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Nonsustainable Use of Renewable Resources: Mangrove Deforestation and Mariculture in Ecuador

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Abstract *The paper provides a conceptual model that examines (i) open-access exploitation and (ii) mangrove deforestation as two potential causes for the scarcity of post-larval shrimp inputs to shrimp mariculture in Ecuador. Results indicate that conversion of mangrove ecosystems to shrimp ponds may have obtained short-term profit at the expense of long-term productivity. Open-access collection of post-larval shrimp may also have contributed to dwindling stock levels. Specific policy recommendations are presented, and future empirical studies are proposed.*

Keywords Mariculture, mangroves, deforestation, shrimp, fisheries, Ecuador.

Introduction

Ecuador's shrimp industry grew rapidly during the past fifteen years, to become by 1988 the country's second largest earner of foreign currency. At that time, Ecuador was the largest supplier of shrimp to the United States and one of the largest mariculture producers in the world (Instituto de Estrategias Agropecuarias 1989). However, recent decline in the competitiveness of the industry has raised concerns about its future stability, and has focused national attention on how to develop policies to sustain the productivity and competitiveness of shrimp mariculture in Ecuador.

Important factors contributing to the decline of shrimp mariculture include (*i*) the reduced availability of post-larval shrimp (PLS) to stock shrimp ponds, (*ii*) low productivity of mature shrimp per hectare of ponds, (*iii*) fluctuations of international market prices for mature shrimp and (*iv*) growing competition from Asian

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producers. While general policy guidelines have been developed to address some of these factors (*e.g.*, Olsen and Arriaga 1989, Southgate and Whitaker 1994), there are relatively few analytical studies that can provide more specific policy recommendations.

This paper provides a conceptual model that examines two potential causes for scarcity of PLS inputs. The model is introduced to clarify the relationships among PLS collection, shrimp production, and mangrove habitat, and to make specific policy recommendations based on these relationships. Causes for PLS scarcity that can be examined include open-access exploitation of the PLS fishery (Instituto de Estrategias Agropecuarias 1989, Thian-Eng and Kungvankij 1989) and the depletion of mangrove habitat for PLS (Jothy 1984, Pauly and Ingles 1986, Turner 1989). Alternative explanations for stock fluctuations, such as the El Niño phenomenon—a southward shift of warm ocean current into Ecuadorian waters—of 1982–83, are considered in the context of comparative statics. The model identifies efficient market policies to correct for open access and deforestation externalities.

Results indicate that if mangrove ecosystems influence PLS stock development, conversion of forests to ponds for shrimp production has obtained short-term profit at the expense of long-term productivity. Specific policy recommendations are presented, and future empirical studies are proposed. If Ecuador's shrimp industry is to maintain its competitiveness in the world market, it must invest in mangrove habitat restoration and technological improvements to increase long-run productivity per hectare, rather than continue to mine the country's renewable mangrove resources for nonsustainable benefit.

The next sections discuss shrimp mariculture in Ecuador and present a conceptual model. The model examines potential links between the current crisis the industry faces, the depletion of mangrove habitats, and the open-access collection of PLS. This is followed by a discussion of results, conclusions, and policy recommendations.

Shrimp Mariculture in Ecuador

This section first describes the shrimp production cycle, collection of PLS inputs to shrimp production by *artesano* fishermen, and the potential links between PLS stocks and mangrove ecosystems. The section concludes by discussing the development of shrimp mariculture in Ecuador from its beginnings in 1979.

Shrimp Production

A shrimp producer enters the production cycle first by obtaining a concession to publicly-owned coastal lands below the high-tide line. If mangroves are present, the producer determines how much of these lands must be cleared for ponds. Trees are typically removed by workers using chainsaws, and the residual biomass is burned. Once the forest has been removed, a bulldozer is used to create a rectangular levee that encloses a flat, rectangular pond. Most ponds are between two and three meters deep and between seven and fifteen hectares. After the pond has been built, it is filled by water pumped from adjacent estuaries and stocked with PLS.

Pennaeus vannamei has proven to be the most robust species for use in stocking shrimp ponds. Stocking densities range from 30,000 to 50,000 PLS per hectare, depending on management intensity. Once the PLS are mature, they are collected by workers in canoes, who sweep nets through the pond until the mature shrimp are removed. The mature shrimp are sold by the shrimp producer to processors who ready them for final consumption. The pond is then pumped dry, and fresh water is input for the next production cycle.

Collection of Post-Larval Shrimp by Artesanos

Pennaeus vannamei PLS are obtained by shrimp producers from middlemen, who in turn purchase them from *artesano* fishermen. *Artensanos* collect PLS in an open-access fishery. In Ecuador, PLS are collected by a few thousand full-time and about 10,000 part-time *artesano* fishermen who make a living collecting PLS with hand-held nets in estuaries and beaches along the coast (Scott and Gaibor 1992). *Artesanos* collect PLS using nets, which are held in knee-deep water (roughly one meter deep). Once the net is full, the *artesano* fisherman returns to the beach, and typically discards species other than *Pennaeus vannamei.* A day's catch of *Pennaeus vannamei* PLS is stored in buckets, which are sold to middlemen. The middlemen, in turn, transport the buckets of PLS to shrimp producers' ponds in unrefrigerated trucks (LiPuma and Meltzoff 1985).

The Shrimp Life Cycle and Mangrove Ecosystems

Shrimp begin life in the open sea. After going through several maturation phases, including a larval phase, the post-larval shrimp move to estuarine waters. Post-larval shrimp remain in estuaries between three and five months before returning to the ocean. The estuarine habitat provides nutrient-rich substrates such as mangrove roots; the mangroves' complex vegetative system may also provide protection from predators (Turner 1989).

Many studies link PLS stocks to mangrove ecosystems. Jothy (1984) and Pauly and Ingles (1986) provide data for Malaysia and the Philippines that suggest that although estuarine salinity and water temperature changes affect the survival rate of PLS, in the long-term, yields are related to both quality and quantity of the mangrove habitat. Similar studies from the Gulf of Mexico, Louisiana and Japan corroborate this hypothesis (Turner 1989).

Mangrove forests are among the most biologically productive marine ecosystems. These forests are essential habitat for many species in addition to PLS. In addition to providing habitat, these ecosystems maintain water quality; they function as "kidneys" for estuarine environments by purifying water and ensuring sufficient oxygen for marine species (Webb-Vidal 1992). Other non-market and market benefits provided by mangrove forests include sediment stabilization, bird habitat and a renewable supply of forest products such as edible fruits, bark for tanning, charcoal and construction wood (Hamilton *et al.* 1989). These benefits are only examples of the types of benefits that can be provided by mangrove ecosystems. Dixon and Lal (1994) give a thorough overview of the functions, products, and attributes provided by eight globally-important wetlands categories, including mangroves.

National Trends in Shrimp Mariculture

Shrimp mariculture has dramatically changed Ecuador's coastal land uses. By 1991, 146,000 hectares had been converted to shrimp ponds (Table 1). The first shrimp ponds were placed on intertidal salt flats, where costs of pumping and PLS stocking are lower; however, since 1979 pond construction has expanded into estuarine ecosystems. This includes the conversion of 41,700 hectares of mangroves, one-fifth of Ecuador's coastal mangrove resources (Table 1). Individual estuaries have lost as much as half the primary mangrove forest (Centro de Levantamientos Integrados de Recursos Naturales 1992). In addition, some low-lying agricultural lands have also been converted to ponds; high residual salinity in the converted lands makes this change practically irreversible.

The shrimp industry expanded most rapidly between 1979 and 1984. In 1978 there were 5,416 hectares of legally authorized shrimp ponds in production. By 1984, authorized pond area grew to 89,400 hectares (Table 1). Meanwhile, annual shrimp production increased more than 600 percent, from less than 5,000 tonnes (one tonne equals 10^6g) of shrimp in 1979 to over 33,000 tonnes by 1984 (Table 2). Currently the industry's pond area has expanded to 146,000 hectares and production has grown to about 100,000 metric tonnes year^{-1} (Centro de Levantamientos Integrados por Sensores Remotos 1992).

International competition in shrimp production is growing. The entry of more efficient and productive producers into the market has caused international prices to fall (Table 2). Ecuador's ability to compete with other countries is in jeopardy. Over half of Ecuador's shrimp industry is dominated by semi-extensive production technologies. These technologies depend primarily on large pond areas and PLS collected in the wild. Average productivity in Ecuador is 0.68 metric tonnes hectare^{-1} (Table 3). This productivity is less than that found in Honduras and Mexico—Ecuador's closes Latin American competitors—and far less than China and Thailand—Asian competitors that have made effective use of hatchery-produced PLS inputs (Rosenberry 1992).

The rapid growth of the industry during the early 1980s can be attributed to the abundance of PLS stock during El Niño, low costs for establishing ponds on intertidal salt flats, and high demand and prices for shrimp in United States markets. In 1983, almost all authorized ponds were placed into production (93 percent, Table 4). However, beginning in the mid-1980s, PLS required to stock ponds became scarce (Instituto de Estrategias Agropecuarias 1989, Iverson *et al.* 1989). Shortages have been severe enough that since 1985 only half of authorized pond

Table 1
Area of Mangrove Swamps, Salt Flats and Shrimp Ponds

Year	Mangrove Swamps (*Hectares*)	Salt Flats (*Hectares*)	Shrimp Ponds (*Hectares*)
1979	203,700	51,500	5,416
1984	182,100	20,000	89,400
1987	175,100	12,400	117,700
1991	162,000	6,320	146,000

(Source: *Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos* 1992).

Table 2
Ecuador's Shrimp Harvest and World Shrimp Prices

Year	Shrimp Production (*Metric Tonnes*)	World Price (*USD per Tonne*)
1979	4,698	—
1980	9,180	10,737
1981	12,100	9,558
1982	21,500	9,709
1983	35,600	10,220
1984	33,600	9,125
1985	30,205	9,222
1986	43,628	10,670
1987	69,153	8,777
1988	77,759	7,438
1989	64,231	7,355
1990	69,620	6,445
1991	101,174	—

(Source: Fishing General Institute, *Reports,* 1992, Central Bank of Ecuador, *Monthly Reports* 1980–1990).

area is used in production (Table 4). In addition to changes in water temperature, loss of habitat and overfishing of PLS stocks decreased the PLS available for pond production of shrimp.

Decreases in stock of a marine species are difficult to document. This is especially true with PLS, which are collected for subsistence income by *artesano* fishermen in an open-access fishery: few, if any, catch-effort studies exist. However, there is some preliminary economic evidence that scarcity has increased: prices paid for PLS inputs have increased (Sutinen *et al.* 1989, Southgate and Whitaker 1994). If marginal extraction costs for a given stock of PLS are relatively constant—an assumption that seems reasonable given harvesting practices (see

Table 3
Shrimp Production and Productivity of Ecuador and Competitors, 1991

Country	Production (*Metric Tonnes*)	Productivity (*Metric Tonnes per Hectare*)
China	230,000	1.33
Thailand	120,000	1.20
Honduras	6,800	1.13
Mexico	6,000	0.96
Philippines	90,000	0.70
Ecuador	100,000	0.68
Indonesia	140,000	0.40

(Source: Rosenberry 1992)

Table 4
Area of Authorized Shrimp Ponds and Percentage Under Production

Year	Authorized for Production (*Hectares*)	In Production (*Hectares*)	Utilization (*Per Cent*)
1978	3,177	5,800	183
1979	5,416	6,400	118
1980	12,351	12,600	102
1981	27,951	16,600	60
1982	39,966	29,553	74
1983	52,856	49,000	93
1984	89,400	53,640	60
1985	92,303	41,533	45
1986	105,294	63,170	60
1987	117,700	56,496	48
1988	118,660	60,500	51
1989	126,160	63,080	50
1990	134,660	60,600	45
1991	146,000	80,300	55

(Source: *Acuacultura del Ecuador,* 1988, *Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos* 1992).

the discussion of *artesanos* above)—then the increasing gap between price and marginal cost may indicate a scarcer stock.

The next section integrates the benefits provided by PLS collection, shrimp production, and mangrove ecosystems into an economic management problem. The problem faced by Ecuador is to determine how to sustain maximum joint benefits from the PLS fishery, shrimp production, and mangrove ecosystems.

The Social Planner's Problem

A social planner[1] for the shrimp mariculture sector will optimize benefits in both the PLS and shrimp sectors by choosing the amounts of shrimp to produce and PLS to harvest, as well as the area of ponds to create from mangroves. Potential benefits from undisturbed mangrove ecosystems include not only PLS habitat but also other benefits that may be unrelated to PLS or shrimp (*e.g.*, water quality improvement). Consider the case where the sector is comprised of n shrimp farmers operating as price-takers in a competitive market. Each farmer determines the amount of shrimp to produce, $y_{s,t}$. Shrimp production is a function of

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[1] A social planner is introduced as a rhetorical device to identify how decisions would be made if all economic benefits and costs were considered by a single decisionmaker. Although no single agency in Ecuador has the authority to control all of the decision variables, this rhetorical strategy identifies policies that—when introduced into individual decisions of *artesanos* and shrimp producers—provide incentives for individual decisions to accomplish collective goals.

the amount of PLS used to stock the ponds, $y_{PLS,t}$, and the area of ponds employed, P_t. (The time subscripts for shrimp production and PLS harvests will be suppressed from this point on.) Each farmer's ability to produce shrimp from these inputs is described by the function $y_s = f_s(y_{PLS},P_t)$. The cost to produce y_s units of shrimp is $c_s(y_s)$[2]. Each unit of shrimp produced can be sold at p_s; demand faced by the industry as a whole is downward-sloping, and is given by the function $p_s(ny_s)$.

The planner must also choose y_{PLS}, the PLS harvests for m price-taking *artesano* fishermen. *Artesanos* sell their harvests at price p_{PLS}; total demand for PLS is downward-sloping, and is given by $p_{PLS}(my_{PLS})$. Each *artesano* incurs a cost $c_{PLS}(y_{PLS},X_{PLS,t})$ for catching y_{PLS} units of PLS; costs depend not only on harvest, but also on the stock of PLS, $X_{PLS,t}$. (The time subscript on stock will be suppressed from this point on.) We maintain the assumption that when PLS are abundant, they are easier (i.e., cheaper) to catch; thus, the marginal cost of PLS harvest decreases with stock, $\partial c_{PLS}/\partial X_{PLS} < 0$. The development of PLS stock over time depends on the relationship between harvest and growth. Total PLS harvest is my_{PLS}; growth is determined by current stock X_{PLS}, as well as by the amount of mangroves present, M_t. The recruitment function for PLS stock is $f_{PLS}(X_{PLS},M_t)$.

The planner determines pond area by choosing d_t, the area of mangrove forests to deforest and place into ponds. The cost of converting mangroves to ponds is $c_d(d_t)$. When left as mangroves, a mangrove area of M_t will provide benefits (*e.g.*, water quality improvement) of $B(M_t)$. The problem below treats all mangroves as potentially eligible for conversion; maintaining some mangroves in preserves yields essentially the same policy conclusions.

In order to maximize joint benefits from shrimp production, PLS harvest, and mangrove ecosystems, the social planner must maximize the discounted sum of consumer surplus, producer surplus and mangrove benefits. The planner obtains benefits by choosing shrimp harvest, y_s, deforestation rate, d_t, and PLS harvest, y_{PLS}. Surpluses are obtained in both the shrimp and PLS sectors. The present value of net benefits is:

$$PVNB = \int_0^\infty \left\{ \left[\int_0^{ny_s} p_s(\zeta)d\zeta - nc_s(y_s) - nc_d(d_t) \right] + \left[\int_0^{my_{PLS}} p_{PLS}(\zeta)d\zeta - mc_{PLS}(y_{PLS},X_{PLS}) \right] + B(M_t) \right\} e^{-rt}dt, \qquad (1)$$

where r is the planner's rate of time preference for benefits. Constraints include shrimp production technology, $f_s(y_{PLS},P_t)$, which depends on PLS input, y_{PLS}, and pond area, P_t, for each of the n firms:

$$y_s = f_s(y_{PLS},P_t). \qquad (2)$$

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[2] Given the variations in PLS availability, the costs of PLS inputs to shrimp production could be considered stochastic. Introducing stochastic costs, PLS harvests, and PLS stocks would clarify the role of risk in the system, but would not substantially change the conclusions of the analysis. A deterministic formulation is used to arrive at conclusions more directly.

Change in pond area, P_t, for each of the n firms changes with the deforestation rate d_t that the planner selects for the firm:

$$\dot{P}_t = d_t. \tag{3}$$

Change in total mangrove area depends on the total deforestation the planner chooses for all n firms:

$$\dot{M}_t = -nd_t. \tag{4}$$

The change in X_{PLS}, the stock of PLS, depends on the existing stock and on the area of mangroves. The rate of change in PLS stock is the difference between recruitment and harvest:

$$\dot{X}_{PLS} = f(X_{PLS},M_t) - my_{PLS}. \tag{5}$$

Finally, available labor and capital may place constraints on rates of deforestation:

$$0 \leq d_t \leq d_{MAX,t} \tag{6}$$

The social planner can obtain maximum benefits by solving the Hamiltonian, H:

$$\begin{aligned} H = \Bigg\{ & \left[\int_0^{ny_s} p_s(\zeta)d\zeta - nc_s(y_s) - nc_d(d_t)\right] \\ & + \left[\int_0^{my_{PLS}} p_{PLS}(\zeta)d\zeta - mc_{PLS}(y_{PLS},X_{PLS})\right] + B(M_t)\Bigg\} \\ & + n\omega[f_s(y_{PLS},P_t) - y_s] + n\lambda_{P,t}d_t - n\lambda_{M,t}d_t \\ & + \lambda_{X,t}[f_{PLS}(X_{PLS},M_t) - my_{PLS}]. \end{aligned} \tag{7}$$

Where ω represents the marginal value of an additional unit of shrimp. The variables $\lambda_{P,t}$, $\lambda_{M,t}$, and $\lambda_{X,t}$ are the marginal values assigned by the planner to additional hectares in ponds and mangroves, and to an additional unit of PLS harvest, respectively. The social planner's optimal choice for shrimp production is given by:

$$\frac{\partial H}{\partial y_s} = p_s(ny_s)n - nc_s' - n\omega = 0. \tag{8}$$

In order to maximize *PVNB* from shrimp production, the social planner will require ω, the shadow value of an additional unit of shrimp production, to equal marginal revenue less marginal cost, $p_s - c_s'$. The planner's best choices for PLS harvests are given by:

$$\frac{\partial H}{\partial y_{PLS}} = p_{PLS}(my_{PLS})m - m\frac{\partial c_{PLS}}{\partial y_{PLS}} + n\omega\frac{\partial f_s}{\partial y_{PLS}} + \lambda_{X,t}(-m) = 0. \tag{9}$$

To maximize *PVNB* from PLS harvests, the planner must balance the net benefits obtained by harvesting PLS with the opportunity costs of decreasing the PLS stock. Net benefits consist of (*i*) marginal surpluses in the PLS sector, $m[p_{PLS} - \partial c_{PLS}/\partial y_{PLS}]$, and (*ii*) marginal surpluses in the shrimp sector (provided by an additional unit of PLS harvest), $n\omega[\partial f_s/\partial y_{PLS}]$. Marginal opportunity costs of reducing PLS stock are given by $m\lambda_{X,t}$. In addition to these static results, the costate equations for $\lambda_{P,t}$, $\lambda_{M,t}$, and $\lambda_{X,t}$ can give the social planner insight into how the values of ponds, mangroves, and PLS stocks should be managed over time.

The costate equation for ponds is given by:

$$\dot{\lambda}_{P,t} = r\lambda_{P,t} - \left(\frac{\partial H}{\partial P_t}\right)\Big/ n. \tag{10}$$

Which, after solving for the planner's valuation of land in ponds, becomes

$$\lambda_{P,t} = \left(p_s\frac{\partial f_s}{\partial P_t} - c_s'\frac{\partial f_s}{\partial P_t}\right)\Big/ r + \frac{\dot{\lambda}_{P,t}}{r}. \tag{11}$$

The marginal value of an additional hectare of ponds, $\lambda_{P,t}$, is the sum of discounted marginal benefits in shrimp production (the first term on the right-hand side above) and discounted capital gains. This definition for the value of land in ponds provides context for the planner's problem of deciding how much (if any) to deforest.

The planner's decisions for optimum deforestation (indicated by d_t^*) are guided by the following conditions:

$$\begin{aligned} d_t^* &= 0 \; if \frac{\partial H}{\partial d_t} < 0, \\ d_t^* &= d_t^* \; if \frac{\partial H}{\partial d_t} = 0, \; and \\ d_t^* &= d_{MAX,t} \; if \frac{\partial H}{\partial d_t} > 0. \end{aligned} \tag{12}$$

The intuition behind the planner's optimum deforestation choices lies in the potential effects of deforestation:

$$\frac{\partial H}{\partial d_t} = -nc_d'(d_t) + n\lambda_{P,t} - n\lambda_{M,t}. \tag{13}$$

When the marginal benefits of converting land to ponds, $\lambda_{P,t}$, minus marginal costs of deforestation, c_d', exceeds the marginal value of land in mangroves, $\lambda_{M,t}$, the planner will maximize *PVNB* by clearing mangroves as rapidly as possible. In contrast, if marginal benefits from preserving mangroves exceeds marginal (net) value in ponds, then the planner will maximize *PVNB* by ceasing deforestation. (As the mangrove ecosystems become scarcer and scarcer, it is possible that marginal benefits contributed by these ecosystems, $B'(M_t)$, increase. Arguments for a moratorium on mangrove conversion would depend in part on this assumption.) The Planner's marginal value for a hectare of mangroves deserves more attention.

As with the ponds, the costate equation for mangroves reveals to the planner the components of this value:

$$\begin{aligned}\dot{\lambda}_{M,t} &= r\lambda_{M,t} - \frac{\partial H}{\partial M_t} \\ &= r\lambda_{M,t} - \left[B'(M_t) + \lambda_{X,t}\frac{\partial f_{PLS}}{\partial M_t}\right]. \qquad (14)\end{aligned}$$

With some rearranging, the planner's marginal value for a hectare in mangroves can be seen to consist of the sum of (*i*) discounted value of additional PLS stocks, (*ii*) discounted marginal ecosystem benefits, and (*iii*) discounted capital gains. These terms are shown in order on the right-hand side below:

$$\lambda_{M,t} = \left[\lambda_{X,t}\frac{\partial f_{PLS}}{\partial M_t}\right]\Big/ r + \frac{B'(M_t)}{r} + \frac{\dot{\lambda}_{M,t}}{r}. \qquad (15)$$

The final shadow price required is $\lambda_{X,t}$, the value of an additional unit of PLS stock; this is the planner's marginal value per unit of additional PLS stocks (i.e., the "price" of additional stock in the first term on the right-hand side above). The planner's valuation of additional PLS stock can be obtained from the costate equation for PLS stock:

$$\begin{aligned}\dot{\lambda}_{X,t} &= r\lambda_{X,t} - \frac{\partial H}{\partial X_{PLS}} \\ &= r\lambda_{X,t} - \left[-m\frac{\partial c_{PLS}}{\partial X_{PLS}} + \lambda_{X,t}\frac{\partial f_{PLS}}{\partial X_t}\right]. \qquad (16)\end{aligned}$$

If we consider $r - \partial f/\partial X_t$ to be the planner's rate of time preference, adjusted for the growth of stock (*e.g.*, the adjusted opportunity cost of a growing capital stock), we obtain a result analogous to the results for pond and mangrove shadow values:

$$\lambda_{X,t} = \left(-m\frac{\partial c_{PLS}}{\partial X_{PLS}}\right)\Big/\left(r - \frac{\partial f_{PLS}}{\partial X_t}\right) + \dot{\lambda}_{X,t}\Big/\left(r - \frac{\partial f_{PLS}}{\partial X_t}\right). \qquad (17)$$

The first term includes the stock effect of a cost savings for each of the *m artesanos*. Since the costs of catching PLS decrease when PLS are abundant, we can conclude that $\partial c_{PLS}/\partial X_t < 0$; thus, the stock effect adds a positive amount to the planner's valuation of additional PLS. The second term is the planner's expected capital gain in the value of the stock, discounted using the adjusted rate.

In summary, the planner can obtain maximum benefits by equating marginal benefits with marginal costs for shrimp production, PLS harvests, and deforestation. Benefits from conserving the mangrove endowment include increased PLS stocks (cf. Swallow 1990) and other benefits unrelated to PLS and shrimp. To facilitate the design of market policies, the next section develops a model of individual shrimp producer and *artesano* decisions. Policies are identified by comparing the individual solutions with the planner's benefit maximizing choices. Instruments are proposed that provide incentives for individual behavior to optimize social economic welfare.

The Shrimp Farmer's Problem

With the social planner's problem complete, we can now examine the problem from the perspective of the private shrimp producer. The goal of each of the n shrimp producers is select shrimp production, y_s, and deforestation, d_t, in such a way as to maximize producer surplus, which is

$$\int_0^{\infty} [p_s y_s - c_s(y_s) - c_d(d_t)]e^{-rt}dt. \tag{18}$$

The parameter r is the producer's rate of time preference (e.g., the opportunity cost of capital devoted to shrimp production). It should be noted that the discount rate used by the producer and social planner need not be equal. When private and social rates are different, discounted values assigned to future mangrove or pond benefits will differ. In this case, empirical simulations can be used to identify the values required for policy instruments (see below).

The development of pond area over time is given by the deforestation rate (as in the planner's problem), and shrimp production technology remains the same. However, the mangrove endowment for a single firm is M_t/n, so that the development of mangrove area over time appears differently than in the planner's problem:

$$\dot{M}_t/n = -d_t. \tag{19}$$

The producer can determine optimum PLS inputs, y_{PLS}, and pond inputs (*i.e.*, deforestation), d_t, from the Hamiltonian:

$$\begin{aligned} H = {} & p_s y_s - c_s(y_s) - c_d(d_t) \\ & + \omega[f_s(y_{PLS}, P_t) - y_s] + \lambda_{P,t} d_t - \lambda_{M,t} d_t. \end{aligned} \tag{20}$$

From the producer's perspective, PLS harvests are exogenously determined by *artesanos*, and thus do not appear in the producer's benefit function. The producer can determine optimum PLS from:

$$\frac{\partial H}{\partial y_{PLS}} = \omega\left(\frac{\partial f_s}{\partial y_{PLS}}\right) = 0. \tag{21}$$

Because the marginal value of an additional unit of shrimp, ω, is $p_s - c_s'$, the producer will maximize profits by selecting PLS inputs until the value of the marginal product of PLS, $p_s[\partial f_s/\partial y_{PLS}]$, is equal to its marginal cost, $c_s'[\partial f_s/\partial y_{PLS}]$. This is the producer's derived demand for PLS inputs.

In order to maximize profit from deforestation, the producer uses the same principle as the planner: convert mangroves to shrimp ponds when benefits in ponds exceed the marginal value of land in mangroves. The costate equation for pond growth shows that $\lambda_{P,t}$, the value to the producer of an additional hectare of ponds, is the sum of discounted net benefits and capital gains. So far, the producer's rule is the same as the planner's. However, profit maximizing deforestation choices for the producer diverge considerably, because the value of mangroves to the producer is very different than the value to the planner. For example, consider the costate equation for mangroves derived from the producer's problem:

$$\begin{aligned} \dot{\lambda}_{M,t} &= r\lambda_{M,t} - \frac{\partial H}{\partial M_t} \\ &= r\lambda_{M,t}. \end{aligned} \tag{22}$$

Taken together, the costate equation and the producer's optimum deforestation condition (*i.e.*, $-nc_d'(dt) + n\lambda_{P,t} - n\lambda_{M,t} = 0$) show that the mangroves' value to the producer derives only from the potential for pond conversion. When conversion is not profitable, the mangrove endowment is worthless; in contrast, when profits are to be made, the producer maximizes profits by deforesting as rapidly as available labor and capital will permit.

Economic Policy Instruments

In order to reconcile the producers' profit-maximizing deforestation rate with the social planner's benefit-maximizing rate, discounted benefits provided by mangroves must be internalized by the producer. A tax that includes (*i*) discounted stock effects of additional mangrove habitat, and (*ii*) discounted non-PLS mangrove benefits, would internalize the environmental opportunity costs currently omitted in the producer's problem. Making these costs internal to the producer's decisions would lead the individual producers, acting to maximize their own benefits, to accomplish the collective welfare-maximizing solution sought by the planner. A tax on mangrove-clearing would ultimately provide more PLS habitat, which could in turn help replenish the dwindling stock. However, this is only part of an integrated solution.

Individual choices by producers and *artesanos* also determine the level of PLS harvest. Producers determine demand for PLS inputs, which in turn are supplied by *artesanos*. The aggregate harvest by *artesanos* influences the development of PLS stock over time. We have already seen how the producer will demand PLS in order to maximize profits. In an open-access PLS fishery with minimal costs of entry (*i.e.*, the cost of a hand-held net), *artesanos* determine the supply of PLS by harvesting until all rents are dissipated. The supply of PLS is given by

$$p_{PLS} - \frac{c_{PLS}}{y_{PLS}} = 0. \tag{23}$$

The producer's derived demand for PLS inputs and the *artesanos'* supply of PLS can be rewritten for comparison to the social planner's solution:

$$n\left[p_s \frac{\partial f_s}{\partial y_{PLS}} - c_s' \frac{\partial f_s}{\partial y_{PLS}}\right] + m\left[p_{PLS} - \frac{c_{PLS}}{y_{PLS}}\right] = 0. \tag{24}$$

From this, we can see that the shrimp producers and *artesanos* will interact to exploit the PLS stock at greater harvests than the social planner. A tax of $\partial c_{PLS}/\partial y_{PLS} - c_{PLS}/y_{PLS}$ will correct for the open-access externality, and an additional $\lambda_{X,t}$ will account for opportunity costs of decreases in stock. Making these costs internal to the *artesanos'* decisions would accomplish the collective welfare-maximizing solution sought by the planner. Although these taxes would enable the PLS stock to recover, such instruments may be costly to administer and enforce (see below). While licensing fees that approximate these costs are a possibility, other regulatory instruments to reduce catch, such as quotas or equipment restrictions, may be more feasible.

The next section will argue that weak regulations and institutions may have led the industry to assign a value of zero to all costs of mangrove conversion other than the direct costs of clearing. The long-term consequences of this are decreased PLS stocks for individual farmers, and national productivity declines for the industry as a whole.

Discussion

If mangrove habitat effects PLS stock, then the increasing scarcity of PLS represents a growing opportunity cost for the industry and fishermen in the form of foregone future benefits. By selecting excessive deforestation rates, the industry may have purchased short term profits at the expense of long-term sustainable productivity.

One of the most critical consequences of the crises of the mid-1980s was the generation of a vicious cycle between mature shrimp prices and PLS fishing rates. This occurs in the market for PLS as a factor input. The supply of PLS is determined by open-access collection by *artesanos*. The demand for PLS inputs is the derived demand of shrimp producers for a production input. The rapid expansion of the industry's pond hectarage (Table 1) precipitated increased demand for PLS inputs. This created excess rents in the PLS market, and encouraged *artesanos* to increase PLS harvest rates, ultimately leading to the overexploitation of the resource. Diminished PLS stocks leads producers to compete for smaller and smaller amounts of PLS inputs, while at the same time, *artesanos* must continue to increase their effort to support their families from a dwindling PLS stock.

Exogenous shocks to the PLS input market, such as El Niño, provide transitory windfalls to both producers and *artesanos*. The warmer temperatures may be favorable to recruitment, which increases stock and lowers extraction costs to *artesano* suppliers. (The abundant PLS are easier to catch.) This downward shift in PLS supply decreases the marginal factor cost to shrimp producers, leading to increased equilibrium demand for PLS inputs. Equilibrium extraction (after El Niño causes a downward shift in PLS supply) may be greater than under normal ocean temperatures; however, this can only be temporarily supported. If capacity expands to take advantage of these ephemeral conditions, overcapacity (Table 4) is a natural consequence when the ocean (and PLS stocks) return to normal conditions.

The economic interaction between shrimp farmers demanding PLS inputs and *artesano* fishermen collecting these inputs can be environmentally devastating. Their unregulated interaction may perpetuate the crisis that the shrimp industry suffers. There are no public agencies regulating the activities of the *artesano* fishermen and, in fact, there is a government decree clearly stating that all beaches, estuaries and mangrove ecosystems of public access are open to PLS fishing (Instituto de Estrategias Agropecuarias 1989).

Much of the alteration of coastal ecosystems in Ecuador can be attributed to the legal standing of coastal resources. Although a legal and institutional framework has been in place to regulate the development of the industry, for all practical purposes access to the resources has been completely free (LiPuma and Meltzoff 1985, Perez and Robadue 1989). According to Ecuadorian laws all coastal land lying below the highest tide line belongs to the government (LiPuma and Meltzoff 1985, Instituto de Estrategias Agropecuarias 1989). That is, coastal beaches, large portions of salt flats and of course, all mangrove forests and estuarine ecosystems. The most critical example of the weakness of laws and government institutions is the total failure to protect the mangrove forests.

A 1975 regulation and its 1985 amendment contain specific articles prohibiting the conversion of mangrove forests to shrimp ponds. In addition, a law concerned with forestry and conservation of flora and fauna enacted in 1978 prohibits the construction of ponds in mangrove areas. Moreover, there are other laws and decrees enacted by several government agencies which created protected areas and declared the conservation of mangrove forests as "in the public interest" (Instituto de Estrategias Agropecuarias 1989). In spite of these laws, the rate of mangrove deforestation between 1979 and 1991 averaged about 3000 hectares per year, resulting in the loss of one-fifth of Ecuador's mangrove forests (Table 1).

The laws and regulations governing the industry were not designed to encourage a sustainable relationship between economic objectives and ecosystem management. In 1975 the government issued a regulation allowing the construction and operation of shrimp ponds on public lands under a renewable 10-year concession. Although the system of concessions was well intentioned, it very quickly became an open source of corruption and a critical policy issue affecting resource management. A longer concession that allowed producers to reap the PLS stock benefits from mangrove conservation would make more economic sense. The short length of current concessions may contribute to incentives for the short-term mining of mangrove resources as a location for ponds. In addition, the government sells concessions for far below their value: the annual charge, equal to 11 percent of a minimum monthly wage per hectare, is generally less than $10. This captures less than one percent of the economic rent that can be obtained from placing these lands in ponds; this rent can exceed $2000 per hectare per year (Southgate and Whitaker 1994).

Short-term concession arrangements and poorly-enforced laws are among the main causes for the excessive deforestation and degradation of Ecuador's coastal ecosystems. Although government agencies must take much of the blame for the problems that the industry faces, it is also possible that shrimp farmers' failure to recognize the costs of environmental disturbance are critical components for understanding the industry's dilemma. One of the most dramatic consequences of the lack of planning and regulation of the industry is the excessive amount of land in ponds relative to the availability of PLS (Table 4). The result of this imbalance is that the industry's installed capacity has been largely under-used (Instituto de Estrategias Agropecuarias 1989), and the ratio of shrimp produced to area in ponds has fallen below those of competing countries (Table 3).

Due to the lack of integrated planning, short term rent-seeking behavior of the industry, and unenforced laws, Ecuador's mariculture industry has developed without considering environmental costs. This has cost the industry competitiveness, and resulted in excessive deforestation and the uncontrolled collection of PLS. The industry's failure to recognize these opportunity costs is jeopardizing the long-term sustainability of the industry itself.

Policy Recommendations

The conceptual model explores the consequences of a relationship between mangrove habitat and PLS stocks and concludes that deforestation may have been excessive. The most important policy implication of these results is that command and control approaches have completely failed to regulate the industry's economic development. In addition, public policies have encouraged the overexploitation of PLS stocks through open-access collection by *artesanos*. If drastic policy measures are not implemented, ecosystem destruction will continue as long as there are profits to be made from mangrove forest conversion and PLS collection.

Had it been implemented and enforced before the expansion in the early 1980s, an incentive-based tax approach could have encouraged recognition of the full costs of deforestation. While it is true that the industry has been subjected to a tax on shrimp exports (Sutinen *et al.* 1989 p31), this has failed to slow conversion of mangroves (Table 1). A tax that is more directly linked to pond construction would help internalize the opportunity costs of deforestation. The addition of these costs into the shrimp producers decisions could prevent excessive conversion of mangroves to ponds.

In the long term, there may be opportunities for tax revenues to be recycled into profitable investments in mangrove reforestation. Incentives to supplement these public investments with private funds could be strengthened by increasing the length of the land concessions. Concession length should be sufficient to allow concession holders to benefit from reforestation activities that they undertake (*e.g.*, sufficiently long for PLS stocks to respond to increased habitat area).

If the effects of mangrove deforestation on PLS stocks are fairly localized (*e.g.*, within an estuary) it may be feasible to internalize the opportunity costs of deforestation to cooperatives of shrimp producers within an estuary. Cordell and McKean (1992) identify physical and technical attributes and decisionmaking arrangements that have led to sustainable management of fisheries commons in Bahia, Brazil. These commons have flourished with minimal reliance government agencies or policies. Provided that similar conditions are present in Ecuador, private solutions to excess exploitation of mangrove stocks by shrimp producers—or of PLS stocks by *artesanos*—may be possible.

At the same time, if Ecuador is to maintain its competitiveness in the world shrimp market it is also critical that the industry's productivity per hectare be increased. To accomplish this, investments in human capital and scientific research must be encouraged. The development of a sustainable and profitable hatchery industry is a viable short- and long-term alternative to the unreliable supply of PLS collected in the wild. By providing a larger, more stable supply of PLS inputs, hatcheries will increase the industry's productivity per hectare. Improving the ability of hatchery-produced PLS to survive the production cycle is essential.

This approach represents a shift from land-intensive shrimp technology to capital-intensive technology; a shift that has already succeeded in Asia (Table 3). The change in inputs from land toward capital will also help prevent future conversion of mangrove forests and agricultural land. An expanded model of the shrimp mariculture sector that includes both wild and hatchery-produced PLS inputs could clarify the incentives necessary for these shifts. Producing more shrimp from a relatively stable land base is clearly a step toward restoring and sustaining Ecuador's competitive position in the global shrimp market.

Although PLS hatcheries may contribute to a sustainable shrimp industry for Ecuador, their economic viability is uncertain. For example, equilibrium demand for PLS produced in hatcheries may fluctuate with changes in ocean temperature. When the El Niño effect is present, wild PLS is abundant and cheap; profit-maximizing shrimp producers may displace PLS produced in hatcheries with cheaper wild PLS. Therefore, quantifying and planning for temperature effects on the hatchery industry is essential before any program designed to support this industry can be developed.

Conceptual extensions of the model can help by examining the economic connection between ocean temperature fluctuations and the returns to hatchery investment. As a starting point, one can recognize that since temperature is exogenous, the supply of wild PLS and derived demand for PLS inputs will depend on temperature levels. If wild PLS and PLS produced in hatcheries are substitutable inputs, then comparative statics could subsequently be used to anticipate how shrimp producers would change demand in response to changes in the availability of both types of PLS.

Finally, it is important to point out that many of the policies encouraging the mismanagement of coastal ecosystems are similar to the policies stimulating tropical deforestation. For example, the lack of enforceability of laws that prevent the use of forests in an open access fashion and the failure to recognize the opportunity costs of tropical forest conversion are parallel issues to the case of coastal resource management. Therefore, this study's arguments and results could cautiously be extended to analyze some of the socio-economic forces and policies behind rainforest conversion. Extension of these policy recommendations presumes a positive economic feedback for those who make conservation decisions (*i.e.*, increased PLS stocks and lower input costs for shrimp producers). In the case of tropical forests, conservation benefits directly accrue to decisionmakers in some contexts (*e.g.*, ecotourism revenues, marketed rain forest products), but not everywhere that deforestation is of concern.

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