Endangered Ecosystem Conservation:

The dynamics of direct and indirect transfers

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Abstract

International donors invest billions of dollars to stem the loss of native ecosystems in low-income nations. The most common investments aim to encourage commercial activities, such as ecotourism, that *indirectly* generate ecosystem protection as a joint product. We contrast the dynamic efficiency and cost-effectiveness of indirect subsidy approaches with an approach that has been gaining attention in recent years: paying for ecosystem protection *directly* through performance payments. We demonstrate that although the direct payment approach achieves a given level of ecosystem protection with the least overall distortion to the economy, a conservation agent with a limited budget may find the indirect subsidy approach more cost-effective when (1) own-price input effects are only moderately larger than cross-price effects, (2) the discount rate is high, (3) the conservation agent is unable to identify *ex ante* the specific units of ecosystem stock that will be protected in the steady state, and (4) policy objectives are "modest." We argue, however, that policy objectives typically imply large changes in the privately optimal steady-state ecosystem stock, and thus the direct payment approach will be substantially more cost-effective. An empirical example illustrates that direct payment initiatives can generate dramatically lower costs for the conservation agent and higher profit levels for the rural residents who control the fate of the ecosystem. Although direct payment initiatives have imposing institutional requirements, we argue that *all* conservation initiatives face similar challenges and we note that recent analyses suggest that direct payment approaches can have lower transaction costs.

Keywords: Economics; conservation; dynamic efficiency; subsidies

JEL classification: H21; Q28

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> "[W]e (the conservation community collectively) have had little impact on stemming or even slowing the rising tide of biodiversity loss. We do not have the luxury to waste time or money on unsuccessful or highly constrained approaches. We must re-examine our paradigms and approaches to increase our effectiveness and efficiency."
>
> - Agi Kiss, Environment Lead Specialist of The World Bank (2001)

I. Introduction

Intact ecosystems provide important global services, including the regulation of climate and the protection of biodiversity. Many valuable and biologically diverse ecosystems, including the majority of tropical rainforests, are located in low-income countries. Low-income nations, however, have limited resources with which to protect their ecosystems and, to date, they have been unable to stem the loss of their native ecosystems. Since the mid-1980s, conservationists have realized that if meaningful ecosystem conservation is to occur in the low-income nations, wealthy nations must provide the citizens of low-income nations with effective incentives.

To help low-income nations conserve their endangered ecosystems, international conservation and development donors have made substantial investments over the last two decades. Between 1988 and mid-1995, the World Bank committed $1.25 billion in loans, credits, and grants for projects with explicit objectives of conserving biodiversity. This money leveraged an additional half billion dollars (Jana and Cooke 1996, p. 107). The United States Agency for International Development spent $650 million each year on its environmental portfolio during the early 1990s (USAID 1994). Non-governmental organizations like Conservation International and the U.S. office of World Wildlife Fund have budgets of up to $100 million a year to spend on international conservation (WWF 2000; CI 2000). Private philanthropic foundations have also spent millions of dollars per year on international biodiversity conservation (MacArthur 2000). In our analysis below, we examine the effectiveness of different approaches to encouraging ecosystem protection in low-income nations.

Among the more common approaches is assistance to ventures that yield commercial outputs and ecosystem protection as joint products. Examples include ecotourism, biodiversity prospecting, non-timber forest product extraction, and low-impact selective logging. These activities typically employ relatively undisturbed ecosystems as inputs. The ecosystems are combined with purchased inputs such as capital and labor to produce a valuable output, such as tourist excursions, novel chemical compounds, fruits, or eco-certified timber. Interventions to support these activities have been initiated by the World Bank, United Nations Environment Program, the Inter-American Development Bank, the Asian Development Bank, the European Union, the bilateral aid organizations of Canada, Germany, the Netherlands, Norway, Sweden, Switzerland, and the United States, and non-governmental organizations such as the World Wildlife Fund, Conservation International, Cultural Survival, and the International Union for the Conservation of Nature (Wells et al. 1992; Brown and Wyckoff-Baird 1994; Conservation International 1994; Cultural Survival 1994; Simpson and Sedjo 1996; Southgate 1998; Honey 1999).

To encourage commercial eco-friendly activities, donor funds are often aimed towards increasing the eco-output price or facilitating the acquisition of complementary inputs, such as tourism infrastructure, product marketing, and processing facilities. The assumption underlying such interventions is simple: local agents, faced with cheaper inputs or higher output prices for an eco-friendly activity, will demand a greater area of intact ecosystem, thereby *indirectly* protecting ecosystems and their constituent services. Indirect approaches that motivate conservation by subsidizing related activities have, in the words of one survey of the subject, "become the predominant approach to most large-scale internationally financed conservation efforts in developing countries" (CIFOR et al. 1999).[1]

An alternative approach to encouraging the conservation of endangered natural ecosystems is to pay for conservation performance *directly*. In this approach, domestic and international actors make payments to individuals or groups that protect ecosystems and thereby supply public services of ecological value. The idea of directly contracting with individuals to maintain resources that have global value is not new (e.g., Barbier and Rauscher 1995; Barrett 1995; Simpson and Sedjo 1996; Ferraro and Simpson 2000; Ferraro 2001a). We are not aware, however, of any analysis comparing the dynamic efficiency of direct payment interventions to the indirect interventions that have, to date, been more widely adopted in low-income countries. Our intention is to begin to fill this analytical gap.[2]

We examine the dynamic efficiency of direct and indirect subsidies to preserve a given area of ecosystem. We demonstrate that, consistent with standard results in the public finance literature, the direct payment achieves a given level of ecosystem protection with the least

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1 Such approaches occur as elements of "integrated conservation and development projects (ICDPs)," "gestion de terroirs" and "community-based natural resource management."

2 There have been a number of contributions to the public finance and environmental economics literatures that consider choices between taxes or subsidies and interactions between them; e. g., Fullerton and Wolverton, 1997; Goulder, *et al*., 1997; Eskeland and Devarajanm, 1996. Little previous work, however, has focused on the cost-effectiveness of alternative subsidies. Exceptions include Fuest and Huber (2000), who use a static bargaining argument to explain why governments often choose indirect investment subsidies rather than wage subsidies to boost employment, and Ferraro and Simpson (2000), who analyze the static efficiency of direct payments in the conservation context. We are not aware, however, of any previous work focusing on the dynamic efficiency of alternative subsidies.

overall distortion. However, from the perspective of the conservation agent who is spending funds from a limited budget to protect an ecosystem, we demonstrate that the direct payment will not necessarily be the most cost-effective policy. The indirect payment approach can be more cost-effective in the eyes of the conservation agent when four conditions hold: (1) the discount rate is high, (2) own-price input effects are only moderately larger than cross-price effects, (3) conservation objectives are "modest" (i.e., the socially desired stock of ecosystem is only slightly higher than the privately optimal stock), and (4) the conservation agent is unable to identify *ex ante* the specific units of ecosystem stock that will be protected in the steady state. The fourth condition implies that a conservation agent must pay for ecosystem stock that is protected in the transition but may be ultimately cut before arrival at the steady state. This condition makes it possible for the other three conditions to render the indirect subsidy approach more cost-effective. The possibility that the indirect subsidy approach can be more cost-effective for a conservation funding agent arises only in a dynamic model and has no counterpart in the static literature on direct versus indirect subsidies for ecosystem protection (Ferraro and Simpson 2000).

Our results also indicate, however, that when conservation agents wish to conserve a large proportion of the original standing stock of ecosystems that would otherwise be converted to other uses, the direct payment can be dramatically more cost-effective. We use numerical analysis to illustrate each possible outcome and, using data from Africa, we offer an empirical example that suggests direct payment conservation initiatives may offer substantial cost-savings to global conservation initiatives. We conclude our analysis by discussing the institutional aspects of direct and indirect ecosystem conservation approaches.

II. Direct Payment Programs in Action

Paying individuals or groups for supplying goods and services of ecological value is not merely a speculative proposal. Ferraro and Simpson (2000) and Ferraro (2001a) describe a variety of such programs already in operation. The best-known conservation payment initiatives are those found in Europe and the United States, where government agencies spend several billion dollars annually on conservation payments to farmers. Local and state governments and non-governmental organizations (NGOs) worldwide are also actively involved in direct approaches to ecosystem conservation. For example, local and state governments in the U.S., Costa Rica, and Brazil give property tax breaks to landowners who manage their land for environmental amenities. In North America, the Delta Waterfowl Foundation's "adopt-a-pothole" program pays prairie farmers who protect nesting areas for ducks (Delta Waterfowl Foundation 2000). In the United States, the Nature Conservancy pays landowners an annual annuity in return for the rights to log the forest in ways that are compatible with the protection of terrestrial and aquatic biodiversity (Gilges 1999).

Although rare outside of high-income countries, nascent direct payment programs can also be found in the low-income nations. In Guatemala, the Forestry Incentives Program (PINFOR) delivers direct payments to forest stewards who manage forests for conservation goals (World Bank 2000a). In the last four years, Costa Ricans have created institutional mechanisms through which local, national, and international beneficiaries of ecosystem services compensate those who protect ecosystems (Castro et al. 1998; Calvo and Navarrete 1999). Conservation International (CI) recently negotiated "conservation concessions" (long-term leases) that stipulate CI will make periodic payments to the governments of Guyana and Peru in return for the right to protect rain forest concessions for conservation goals (Abelson 2000). Conservation payment programs are underway in El Salvador, Colombia, Honduras, and Panama (Stefano Pagiola, World Bank, per. comm. 2000) and are being considered in Madagascar (PAGE 2001).

Reading the project documents that outline the rationale for these nascent direct payment programs, we observed that political issues (e.g., justice and fairness) and concerns over the ineffectiveness of indirect conservation investments (e.g., investments send unintended signals to rural residents) motivate the current experimentation with conservation performance payments. The dynamic efficiency aspects of direct payment programs have been ignored, yet for budget-constrained conservation agents, efficiency is an absolutely critical criterion. In the remainder of the paper we look at conditions under which direct conservation payment initiatives can be more cost-effective than the indirect conservation interventions more commonly encountered in low-income nations.

III. Model

Rural Resident

A rural resident stands on the edge of a forest frontier with a fixed stock of forest in front of her. She can clear the forest for agriculture or maintain the land under forest cover. Clearing the forest for agriculture yields private benefits to the farmer in the form of agricultural output that can be consumed or sold. Maintaining the forest in its natural state produces social benefits to the global community by providing ecosystem services (e.g., hydrological regime maintenance, carbon sequestration) and shelter to endangered species. Maintaining the forest in its natural state can also produce private benefits for the farmer through "eco-friendly" production activities, which are described below.

We will refer to $F_t \geq 0$ as hectares of forest in period t = 0, 1, 2,…, ∞, but F_t can represent any type of ecosystem. Normalizing the size of the tract of forest, we write $F_0 = 1$. Let $A_t \geq 0$ denote the fraction of the original forest stock in agriculture, where initially $A_0 = 0$. In any period, $F_t + A_t = 1$. Let $C_t \geq 0$ denote the fraction of the original forest stock cleared of timber in period t. The dynamics of forest and agricultural land are given by the first-order difference equations $F_{t+1} - F_t = -C_t$ and $A_{t+1} - A_t = C_t$. We assume that it is impossible to recreate, on an economically relevant time horizon, the complex ecological functions of ecosystems like a tropical rain forest and thus we model the ecosystem as a nonrenewable resource.

In addition to having the option of clearing the forest for agriculture, the rural resident can also use the forest to produce a quantity Q_t of an "eco-friendly" product using a concave production technology, $Q_t = Q(K_t, F_t)$. The eco-production technology represents an economic activity (e.g., tourism) that allows ecosystem services (e.g., biodiversity) to flow relatively unimpeded from the ecosystem used in eco-production.[3] Examples of eco-friendly activities include eco-tourism, non-timber forest product extraction and bioprospecting (the search among diverse natural organisms for commercial products of industrial, agricultural, or pharmaceutical value). The eco-production process requires <u>intact</u> forest for production. Agriculture, which requires that forest be cleared, and eco-production are thus mutually exclusive.

We will refer to $K_t \geq 0$ as the accumulated stock of capital, but it might be more broadly interpreted as any input or aggregate of other durable inputs. What we are calling "capital"

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3 A concave production function assumption is warranted for reasons other than simply ensuring that the Maximum Principle conditions will be sufficient for identifying a maximum. Eco-production processes are unlikely to be replicable and thus unlikely to exhibit constant returns to scale. Many eco-friendly production processes, like eco-tourism, are centered on unusual and unique features. Moreover, surviving areas of natural habitat are often found in landscapes that are not served by dense road networks. The replication of production processes would involve the replication of transportation opportunities. Improved rural transportation networks, however, have consistently been identified as playing an important role in ecosystem degradation and loss (Kaimowitz and Angelsen 1998).

would include inputs like hotels, trails, collecting equipment and human capital, such as knowledgeable guides or individuals with taxonomic skills. Let $I_t \geq 0$ denote the investment in capital infrastructure. The change in the capital stock follows the first-order difference equation $K_{t+1} - K_t = -vK_t + I_t$, where $v > 0$ is the depreciation rate on capital and $K_0 = 0$. The eco-production model could be generalized to consider multiple inputs and quality-adjusted quantities of eco-output.

We assume that the rural resident behaves as a present-value profit maximizer with competitive conjectures in both input and output markets. Prices are assumed constant. Let $P_Q > 0$ denote the unit price of eco-output, $P_K > 0$ the unit cost of investment, $P_T > 0$ the net revenue from timber harvested from a hectare of forest, and $P_A > 0$ the net revenue from agricultural yields on a hectare of agricultural land.

International Conservation Organization (ICO)

We assume that in the absence of outside intervention, the rural resident uses, and thus protects, a portion of the original forest stock for eco-production. However, an outside agent, the "International Conservation Organization (ICO)," also receives benefits from intact forest and wishes to induce a greater area of locally protected forest than the rural resident would achieve under prevailing private incentives.

In our analysis, the ICO has two options: an *indirect* intervention or a *direct* intervention. An indirect intervention renders eco-production more profitable by subsidizing the eco-output price or the acquisition of capital. Indirect subsidies induce the rural resident to use more forest in eco-production, thereby *indirectly* protecting a greater area of forest. In the analysis below, we consider the ICO offering a subsidy, $S_K \geq 0$, on each unit of capital purchased by the rural resident for eco-production. The qualitative results of the analysis of a subsidy on eco-output are similar and are not reproduced here.

A direct intervention refers to performance payments made by the ICO for forest protection. Let $S_F \geq 0$ denote the payment made by the ICO for each hectare of intact forest in period t.

In period t, the rural resident would have a net cash flow given by

$$\pi_t = P_Q Q(K_t, F_t) - (P_K - S_K) I_t + P_T C_t + P_A (1 - F_t) + S_F F_t \qquad [1]$$

Let $\rho = 1/(1+\delta)$ be the discount factor employed by the rural resident, where δ is the per period rate of discount. Our specification of the profit function implies that the ICO makes a payment (S_F or S_K) for every unit of forest or capital used in eco-production in period *t*.

In particular, we are implicitly assuming that the ICO is unable to identify *ex ante* the specific units of ecosystem stock that will be protected in the steady state and thus the ICO may make payments in period *t* for protected forest that will be cleared in subsequent periods. We believe the assumption is reasonable. Conservation donors recognize that enforcement institutions are weak in low-income nations. The increasing popularity of conservation performance payments stems in part from their ability to allow the conservation donor to retain leverage to induce the local agent to continue protecting forest over time. The donor cannot credibly commit to recovering a lump-sum payment, or to stopping payments on other areas that are still intact, if a rural resident converts a forest parcel to other uses. With periodic payments, however, the donor can stop the flow of payments if a parcel is deforested. The donor pays for intact forest each period. If a rural resident cuts a unit of forest in period *t*, she receives no payment for that unit from the point at which it was cut into perpetuity. Even in a world of medium-term conservation contracts (e.g., U.S. Conservation Reserve Program), farmers often calculate that it is not optimal to put certain areas of land into production over the next 5-10 years and so they allocate the areas to conservation contracts. When the contracts are up, however, farmers often convert the ecosystem to agriculture, housing developments or other non-environmental uses. The farmers do not receive any future payments via contract renewal, but there is nothing the conservation agent can do about recovering previous payments: the contract stipulated that payments would be made as long as the forest remained intact during the relevant period.

The rural resident's problem is

$$\max_{C_t, I_t} \sum_{t=0}^{\infty} \rho^t \pi_t$$

Subject to $F_{t+1} - F_t = -C_t$

$$K_{t+1} - K_t = -\nu K_t + I_t \qquad [2]$$

$$F_0 = 1,\ K_0 = 0$$

The current-value Hamiltonian for this optimization problem is

$$H_t = \pi_t - \rho\lambda_{F,t+1} C_t + \rho\lambda_{K,t+1}(-\nu K_t + I_t) \qquad [3]$$

The Hamiltonian is linear in the control variables. The optimal controls are determined by the switching functions, $\sigma_{C,t} = P_T - \rho\lambda_{F,t+1}$ and $\sigma_{I,t} = -(P_K - S_K) + \rho\lambda_{K,t+1}$. We assume that fixed factors may lead to upper-bound constraints on the rate of forest clearing and investment so that $C_{max} \geq C_t \geq 0$ and $I_{max} \geq I_t \geq 0$. These constraints may or may not be binding. When the constraints are not binding, the approach path to the steady state is a Most Rapid Approach Path. With binding control constraints in a two-state variable, two-control variable problem, the dynamics are more complicated (see, for example, Clark et al. 1979). In the Section VI, we discuss in more detail the role that the upper-bound constraints play in determining the optimal approach.

Along an optimal approach, and at the steady-state optimum, the multipliers on the forest and capital stocks must satisfy the following equations:[4]

$$\rho\lambda_{F,t+1} - \lambda_{F,t} = \frac{-\partial H}{\partial F_t} = -[P_Q Q_F(\cdot) - P_A + S_F] \qquad [4]$$

and

$$\rho\lambda_{K,t+1} - \lambda_{K,t} = \frac{-\partial H}{\partial K_t} = -[P_Q Q_K(\cdot) - v\rho\lambda_{K,t+1}] \qquad [5]$$

where $Q_F(\cdot)$ and $Q_K(\cdot)$ are the partial derivatives of $Q(K_t, F_t)$ with respect to F_t and K_t. At the steady-state optimum, $\sigma_{C,t} = 0$, $\sigma_{I,t} = 0$, $\lambda_{F,t+1} = \lambda_{F,t} = \lambda_F$ and $\lambda_{K,t+1} = \lambda_{K,t} = \lambda_K$. At the steady state, the switching functions and the last two equations imply

$$P_Q Q_F(\cdot) = \delta P_T + P_A - S_F \qquad [6]$$

$$P_Q Q_K(\cdot) = (\delta + v)(P_K - S_K) \qquad [7]$$

Equation [6] says that, at the steady-state optimum, the marginal value product of forest in eco-production must equal the interest foregone on net timber revenue per hectare plus the net revenue foregone on an additional increment of land in agriculture less any direct subsidy paid by the ICO per hectare of intact forest. Equation [7] says that, at the steady-state optimum, the marginal value product of capital in eco-production must equal the foregone interest on the net cost of investment, where the discount rate is augmented by the depreciation rate on capital.

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[4] These conditions hold as long as I_{max} is not very small. If it is very small, the approach path and the steady state itself may change; specifically, $\sigma_{C,t}$ and $\sigma_{I,t}$ may not equal zero and one could observe values of forest and capital stock in the steady state that are lower than predicted by equations [6] and [7]).

IV. The Overall Costs of Conservation

Let us first compare the overall costs of the indirect and direct conservation interventions. Overall costs are defined as the cost to the ICO, less the additional profits to the rural resident, from achieving a given level of steady-state protected forest. Thus we compare the costs of a forest payment and a capital subsidy that generate the *same* increase in protected forest (and hence, under our assumptions, used in eco-production).

In the appendix, we demonstrate that one can approximate the incremental overall cost of using the indirect conservation approach instead of the direct payment approach by

$$S_K \frac{(dK_I - dK_D)(v+\delta)}{2\delta} > 0 \qquad [8]$$

where dK_I is the additional steady-state capital used beyond the privately optimal steady-state level when the rural resident is faced with an indirect capital subsidy and dK_D is the additional steady-state capital used beyond the privately optimal steady-state level when the rural resident is faced with an equivalent direct forest payment. We demonstrate in the appendix that $dK_I >$ dK_D; i.e., the indirect intervention induces higher capital use than does the direct intervention. The positive sign of expression [8] implies that the direct payment for forest protection achieves a one unit increase in intact forest with the least overall distortion. [5]

For linear capital demand, unbinding upper-bound constraints and small changes in the steady-state protected forest area, the approximation in [8] is exact. Note that the term $(v + \delta)/2\delta$ is greater than one when depreciation is greater than the discount rate and less than one otherwise. In either case, the overall cost of using the indirect approach increases at a faster rate than an increase in the indirect subsidy (e.g., double the indirect subsidy and the overall costs

[5] The lower capital use of the direct payment approach is also desirable if one considers that even "eco-friendly" activities may result in some degradation of ecosystem quality, and such degradation is often positively correlated with the employment of capital and other inputs (e.g., more hotel rooms shelter more tourists who increase the impact on a park).

more than quadruple). As we demonstrate in the empirical example of section VII, the overall cost differences between direct and indirect approaches can be substantial.

V. The Costs to the International Conservation Organization

Although a direct payment may achieve a given level of conservation at the least overall cost, conservation agencies with limited budgets, not a social planner, dictate the choice of intervention. Thus, the "cost to the ICO" might be a more important criterion for comparing direct and indirect approaches than "overall cost."[6] Although one might think that achieving a socially desirable allocation at least cost would also ensure the lowest cost for the ICO, our analysis shows otherwise. We demonstrate that there are conditions under which the ICO would find it cheaper to achieve a given level of conservation under an indirect incentive approach. Such an outcome can occur because an ICO may pay for ecosystem stock that is protected in the transition but is ultimately cut before arrival at the steady state. An ICO is more likely to find the indirect approach cheaper when (1) the own price effects for inputs are not much stronger than their cross-price effects, (2) the discount rate is high, and (3) the ICO desires only a small increase in the steady-state forest stock above the private, no-subsidy steady-state forest stock. We argue in later sections that such conditions, particularly the third one, are unlikely to be widespread in areas of high conservation priority, and thus the ICO will generally find the direct payment approach to be more cost-effective.

In the following analysis, we assume that $C_{MAX} \geq (F_0 - F^*) = (1 - F^*)$ and $I_{MAX} \geq K_I^*$, and thus the optimal forest stock and the optimal capital stock are reached at the beginning of

[6] If the ICO purchases or leases an area of ecosystem *and* performs the eco-friendly activity (or sells a concession), "overall costs of conservation" and "ICO costs" are the same (see, for example, The Nature Conservancy forestry initiative described in Section II).

t=1. The effects of clearing and investment constraints (i.e., C_{max} and I_{max}) on the approach path to the steady-state stocks are considered in the next section.

If the ICO uses a direct payment, its costs are the payment it makes in the first period and the discounted stream of payments it makes in every other period when forest is at its steady-state level; i.e., $S_F F^0 + \frac{1}{\delta} S_F F^*$, where S_F is the per unit direct payment, F^* is the steady-state stock of forest when the ICO pays S_F, $F^0 = 1$ is the initial forest stock, and d is the discount rate.

If the ICO uses an indirect capital subsidy, its costs will be

$S_K K_I^* + \frac{1}{\delta} S_K I_I^* = S_K K_I^* + \frac{1}{\delta} S_K v K_I^*$, where S_K is the per unit capital subsidy, *v* is the depreciation rate, I_I^* is the steady-state investment level when the ICO pays S_K, and K_I^* is the steady-state stock of capital when the ICO pays S_K.

We want to know when the direct payment approach will cost the ICO more than the indirect capital subsidy approach to achieve the <u>same</u> <u>level</u> of protected forest; i.e., when is

$S_F F^0 + \frac{1}{\delta} S_F F^* > S_K K_I^* (1 + \frac{v}{\delta})$?

We demonstrate in the appendix that, for small payment levels, a necessary and sufficient condition for the direct payment approach to cost more is

$$S_F \left(\frac{Q_{KK}}{Q_{FK}^2 P_Q} \right) > \frac{-Q_{KK}}{Q_{FK}} K_P^* - (F_P^* + \delta) \qquad [9]$$

where Q_{ij} are second partial derivatives of the production function evaluated at the steady state (K_P^*, F_P^*), where K_P^* is the original, privately-optimal steady-state capital stock and F_P^* is the original, privately-optimal steady-state forest stock when there are no ICO payments. The term $\frac{-Q_{KK}}{Q_{FK}} K_P^*$ is positive but $-(F_P^* + \delta)$ is negative, so the right-hand side of [9] is ambiguous. The left-hand side of [9] is negative. Thus, the only way that [9] can be satisfied is when both sides are negative and $\left| S_F \left(\frac{Q_{KK}}{Q_{FK}^2 P_Q} \right) \right| < \left| \frac{-Q_{KK}}{Q_{FK}} K_P^* - (F_P^* - \delta) \right|$.

The greater the forest payment, S_F, is, the less likely expression [9] will be satisfied and the less likely that the ICO would find the indirect subsidy approach to be more cost-effective than the direct payment approach. The smaller F_P^* is, the less likely that the right-hand side of [9] will be negative and the less likely that the ICO would find the indirect subsidy approach to be more cost-effective than the direct payment approach. In other words, the greater the distance between the privately optimal forest stock level of the rural resident and the forest stock level desired by the ICO (implying S_F and F* relatively large and F_P^* relatively small), the more likely that the ICO will find the direct payment approach more cost-effective than the indirect subsidy approach. The intuition underlying expression [9] is simple: when the distance between the privately optimal forest stock level chosen by the rural resident and the forest stock level desired by the ICO is small, an ICO adopting a direct payment approach pays for a substantial amount of forest that is protected in the transition to the steady state, but is ultimately converted to agriculture. Since (1) conservation biologists generally believe that most endangered ecosystems are threatened with severe depletion and fragmentation (i.e., F_P^* small; Pimm et al. 2001); and (2) conservation practitioners generally aim their interventions at protecting the majority of the targeted ecosystem (i.e., S_F and F* large), conservation groups and donors will likely find that direct payments are more cost-effective.

Requiring the right-hand side of expression [9] be negative gives us a sufficient condition for the ICO to prefer the direct payment approach:

$$\frac{-Q_{KK}}{Q_{FK}} K_P{}^* - F_P{}^* - \delta > 0 \qquad [10]$$

For any positive direct payment offered, the direct approach could never be more costly than an equivalent indirect subsidy if expression [10] is satisfied. With the exception of the discount rate, expression [10] is identical to the sufficient condition derived in the static framework by Ferraro and Simpson (2000) that indicates when direct payments are more cost-effective than indirect subsidies.[7] They show that their condition holds as long as own-price input effects are larger than cross-price effects, which they note holds for most commonly specified production functions including homothetic production technologies. In the dynamic context, however, the discount rate drives an additional wedge between own-price effects and cross-price effects by capturing the effect of payments made on forest stock protected in transition but ultimately cut before the steady state is reached.[8] Thus under scenarios of high discount rates and moderate own-price effects relative to cross-price effects, expression [10] may not be satisfied and it is possible, depending on the payment levels offered, that the direct payment approach could be more costly to the ICO (i.e., when payments are small or, equivalently, when policy objectives are modest). In the next section, we examine such a case.

VI. Empirical Example: Ranomafana National Park, Madagascar

From 1991-1995, one of the authors participated in a conservation field initiative in the eastern rain forests of Madagascar.[9] Since 1990, conservationists working at the 41,500 hectare Ranomafana National Park have been attempting to encourage local residents living around the

[7] Ferraro and Simpson actually use a dual formulation, but Ferraro (2001b) presents the same results using the primal approach.
[8] Allowing the ICO to pay only for those units of forest that are protected in the steady state yields the equivalent of expression [9] with $\delta = 0$.
[9] The project was funded by the Sophie Danforth Conservation Biology Fund of the Rhode Island Zoological Society, by the Rainforest Alliance's Kleinhan's Fellowship, and by the Biodiversity Support Program (Grant #7529) of the World Wildlife Fund, World Resources Institute and the Nature Conservancy.

park to protect the park's rain forest ecosystem. The goal of the project in which the author was involved was to increase the value of intact ecosystems by providing support for three commercial eco-production activities: forest management, bee-keeping, and aquatic species management (Ferraro and Razafimamonjy 1993). In the following empirical example, we compare the cost-effectiveness of the bee-keeping initiative to that of a direct forest subsidy scheme.

The underlying assumption of the apiculture initiative is simple. The production of honey and beeswax requires nectar and pollen inputs from melliferous plants, which are found in the rain forest. Larger apiculture operations around the park require larger areas of forest protected and thus *indirectly* generate local conservation incentives. Bee-keeping as a means to promote conservation is quite popular and descriptions of such initiatives can be found in many conservation project documents (e.g., Ambougou 1993; PPNR 1995; Borrini-Feyerabend 1997).

The bee-keeping initiative targets the semi-modern regional apiculture technology that uses top-bar hives housed in wooden boxes. As in our previous analytical exercises, we view the production of honey as a function of forest, F, and capital, K. An apiculturalist allocates a fixed number of labor units per bee-box and thus we take advantage of this complementarity to combine labor and bee-boxes into the variable K. The bee-boxes are placed near villages at the edge of forests. The foraging pattern of bees, the finite supply of food per unit area of forest and the prohibitive labor cost of safeguarding hives placed inside the forest lead to a decreasing returns to scale production technology. Our estimate of the production technology is based on data from Ferraro and Razafimamonjy (1993) and Ralimanan (1994): $Q_t = 70\,K_t^{0.36} F_t^{0.15}$, where Q is liters of honey, K represents two bee boxes, and F is hectares of forest. As in the analytical work in section III, we normalize each household's available forest area to one. Price data come from Ferraro and Razafimamonjy (1993) and Ferraro (1994). Analytical solutions for a Cobb-Douglass eco-production specification and our finite-horizon approximation to the infinite-horizon problem are described in the appendix.

The current approach in Ranomafana is to subsidize the construction and acquisition of bee-boxes. In the analysis below, we compare the current capital subsidy approach to a conservation approach that relies on direct forest payments. We assume all prices are exogenous because the Ranomafana region is a small part of the total amount of honey produced in Madagascar. Based on data from household surveys conducted around the park (Ferraro 1994) and an assumed park management objective of preventing deforestation in an area of 30,000 hectares around the park's core of 11,500 hectares, we estimate that there are 2000 households immediately at the frontier of the park's boundary and each household has access to 15 hectares of forest. A 30,000 hectare ring around the core represents a penetration by rural residents of 5 kilometers from the park's boundary, which is considered the maximum likely penetration given the location of existing social and transportation infrastructure. The parameter values and the privately optimal steady-state solution are presented in Table 1. Without any intervention by an outside conservation agent, less than 4% of the existing stock of forest would remain standing in the steady state (t = 20 years and beyond).

Expression [10] is not satisfied for the apiculture parameter values and thus for any small incremental increase in forest stock desired by an ICO we anticipate that the indirect payment approach could be more cost-effective, but for large incremental increases in forest stock the direct payment approach would be more cost-effective. In fact, this is what we observe. If the ICO desires to increase the steady-state stock of forest by about 2% over F_P^*, it can make a direct payment of \$6.67/ha or a capital subsidy of \$0.81/bee-box. The costs of the capital subsidy to the ICO are about 40% of the costs of the direct payment approach. The rural resident, however, prefers the direct payment approach because profits are higher by 16%. Our results stand in stark contrast to those derived by Ferraro and Simpson (2000) in their static apiculture example: for a conservation objective of inducing each household to increase their forest stock by 0.10 hectares (an increase of < 1% from F_p^*), they found that an ICO incurs substantially fewer costs under the direct approach and the rural resident enjoys higher profits under the indirect approach. In a dynamic context, the policy implications are reversed.

Table 1 – Ranomafana National Park: Parameter Values and Solution

Parameters		**Solution**	
α	70	F_P^* (% F_0)	0.038
β	0.36	K_P^* (2 boxes)	11.33
γ	0.15	Q_P^*	102.72
δ	0.20	I_P^*	6.80
v	0.60	A_P^* (% F_0)	0.962
P_T	$10/ha	C_P^*	0.00
P_K	$2.04/ beebox plus labor	*Present Value of* π	$1418
P_A	$25/ha		
P_Q	$1/liter		
C_{max}	0.075		
I_{max}	15		

As the ICO's conservation target increases, however, the direct payment will become more cost-effective. At a conservation target of 11% of the original forest stock ($15/ha or $1.56/box), the costs to the ICO are 42% lower under the direct payment approach *and* rural resident profits 9% higher. Based on results from numerical simulations in Section VII, we expect that the direct payment approach will remain preferred by the ICO for further increases in the conservation target, but eventually the profits to the rural resident will be higher under the indirect subsidy approach.

Based on documents of the Ranomafana National Park Project (PPNR 1995), we anticipate that the conservation target in Ranomafana is likely to be much higher than a few percentage points above the privately optimal steady-state forest stock. For three realistic conservation targets (67%, 75%, and 100% of the original stock F_0), we present, in Table 2, (1) the required forest payment and capital subsidy; (2) the steady-state capital values; (3) the ICO's costs under the direct and indirect approach; (4) the incremental profits to the rural resident under each approach; (5) the payments made under each approach for each incremental hectare above the privately optimal steady-state forest stock; and (6) the incremental overall cost of using the indirect approach.[10] Table 3 presents the results at the level of the entire Ranomafana National Park (all 2000 households).

There are several important points that can be derived from Tables 2 and 3:

(1) The costs to the ICO when it uses an indirect subsidy approach are eighty-four to one hundred and sixty-seven times the costs incurred under the direct payment approach.[11]

(2) The total profits to the rural agent are two to three times higher when the ICO chooses the indirect subsidy approach.

[10] If we assumed a 20-year contract rather than an infinite horizon, the cost and incremental profit values change by only a few dollars.
[11] If the ICO uses a 5% discount rate, the total costs of the indirect approach would be ninety-three to one hundred sixty-six times the total costs of the direct approach. Allowing for differing discount rates between the ICO and the rural resident can make the dynamics more complicated for some parameter values and is addressed in a different paper.

Table 2 – Ranomafana National Park (Household Level)

Per Household Values Using Indirect Capital Subsidies (S_K) and Direct Forest Payments (S_F)									
Forest Target	*Direct Pay/ha (S_F)*	*Indirect Pay/box (S_K)*	K_D^*	K_I^*	*ICO Cost Direct*	*ICO Cost Indirect*	*Incremental π Direct*	*Incremental π Indirect*	*Overall Cost*
67%	$24.00	$2.00	22	9900	$1,714	$143,359	$1,455	$4,967	$138,132
75%	$24.25	$2.01	23	12921	$1,811	$187,213	$1,473	$5,507	$181,368
100%	$24.79	$2.02	24	25486	$2,231	$372,824	$1,516	$7,165	$364,944

Table 3 – Ranomafana National Park (Park Level)

Total Values Using Indirect Capital Subsidies (S_K) and Direct Forest Payments (S_F)									
Forest Target	*Direct Pay/ha (S_F)*	*Indirect Pay/box (S_K)*	K_D^*	K_I^*	*ICO Cost Direct*	*ICO Cost Indirect*	*Incremental π Direct*	*Incremental π Indirect*	*Overall Cost*
67%	$24.00	$2.00	44,383	19,800,055	$3,428,729	$286,718,270	$2,909,443	$9,934,584	$276,264,400
75%	$24.25	$2.01	45,572	25,842,317	$3,622,078	$374,426,880	$2,945,692	$11,014,123	$362,736,371
100%	$24.79	$2.02	48,751	50,971,266	$4,462,190	$745,648,878	$3,032,816	$14,330,804	$729,888,700

(3) Without relaxing I_{max} substantially, the ICO could not achieve *any* of the three conservation targets by using an indirect capital subsidy approach (we relaxed I_{max} to a value slightly above I_I^* for the indirect subsidy analysis). Furthermore, the steady-state capital under the indirect approach is unrealistically high – at much lower stocking rates, crowding among bee populations would lead to colony flight.

Some readers might interpret point (2) above as suggesting that the rural resident will always prefer the indirect approach at high conservation target levels, but it is important to note that we did not consider the ICO's budget constraint in the analysis above. In general, an ICO may have a conservation target in mind, but it is constrained by its available funds. In 1991, the Ranomafana National Park Project received $3.237 million dollars from the U.S. Agency for International Development, $29,000 from the Government of Madagascar, and $654,000 from other participating organizations (USAID/Madagascar 1991). If we assume that 5% of that money would be spent on administration no matter which approach was adopted, $3.724 million dollars remains for conservation investment. If the ICO adopts the direct approach, $3.724 million dollars would protect 80% of the original forest stock, while only protecting 12% using the indirect subsidy approach. Furthermore, rural resident profits would increase by more than 100% under the direct payment approach, while only increasing 44% under the indirect approach. Thus given an ICO budget constraint, both the ICO and rural residents are better off under a direct payment approach.

VI. Numerical Simulations

In this section, we explore in more depth the factors that affect the performances of direct and indirect conservation approaches and we characterize the possible policy outcomes. As in the previous section, we consider the case when the eco-production function takes the Cobb-Douglas form, $Q_t = \alpha K_t^{\beta} F_t^{\gamma}$. With a Cobb-Douglas eco-production specification, expression [10] reduces to:

$$\frac{(1-\beta-\gamma)}{\gamma} F^{*} > \delta \qquad [12]$$

In the static framework of Ferraro and Simpson (2000), the ICO finds the direct payment approach more cost-effective as long as the Cobb-Douglas production function exhibits decreasing returns to scale, so that the left-hand side of [12] need only be greater than zero. In the dynamic case, the presence of a positive discount rate opens up the possibility that the indirect subsidy approach could be more cost-effective. The discount rate captures the value of direct payments that an ICO makes for protected forest stock that may ultimately be cut before the steady state is reached.

Table 2

Parameter Values: $P_K = 1.5$; $P_A = 0.4$; $P_T = 1.4$; $\alpha = 1$						
% Increase in Privately Optimal Steady-State Forest Stock	**Case A: $\beta = 0.5$; $\gamma = 0.3$; $\delta = 0.1$; $v = 0.1$**			**Case B: $\beta = 0.25$; $\gamma = 0.3$; $\delta = 0.3$; $v = 0.3$**		
	Indirect Cost – Direct Cost	Indirect π – Direct π	Overall Costs Using Indirect	Indirect Cost – Direct Cost	Indirect π – Direct π	Overall Costs Using Indirect
< 1 %	0.0054	0.0052	0.0002	-0.0051	-0.0053	0.0002
6 %	0.1097	0.0073	0.0325	0.1403	-0.0536	0.1940
20 %	0.4222	0.2330	0.1892	3.3372	0.1603	3.1769
95%	2.9950	1.0690	1.8860	150.18	2.3997	147.78
				$\underline{S}_F = 0.145$; $\overline{S}_F = 0.310$		

In Table 2, Case A represents the case in which expression [10] is satisfied and thus the direct payment is more cost-effective than the indirect subsidy for any incremental increase in the steady-state forest stock protected (i.e., Present Value of Indirect Cost – Present Value of Direct Cost > 0). Case B represents the case in which expression [10] is not satisfied and the ICO finds that the indirect subsidy approach has a lower present-value cost for small incremental increases in the steady-state forest stock (i.e., the case examined in Section VI).

These cases are represented graphically in Figures 1 and 2. Case A is illustrated in Figure 1. The direct payment level, S_F, is on the horizontal axis and ICO costs and rural resident incremental profits are on the vertical axis. Indirect cost and incremental profit curves represent the cost and profit of an equivalent capital subsidy that induces F^*. Thus each curve traces out the steady-state equilibria as the direct payment and equivalent indirect subsidy increase from zero. In Case A, the indirect approach is always more costly than the direct payment approach and thus the indirect subsidy cost curve is everywhere higher than the direct payment cost curve. The profit to the rural resident under the indirect subsidy is always higher than the profit under the direct payment. Thus, for a given conservation target, the preferences of the ICO and the rural resident are opposed. This outcome is the only possible outcome in the static framework of Ferraro and Simpson (2000).

In the dynamic framework, however, the ICO and the rural resident can prefer the direct approach simultaneously. In cases where expression [10] is not satisfied, the cost curves cross as they do in Figure 2 at payment level $\underline{S_F}$. Given our result from section IV, indicating that the direct payment approach generates the least overall costs (i.e., both agents never simultaneously prefer the indirect approach), the incremental profit curves must cross at some payment level

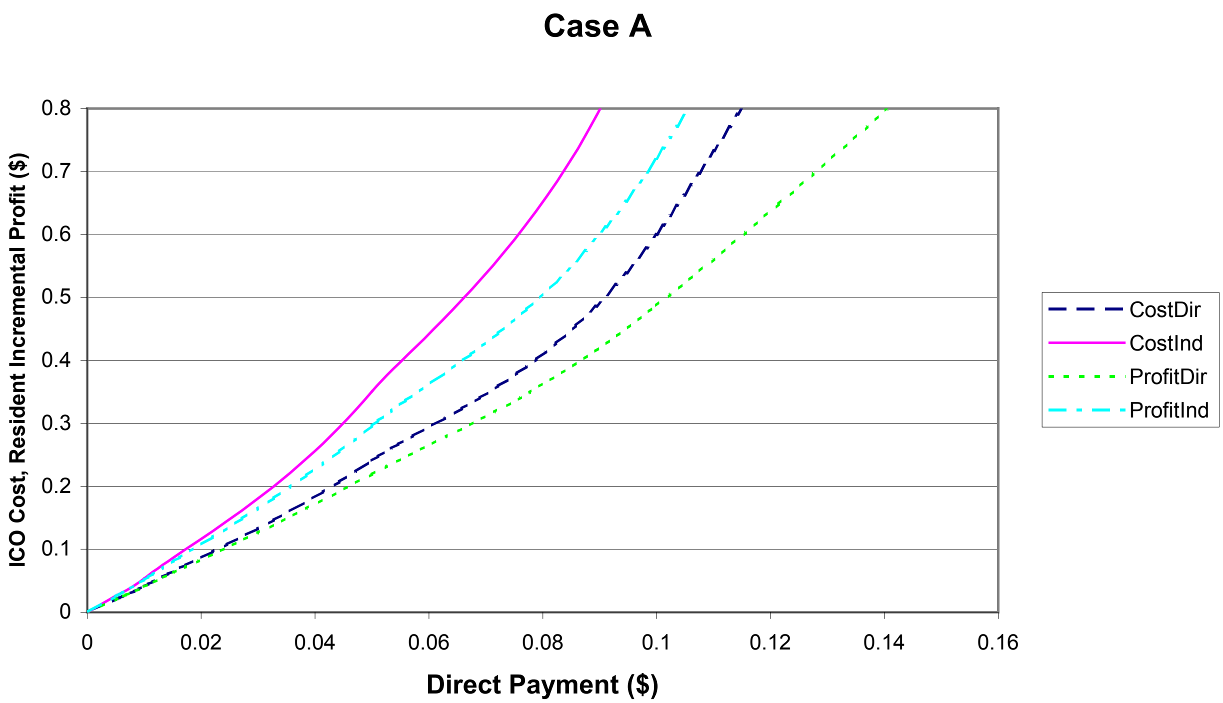

Figure 1

$\overline{S_F} > \underline{S_F}$.[12] When the payment level, S_F, is small, the ICO prefers the indirect approach and the rural resident prefers the direct approach. As the ICO raises its target level of protected forest, the requisite payment level increases and there is a range of payment levels in which both agents prefer the direct approach; namely on the interval $[\underline{S_F}, \overline{S_F}]$. As the required payment becomes large, however, the rural resident will begin to prefer the indirect approach. Not indicated on the figures is the payment level, $S_F^{100\%}$, at which the entire original forest stock, F_0, is conserved in the steady state.[13] Based on the efficiency results in Section IV, $S_F^{100\%} > \underline{S_F}$, but it is possible that $S_F^{100\%} < \overline{S_F}$ (the direct payment approach is always preferred by the rural resident).

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[12] One can show that the cost and incremental profit curves are convex and thus cross a maximum of one time.
[13] In Case A, $S_F^{100\%} = 0.21$, and in Case B, $S_F^{100\%} = 0.62$.

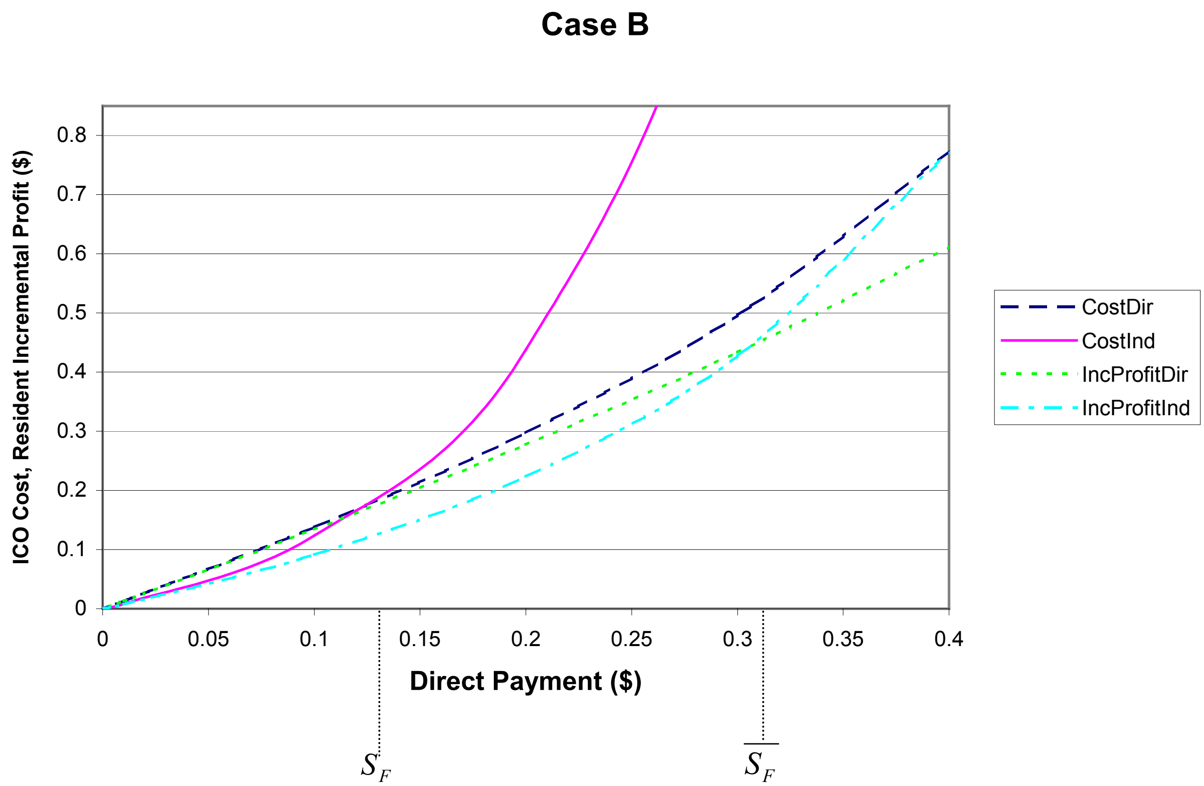

Figure 2

Thus, we identify three possible outcomes depending on the parameter values and the ICO's conservation objective: (1) the ICO prefers the direct approach and the rural resident prefers the indirect approach; (2) the ICO and rural resident both prefer the direct approach; and (3) the ICO prefers the indirect approach and the rural resident prefers the direct approach. When the policy preferences of the rural resident and ICO are opposed, the direct payment approach has the lowest overall costs and thus there is always the potential for the agent benefiting from the direct approach to compensate the other agent so that they both prefer the direct approach.

We also explored numerically the role that the parameters have on ICO policy preferences.[14] As predicted in Section IV, lower discount rates make it more likely that the ICO finds the direct payment approach more cost-effective. The depreciation rate has an effect similar to, but less powerful than, the effect of the discount rate. High depreciation rates make maintaining eco-production capital expensive and thus the rural resident will substitute forest for capital, thereby rendering the indirect approach less expensive to the ICO. Higher values of α increase the likelihood that the ICO finds the direct approach more cost-effective. Higher values of the coefficient of forest productivity, γ, decrease the likelihood that the ICO finds the direct approach more cost-effective. Increasing the coefficient of capital productivity, β, has an ambiguous impact on the ICO's policy preference. Larger β values decrease the value of $-Q_{KK}$, and thus the ICO is more likely to prefer the direct payment approach (i.e., expressions [10] and [13] are more likely to be satisfied). However, as β increases, K_P^* also increases and Q_{FK} may increase or decrease, thus making the ICO's policy preference depend on all of the parameter values.

Finally, we examined the impact on the optimal approach path of changes to the constraints on clearing and investment that the local agent could accomplish in any given period (i.e., C_{max} and I_{max}). If $I_{max} < I_I^*$, the ICO cannot achieve its conservation objective with an indirect subsidy approach (see Section VI). Decreasing the control variable constraints has two impacts on the costs of the direct payment approach: (1) a *delayed clearing effect* (when C_{max} declines) and (2) a *capital adjustment effect* (when either C_{max} or I_{max} decline). The delayed clearing effect always raises the cost of the direct payment approach, but the capital adjustment effect can raise or lower the cost of the direct payment approach depending on the values of the

[14] Contact the authors for detailed results.

constraints. Changes in the control variable constraints also have two impacts on the costs of the indirect subsidy approach: (1) a *capital adjustment effect* and (2) a *forest adjustment effect*. The combined impact of these two effects on the cost of the indirect approach is ambiguous. These effects are explained in more detail elsewhere.[15] Numerical results suggest that low values of I_{max} and C_{max} simultaneously can make the indirect approach more cost-effective even when expression [10] is satisfied.

VIII. Discussion

Hanley et al. (1997, p.91) write that "the usefulness and practicality of economic incentives…can be based on the extent to which they meet four criteria: effectiveness, efficiency, equity and flexibility." Issues associated with the effectiveness, equity and flexibility of direct and indirect payment initiatives have been addressed elsewhere (Simpson and Sedjo 1996; Ferraro and Simpson 2000; Ferraro 2001a; project documents cited in Section II).[16] The authors of these articles and reports have argued that direct payment initiatives are likely to be more effective in achieving the ICO's objective, and more flexible in maintaining the ICO's objective over time, because of the unambiguous connection between the payments and the ICO's goal of ecosystem protection. Our analysis suggests that direct payment initiatives will also be more efficient at achieving the ICO's objective and that, given limited conservation budgets, they will also result in larger welfare gains for the rural residents in whose hands lies the fate of endangered ecosystems.

[15] Ferraro (2001c).

[16] There have also been numerous articles and reports that have focused specifically on the difficulties associated with implementing indirect conservation approaches in low-income nations (e.g., Wells and Brandon 1992; Ferraro et al. 1997; World Bank 1997; Southgate 1998; Chomitz and Kumari 1998; Simpson 1999; Oates 1999; Kiss 2001; and Rice et al. 2001)

Although we highlighted recent experimentation with direct payment conservation initiatives in Section II, there are clearly barriers to implementing the approach in low-income nations. We ignored a variety of issues that will be important in conservation performance payment initiatives in low-income nations. These issues include minimizing transaction costs, designing and targeting effective contracts, and developing appropriate institutional rules and roles. Despite its imposing institutional needs, however, a system of direct conservation payments has much in common with indirect conservation interventions. Both approaches require institutions that can monitor ecosystem health, resolve conflict, coordinate individual behavior, and allocate and enforce rights and responsibilities.

Unlike more complex indirect subsidy interventions, however, a system of conservation payments allows practitioners to focus their energies on designing these requisite institutions. In contrast, conservation practitioners using indirect approaches must allocate their resources across many more tasks in order to turn residents in remote rural areas into entrepreneurs who can cater to national and world markets. A recent World Bank report (2000b) estimated that the administrative costs of running the Costa Rican Environmental Services Payment program (Section II) were about 5% of the total program budget (i.e., 95% of the budget went to conservation payments). Canada's Permanent Cover Program (PCP), a conservation payment program that, in 1991, was closely integrated with its North American Waterfowl Management Plan, spent an estimated 25% of its budget on administration (OECD 1997). In contrast, Joseph Peters, former Conservation Technical Consultant with the Ranomafana National Park Project (Section VI), estimated that the less than 2% of the Ranomafana project's budget went to rural residents around the park; about 55% went to administrative (US-based) overhead and expatriate technical consultants and the rest went to capital expenditures and host-country technical consultants (Peters 1998). Thus in the presence of transaction costs, the direct payment conservation approach may be even more attractive to conservation organizations and rural residents than our efficiency analysis suggests.

IX. Conclusion

In order to achieve ecosystem conservation objectives in low-income nations, conservation practitioners have invested billions of dollars in promoting commercial enterprises intended to generate local incentives for conservation. By virtue of their complicated and indirect linkages to conservation objectives, however, development interventions are often ill suited for achieving ecosystem conservation.

In contrast to the emphasis on indirect approaches to ecosystem conservation in low-income nations, high-income nations, and a few low-income nations, have been experimenting with approaches based on conservation performance payments. Despite the increasing use of direct payment approaches, the role that they can play in low-income countries has been largely overlooked. In particular, the dynamic efficiency of direct payment approaches has been completely ignored.

Our results suggest that, under some circumstances, an indirect subsidy approach to conservation can be more cost-effective for a conservation donor seeking to halt the conversion of globally valuable ecosystems to alternative uses. However, the conditions under which the conservation donor will find the indirect approach more cost-effective are not likely to be observed in many conservation contexts. In particular, the desire of conservationists to halt most, if not all, of the conversion of endangered ecosystems at their "frontiers" leads us to conclude that the use of direct payments for ecosystem conservation are likely to be substantially more cost-effective than the current dominant approach of using indirect subsidization of eco-friendly production activities. Hence, we believe that continued experimentation with conservation performance payments in the developing world is warranted and that such payments may ultimately prove to be the most effective conservation investment.

Appendix

A.1 Overall Costs of Indirect Approach are Greater

To show that the overall costs (incremental profits – payment costs) of the indirect subsidy approach are greater than those of the direct payment approach, we show first that capital use under the indirect approach is greater for a given increase in forest protected at the steady-state optimum. Let $F_I = F_D = F^*$ indicate that the level of forest preserved under the indirect subsidy (F_I) and the level of forest preserved under the direct (performance) payment (F_D) is the same as the level desired by the ICO (F^*). We assume that $C_{MAX} \geq (F_0 - F^*) = (1 - F^*)$ and $I_{MAX} \geq K_I^*$, where K_I^* represents the optimal steady-state capital stock under the indirect payment. Thus in period t = 0, $C_0^* = 1 - F^*$ and $I_0^* = K^*$, and in all subsequent periods, $C^* = 0$ and $I^* = vK$ (i.e., a Most Rapid Approach Path). We will demonstrate that $K_I^* > K_D^*$, where K_D^* represents the optimal steady-state capital stock under the direct payment.[17]

[17] The results obtain when low values of C_{max} lead to a capital accumulation path that overshoots the steady state and then returns to the steady state over time through depreciation, but they will not necessarily obtain when I_{max} is very small, in which case the capital accumulation path can undershoot the steady state because the rural resident decides the opportunity costs of waiting for capital to accumulate are too great.

We totally differentiate expressions [6] and [7], set all differentials except dS_F and dS_K to zero, and solve for dF under a small change in the forest payment and a change in the capital subsidy. We obtain

$$dF_D = \frac{-Q_{KK}\, dS_F}{(Q_{KK}Q_{FF} - Q_{FK}{}^2)P_Q} \qquad \text{[A1]}$$

and

$$dF_I = \frac{(v+\delta)Q_{FK}\, dS_K}{(Q_{KK}Q_{FF} - Q_{FK}{}^2)P_Q} \qquad \text{[A2]}$$

We use a standard comparative statics approach to compare two hypothetical steady-state equilibria; i.e., one that uses a "small" direct payment to protect more forest and one that uses a "small" indirect subsidy. Since $S_K = S_F = 0$ in the original steady-state equilibrium, $dS_F = S_F$ and $dS_K = S_K$.

The thought experiment then proceeds as follows: given a (small) direct payment, $\overline{S_F}$, what is the indirect payment that generates the same increase in the use of forest engaged in eco-production? We solve for the indirect payment, S^*_K, that generates the same increase in the use of forest as a given (small) direct payment, $\overline{S_F}$:

$$dF_D = dF_I \qquad when\, dS_K = S^*{}_K \; and \; dS_F = \overline{S_F} \qquad \text{[A3]}$$

$$\overline{S_F}\, \frac{-Q_{KK}}{(Q_{KK}Q_{FF} - Q_{FK}{}^2)} = S^*{}_K\, \frac{(v+\delta)\,Q_{FK}}{(Q_{KK}Q_{FF} - Q_{FK}{}^2)} \qquad \text{[A4]}$$

$$S_K{}^* = -\overline{S}_F\, \frac{Q_{KK}}{Q_{FK}}\, \frac{1}{(v+\delta)} \qquad \text{[A5]}$$

Given the original steady-state equilibrium, we want to compare capital use under the direct payment, $\overline{S_F}$, and under an indirect payment, S^*_K, that generates the same increase in forest used in eco-production as $\overline{S_F}$ does. Let dK_I be the additional capital used beyond the privately optimal stock level when the rural resident is faced with an indirect capital subsidy and dK_D be the additional capital used beyond the privately optimal stock level when the rural resident is faced with a direct forest payment. When is the additional capital employed under the indirect payment greater than the additional capital employed under the direct payment; i.e.,

$$dK_I > dK_D \qquad when\, dS_K = S^*{}_K \; and \; dS_F = \overline{S_F}\,?$$

After deriving dK_I and dK_D through total differentiation of expressions [6] and [7] and using equation [A5] to substitute for S^*_K, we obtain

$$\frac{Q_{FF}(v+\delta)}{(Q_{FK}{}^2 - Q_{FF}Q_{KK})\,P_Q}\left(\frac{-Q_{KK}}{Q_{FK}(v+\delta)}\right)\overline{S_F} > \frac{-Q_{FK}}{(Q_{FK}{}^2 - Q_{FF}Q_{KK})\,P_Q}\overline{S_F} \qquad [A6]$$

Recall that in section III, we assumed that the eco-production function, Q_t, was strictly concave. Thus $(Q_{FK}{}^2 - Q_{FF}Q_{kK})$<0 and

$$\frac{-Q_{FF}Q_{KK}}{Q_{FK}} < -Q_{FK} \qquad [A7]$$

$$\Rightarrow Q_{FF}Q_{KK} > Q_{FK}{}^2 \qquad [A8]$$

Thus, for any strictly concave production technology, the direct payment approach requires less capital to achieve a given level of forest protection.

The overall incremental cost of using the indirect approach instead of the direct approach would then be the present value of the “deadweight losses” associated with the indirect approach minus the “deadweight losses” associated with the direct approach.[18] Since forest use is the same by assumption under both approaches, we can approximate the incremental overall cost of using the indirect conservation approach instead of the direct payment approach by

[18] These losses are not true deadweight losses since the ICO values the ecosystem services that it is paying for. The true deadweight loss in our analysis is the overall incremental costs of using the less efficient policy.

$$\frac{1}{2}S_K(dK_I - dK_D) + \frac{1}{2}\frac{S_K}{\delta}(v\,dK_I - v\,dK_D) = S_K\frac{(dK_I - dK_D)(v+\delta)}{2\delta} > 0. \qquad \text{[A9]}$$

A.2. International Conservation Organization Cost Analysis

We assume again that $C_{MAX} \geq (F_0 - F^*) = (1 - F^*)$ and $I_{MAX} \geq K_I^*$, where K_I^* represents the optimal steady-state capital stock under the indirect payment (see A.1). If the ICO uses a "small" direct payment, its costs will be

$$S_F F^0 + \frac{1}{\delta}S_F F_D^* = S_F + \frac{1}{\delta}S_F\left(F_P^* + S_F\frac{\partial F}{\partial S_F}\right) \qquad \text{[A10]}$$

where S_F is the per unit direct payment, F_P^* is the original steady-state area of forest, F_D^* is the post-direct payment stock of forest, $F^0 = 1$ is the original forest stock, and d is the discount rate. The term $\frac{\partial F}{\partial S_F}$, evaluated at the original steady state, can be derived from totally differentiating equations [6] and [7]. Thus

$$\begin{aligned} S_F + \frac{1}{\delta}S_F\left(F_P^* + S_F\frac{\partial F}{\partial S_F}\right) &= S_F + \frac{1}{\delta}S_F\left(F_P^* + S_F\frac{-Q_{KK}}{(Q_{KK}Q_{FF} - Q_{FK}^2)P_Q}\right) \\ &= S_F\left(1 + \frac{1}{\delta}\left(F_P^* + S_F\frac{-Q_{KK}}{(Q_{KK}Q_{FF} - Q_{FK}^2)P_Q}\right)\right) \end{aligned} \qquad \text{[A11]}$$

If the ICO uses a "small" indirect capital subsidy, its costs will be

$$S_K K_I^* + \frac{1}{\delta}S_K I_I^* = S_K K_I^* + \frac{1}{\delta}S_K v K_I^* = S_K K_I^*(1 + \frac{v}{\delta}) = S_K(K_P^* + S_K\frac{\partial K}{\partial S_K})(1 + \frac{v}{\delta}) \qquad \text{[A12]}$$

where S_K is the per unit capital subsidy, *v* is the depreciation rate, I_I^* is the post-indirect subsidy steady-state investment rate, K_P^* is the original steady-state capital stock, and K_I^* is the post-indirect subsidy steady-state capital stock. The term $\frac{\partial K}{\partial S_K}$, evaluated at the original steady state, can be derived from totally differentiating equations [6] and [7]. Substituting S^*_K from [A5] into expression [A12], we obtain

$$S_K(K_P{}^* + S_K \frac{\partial K}{\partial S_K})\ (1+\frac{v}{\delta}) = S_F \frac{-Q_{KK}}{Q_{FK}} \frac{1}{v+\delta}\left(K_P{}^* + S_F \frac{-Q_{KK}}{Q_{FK}} \frac{1}{v+\delta} \frac{Q_{FF}(v+\delta)}{(Q_{FK}{}^2 - Q_{FF}Q_{KK})\,P_Q} \right)\left(\frac{\delta+v}{\delta}\right) \quad \text{[A13]}$$

We want to know when will the cost of the direct payment approach [A11] be greater than the cost of the indirect capital subsidy approach [A13] to achieve a given level of post-intervention forest stock; i.e., when is

$$S_F\left(1+\frac{1}{\delta}\left(F_P{}^* + S_F \frac{-Q_{KK}}{(Q_{KK}Q_{FF} - Q_{FK}{}^2)\,P_Q}\right)\right) > S_F \frac{-Q_{KK}}{Q_{FK}} \frac{1}{v+\delta}\left(K_P{}^* + S_F \frac{-Q_{KK}}{Q_{FK}} \frac{1}{v+\delta} \frac{Q_{FF}(v+\delta)}{(Q_{FK}{}^2 - Q_{FF}Q_{KK})\,P_Q} \right)\left(\frac{\delta+v}{\delta}\right) ?$$

Cancel out the first $S_F > 0$ on either side and the $(v+\delta) > 0$ inside and outside of the parenthesis on the right-hand side, and multiply $\frac{-Q_{KK}}{Q_{FK}}$ and $1/\delta$ through on the right-hand side:

$$1+\frac{1}{\delta}F_P{}^* + \frac{1}{\delta}S_F \frac{Q_{KK}}{(Q_{FK}{}^2 - Q_{FF}Q_{KK})\ P_Q} > \frac{-Q_{KK}}{Q_{FK}}\frac{1}{\delta}K_P{}^* + S_F \frac{1}{\delta}\frac{Q_{KK}{}^2}{Q_{FK}{}^2}\frac{Q_{FF}}{(Q_{FK}{}^2 - Q_{FF}Q_{KK})\,P_Q} \quad \text{[A14]}$$

Place all terms with S_F on the left-hand side of [A14] and the rest of the terms on the right-hand side:

$$\frac{1}{\delta}S_F \frac{Q_{KK}}{(Q_{FK}^{\ 2}-Q_{FF}Q_{KK})\ P_Q} - S_F\frac{1}{\delta}\frac{Q_{KK}^{\ 2}}{Q_{FK}^{\ 2}}\frac{Q_{FF}}{(Q_{FK}^{\ 2}-Q_{FF}Q_{KK})P_Q} > \frac{-Q_{KK}}{Q_{FK}}\frac{1}{\delta}K_P^{\ *} - \frac{1}{\delta}F_P^{\ *} - 1 \qquad \text{[A15]}$$

Factor out S_F and $1/\delta$ on the left-hand side of [A15] and place the rest of the terms on the right-hand side over a common denominator:

$$\frac{1}{\delta}S_F\left(\frac{Q_{KK}Q_{FK}^{\ 2}-Q_{KK}^{\ 2}Q_{FF}}{Q_{FK}^{\ 2}(Q_{FK}^{\ 2}-Q_{FF}Q_{KK})\ P_Q}\right) > \frac{-Q_{KK}}{Q_{FK}}\frac{1}{\delta}K_P^{\ *} - \frac{1}{\delta}F_P^{\ *} - 1 \qquad \text{[A16]}$$

Multiply both sides of [A16] by $\delta > 0$:

$$S_F\left(\frac{Q_{KK}Q_{FK}^{\ 2}-Q_{KK}^{\ 2}Q_{FF}}{Q_{FK}^{\ 2}(Q_{FK}^{\ 2}-Q_{FF}Q_{KK})\ P_Q}\right) > \frac{-Q_{KK}}{Q_{FK}}K_P^{\ *} - F_P^{\ *} - \delta \qquad \text{[A17]}$$

Factor out a Q_{KK} in the numerator of the parenthetical expression on the right-hand side of [A17] and cancel like terms:

$$S_F\left(\frac{Q_{KK}}{Q_{FK}^{\ 2}\ P_Q}\right) > \frac{-Q_{KK}}{Q_{FK}}K_P^{\ *} - F_P^{\ *} - \delta \qquad \text{[A18]}$$

A.3. Derivation Steady-State Forest Stock for Cobb-Douglas Eco-Production

The eco-production function takes the Cobb-Douglas form, $Q_t = \alpha K_t^{\beta} F_t^{\gamma}$. The marginal products of capital and forest are thus $Q_K = \alpha\beta K_t^{\beta-1}F_t^{\gamma} = \beta\, Q/K$ and $Q_F = \alpha\gamma K_t^{\beta}F_t^{\gamma-1} = \gamma Q/F$, respectively. Equations [6] and [7] therefore imply

$$F = \frac{\gamma P_Q Q}{(\delta P_T + P_A - S_F)} \qquad \text{[A19]}$$

and

$$K = \frac{\beta P_Q Q}{(\delta + v)(P_K - S_K)}. \qquad \text{[A20]}$$

Equations [A19] and [A20] imply

$$f \equiv \frac{F}{K} = \frac{\gamma(\delta + v)(P_K - S_K)}{\beta(\delta P_T + P_A - S_F)}.$$

Let $g \equiv \frac{(\delta P_T + P_A - S_F)}{\gamma P_Q}$. We can then express Q as a function of g and F:

$$Q = \left[\frac{(\delta P_T + P_A - S_F)}{\gamma P_Q}\right] F = gF.$$

Given that [A20] implies K = F/*f*, the production function implies that

$$G(F) = g\,F - \alpha(F/f)^{\beta} F^{\gamma} = [g - \alpha(F/f)^{\beta} F^{\gamma-1}]F = 0.$$

Assuming that it is optimal for the rural agent to retain some positive amount of forest, then $[g - \alpha(F/f)^{\beta} F^{\gamma-1}] = 0$, and this implies that the steady-state forest stock can be expressed as

$$F^* = \left[\frac{gf^{\beta}}{\alpha}\right]^{1/(\beta+\gamma-1)} \qquad \text{[A21]}$$

With a Cobb-Douglas specification of the eco-production function, expression [10] in the main text reduces to:

$$\frac{-\alpha\beta(\beta-1)K^{*\beta-2}F^{*\gamma}}{\alpha\beta\gamma K^{*\beta-1}F^{*\gamma-1}}K^* - F^* - \delta > 0 \qquad \text{[A21]}$$

$$\Rightarrow \frac{(1-\beta-\gamma)}{\gamma}F^* > \delta \qquad \text{[A22]}$$

To approximate the steady-state solution through a discrete-time, finite-horizon framework, we construct a final function in t = T =10 given by

$$\phi(K_{10},F_{10})=\rho^{10}[P_Q Q(K_{10},F_{10})-(P_K-S_K)vK_{10}+P_A(1-F_{10})+S_F F_{10}]\frac{(1+\delta)}{\delta} \qquad \text{[A23]}$$

This final function requires that, whatever the resulting values for K_{10} and F_{10}, they must be maintained forever. This final function forces the desired intertemporal trade-off between the present value during transition, t = 0,1,….,9 and the present value of maintaining (K_{10}, F_{10}) for t = 10,11,…..,∞. In the empirical analysis of Section VI, T= 20.

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