*	*Without using village dummy variables*
Constant	-2.52	-2.97
	(-2.85)	(-3.44)
Agricultural wage, w	-1.09	-1.08
	(–6.09)	(–6.02)
Land cultivated by farmer j, x^j	-1.39	-1.31
	(-1.71)	(-1.60)
Stock of village biomass, θ	1.40	1.36
	(7.75)	(8.24)
Capital owned by farmer j, k^j	2.34	2.31
	(4.54)	(4.49)
Price of cereals, p_c	0.95	0.82
	(2.18)	(1.88)
Price of other crops, p_o	0.02	–0.05
	(0.05)	(–0.11)
Agricultural wage squared, w^2	0.11	0.11
	(2.05)	(1.95)
Land cultivated by farmer j squared, $(x^j)^2$	-1.22	-1.26
	(-15.82)	(-16.48)
Stock of village biomass squared, θ^2	–0.20	–0.19
	(-7.52)	(-7.97)
Capital owned by farmer j squared, $(k^j)^2$	–0.33	–0.33
	(-1.38)	(-1.37)
Price of cereals squared, $(p_c)^2$	–0.38	–0.47
	(-1.24)	(-1.53)
Price of other crops squared, $(p_o)^2$	0.38	0.38
	(0.97)	(0.95)
Interaction with agricultural wage		
Land cultivated by farmer j, wx^j	0.00	–0.008
	(0.00)	(–0.08)
Stock of village biomass, $w\theta$	–0.003	–0.0022
	(–0.33)	(–0.28)
Capital owned by farmer j, wk^j	–0.10	–0.10
	(-2.90)	(-2.77)
Price of cereals, wp_c	–0.30	–0.30
	(-3.30)	(-3.30)
Price of other crops, wp_o	–0.18	–0.20
	(-1.83)	(-1.87)
Interaction with land cultivated by farmer j		
Stock of village biomass, $x^j\theta$	0.04	0.05
	(1.23)	(1.37)
Capital owned by farmer j, k^jx^j	–0.66	–0.67
	(-10.44)	(-10.54)
Price of cereals, x^jp_c	0.81	0.84
	(3.55)	(3.61)
Price of other crops, x^jp_o	0.69	0.72
	(2.56)	(2.64)

(Table continues on the following page.)

Table 2. *(continued)*

Variable	*Using village dummy variables*	*Without using village dummy variables*
Interaction with stock of village biomass		
Capital owned by farmer j, θk^j	0.03	0.04
	(1.06)	(1.08)
Price of cereals, θp_c	–0.15	–0.14
	(–7.23)	(–6.91)
Price of other crops, θp_o	–0.06	–0.05
	(–3.72)	(–3.33)
***Interaction with capital owned by farmer* j**		
Price of cereals, $k^j p_c$	0.36	0.36
	(4.12)	(4.11)
Price of other crops, $k^j p_o$	0.15	0.15
	(1.78)	(1.69)
Interaction between price of cereals and price of other crops	0.67 (2.81)	0.65 (2.71)
Biomass efficiency parameter, λ	0.03	0.008
	(0.30)	(0.07)
Private cost of land clearing, c	1.39	1.55
	(2.13)	(2.46)
Dummy year 1986	–1.92	–2.57
	(–3.19)	(–5.47)
Dummy year 1987	–1.79	–2.33
	(–2.00)	(–4.05)
Number of observations	458	458

Note: Full information maximum likelihood was used to estimate the model (equations 9, 10, and 11 in the text), assuming a discount rate of 0.2. Five household demographic characteristics were included in the regressions: age of household head, education of household head, number of children, number of female adult members, and distance to health care facilities. t-statistics are in parentheses.

Source: Author's calculations.

closed-access form. The monitoring and other transaction costs involved in the implementation and design of institutional mechanisms to exploit the resource efficiently might be very large, particularly given the high population density prevailing in most villages. This may prevent the development of such mechanisms. Another explanation could be that most farm communities may operate at subsistence levels and, thus, cannot afford investing in the resource by reducing the cultivated area. Equivalently, the true discount rate that communities use is even higher than the 60 percent annual rate used as an upper bound in the estimation. It could be that their true discount rate is almost infinity. The analysis shows, however, that the way in which farmers respond to price incentives does not seem to be consistent with the subsistence story.

The significance of the coefficients associated with biomass (the A_{3j} coefficients) and the net positive effect of biomass on total revenues when evaluated at the data points show the importance of biomass as a factor of production. Using equation 9, the effect of biomass on total revenues is

$$(13)\qquad \frac{\partial \ln R}{\partial \ln \theta} = [A_3 + A_{33}\theta + A_{13}w + A_{23}x + A_{34}k^j + A_{35}p_c + A_{36}p_o]\frac{\theta}{R}.$$

The effects of land cultivated and capital can be derived in similar fashion. Table 3 presents the values of these elasticities evaluated at the mean sample levels. The values of these elasticities are not very different from the coefficients obtained when a Cobb-Douglas aggregate production function is estimated (see López 1993).

The contribution of biomass to gross agricultural revenues is comparable to the contribution of labor and less than that of capital and cultivated land. In any case, the estimates in table 3 show that biomass makes an important contribution to agricultural revenues and that a further loss of biomass would likely have a serious impact on agricultural production.

The estimated contribution of biomass to gross agricultural revenues for Côte d'Ivoire is very similar to the values estimated for Ghana (López 1997). In fact, the Ghana estimates range between 0.15 and 0.20, compared with 0.17 for Côte d'Ivoire. Moreover, several agronomic studies in tropical countries have shown that the fallow period makes a large contribution to agricultural productivity. Ellis and Mellor (1995), for example, have found that by reducing fallow periods from five to two years in Zaire, the nutrients left in the soils decline significantly. Nitrogen falls by more than 50 percent, calcium/magnesium and potassium fall by about 45 percent. This dramatic fall in nutrients is likely to have serious detrimental effects on yields, particularly if few fertilizers are used, as happens in most of Sub-Saharan Africa. Thus, the agronomic evidence is consistent with the estimates here for the effect of biomass on farm revenues.

Table 4 shows the partial elasticities of supply for the three outputs, land cultivated, and labor demand with respect to the output prices and the wage rate. The most striking finding shown in table 4 is the fact that, although higher prices of cereals and other annual crops cause a very large expansion in area cultivated, an increase in the price of tree crops induces a reduction in the area

Table 3. *Implicit Factor Shares in the Total Value of Production, Côte d'Ivoire, 1985–88*

Factor	*Share*[a]
Biomass	0.17
Land cultivated	0.38
Capital	0.23
Labor	0.18

Note: Shares are evaluated at the means of the variables. See section V in the text.
a. All of the factor share values are significant at the 10 percent level.
Source: Author's calculations.

Table 4. *Elasticities of Supply for Outputs, Land Cultivated, and Labor in Côte d'Ivoire, 1985–88*

Output supply or factor demand	*Output price*			
	Cereals	*Other annual crops*	*Tree crops*	*Wage rate*
Cereals	–0.39	0.70*	–0.02*	–0.29*
Other annual crops	0.66*	0.19	–0.74*	–0.11
Tree crops	–0.12*	–0.68	0.58*	0.22
Land cultivated	0.60*	0.49*	–0.95*	–0.14*
Total labor	0.29*	0.11	–0.24	–0.16*

* Significant at the 10 percent level.

Note: Values are partial elasticities with respect to output price or the wage rate, evaluated at the mean values of the variables.

Source: Author's calculations.

cultivated. One possible explanation for this result is that annual crops are much more land-intensive than tree crops, which are likely to be capital-intensive. This may give rise to a Rybcynski-type of effect.

An increase in the price of tree crops induces two conflicting effects. First, an increase in the relative profitability of tree crops causes an expansion of the area planted with tree crops. Second, a fall in the relative profitability of cereals and other annual crops causes a reduction in the area planted with annual crops. The empirical results suggest that the second effect dominates; that is, the reduction in the land devoted to annual crops is greater than the increase in the area devoted to tree crops. This implies that an increase in the price of tree crops leads to less land cultivated, longer fallow periods, and more natural biomass. Why does the area under annual crops fall more than the increase in the area under tree crops? Tree crops and nontree crops compete for other resources that are more or less in fixed supply (capital, credit, managerial skills). Therefore, the increase in the price of tree crops might absorb a sufficiently large volume of these resources from the annual crop sectors to force the area cultivated under those crops to fall more than the increase in the demand for land for tree crops. Tree crops and nontree crops compete not only for land but also for other resources in more or less inelastic supply.

The extent of cultivated land, however, significantly increases if the prices of the three agricultural outputs rise proportionally, as shown by the negative and significant wage elasticity in table 4. Given the homogeneity conditions, the wage elasticity equals minus the sum of the three output price elasticities. That is, a 10 percent rise in all agricultural prices would lead to an increase in the total area cultivated by about 1.4 percent. Or, equivalently, a 10 percent fall in wages maintaining output prices constant would cause a similar increase in area cultivated.

The long-run elasticity of biomass with respect to cultivated land is about –1.3 when evaluated at the average levels of the variable. This means that an across-the-board increase in farm output prices of 10 percent would cause the stock of biomass to fall about 1.3 percent in the long run. This, in turn, would have negative consequences for agricultural productivity and income. The fact that producers do not consider the total social cost of biomass in their land allocation decisions (as shown by the fact that λ is not significantly different from 0) implies that biomass is overexploited and that agricultural income is below its optimal. A further increase in agricultural prices aggravates the distortion by causing further losses in biomass and long-run agricultural productivity that outweigh the short-run benefits of expanding the land under cultivation.

According to the econometric estimates, the agricultural income of an average village could be increased by 14 percent in the long run if the total cost of biomass were internalized by individual cultivators. This represents a large loss, many times larger than the losses usually estimated for price or trade distortions. The main source of this income loss is the fact that land is overcultivated by about 23 percent. That is, a land allocation that would maximize the income of the average village requires a 23 percent decrease in the amount of cultivated land. An increase in all three agricultural prices or a fall in wages would substantially increase the magnitude of these losses by increasing the incentives to cultivate land.

VI. AGRICULTURAL PRICE POLICIES AND TRADE REFORMS

From the previous discussion it is clear that policies that improve all or most agricultural commodity prices are likely to reduce agricultural productivity and to cause more deforestation and a reduction of fallow periods, further deteriorating the natural resources. The net effect on agricultural income of raising agricultural prices across-the-board is still positive, however. The reason for this is that the fall in agricultural productivity and the increased direct cost of clearing more land do not offset the increase in farm revenues due to the higher farm commodity prices. That is, farmers have a net gain, but only because of the redistributional effect of improved relative prices. Similarly, policies that have a negative impact on wages are also likely to be deleterious for natural resources and agricultural productivity.

By contrast, price policies that improve the terms of trade of agriculture by reducing the taxation of the tree crop sector alone are likely to be of the win-win type. They may induce social gains through conventional price efficiency (by reducing the distortionary tax on tree crops) and by reducing total land cultivated and, hence, increasing biomass and agricultural productivity. Thus, the effect of trade liberalization on the environment and on national income is likely to vary according to the initial structure of protection.

If trade reform improves the prices of all agricultural subsectors or if it causes a rise in the relative price of land-intensive (nontree crops) compared with capital-intensive agricultural commodities (tree crops), it may have deleterious effects for the environment and may even cause a net fall in national income. That is, complete trade liberalization without, for example, stronger communal control institutions could be counterproductive not only for the environment but also for national income. Thus, trade liberalization makes even more urgent the need for strengthening village institutions. Fine-tuning of trade policies is not, however, feasible in many developing countries. Although this might be easier than applying first-best policies, some of the same institutional weakness that makes first-best policies difficult to apply could affect the implementation of trade policies as well.

If, however, the initial distortions tax tree crops more than nontree crops, trade liberalization would improve the prices of tree crops relative to annual crops as well as relative to the rest of the economy. In this case, trade liberalization or, more generally, the removal of price distortions is likely to be a win-win policy causing an even greater expansion of income and an improvement in the level of natural resources.

Economywide reforms that induce a fall in wages are likely to impose greater pressures on the natural resource base of agriculture. Macroeconomic policies such as real devaluation and measures to reduce fiscal disequilibria typically cause a fall in real wages. Thus, if those policies are not accompanied by complementary measures to internalize the costs of natural resources, the loss of biomass, with the consequent fall in agricultural productivity over the medium term, is likely to be significant. According to my estimates, a macroeconomic adjustment that causes real wages to fall 10 percent, for example, would cause an increase in area cultivated of about 1.4 percent. This, in turn, would reduce biomass over the long run about 1.8 percent. This fall in biomass reduces the supply responsiveness of agriculture in the long run by a wide margin.

VII. Conclusions

Biomass is an important factor of production, accounting for roughly 17 percent of the agricultural gross domestic product in Côte d'Ivoire. The large losses of forest and the considerable reduction in fallow periods observed in Côte d'Ivoire over the past few decades have implied a considerable loss of productive natural capital that is likely to have reduced the productivity of labor and other resources.

Individual cultivators act as if the biomass resource has no social costs beyond the purely private costs of clearing the land. The hypothesis that communities develop adequate controls on the use of communal resources to maximize their collective income does not appear to be valid for villages in Côte d'Ivoire. There are several possible reasons for this. Extremely fast population growth may have caused a significant increase in monitoring and transaction costs in the villages. The greater density of the village population is likely to have substantially increased the pressure on village resources and made it more difficult to control for violations of the implicit or explicit village regulations on the use of communal resources. At the same time, the significant immigration into certain villages from both inside and outside Côte d'Ivoire and the rapid westernization of traditional values may have deteriorated the village hierarchies, making social controls more difficult to implement.

The lack of internalization of the social cost of the biomass resource leads to large income losses at the village level. This article estimated losses on the order of 14 percent of village income. These losses are many times larger than the usual estimates for conventional distortions.

The main response of annual crops to price incentives is to increase the area cultivated. The output response of tree crops, however, relies much less on expanding the area cultivated. An improvement in tree crop prices, keeping annual crop prices constant, is likely to cause a net reduction in cultivated area and an improvement in the natural resource. Thus, the potential for win-win policies exists in cases where, initially, tree crops (typically export crops) are taxed while annual crops (commonly import substitutes) are protected. In this case, the removal of trade distortions is likely to induce both the gains in price efficiency and a reduction in environmental losses. By contrast, reforms that cause an increase in the prices of all or most agricultural commodities (or reforms that reduce wages) are likely to deepen the environmental distortion and, thus, to reduce agricultural productivity in the long run.

The analysis for Côte d'Ivoire refutes the hypothesis that common property resources are efficiently allocated; in other places common resources might be more efficiently used. Similar tests for villages in the eastern part of Ghana produced results similar to those for Côte d'Ivoire (López 1997). More case studies like these are needed to analyze whether common resources in developing countries are allocated efficiently and to elucidate the conditions that determine the degree of efficiency in the allocation of common resources. It is possible that an efficient allocation of common resources requires certain specific conditions to facilitate collective action and that such conditions are not always present in most poor countries. In general, it appears that efficiency of the commons tends to be present in communities with low population density where the transaction and monitoring costs are low (Baland and Platteau 1996). The paradox is that it is precisely in cases of high and rapidly increasing population density that collective action is most needed to achieve an efficient use of common resources.

APPENDIX A. A NEOCLASSICAL GROWTH MODEL OF CAPITAL AND BIOMASS ACCUMULATION

As a benchmark model, assume that the village maximizes the sum of the discounted present values of the utilities of the village households, subject to the budget constraint and the biomass constraint.

$$\max \int_0^\infty \sum_i U(y^i) e^{-rt} dt \tag{A-1}$$

subject to

$$\text{(i)}\ \sum_j \dot{k}^j = \sum_j \left\{ R^j\left[w, x^j, \eta(1 - \sum x^i/\bar{x})k^j\right] - \delta k_j - cx^j - y^j \right\}$$

$$\text{(ii)}\ \dot{\eta} = \bar{\gamma} - \left(\eta \sum_i x^i/\bar{x}\right)$$

$$\text{(iii)}\ k^j(0) = \bar{k}_0^j, \qquad j = 1, \ldots N; \eta(0) = \eta_0; \quad \sum x^i \le \bar{x}$$

where $U(\cdot)$ is an increasing and strictly concave utility function of the village households, y^j is consumption of household j, r is the discount rate, t is time, k^j is capital, R^j is revenue of farmer j, w is input prices other than biomass, land, and capital, x^j is land cultivated by farmer j, η is the average density of biomass per acre in the land that is not cultivated, $\bar{x}$ is total land available, δ is the (constant) rate of depreciation of the capital stock, c is the private cost of clearing the land, $\dot{\eta}$ is the change in η, $\dot{k}$ is the change in k, $\bar{\gamma}$ is the natural increase of biomass in the areas not under cultivation, x^i is the total land under cultivation by farmer i, and $\bar{k}_o^j$ is the initial level of capital of farmer j.

The first-order conditions of this problem are

$$\text{(A-2) (i)} \qquad U'(y^j) = \varepsilon \qquad j = 1, \ldots, N$$

$$\text{(ii)} \qquad R_2^j = c + \eta \sum_i R_3^i(\cdot) + \frac{\mu}{\varepsilon}\eta / \bar{x} \qquad j = 1, \ldots, N$$

$$\text{(iii)} \qquad \dot{\varepsilon} = (r + \delta - R_4^j)\varepsilon \qquad j = 1, \ldots, N$$

$$\text{(iv)} \qquad \dot{\mu} = \left(r + \sum x^i/\bar{x}\right)\mu - \varepsilon \sum_i R_3^i\left(1 - \sum x^i/\bar{x}\right)$$

$$\text{(v)} \qquad \text{A-1, parts i and ii}$$

where ε is the shadow value of the stock of capital, μ is the shadow value of biomass, a dot over a variable indicates rate of change, and subscripts indicate partial derivatives. It is important to note that for ε to be identical for all households, it is necessary to assume that R_4^j is identical for all households. That is, assume that in equation A-2 the production technology is identical for all farmers and that they face the same prices w (conditions that are sufficient to assure that x^j is equal for all farmers) and start with identical capital stocks. This is equivalent to postulating the model using a representative consumer/producer fiction, as is usually done.

Equation A-2, part ii, dictates the land allocation decisions in the short run. It is analogous to the short-run land allocation derived from equation 4 in the text, with the only exception being that now the shadow value of capital (or marginal utility of consumption), ε, appears. Equation A-2, part ii, indicates that the social cost of expanding the cultivated area should be weighted by the marginal utility of consumption. That is, if ε is large—that is, households are poor in the sense that their consumption is low, in which case $U'(y^j)$ is high—the social cost of expanding the area cultivated (and, hence, of depleting biomass) is less than if households have a higher consumption level and consequently a lower $U'(\cdot)$ and ε. This implies that, ceteris paribus, as a way of financing their capital buildup, capital-poor societies tend to deplete biomass more intensively than richer societies. Thus, this model, unlike the one in the text, allows for a mechanism by which poverty may lead to greater resource degradation beyond the discount rate and the direct production substitution effects associated with capital or other factors.

Compared with the model in the text, the steady state model has the same land allocation decision, but in addition it has an equilibrium equation for the optimal capital stock. It thus makes it possible to determine simultaneously the long-run equilibrium values of x and k,

$$\text{(A-3) (i)} \qquad R_2^j(\cdot) = c + \frac{\eta}{N\bar{x}} \frac{1+r}{1+z} \sum_{i=1}^{N} R_3^i(\cdot) \qquad j = 1, \ldots, N$$

$$\text{(ii)} \qquad R_4^j(\cdot) = r + \delta \qquad j = 1, \ldots, N$$

$$\text{(iii)} \qquad \sum_{i=1}^{N} x^i / \bar{x} = \gamma / \eta$$

where the functions $R_2^j(\cdot)$, $R_3^j(\cdot)$, and $R_4^j(\cdot)$ are evaluated at the steady-state equilibrium values of x^*, k^*, and η^* derived from the solution of equation A-3. The land allocation equation (A-3, part i) is analogous to equation 7 in the text, except that it needs to be evaluated at k^* instead of at k.

For the empirical model, however, apart from being more difficult to implement, it is not clear that using this specification (equation A-3), which imposes a certain structure on the level of k, is necessarily superior to a specification based on equation 7 in the text, which does not impose any specific mechanism for the derivation of k. A more eclectic empirical approach is simply to instrumentalize variable k.

APPENDIX B. DATA

Part of the data used in this article comes from the Living Standards Survey (LSS) conducted in Côte d'Ivoire. About 50 percent of the sample is reinterviewed every year. These data provide information on demographic, labor, and production characteristics as well as the time allocation of households. The data used correspond to the period 1985–87.

Statistics on agricultural land and biomass density at the village level were provided by a special study done for this project by EARTHSAT (1991) based on satellite images of 20 villages in the western region of Côte d'Ivoire for the years 1985, 1986, and 1988. These statistics were incorporated into the LSS panel data. Matching the LSS and EARTHSAT data gives a panel data set of household observations that combine the usual individual characteristics of the households with information on biomass density and area at the village level.

Detection of Biomass Change Based on Remote Sensing Data

Land was first classified into five categories: forestlands (areas with large and highly dense trees that do not appear to have been cultivated for at least 50 years), low-impact agriculture or bush fallow, high-impact agriculture (including sites of active agriculture or recently fallowed fields with negligible regeneration), human settlement areas (including villages and areas of construction), and other lands (including unproductive lands with little or no soil).

The 1985 and 1986 imagery was geometrically corrected to fit the image space of the 1988 imagery, allowing comparative evaluations of the same areas over time. A principal components analysis was carried out on all imagery to normalize the data and to isolate radiometric anomalies.

A statistical evaluation was carried out to determine the mean digital number value for each land-cover category, as represented by the principal component vectors from the various dates of imagery. Pixel counts were then carried out to determine the quantity of change in each of the five categories of land. The pixels were then converted to hectares (the pixel size was 28.5 square meters). From this information, it was possible to determine the change in area for each of the five categories of land over time for each of the village areas.

The digital numbers of band four were divided by those of band three to produce a vegetation density index for the forest and low-impact agriculture areas for each of the study units. The total biomass value in fallow was defined as the vegetation density index times the areas under low-impact agriculture and that of the forest area as the forest vegetation index times the areas under forest. Thus, an index of total biomass in each land category was obtained for each village area.

Variable Definitions and Summary Statistics

Table B-1 provides the means and standard deviations for some of the most important variables. All the figures are in 1985 CFA francs. The deflator used was the African Food Price Index with base 1985 = 100.

Table B-1. *Means and Standard Deviations of Selected Variables Used in the Regressions for Côte d'Ivoire, 1985–88*

Variable	*Mean*	*Standard deviation*
Net revenue per household (1985 CFA francs)	668,990	647,200
Land cultivated per household (hectares)	7.2	4.23
Biomass per hectare of fallow (index number)	6.50	3.56
Total days of work per household per year	1,428	867
Real wage rate (1985 CFA francs per hour)	450	216
Number of agricultural tools or implements per household	12.3	11.6

Source: Author's calculations.

The variables used as well as their definitions are presented below, where i denotes the index for household $i = 1, \ldots, n$, and j denotes the village.

$$\text{(i) } R^j_{it} \equiv S^j_{it} + PHL^j_{it} + SK^j_{it} + HC^j_{it} + HP^j_{it} - w^j_{Mt} + LH^j_{it} - w^j_{HA_t} LHMA^j_{it} - w_{HP_{t,j}} LHMP^j_i$$

$$\text{(ii) } w^J_{HA} \equiv b_F w^j_F + b_m w^j_M + b_c w^j_C, \text{ where } b_{M,F,C} \equiv \frac{LHMA_{M,F,C}}{LHMA} \sum b = 1$$

$$\text{(iii) } w^j_{HP} \equiv C_F w^j_F + C_M w^j_M + C_c w^j_C, \text{ where } C_{M,F,C} \equiv \frac{LHMP_{M,F,C}}{LHMP} \sum C = 1$$

$$\text{(iv) } w^j \equiv a_M w^j_F + a_{HA} w^j_{HA} + a_{HMP} w^j_{HP}, \text{ where } a_M = \frac{LH}{LL} a_{HMP} = \frac{LHMP}{LL} a_{HA} = \frac{LHMA}{LL}, \sum a_M, a_{HMP}, a_{HA} = 1$$

$$\text{(v) } LL^j_i \equiv LH^j_i + LHMA^j_i + LHMP^j_i$$

$$\text{(vi) } \theta^j \equiv \overline{\eta}^j (1 - z^j)$$

$$\text{(vii) } z^j \equiv \frac{X^j}{\overline{X}^j}$$

R^j_i = Real revenue of farmer i in village j

S^j_i = Real total sales to the market of farmer i in village j

PHL^j_t = Real value of payments in kind to hired labor by farmer i in village j

SK^j_i = Real value of seeds kept by farmer i in village j

HC^j_i = Real value of home consumption of farmer i in village j

HP^j_i = Real value of home production or transformation of farmer i in village j

LH^j_i = Number of days hired by farmer i in village j during the last 12 months

$LHMA^j_i$ = Number of days worked in the field by members of the household i in village j during the last 12 months

w^j_P = Agricultural real wage per day earned by a female in village j

w^j_M = Agricultural real wage earned per day by a male in village j

w^j_C = Agricultural real wage earned per day by a child in village j

w^j_{HA} = Average agricultural real wage earned per day by a member of a household working in his or her own field in village j

w^j_{HP} = Average agricultural real wage earned per day by a member of a household working in the transformation of agricultural products in village j

w^j = Average real wage earned by a member of the household working in his or her own field or in the transformation of his or her agricultural products or by a worker hired by farmer i in village j

LL_i^j = Total number of days worked in the field or in home production by members of household *i* plus days hired by farmer *i* in village *j*

θ^j = Total biomass in village *j*, normalized by its total land area

$\bar{\eta}^j$ = Average biomass density per acre of land under fallow in village *j* (from EARTHSAT)

X^j = Total land cultivated in village *j* (from EARTHSAT)

$\bar{X}$ = Total agricultural land (cultivated plus fallow) in village *j* in hectares (from EARTHSAT)

z^j = Fraction of cultivated land to agricultural land in village *j*

γ = Marginal biomass density

x_i^j = Land cultivated by farmer *i* in village *j* in hectares

$\dfrac{\sum_{i=1}^{n} x_i^j}{n}$ = Average land cultivated in village *j* in hectares

N^j = Number of farms in village *j*

E_i^j = Years of education of the head of household *i* in village *j*

L_i^j = Number of family members in household *i* of village *j*

T_i^j = Number of tree crops in farm *i* of village *j*

E = Minimum value of E_i^j in the sample = 0

L = Minimum value of L_i^j in the sample

k_i^j = The sum of the agricultural tools and implements used by household *i* in village *j*

T = Minimum value of T_i^j in the sample = 0

r = Time discount rate

REFERENCES

The word "processed" describes informally reproduced works that may not be commonly available through library systems.

African Development Bank (ADB), Economic Commission for Africa (ECA), and Organization of African Unity (OAU). 1984. "The African Food Crisis and the Role of the African Development Bank in Tackling the Problem." Paper presented jointly by the staff of the ADB, ECA, and the OAU to the symposium on the future of ADB and the food crisis of Africa, Tunis, Tunisia, May. Processed.

Allen, Julia. 1985. "Wood Energy and Preservation of Woodlands in Semi- and Developing Countries, The Case of Dodoma Region, Tanzania." *Journal of Development Economics* 19(1):59–84.

Baland, J. M., and J. P. Platteau. 1996. *Halting Degradation of Natural Resources.* Oxford: FAO and Clarendon Press.

Basu, K. J. 1989. "Rural Credit Markets: The Structure of Interest Rates, Exploitation, and Efficiency." In Pranab Bardhan, ed., *The Economic Theory of Agrarian Institutions.* Oxford: Clarendon Press.

Binswanger, Hans, and Robert Evenson. 1984. "Labor Demand in North India Agriculture." In Hans Binswanger and Mark Rosenzweig, eds., *Rural Labor Markets in Asia: Contractual Arrangements, Employment, and Wages.* New Haven, Conn.: Yale University Press.

Dasgupta, Partha, and Karl-Göran Mäler. 1991. "The Environment and Emerging Development Issues." In *Proceedings of the World Bank Annual Conference on Development Economics.* Washington, D.C.:World Bank.

Diewert, W. E. 1973. "Functional Forms for Profit and Transformation Functions." *Journal of Economic Theory* 6(3):284–316.

Diewert, W. E., and Catherine Morrison. 1988. "Export Supply and Import Demand Functions: A Production Theory Approach." In Robert Feenstra, ed., *Empirical Methods for International Trade.* Cambridge, Mass.: MIT Press.

EARTHSAT (Earth Satellite Corporation). 1991. "Ivory Coast Change Detection: Quantitative Assessment for Basic Land-Cover Categories for the Years 1985, 1986, and 1988." Bethesda, Md. Processed.

Ellis, Stephen, and Albert Mellor. 1995. *Soils and Environment.* London: Routledge.

FAO (Food and Agricultural Organization of the United Nations). 1986. "Natural Resources and Human Environment for Food and Agriculture in Africa." Environment and Energy Paper 6. Rome. Processed.

Geertz, Clifford. 1963. *Agriculture Involution: The Process of Ecological Change in Indonesia.* Los Angeles: University of California Press.

Glantz, Michael. 1977. *Desertification: Environmental Degradation in and around Arid Lands.* Boulder, Colo.: Westview Press.

Jones, William I., and Roberto Egli. 1984. *Farming Systems in Africa: The Great Lakes Highlands of Zaire, Rwanda, and Burundi.* World Bank Technical Paper 22. Washington, D.C.: World Bank.

Lagemann, Johannes. 1977. *Traditional African Farming Systems in Eastern Nigeria.* Munchen: Weltforum Verlag.

Larson, B. A., and D. W. Bromley. 1990. "Property Rights, Externalities, and Resource Degradation." *Journal of Development Economics* 33:235–62.

López, Ramón. 1985. "Structural Implications of a Class of Flexible Functional Forms for Profit Functions." *International Economic Review* 26(2):593–601.

———. 1993. "Resource Degradation, Community Controls, and Agricultural Productivity in Tropical Areas." Department of Agricultural and Resource Economics, University of Maryland, College Park. Processed.

———. 1997. "Environmental Externalities in Traditional Agriculture and the Impact of Trade Liberalization: The Case of Ghana." *Journal of Development Economics* 78(1):508–16.

López, Ramón, and Mario Niklitschek. 1991. "Dual Economic Growth in Poor Tropical Areas." *Journal of Development Economics* 36(2):189–211.

Ludwig, H. D. 1968. *Ukare: Ein Sonderfall Tropischer Bodennutzung in Raum des Victoria-Sees.* Munchen: Weltforum Verlag.

Niklitschek, Mario. 1990. "Economic Growth in Sub-Saharan Africa: The Implication of the Environmental Degradation." Ph.D. diss., University of Maryland, College Park. Processed.

Perrings, Charles. 1989. "An Optimal Path to Extinction? Poverty and Resource Degradation in the Open Agrarian Economy." *Journal of Development Economics* 30(1):1–24.

Sánchez, Pedro. 1976. *Properties and Management of Soils in the Tropics.* New York: John Wiley and Sons.

Sinn, Hans-Werner. 1988. "The Sahel Problem." *KIKLOS* 41(2):187–221.