# Payments for environmental services: Coasian transactions or something else?

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# Payments for environmental services: Coasian transactions or something else? [*]

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## Abstract

Payments for environmental services (PES) are based on the beneficiary-pays rather than the polluter-pays principle. In this paper we argue that this is a key factor for identifying what ecosystems are amenable to PES. We build a general equilibrium framework to identify what ecosystems are amenable to PES as an efficient solution. In economies where society has a higher degree of environmental responsibility and produces a low level of alternative land services income efficient transfers cannot be financed with voluntary payments. Therefore PES programs must be seen as environmental subsidies (to ES providers) and must be combined with a user fee (on ES users). We use Costa Rica's Payments for Environmental Services program (PSA) to illustrate our findings. We find that the efficient payments for forest conservation are higher than the value reported by Pagiola (2008). Implementing an efficient system implies an increase in payments for forest conservation by 4.15-fold.

Keywords: PES, Coase, Efficiency
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# 1 Introduction

Payments for environmental services (PES) have been broadly used to make conservation a more attractive option for ecosystem managers. Are PES programs an attempt to put the Coase theorem into practice? Answering this question is crucial in identifying what ecosystems are amenable to PES programs: Engel et al. (2008) and Tacconi (2012). The consensus appears to be that voluntary participation is the key element for identifying efficient PES programs. PES programs where buyers are the users of the ES are more likely to be efficient than those where a third party, e.g. the government, acts on behalf of ES users.

Unlike other instruments –which can be applied to overcome problems of external effects– PES is based on the beneficiary-pays rather than the polluter-pays principle. In this paper we argue that this is a key factor for identifying what ecosystems are amenable to PES.

In a general equilibrium framework, we consider an economy where an ecosystem –a natural capital- can be exploited to produce land services. We prove that efficient conservation can be obtained when a complete number of competitive markets can be designed. The key market is the conservation market where ecosystem services are traded at positive prices. We show that the efficient level of conservation depends on the degree of environmental responsibility of siciety. When society has a higher degree of environmental responsibility more ecosystems are saved for the future, thus increasing the size of the ecosystem allocated to provide ES. More productive economies, which are able to produce the same amount of land services by exploiting a smaller proportion of the ecosystem, also increase the size of the ecosystem allocated to provide ES.

In this general equilibrium framework we identify what ecosystems are amenable to PES as an efficient solution. In less productive economies PES programs always implement efficient allocations. However, in highly productive economies the efficient allocations for PES programs cannot be always implemented. In economies where society has a higher degree of environmental responsibility and produces a low level of alternative land service income efficient transfers cannot be financed with voluntary payments. Therefore PES programs that implement efficient allocations must be designed by a government . Payments must be seen as environmental subsidies (to ES providers) and must be combined with a user fee (on ES users).

We use the Costa Rica's Payments for Environmental Services program (PSA) to illustrate our findings. Using data from pollination experiments at Finca Santa Rita conducted by Ricketts et al. (2004), we calibrate the model to match the fraction of total biomass forestry allocated to forest conservation uses. We find that the efficient payments for forest conservation are higher than the value reported by Pagiola (2008). Implementing an efficient payment implies an increase in payments for forest conservation by 4.15-fold.

The rest of the paper is organized as follows: Section 2 presents the model and characterizes the Pareto efficient allocation and the competitive equilibrium with a complete number of markets. Section 3 establishes conditions for the existence of Coasian PES programs. Section 4 illustrates the model. Section 5 concludes.

## 2 The model

Consider the illustration in Pagiola and Platais (2007) of the logic of payments for environmental services. Land ecosystem managers benefit from uses such as, for example, forest conservation. These benefits are normally lower than the benefits they would receive from alternative land uses, such as conversion to cropland or pasture. However deforestation derived from these alternative uses affects the global community because of the loss of water services, biodiversity, carbon sequestration, etc. The idea of a PES is to internalize these negative effects by making forest conservation more attractive to ecosystem managers.

We formalize this logic by considering an economy where an ecosystem, $X_t$, can be exploited to produce alternative land services. This production of land services is denoted as ht. Assume that the ecosystem dynamics are given by $X_{t+1} = AX_t^\alpha - h_t$ where $AX_t^\alpha$ is the natural gross growth of the ecosystem with $\alpha \in (0, 1)$ representing the growth elasticity and $A > 0$ the total factor productivity.

Land services are produced with a technology that uses labor, $l_t$, and the ecosystem as inputs, that is $h_t = AX_t^\alpha l_t$. Under these assumptions $(1 - l_t)$ represents the fraction of total biomass forestry, $AX_t^\alpha$, that is allocated to provide environmental services.

Beneficiaries of environmental services (ES) have (additively separable) preferences over the land services, $h_t$ and the fraction of the total ecosystem allocated to conservation uses, $(1-l_t)$. We assume that the utility function is given by

$$u(h_t, 1 - l_t) = \log h_t + e \log(1 - l_t),$$

where $e$ represents the degree of environmental responsibility of consumers.

In this economy the (Pareto) efficient level of conservation, $(1 - l)^*$, is chosen such that the marginal rate of substitution between present and future consumption is equal to the net marginal product of the natural ecosystem. Lemma 1 characterizes this.

**Lemma 1.** *The optimal level of ecosystem conservation is given by* $(1-l)^* = \dfrac{\alpha\beta + e(1 - \alpha\beta)}{1 + e(1 - \alpha\beta)}$ *with* $\partial(1 - l)^* \setminus \partial\alpha > 0$, $\partial(1 - l)^* \setminus \partial\beta > 0$ *and* $\partial(1 - l)^* \setminus \partial e > 0$.

**Proof** See Appendix A.1.

Notice that the efficient level of conservation depends positively on the parameters $e$, $\alpha$ and $\beta$. These results are quite intuitive. When society has a higher degree of environmental responsibility (higher $e$), or cares more about the future (higher $\beta$), it saves more for the future. More productive economies (higher $\alpha$) are able to produce the same amount of land services with less ecosystem services, thus increasing savings for the future and increasing the size of the ecosystem allocated to provide ES.

If a whole number of competitive markets can be designed, Pareto-efficient allocation can be implemented as a competitive equilibrium. The key market is the *conservation market* where the ecosystem is traded. This market works in the following way: Divide each period (of 1 day) into two subperiods (morning and evening). Each morning, firms that produces land services can buy the ecosystem at a price $r_t$. The market is competitive and nobody can be excluded. In the evening consumers redeem the ecosystem, paying $q_t$ per unit of the ecosystem not exploited.

In this economy, ecosystem managers receive benefits from the alternative land uses, ht, and from ecosystem conservation $X_{t+1} = AX_t^\alpha - h_t$, the ecosystem services (ES). Therefore they introduce into their calculations the fact that their income does not come solely from the sale of their land services, ht, but that they can also sell that part of the ecosystem in the conservation market. Thus, in each period they pay $r_t X_t$ for the right to access the ecosystem, hire $l_t$ units of labor at a wage of $w_t$ and decide how much to extract, $h_t$, considering that they can sell the ecosystem, $X_{t+1}$ on the conservation market at price $q_t$. That is, the ecosystem is exploited by solving the following problem:

$$\begin{aligned} \max_{\{h_t, l_t\}} \quad & h_t + q_t\left(AX_t^\alpha - h_t\right) - w_t l_t - r_t X_t, \\ s.t. \quad & \begin{cases} h_t = AX_t^\alpha l_t, \\ h_t, X_{t+1}, l_t, X_t \geq 0. \end{cases} \end{aligned} \tag{1}$$

From the first order conditions of this problem, the prices of the factors can be written as follows:

$$w_t = (1 - q_t) AX_t^\alpha, \tag{2}$$

$$r_t = \alpha AX_t^{\alpha-1}[(1 - q_t) l_t + q_t]. \tag{3}$$

As usual, conditions (2) and (3) indicate that potential ES providers exploit the ecosystem until their marginal products equal their factor price (the opportunity cost of conservation). Producing one more unit of alternative land uses, $h_t$, will reduce the ecosystem, and therefore the income that can be obtained in the conservation market.

In this Coasian economy, the buyers of ES are also the owners of the ecosystem. Therefore, they receive $r_t X_t$, in the morning for the ecosystem and pay $q_t X_{t+1}$ in the evening to reedem it. Formally the budget constraint is $h_t + q_t X_{t+1} = w_t l_t + r_t X_t$. Therefore, buyers of the ES invest in the future of the ecosystem by solving the following problem:

$$\max_{\{h_t, l_t^s, X_{t+1}\}_{t=1}^{\infty}} \quad \textstyle\sum_{t=0}^{\infty} \beta^t \left[\log h_t + e \log(1 - l_t)\right], \qquad s.t. \begin{cases} h_t + q_t X_{t+1} = w_t l_t + r_t X_t, \\ X_{t+1} = A X_t^{\alpha} - h_t, \\ h_t, l_t, X_{t+1} \geq 0, \\ X_0 \ \text{ is given.} \end{cases} \tag{4}$$

A competitive equilibrium in this economy is given by an allocation that solves the optimization problems (1) and (4), and markets clear. Lemma 2 shows that the competitive equilibrium implements thethe Pareto-efficient allocation, i.e. Coase's theorem applies.

**Lemma 2.** *The competitive equilibrium associated with the existence of conservation markets is efficient. Moreover, the conservation price* $q_t$ *is*

$$q_t = \frac{\alpha l_t}{1 - \alpha (1 - l_t)} = \frac{\alpha (1 - \alpha\beta)}{1 - \alpha^2 \beta + e(1 - \alpha\beta)(1 - \alpha)} > 0.$$

**Proof** See Appendix A.2.

# 3 Coasian PES programs

Wunder (2005), defines a PES program as *a 'voluntary transaction where a well-defined environmental service (or a ecosystem use likely to secure that service) is being 'bought' by a service buyer from a service provider, if and only if, the service provider secures service provision (conditionality)'.* Therefore, consider that a government designs a PES program to implement a Coasian allocation, $X_{t+1}$. The total payments for ecosystem services (PES) that induce ecosystem managers to ensure the conservation of the efficient level of ecosystem, $X_{t+1}$, are $T(X_{t+1}) = q_t X_{t+1}$. Ecosystem managers also receive a (potential) positive payment from the sale of their land services, $P(h_t)$. Therefore, in our general equilibrium framework consumers pay $P(h_t)$ to the ecosystem managers and a transfer v to the government. Figure 1 illustrates the transactions in PES programs.

Coasian PES programs can be implemented if there is a positive payment, $P(h_t)$, and a positive *voluntary transaction*, $T(X_{t+1})$ that satisfies the ES buyers' budget constraint

$$P(h_t) + T(X_{t+1}) = w_t l_t,$$

where $T(X_{t+1}) = q_t X_{t+1}$ and $P(h_t) = h_t \left[1 - \frac{q_t}{l_t}\right]$.[1]

Lemma 2 shows that the conservation price, $q_t$, is positive. Therefore, *voluntary transfers* are always positive. The Proposition below characterizes the $P(h_t)$ associated with EPS Programs.

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[1] Note that from equation (3), $h_t - r_t X_t = h_t - \frac{h_t}{l_t}[\alpha(1-q_t)l_t + \alpha q_t]$. Given that from Lemma 2 $\alpha(1-q_t)l_t = q(1-\alpha)$ ) it holds that $P(h_t) = h_t \left[1 - \frac{q_t}{l_t}\right]$.

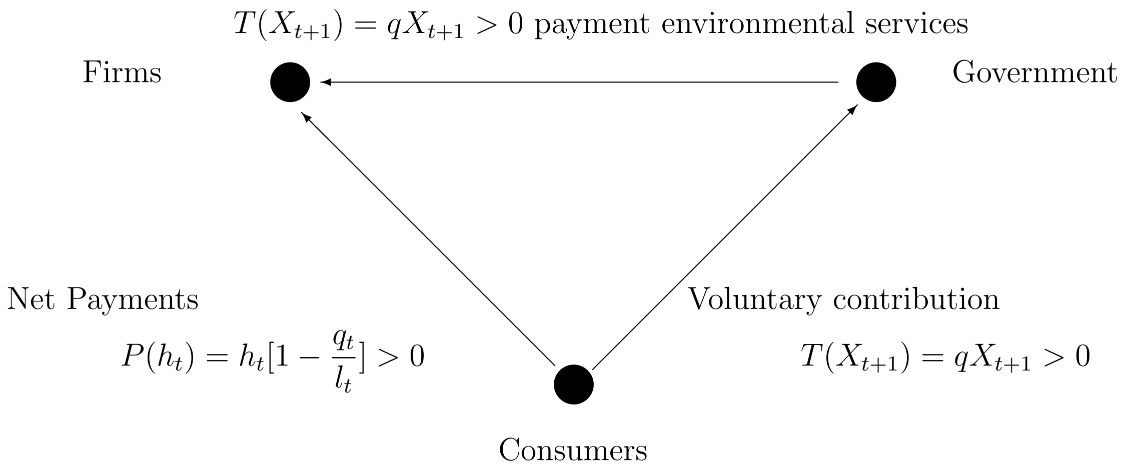

Figure 1: PES program. The government pays ecosystem managers to induce them to ensure the conservation of the efficient level of the ecosystem, $X_{t+1}$. Total payments for ecosystem services (PES) are $T(X_{t+1})$. Payment from the sale of their land services is $P(h_t)$.

**Proposition 1.** *$P(h_t)$ is given by*

$$P(h_t) = h_t \left[ 1 - \frac{1}{\dfrac{1 - \alpha^2\beta + e(1 - \alpha\beta)(1 - \alpha)}{\alpha + e\alpha(1 - \alpha\beta)}} \right].$$

**Proof** See Appendix A.3.

Note that $P(h_t)$, given by Proposition 1 depends on the degree of environmental responsibility, $e$. An increase in willingness to pay for environment conservation increases the fraction of the resource allocated to conservation uses ($\partial(1-l)/\partial e > 0$) and they save more ecosystems for the future ($\partial X_{t+1}/\partial e > 0$). Therefore a higher degree of environmental responsibility increases transfers (higher $T$) and reduces the income obtained from harvesting, $w_t l_t$. Thus, in order to satisfy the consumer budget constraint, $P(h_t)$ must be lower. Proposition 2 shows that there is a maximum level of environmental responsibility, $\overline{e}$ , such that $P(h_t) = 0$. For higher levels of environmental responsibility, $e > \overline{e}$, the implementation of the Coasian equilibrium implies a negative $P(h_t)$ (see Figure 2).

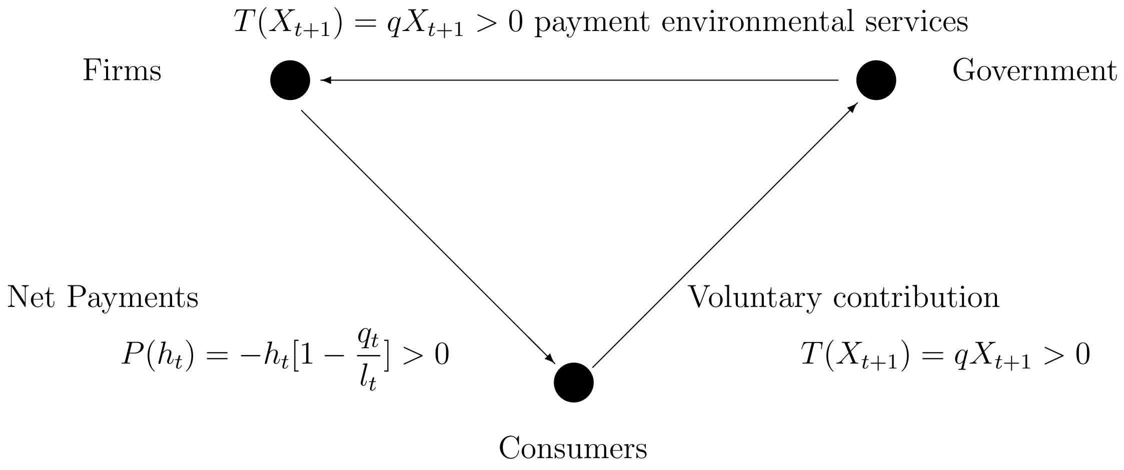

Figure 2: PES program in societies with high degree of environmental responsibility ($e > \overline{e}$). Consumers receive a payment, $P(h_t)$, from the conumption of land services, $h_t$.

**Proposition 2.** *Let* $\alpha > 1/2$*. If* $e > \overline{e} = \dfrac{1-\alpha(1+\alpha\beta)}{(2\alpha-1)(1-\alpha\beta)}$, $P(h_t) < 0$.

**Proof** See Appendix A.3.

Proposition 2 bounds the degree of environmental responsibility that sustains Coasian PES programs. These constraints on preferences and productivity can be rewritten in a more suitable way. The size of voluntary transfers (as a fraction of total income), $\dfrac{T}{wl}$, is given by

$$\frac{T}{wl} = \frac{\left(\dfrac{\alpha}{1-\alpha}\right)}{\left[1 + \left(\dfrac{h}{X}\right)\right]} = \left(\frac{\alpha}{1-\alpha}\right)(1-l). \tag{5}$$

Equation (5) represents the set of all Coasian allocations. Any allocation $l \in (0,1)$, associated with conservation prices $q$, that generates a transfer $T = qX_{t+1}$ can be implemented by generating a complete number of competitive markets. However, $P(h_t) = 0$ when $l =$

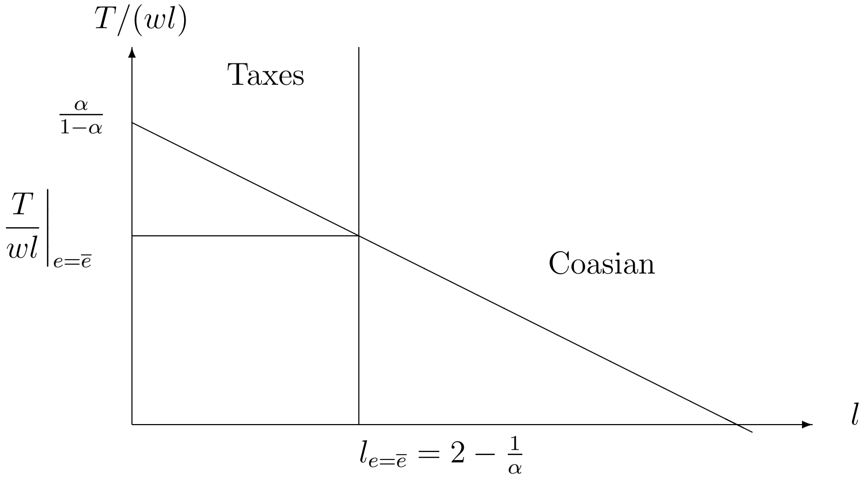

Figure 3: The horizontal axis represents the fraction of total biomass forestry, $l$, allocated to produce the alternative land services (pasture or conversion to cropland); the vertical axis represents the size of voluntary transfers (as a fraction of total income). The curve represents the set of Coasian allocations. PES programs implement Coasian allocations if $l \geq l_{e=\overline{e}}$. In societies with a high degree of environmental responsibility ($e$ higher than $\overline{e}$), voluntary transfers cannot implement Coasian allocations (where $l < l_{e=\overline{e}}$) and PES programs must be based on taxes.

$2 - 1/\alpha$.[2] That is, the maximum degree of environmental responsibility compatible with Coasian PES programs, $\overline{e}$, generates $l_{e=\overline{e}} = 2 - \frac{1}{\alpha}$. In societies with a higher degree of environmental responsibility ($e$ higher than $\overline{e}$), where $l < l_{e=\overline{e}}$ PES programs cannot be based on voluntary transfers.

The implementation of the Coasian equilibrium with PES programs depends on the ecosystem productivity, $\alpha$. PES programs are based on (conditional) transfers to ecosystem managers. Those transfers are voluntary if consumers receive the return on their investments (the voluntary transfer). The capital income -associated with a level of conservation, $X_t$,

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[2] Note that

$$1 - \frac{q_t}{l_t} = 1 - \frac{\alpha}{1 - \alpha\,(1 - l_t)} = \frac{1 + \alpha l - 2\alpha}{1 + \alpha l - \alpha} = 0 \Rightarrow l = 2 - \frac{1}{\alpha}.$$

per unit of $h_t$ is equal to

$$\frac{r_t X_{t+1}}{h_t} = \frac{q_t}{l_t} = \frac{\alpha}{1-\alpha(1-l_t)}.$$

Note that in low productive economies $\alpha < \frac{1}{2}$) this capital income is always lower than the alternative land service payments(i.e. $\frac{r_t X_{t+1}}{h_t} \leq 1$). However, in high productive economies ($\alpha > \frac{1}{2}$) capital income is higher than the alternative land service payments (i.e. $\frac{r_t X_{t+1}}{h_t} > 1$) when $e > \bar{e}$. In that case the alternative land service payments are not able to generate the necessary income to implement PES programs based on voluntary transfers.

## 4 A numerical illustration: The Costa Rica's PES

PES schemes have been successfully implemented in Mexico, Muñoz-Piña et al. (2003), and Muñoz-Piña et al. (2008), Nicaragua, Pagiola et al. (2007) and Costa Rica Pagiola (2008).[3] We use the Costa Rica's Payments for Environmental Services program (PSA) to illustrate our findings.

In order to calculate the competitive equilibrium associated with a complete number of markest (Coase allocations) we need to calibrate four parameters, $e$, $\alpha$, $\beta$ and $A$. We set the discount factor, $\beta = \frac{1}{1+r}$, at 0.8649 to match the (average) interes rate in Costa Rica from 2000 to2003.[4] TFP parameter, $A$, is normalized equal to 1.

Environmental responsibility $e$, and the elasticity of the resource $\alpha$ are calibrated to match the fraction of total biomass forestry allocated to forest conservation uses, $(1 - l_t)$ and the impact of the Costa Rica's forest on harvesting income reported by Ricketts et al. (2004). In 2002-2003, Ricketts et al. (2004) conducted pollination experiments at *Finca Santa Fe*, a

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[3] For a survey of payments for environmental services programs in developed and developing countries, see Wunder et al. (2008)

[4] We use real interest rates reported by the World Bank. The real interest rate is the lending interest rate adjusted for inflation as measured by the GDP deflator. In 2000-2003 it was 16.7%, 14.0%, 15.8% and 16.0%. Setting $r = 15.62\%$, the mean value over the period, yields $\beta = 0.8649$.

Table 1: PSA (Costa Rica) Calibration

|  | target |  | Parameter |  |
|---|---|---|---|---|
| Discount Factor | Real interest rate | 15.62 % | $\beta$ | 0.8649 |
| Environmental responsibility | % of Forestry Land | 54.56 % | $e$ | 0.2829 |
| Priv. elasticity of the resource | *Finca Santa Fe*'s $\Delta$ Income | 7.00 % | $\alpha$ | 0.5533 |

1,065 ha coffee farm in Valle General (Costa Rica), to estimate the economic value of forest conservation on coffee farms. They found that pollination services from two forest fragments increased total coffee farm income by 7%. Formally, if the stationary production of 'coffee' is $h = (1-l)^{\frac{\alpha}{1-\alpha}} l$ then

$$\frac{dh/dl}{h} = -\left(\frac{\alpha}{1-\alpha}\right)\left(\frac{1}{1-l}\right) + \frac{1}{l} = -0.07. \tag{6}$$

Bertsch (2004) reports Land uses in Costa Rica. In 2001, forestry represented 54.56% of total land resources.[5] Therefore

$$1 - l = \frac{\alpha\beta + e(1-\alpha\beta)}{1 + e(1-\alpha\beta)} = 0.5456. \tag{7}$$

Equations (6) and (7) yield $\alpha = 0.5533$ and $e$ is equal to 0.2829 (see Table 1). Once the model is calibrated, we solve for the stationary equilibrium (See Appendix A.5.)

We divide the quantitative experiments into two parts. (1) We study the impact of the degree of environmental responsibility on prices and allocations in the economy by comparing statistics for the economy with $e = \overline{e}$ relative to the benchmark economy. (2) We study the contribution of the resource productivity on the existence of Coasian PES programs by comparing the predictions of the model to three versions of the model where $\alpha$ is lower than the calibrated value.

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[5] See, '*Cuadro 1*', on pag 138.

Table 2: PSA (Costa Rica) Accounting

| | Data | | Benchmark Economy | |
|---|---|---|---|---|
| $\Delta$ Coffe income per ha | Ricketts et al. (2004) | USD 128.57 | $P(h)$ | USD 128.57 |
| Forestry / Land | Bertsch (2004) | 54.56 % | $(1-l)$ | 54.56 % |
| Payments for conservation | Average 2003 per ha | USD 64.62 | $T$ | USD 267.98 |
| | ratio over Coffee income | 50.26 % | $T/P(h)$ | 208.43 % |

The first column of Table 3 reports the stationary equilibrium associated with the calibrated values (the benchmark economy). Column two reports the equilibrium associated with the maximum level of environmental responsibility, e, compatible with Coasian PES programs. Table 3 shows that $T/P(h)$ in the benchmark economy is 208.43 %. Ricketts et al. (2004) provide data for calculating $T/P(h)$ in Costa Rica. Coffee productivity per ha (in areas affected by pollinization) increased 3.75 fanegas per ha times USD 34.75 per fanega, yielding USD 128.575 per ha. Pagiola (2008) reports that in 2006 annual payments for forest conservation, $T$, averaged USD 64/hectare (ha). Therefore, the voluntary contributions over coffee income ratio, $T/P(h)$ is 50.26 % (see Table 2). This is lower than the value obtained in the model.

Therefore, we recalibrate $\alpha$ to match the $T/P(h)$ ratio. Column four of Table 3 reports the recalibrated economy, with $\alpha = 0.4206$, and columns five and six report economies without environmental responsibility ($e = 0$) and with a high level of environmental responsibility ($e = 100$, implies $1 - l \simeq 1$).

Table 3 shows that societies with a higher degree of environmental responsibility (higher $e$) allocate a higher fraction of total biomass forestry to providing environmental services (higher$1-l$) by reducing the production of alternative land services (lover $h_t$) and increasing the savings of ecosystems for the future (higher $X$). Prices associated with the competitive equilibrium, $q$, $r$ and $w$ are well defined in all the economies. Societies with a high degree of

Table 3: PSA (Costa Rica) Coasian Economies

| | Calibration | | | Low productive | | |
|---|---|---|---|---|---|---|
| | Baseline | $\overline{e}$ | High $e$ | Baseline | Low $e$ | High $e$ |
| **Parameters** | | | | | | |
| $e$ | 0.2829 | 3.2727 | 100.00 | 0.2829 | 0.0000 | 100.00 |
| $\alpha$ | 0.5533 | 0.5533 | 0.5533 | 0.4206 | 0.4206 | 0.4206 |
| $\beta$ | 0.8649 | 0.8649 | 0.8649 | 0.8649 | 0.8649 | 0.8649 |
| $A$ | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| **Equilibrium** | | | | | | |
| $1-l$ | 0.5456 | 0.8073 | 0.9902 | 0.4608 | 0.3638 | 0.9902 |
| $l$ | 0.4544 | 0.1927 | 0.0098 | 0.5392 | 0.6362 | 0.0098 |
| $X$ | 0.2576 | 0.6193 | 0.9782 | 0.2626 | 0.1746 | 0.9831 |
| $h$ | 0.2145 | 0.1478 | 0.0097 | 0.3072 | 0.3054 | 0.0098 |
| $w$ | 0.3021 | 0.6193 | 0.9760 | 0.4095 | 0.3283 | 0.9858 |
| $r$ | 0.6601 | 0.2386 | 0.0121 | 0.6104 | 0.8685 | 0,0072 |
| $q$ | 0.3601 | 0.1927 | 0.0120 | 0.2813 | 0.3159 | 0.0071 |
| **Budget Constraint** | | | | | | |
| $rX$ | 0.1700 | 0.1478 | 0.0119 | 0.1603 | 0.1516 | 0.0070 |
| $wl$ | 0.1373 | 0.1193 | 0.0096 | 0.2208 | 0.2089 | 0.0097 |
| Income | 0.3073 | 0.2671 | 0.0214 | 0.3811 | 0.3605 | 0.0168 |
| $h$ | 0.2145 | 0.1478 | 0.0097 | 0.3072 | 0.3054 | 0.0098 |
| $qX$ | 0.0928 | 0.1193 | 0.0117 | 0.0739 | 0.0552 | 0.0070 |
| Expenditures | 0.3073 | 0.2671 | 0.0214 | 0.3811 | 0.3605 | 0.0168 |

environmental responsibility ($e = 100$) allocate the same fraction of total biomass forestry to providing environmental services ($1 - l = 99\%$). Prices ($w$, $r$ and $q$) reflect differences in productivity (in $\alpha$) between those economies.

Table 4 reports the PES programs that implement the allocations reported in Table 3. Note that when $\alpha$ is high, and $e > \overline{e}$, PES that induces ecosystem managers to provide the efficient provision of the ES, $X_{t+1}$, cannot be based on voluntary transfers given that $T/wl$ is greater than 1.

Table 4: PSA (Costa Rica) PES programs

| | Calibration | | | Low productive | | |
|---|---|---|---|---|---|---|
| | Baseline | $\overline{e}$ | High $e$ | Baseline | Low $e$ | High $e$ |
| **Parameters** | | | | | | |
| $e$ | 0.2829 | 3.2727 | 100.00 | 0.2829 | 0.0000 | 100.00 |
| $\alpha$ | 0.5533 | 0.5533 | 0.5533 | 0.4206 | 0.4206 | 0.4206 |
| **Budget with PES** | | | | | | |
| $wl$ | 0.1373 | 0.1193 | 0.0096 | 0.2208 | 0.2089 | 0.0097 |
| Income | 0.1373 | 0.1193 | 0.0096 | 0.2208 | 0.2089 | 0.0097 |
| $T(X)$ | 0.0928 | 0.1193 | 0.0117 | 0.0739 | 0.0552 | 0.0070 |
| $P(h)$ | 0.0445 | 0.0000 | $< 0$ | 0.1469 | 0.1537 | 0.0027 |
| Expenditures | 0.1373 | 0.1193 | $< 0$ | 0.2208 | 0.2089 | 0.0097 |
| **Ratios** | | | | | | |
| $T/wl$ | 0.6758 | 1.0000 | 1.2265 | 0.3345 | 0.2641 | 0.7188 |

# 5 Conclusions

Voluntary transactions and negotiation comprise a necessary but not sufficient condition for designing efficient PES programs. Mechanisms based on the beneficiary-pays rather than the polluter-pays principle suffer from potential inefficiency generated by budget constraints. Ecosystems where externalities are potentially high and low levels of natural capital depletion are socially desirable are not amenable to PES as a solution.

Our calibration shows that Costa Rica's PSA program offers a relatively low payment for conservation of the country's forests. Like Muradian et al. (2010), we argue that in real world situations economic incentives are not the primary factor leading to the provision of the ES. However if there are intrinsic motivations then lower voluntary transitions are necessary to implement efficient allocations and PES is more likely to be a suitable response to environment mismanagement.

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# A Appendix

## A.1 Proof of Lemma 1

The planner chooses the (Pareto) efficient allocation, $\{h_t, 1-l_t\}_{t=1}^{\infty}$, $h_t = AX_t^{\alpha} - X_{t+1}$ and $1 - l_t = \frac{X_{t+1}}{AX_t^{\alpha}}$, which are functions of the size of the environmental system, by solving the following problem:

$$\max_{\{X_{t+1}\}_{t=1}^{\infty}} \sum_{t=0}^{\infty} \beta^t \left[ \log\left(AX_t^{\alpha} - X_{t+1}\right) + e \log\left(\frac{X_{t+1}}{AX_t^{\alpha}}\right)\right].$$

The first order conditions for solving this dynamic problem are given by the following Euler equation:

$$\frac{X_{t+1}}{AX_t^{\alpha} - X_{t+1}} = \frac{\alpha\beta AX_{t+1}^{\alpha}}{AX_{t+1}^{\alpha} - X_{t+2}} + e(1-\alpha\beta), \tag{8}$$

and the transversality condition for the ecosystem $\lim_{t\to\infty} \beta^{t-1} \dfrac{X_{t+1}}{AX_t^{\alpha} - X_{t+1}} = 0$. The Euler equation (8) is a two-order differential equation on the ecosystem variable, $X_t$. It can be reduced to a first order differential equation by defining $z_t = \dfrac{X_{t+1}}{AX_t^{\alpha}}$. Taking this into account, the equation to be solved is:

$$\frac{z_t}{1-z_t} = \frac{\alpha\beta}{1-z_{t+1}} + e(1-\alpha\beta).$$

It is straightforward to see that the Pareto-optimal allocation is given by $z_{t+1} = z_t = z = (1-l)^*$. Therefore $(1-l)^* = \dfrac{\alpha\beta + e(1-\alpha\beta)}{1+e(1-\alpha\beta)}$ with $\partial(1-l)^* \setminus \partial\alpha > 0$, $\partial(1-l)^* \setminus \partial\beta > 0$ and $\partial(1-l)^* \setminus \partial e > 0$. ■

## A.2 Proof Lemma 2

We start by characterizing the solution of the ES user's problem. The Lagrangian associated with this maximization problem is

$$\mathbb{L} = \sum_{t=0}^{\infty} \beta^t \left\{ \log h_t + e\log(1-l_t^s) + \lambda_t \left[w_t l_t^s + r_t X_t - h_t - q_t X_{t+1}\right] + \mu_t \left[AX_t^{\alpha} - h_t - X_{t+1}\right]\right\},$$

where $\lambda_t$ and $\mu_t$ are the Lagrange multipliers. The first order conditions that solve this optimization problem are, $\forall t \geq 0$:

$$\frac{\partial \mathbb{L}}{\partial h_t} = 0, \qquad \Longrightarrow \qquad \frac{1}{h_t} = \lambda_t + \mu_t, \tag{9}$$

$$\frac{\partial \mathbb{L}}{\partial l_t^s} = 0, \qquad \Longrightarrow \qquad \frac{e}{1-l_t^s} = w_t \lambda_t, \tag{10}$$

$$\frac{\partial \mathbb{L}}{\partial X_{t+1}} = 0, \qquad \Longrightarrow \qquad \beta \left\{ \lambda_{t+1} r_{t+1} + \mu_{t+1} \alpha A X_{t+1}^{\alpha-1} \right\} = q_t \lambda_t + \mu_t. \tag{11}$$

Plugging the first order condition of the firms maximization problem, equation (2), into equation (10) and taking into account that in equilibrium $l_t^s = l_t = l_t$, , the following can be written:

$$\frac{e}{1-l_t} \frac{1}{(1-q_t) A X_t^\alpha} = \lambda_t. \tag{12}$$

Substituting this into equation (10), gives:

$$\mu_t = \frac{1}{h_t} - \frac{e}{1-l_t} \frac{1}{(1-q_t) A X_t^\alpha} = \frac{1}{h_t} - \frac{e}{(1-q_t) X_{t+1}}. \tag{13}$$

Plugging the first order condition of the firms maximization problem, equation (3), into equation (11) results in:

$$\beta \alpha A X_{t+1}^{\alpha-1} \left\{ \lambda_{t+1} [(1-q_{t+1}) l_{t+1} + q_{t+1}] + \mu_{t+1} \right\} = q_t \lambda_t + \mu_t. \tag{14}$$

Substituting expressions (12) and (13) into (14), gives:

$$\begin{aligned}
\beta \alpha A X_{t+1}^{\alpha-1} & \left\{ \frac{e}{1-l_{t+1}} \frac{1}{(1-q_{t+1}) A X_{t+1}^\alpha} [(1-q_{t+1}) l_{t+1} + q_{t+1}] + \frac{1}{c_{t+1}} - \frac{e}{1-l_{t+1}} \frac{1}{(1-q_{t+1}) A X_{t+1}^\alpha} \right\} \\
& = \frac{e}{1-l_t} \frac{q_t}{(1-q_t) A X_t^\alpha} + \frac{1}{h_t} - \frac{e}{1-l_t} \frac{1}{(1-q_t) A X_t^\alpha}. \\
\Longrightarrow \qquad & \beta \alpha A X_{t+1}^{\alpha-1} \left\{ \frac{1}{c_{t+1}} - \frac{e}{A X_{t+1}^\alpha} \right\} = \frac{1}{h_t} - \frac{e}{X_{t+1}}.
\end{aligned}$$

Taking into account the constraint of the problem $h_t = A X_t^\alpha - X_{t+1}$, this expression can be rewritten after some manipulation as

$$\frac{X_{t+1}}{A X_t^\alpha - X_{t+1}} = \frac{\alpha \beta A X_{t+1}^\alpha}{A X_{t+1}^\alpha - X_{t+2}} + e(1 - \alpha \beta),$$

which is the Euler equation (8) that solves the efficient solution. This proves that the competitive equilibrium of this economy is Pareto-efficient.

Finally, note that competitive equilibrium implies zero profits. Therefore, taking into account the production function and first order conditions of the firms maximization problem, equations (2) and (3), $q$ is given by $\Pi_t = AX_t^{\alpha}\left[q_t\left(1-\alpha\right) - \alpha l_t\left(1-q_t\right)\right] = 0$. Therefore $q_t = \dfrac{\alpha l_t}{1-\alpha\left(1-l_t\right)} = \dfrac{\alpha\left(1-\alpha\beta\right)}{1-\alpha^2\beta + e(1-\alpha\beta)\left(1-\alpha\right)} > 0$. ■

## A.3 Proof of Proposition 1

Note that $P(h_t) = h_t\left[1-\frac{q_t}{l_t}\right] = h_t\left[1-\dfrac{\frac{1}{1-\alpha^2\beta+e(1-\alpha\beta)\left(1-\alpha\right)}}{\alpha+e\alpha(1-\alpha\beta)}\right]$. ■

## A.4 Proof of Proposition 2

Note that $P(h_t) > 0$ if $\dfrac{1-\alpha^2\beta+e(1-\alpha\beta)\left(1-\alpha\right)}{\alpha+e\alpha(1-\alpha\beta)} > 1 \Rightarrow e < \overline{e} = \dfrac{1-\alpha(1+\alpha\beta)}{(2\alpha-1)(1-\alpha\beta)}$. Consider the value of $\alpha$ such that for each $\beta$, $\overline{e} = 0$. This value is equal to $\alpha_{\overline{e}=0} = \frac{\sqrt{4\beta+1}-1}{2\beta}$. Given that $\alpha\beta < 1$ then $\overline{e} > 0$ if $\alpha > \frac{1}{2}$. ■

## A.5 Solving for the Equilibrium

Given $e$, $A$, $\alpha$ and $\beta$, the equilibrium, $(1-l)$, $X$ $h$, $c$, $q$, $w$ and $r$ are given by the following set of seven equations.

First, from Lemma 1

$$(1-l) = \frac{\alpha\beta+e(1-\alpha\beta)}{1+e(1-\alpha\beta)}.$$

Second, from $X = X^{\alpha} - h$ and $h = X^{\alpha} l$

$$\begin{aligned} X &= (1-l)^{\dfrac{1}{(1-\alpha)}}, \\ h &= (1-l)^{\dfrac{\alpha}{(1-\alpha)}} l, \\ c &= h. \end{aligned}$$

Third, from Lemma 2

$$q = \frac{\alpha l}{1 - \alpha\,(1-l)} = \frac{\alpha\,(1-\alpha\beta)}{1 - \alpha^2\beta + e(1-\alpha\beta)\,(1-\alpha)},$$

and $w$ and $r$ are computed using equations (2) and (3)

$$\begin{aligned} w &= (1-q)X^{\alpha}, \\ r &= \alpha X^{\alpha-1}[(1-q)l + q]. \end{aligned}$$

Finally PES, $T$, and consumption price, $p_c$, are given by

$$\begin{aligned} T &= rX, \\ P &= h\left[1 - \frac{q}{l}\right]. \end{aligned}$$