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Ecological Modelling 112 (1998) 131–150

ECOLOGICAL MODELLING

Ecological–economic model for optimal mangrove trade off between forestry and fishery production: comparing a dynamic optimization and a simulation model

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Abstract

Mangrove ecosystems provide valuable ecological services for the maintenance of the adjacent habitats and wildlife preservation. They also provide a highly caloric timber, used frequently for burning purposes as, e.g. charcoal. The forestry activity usually ignores the capacity of the mangroves to support the local fisheries. Therefore, it is necessary to study the relationship between these activities and how they could be managed in order to maximize their benefits, and at the same time to preserve ecosystem services. This problem was approached by two different modelling procedures, widely used in natural resources management studies: a dynamic optimization and a simulation model. The dynamic optimization model gave us some hints about the best allocation of workers between forestry and fishery sectors. Using the simulation model it was possible to take the data generated and employ it in our first order conditions equations from the optimization model to find the shadow prices for the resources stocks. The most important variable in the simulation is the forest growth rate, since the fishery production is directly dependent on the area of mangrove forest. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Mangrove ecosystem; Forestry–fisheries trade off; Dynamic optimization; Simulation model

1. Introduction

There is a critical need to understand the function of mangroves in tropical ecosystems due to the rate at which these intertidal areas are being converted to alternate land uses. Mangroves are exploited for forestry products, including fuelwood for cooking, fenceposts, charcoal, tannins, pulpwood, chipwood and timber (Polunin, 1983). Areas inhabited by mangroves are also reclaimed for agriculture, aquaculture and residential development. In contrast to forestry, which attempts to maintain some sustainable yield in mangrove ecosystems, reclamation activities such as urban development, agriculture and pond mariculture result in the loss of this resource in the coastal zone areas.

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PII S0304-3800(98)00076-3

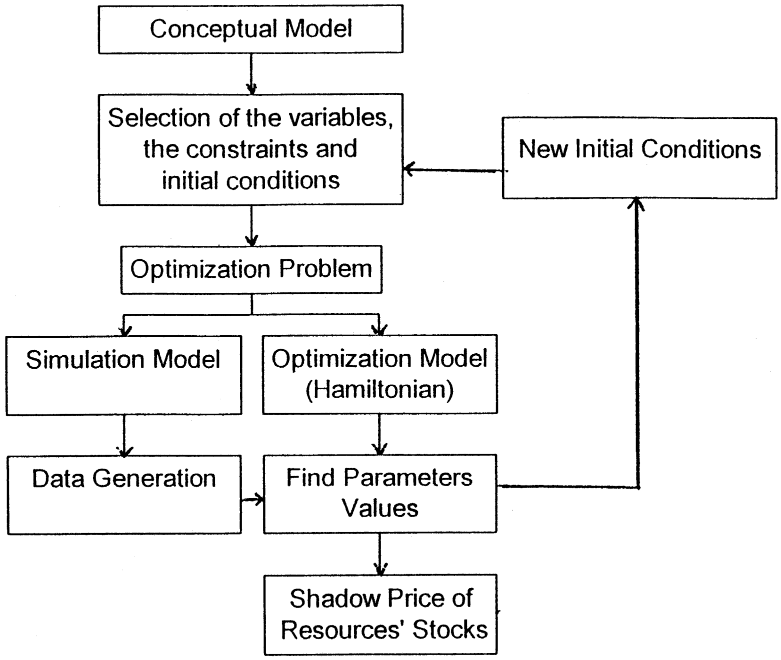


Fig. 1. Structure of the interaction of both models.

Mangroves may indirectly support economically important fisheries by providing free services such as habitat, food and good water quality. Thus the loss of these plant communities would negatively impact industries that rely on productive coastal fisheries. However, to settle these conflicts, information that describes the function of mangroves more clearly is needed for a better understanding of the importance of these systems to the fisheries of tropical estuaries.

The purpose of this paper is to identify the optimum management alternatives that incorporate the ecosystem constraints as well as the needs of the local population. A case study of mangrove exploitation in a developing country (Brazil), where local people depend mainly on natural resources for their survival, was used to validate results obtained from the models. Both models work with some general assumptions of fisheries, forestry and ecosystem functions. The models deal with the interaction between different uses of the ecosystem and how fisheries production is affected by the decrease of mangrove area available. Therefore, both models could also be applied to all types of situations where mangrove areas have been occupied, e.g. aquaculture, real estate enterprises, harbour constructions, and even to oil spill damages.

Two different modelling approaches are used in order to obtain an optimum use of the mangrove resources. Therefore, besides the identification of the management options, this paper focus on the discussion of different modelling procedures. The combination between a simulation and optimization model may be of considerable value in bridging the gap between utilizing the information from basic ecological research (from which many of the flow equations must be built for the simulation model segment) and the pragmatic problems of the field resource planner (as in the optimization model segment); and they can become a very useful tool when data gathering is difficult or highly costly (Swartzman and Van Dyne, 1972).

Combining both simulation and optimization procedures could be an option to check the optimum conditions and the relevance of the chosen variables through sensitivity analysis. The relationship between those models can be illustrated by Fig. 1.

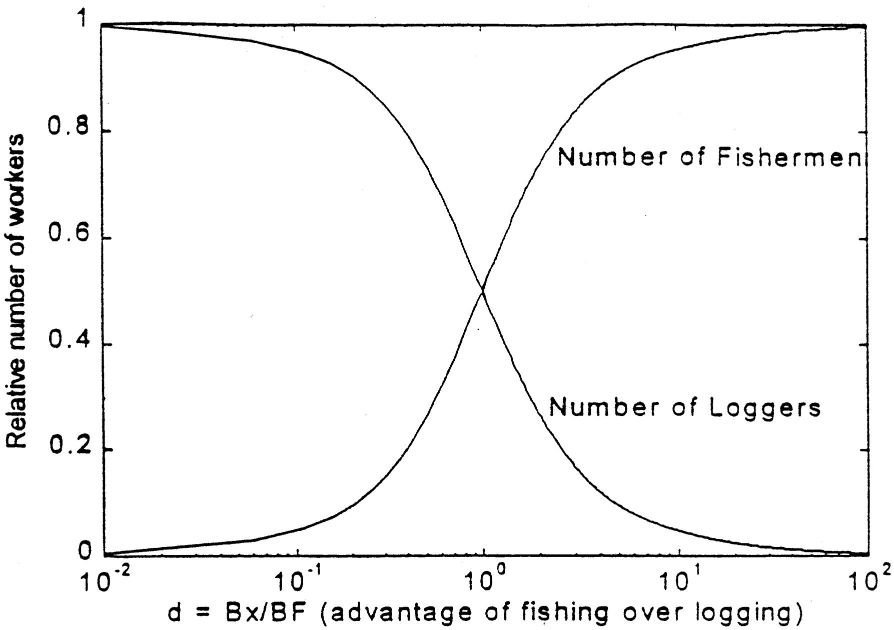


Fig. 2. Fishermen's behavior function.

The simulation model first generates the data to be applied to the optimization procedure and then the feedback from the latter are the new initial conditions to the next simulation. This is a good approach to situations where the scenarios are always changing, as is the case of natural resources uses. If environmental conditions change, as e.g. climate changes, the optimal and the initial conditions will be different.

This paper will focus on the optimal use mangrove ecosystem. A description of the ecosystem as well as its relationship with fisheries production are covered next. After that there will be a description of the models and some discussion about results.

1.1. Productivity and development of mangrove forests

There are several different types of mangrove wetlands, each one having a unique set of topographic and hydrodynamics conditions. Mangroves can develop only where there is adequate protection from wave action. Several physiographic settings favor the protection of mangrove swamps, including (1) protected shallow bays, (2) protected estuaries, (3) protected lagoons, (4) the leeward sides of peninsulas and islands, (5) protected seaways, (6) behind spits and (7) behind offshore shell or shingle islands (Mitsch and Gosselink 1993). In addition to the required physical protection from wave action, the range and duration of the flooding of tides exert a significant influence over the extent and functioning of the mangrove swamp. The tides constitute an important subsidy for the ecosystem to import nutrients, aerating the soil water, and stabilizing soil salinity.

Mangroves provide detrital nutrient input into coastal waters which support the estuarine fauna. The manner in which secondary and tertiary productivity, i.e. harvestable and non-fish resources are affected by the presence of mangrove flora depends not only on the detrital inputs but also on the complex biological and chemical process within the ecosystem and between mangrove and adjacent areas. Mangrove areas act as a habitat as well as spawning and nursery grounds for fish and non-fish fauna (Odum and Heald 1972; Robertson 1988). Not all species caught in mangrove waters are permanent residents.

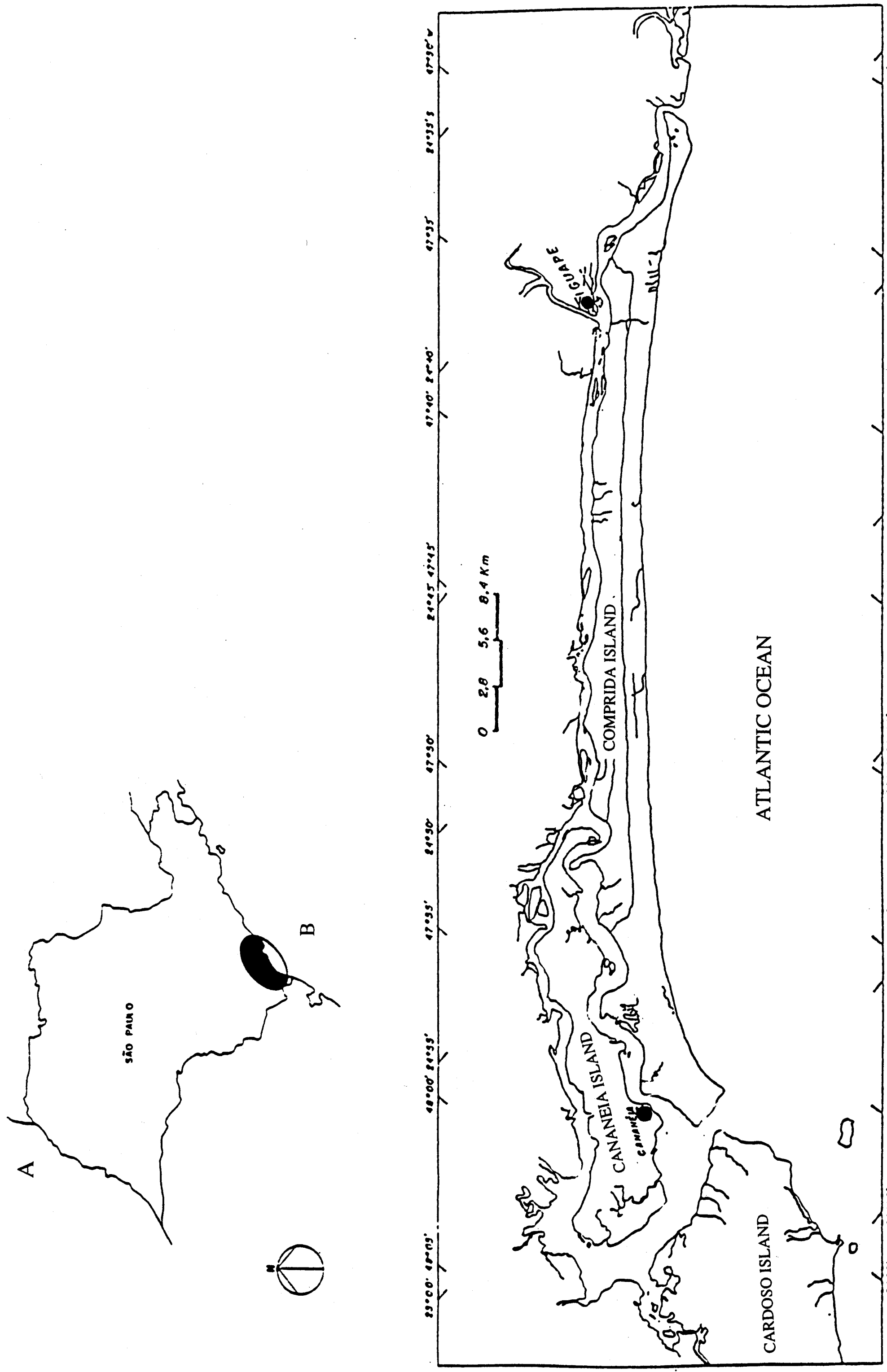


Fig. 3. Area of study.

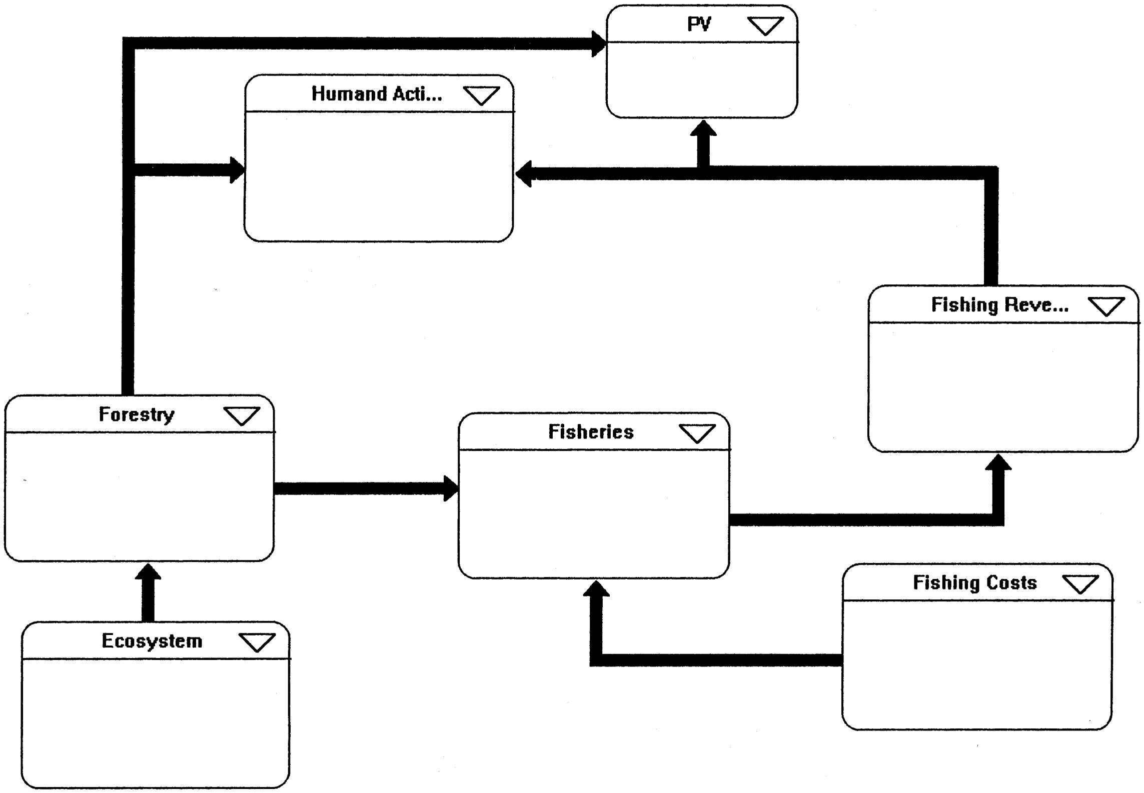


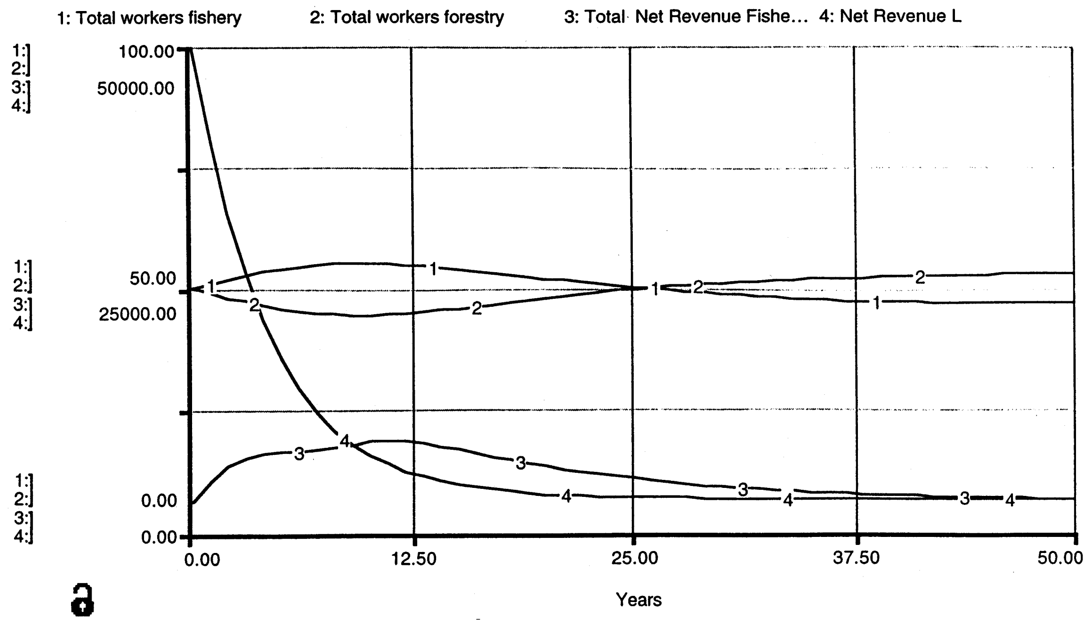
Fig. 4. Model structure.

The tides and runoff control the exchange of materials across the boundaries of the mangrove–estuarine ecosystem and are the major process associated with the exchange of material with this system. The amount of water transported among mangrove, estuary and continental shelf is dependent on this potential hydrologic energy and on the geomorphology of the region (Odum et al., 1979). These two factors also determine the extent to which the intertidal zone is inhabited by mangrove vegetation.

The development of mangrove swamps is the result of topography, substrate and freshwater hydrology, as well as tidal action. All of these factors will determine the resilience and the capacity of support of this ecosystem. It is important to note that mangroves are already under 'stressed' environmental conditions: the linkages between the forest and the physical factors are very sensitive to any change. This is the type of ecosystem that will support only low environmental impact. Once the vegetation is taken away it may not come back again, e.g. if the trees that are in a riverine mangrove are cut down, the chances for a new tree to grow will depend strongly on the intensity of the currents; if they are too strong the erosion will not allow any recovering of the area. It is also important to have in mind that estuarine areas are very dynamic, subject to great change in a short period of time.

When preparing any forestry management plan, it should be taken into account that for each area harvested there will be a percentage of the remaining forest that will disappear due to the secondary effects of cleaning.

A classification of the mangrove wetland ecosystem according to the physical conditions was developed by Lugo and Snedaker (1974) and included as six types. For this work, the classification made by Cintrón et al. (1985) will be used.



Total workers fishery	47%
Total workers fore...	53%

Total number of w...	100%

Total Net Revenu...	$3,304.20
Net Revenue L	$3,338.59

Net PV	$169,680.65

Fig. 5. Graph showing the allocation of workers between activities and their respective revenue (Scenario 1).

After exclusion of scrub type, three types of mangroves can be identified:

1. Fringe mangroves: they are found along protected areas and along canals, rivers and lagoons, usually exposed to daily tides. Because of the shoreline low energy tides and the dense development of prop roots, they tend to accumulate organic debris.
2. Riverine mangroves: tall, productive riverine mangrove forests are found along the edges of coastal rivers and creeks, often several miles inland from the coast. These wetlands my be dry for a considerable time, although the water table is generally just below the surface. They export a significant amount of organic matter because of their high productivity. They are affected by freshwater runoff from adjacent uplands and from water, sediments and nutrients delivered by the adjacent river, and hence can be significantly affected by upstream activities (Mitsch and Gosselink, 1993). Salinity varies but is usually lower than that of the other mangrove types described here.
3. Basin mangroves: they occur in inland depressions or basins, often behind fringe mangrove, and in drainage depressions where water is stagnant or slowly flowing. These basins are often isolated from all but the highest tides and yet remain flooded for long periods once tide water does flood them (Cintrón et al., 1985). Because of the stagnant conditions and less frequent flushing by tides, soils have high salinity and low redox potentials (Mitsch and Gosselink, 1993). These wetlands are often dominated by black mangroves (*Avicennia* spp.).

The hydrologic energy of riverine mangroves is high because it is dominated by river flow and tidal inundation, while fringe mangroves are influenced mainly by frequent tidal inundation. Basin

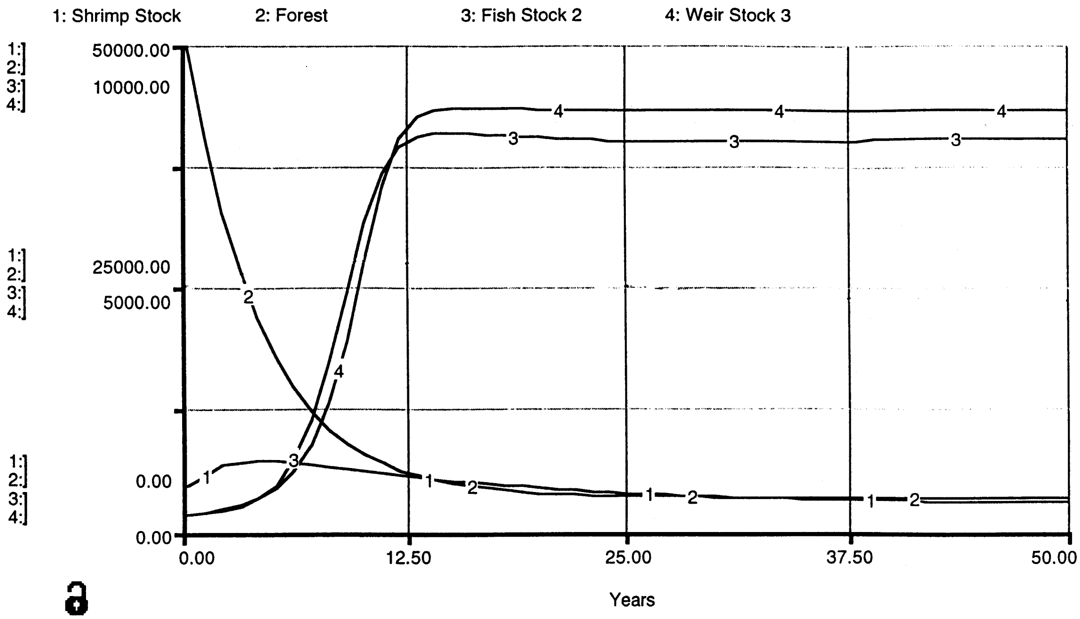


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Fig. 6. Graph showing number of workers in fishery and the behavior of the resources stocks (Scenario 1).

mangroves have less hydrologic energy because they are located inland of fringe or riverine communities and as a result are less frequently inundated by either tides or river floods.

Mangroves and wetlands in general have always been statistically associated with fisheries yield, but the exact functional relationship between mangrove and fish fauna is a complex one. Nevertheless, the major primary producers in all these linkages are mangrove plants, which form the basic energy source for the land–water interface ecosystem. This habitat provides increased physical structural complexity that will decrease the efficiency of predatory fish in feeding on juvenile shrimps and fishes. Turrner (1977) related shrimp yield to acreage of marsh and submerged grassbeds. Mangroves have the same ecological functions in the tropics as marshes in temperate areas. Other works, such as that of Barret and Gillespie (1973) demonstrated a positive correlation between brown shrimp landings in Louisiana and marsh acreage, Zimmerman et al. (1984) showed that juvenile brown shrimp were more abundant in salt marsh areas than in non-vegetated areas, he also found that the entrance of post larval penaied shrimps corresponded to high flow of rivers. Pauly and Ingles (1986) established the relationship between penacids and mangrove habitats in the tropics provided by significant correlation between the estimated maximum sustainable yield of penaeids and the area of mangrove habitats in several regions of the world. The authors suggested that since they have found a logarithmic relationship, the impact of a given reduction of mangrove area on penaeid production will become greater as the remaining area is reduced. This means that destruction of mangrove forests may have the greatest negative impact on penaeid fisheries in regions with only small mangrove areas (Pauly and Ingles, 1986).

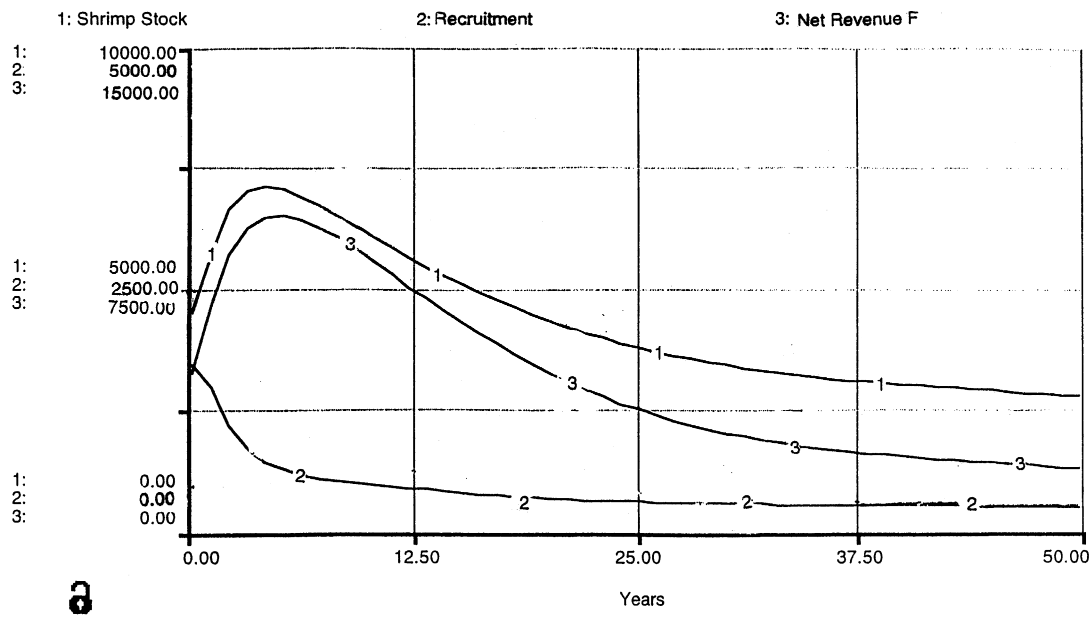


Fig. 7. Behavior of the shrimp stock and net revenue (Scenario 1).

Fish species composition and richness in any tropical mangrove system will depend primarily upon (a) its size and diversity of habitats together with its flood and tidal regimes; (b) its proximity of mangrove and other systems; and (c) the nature of the offshore environment, particularly depth and current patterns (Bell, 1989).

Proximity to other mangrove system ensures colonization by even those species with no or short larval duration, as well as by movements of adults and juveniles. A corollary of this is that proximity to non-mangrove areas, such as coral reefs may influence fish species composition in the mangrove (Parrish, 1987).

2. Bioeconomic model

The model was built in order to optimize the allocation of the workers between the forestry and fishery activities. Taking into account that these activities depend upon the preservation of the ecosystem functions, it should be assumed that the economic and the ecological optima are interdependent. The workers have the opportunity of choosing their activity each year. So, if it is assumed that the benefit from fisheries is bigger than from logging, the majority of the workers will decide on fishing. This kind of behavior will usually lead to over-exploitation and possible extinction of the resource. However, due to the connection between the different economic activities that an ecosystem can support, it will be more rational for the workers to explore the resource at a sustainable level. Since there are no property rights aggregated to the mangrove, the best allocation of workers between activities is based on the per capita benefit of each one. The models should provide tools for decisions about the optimal situation of the economic activity, as well as about the maintenance of the ecosystem, since fishery will be possible only with a minimum of safety standards in the ecosystem.

2.1. Dynamic optimization model for the allocation of workers between forestry and fishery

In this model it will be assumed that there is a social planner trying to make a decision about the possible optimum forestry exploitation of the area

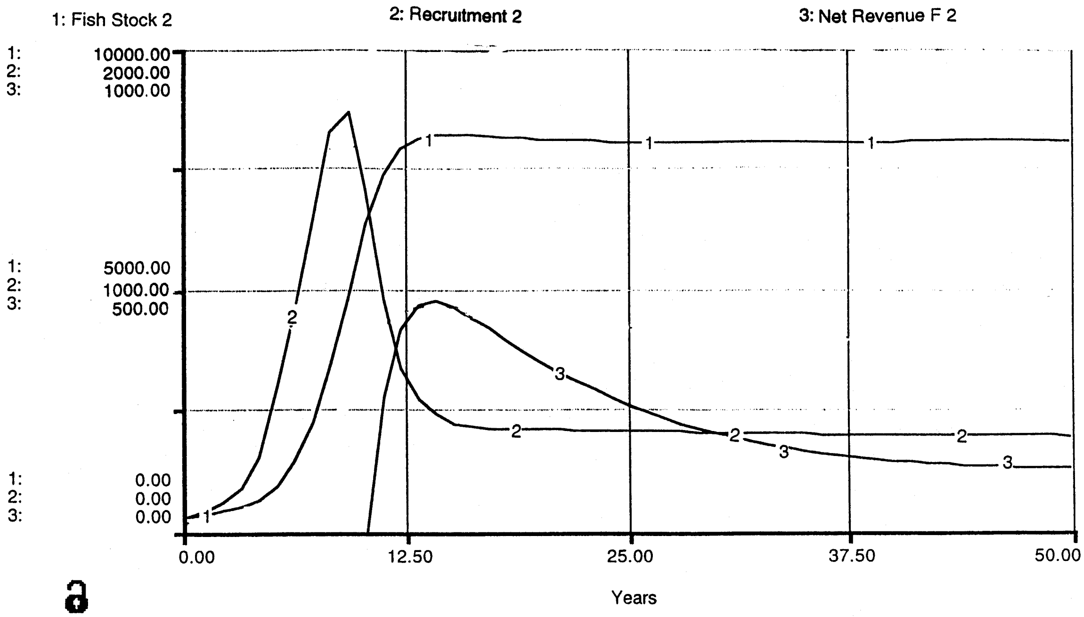


Fig. 8. Behavior of the fish stock 2 (Scenario 1).

that could result in none or very small loss for the local artisanal fishermen. So, there will be two firms, the forestry one whose externalities would directly affect the other firm, fishery, that depends on the mangrove area. The majority of the fish harvested in mangrove embayments depend on this area for growth, development and/or reproduction.

The workers are free to interchange between these two firms and they do not have gear capacity to fish outside the mangrove areas, i.e. in the open ocean. The decrease in the availability of fish would cause a reduction on their net profit. The variables of the model and the basic assumptions used for its construction were based on the work of Lal (1989).

2.1.1. Description of the model

See Appendix A for explanation of variables. The constraints are as follows.

2.1.1.1. Forestry. dF_t/dt = net growth of forestry resource which is a function of intrinsic growth of timber volume;

$$\frac{dF_t}{dt} = G(F) - f_t, \tag{1}$$

where

$$G(F) = \frac{A_t \times V_t}{dt}, \tag{2}$$

andA_t = total area of mangrove at time t; V_t = volume of timber per unit of area at time t.

2.1.1.2. Fishery. dX/dt = net growth of fishery stock.This is assuming that the change in the shrimp stock is:

$$\frac{dX}{dt} = W(X_t) - h_t. \tag{3}$$

$W(X_t)$ is the net growth function describing net biological recruitment to the fish stock, prior to harvest (Conrad, 1995).

Assuming that $W(X_t)$ is of the following form:

$$W(X_t) = rX_t \frac{1 - X_t}{K} \quad \text{(logistic function)}, \tag{4}$$

where r is the intrinsic growth rate and K is the environmental carrying capacity.

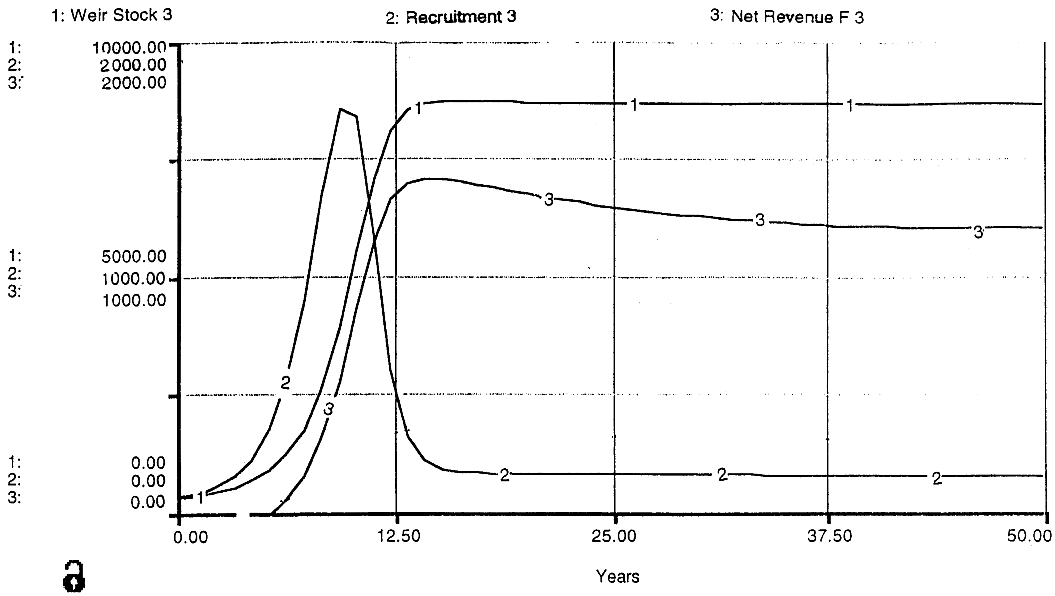


Fig. 9. Behavior of the weir stock 3 (Scenario 1).

2.1.1.3. The optimal management objective function. The optimal management objective function is Max $e^{-\delta_t}[B_F(F_t, f_t)/N_F + B_X(X_t, h_t)/N_x]\,dt$.

N will be the total number of workers, N_F number of workers in forestry activity and N_X number of workers fishing ($N = N_F + N_X$). The following function gives the ideal worker's behavior in switching activities:

$$N_F = \frac{N}{2}(1 + e^{-d} - e^{-1/d}), \tag{5}$$

$$N_X = \frac{N}{2}(1 + e^{-1/d} - e^{-d}), \tag{6}$$

where 'd' is the 'advantage of fishing over logging'. If $d \to 0$, it is much better to log. If $d \to \infty$ it is better to fish. It is possible to represent this function as: therefore, d has to be small when the benefits (per capita) are small compared with the benefits (per capita) of logging:

$$d = \alpha \frac{B_X}{B_F}. \tag{7}$$

It will be assumed that $\alpha = 1$. Define

$$r = e^{-d} - e^{-1/d} \tag{8}$$

where $0 < d < \infty$, $-1 < r < 1$, so

$$N_F = N\frac{1+r}{2}, \tag{9}$$

$$N_X = N\frac{1-r}{2}, \tag{10}$$

(see Fig. 2)

Therefore, the problem is

$$\max e^{-\delta} \frac{2}{N}\left[\frac{B_F}{1+r} + \frac{B_X}{1-r}\right] dt,$$

$$s.t.\ \frac{dF_t}{dt} = G(F_t) - f_t, \tag{11}$$

$$\frac{dX}{dt} = W(X_t, F_t) - h_t. \tag{12}$$

The current value Hamiltonian will be:

$$H(F, f, X, h) = \frac{2}{N}\left[\frac{B_F}{1+r} + \frac{B_X}{1-r}\right] + \mu_F[G(F_t) - f_t] + \mu_X[W(X_t, F_t) - h_t],$$

where,

$$\mu_t = e^{\delta_t} \lambda_t, \tag{13}$$

with the first order necessary conditions included (if it is assumed that the objective function is

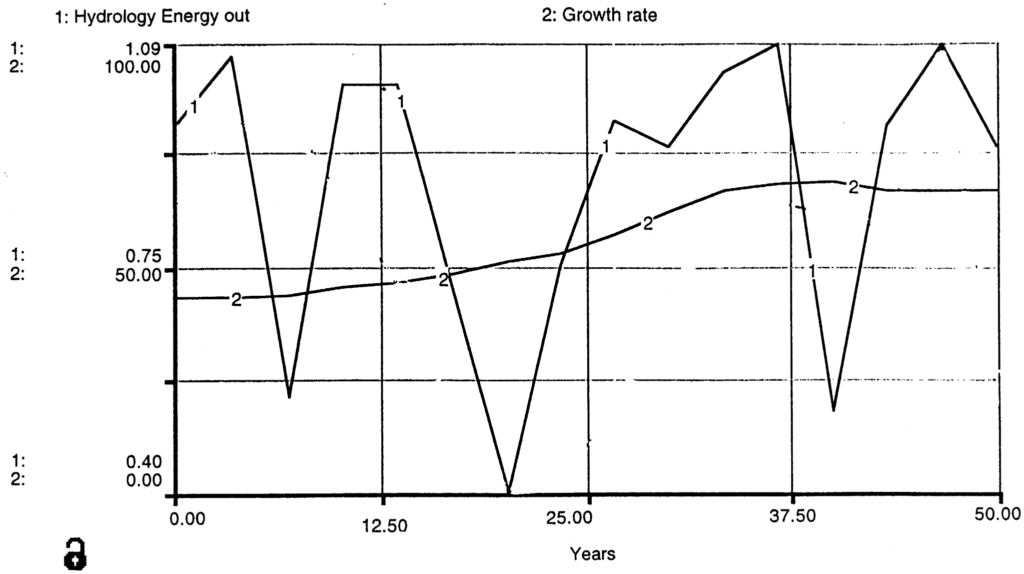


Fig. 10. Environmental aspects of the area of study.

concave, it is possible to say that the necessary conditions are also sufficient).

2.1.1.4. First order conditions.

$$\frac{\partial H(\bullet)}{\partial X}=\frac{2}{N}\cdot\frac{\partial Bx/\partial X}{1-r}-\frac{2}{N}\cdot\frac{B_F(\partial r/\partial X)}{(1+r)^2}+\frac{2}{N}\cdot\frac{Bx(\partial r/\partial X)}{(1-r)^2}+\mu_x\frac{\partial W}{\partial X}=-\mu_x+\delta\mu_x, \quad (14)$$

$$\frac{\partial H(\bullet)}{\partial F}=\frac{2}{N}\cdot\frac{\partial B_F/\partial F}{1+r}-\frac{2}{N}\cdot\frac{B_F(\partial r/\partial F)}{(1+r)^2}+\frac{2}{N}\cdot\frac{Bx(\partial r/\partial F)}{(1-r)^2}+\mu x\frac{\partial W}{\partial X}+\mu F\frac{\partial G}{\partial F}=-\mu F+\delta\mu F, \quad (15)$$

$$\frac{\partial H(\bullet)}{\partial h}=\frac{2}{N}\left(\frac{\partial B_F/\partial h}{1-r}-\frac{B_F(\partial r/\partial h)}{(1+r)^2}+\frac{Bx(\partial r/\partial h)}{(1-r)^2}\right)-\mu_x=0, \quad (16)$$

$$\frac{\partial H(\bullet)}{\partial f}=\frac{2}{N}\left(\frac{\partial B_F/\partial f}{1+r}-\frac{B_F(\partial r/\partial f)}{(1+r)^2}+\frac{Bx(\partial r/\partial f)}{(1-r)^2}\right)-\mu_F=0. \quad (17)$$

Solving for the steady-state and defining $s=1-r^2$; and $D=-1/2[(1-r/1+r)B_F-(1+r/1r)B_X]$, then:

$$\frac{\partial W}{\partial X}+\frac{(\partial B_X/\partial X)+[2D/(1+r)](\partial r/\partial X)}{\partial Bx/\partial h+[2D/(1+r)](\partial r/\partial h)}=\delta, \quad (18)$$

$$\frac{\partial G}{\partial F}+\frac{(\partial B_F/\partial F)-[2D/(1-r)](\partial r/\partial F)+(1+r/1-r)[(\partial Bx/\partial h)(\partial W/\partial F)]}{\partial B_F/\partial f-[2D/(1-r)](\partial r/\partial f)}=\delta. \quad (19)$$

2.1.1.5. Interpretation. According to Conrad (1995) Eq. (18) can be called the 'fundamental equation of renewable resources'. The marginal net growth rate plus the marginal stock effect (relation between marginal value of stock and the marginal value of harvest) is equal to the resource's internal rate of return (δ). Eq. (19) is incorporating the interactions between forestry and the growth of the fish stock. This equation can be used as a decision making function. The resource's internal rate of return will be equal to the marginal net growth rate of timber plus the marginal stock effect plus the ratio of the marginal benefits in each activity multiplied by the marginal net growth rate of fish stock related to the forest volume (this represents the marginal stock effects of timber volume on the fish stock). In each equation there are also indices representing the relationship between the benefits of each activity, that will help to find out the optimum N

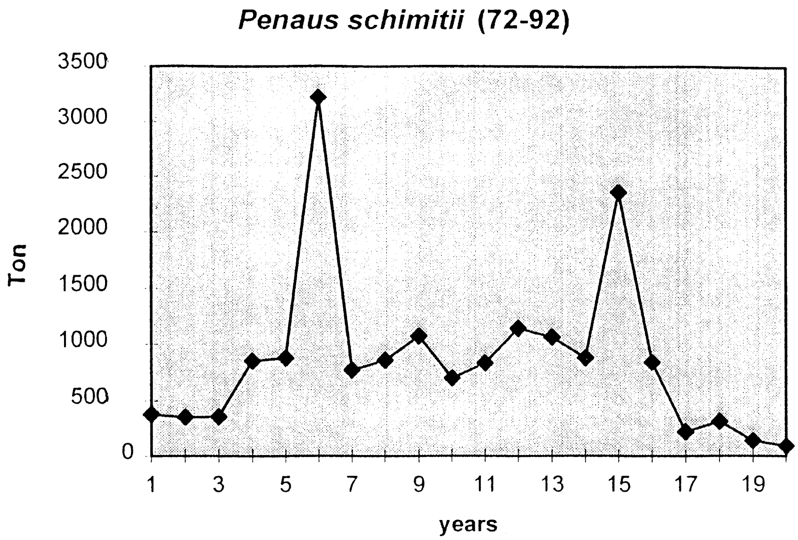


Fig. 11. Actual data of shrimp harvest in Cananéia (Brazil).

in each situation. The parameters r and D are weights coming from the activity's benefits. When $d=1$, i.e. the benefits of fishing are equal to the benefits of logging, the allocation of people will be trivial, with half of the workers in each activity. Therefore the decision about the activities will depend basically on the effects of the forestry on the fishery activity. In this case it will be necessary to make decision about the best regulation for loggers not extinct the fishery activity.

Analyzing Eqs. (18) and (19) in the limits:

$$\frac{B_X}{B_F} \to 0 \Rightarrow r \to 1,\ D \to B_F$$

(logging is more important)

and

$$\frac{B_F}{B_X} \to 0 \Rightarrow r \to -1,\ D \to -B_X$$

(fishing is more important),

both equations will be reduced to:

$$\frac{\partial W}{\partial X} + \frac{\partial h}{\partial X} = \delta \tag{20}$$

$$\frac{\partial G}{\partial F} + \frac{\partial f}{\partial F} = \delta \tag{21}$$

These are exactly the equilibrium equations (steady-state conditions) when fishing and logging activities are completely independent.

It is possible to conclude from this analysis that under equilibrium conditions (steady-state), economic predominance of one of the activities implies independence of the dynamics of the resource's stocks. This happens mathematically, because the terms proportional to $\mathrm{d}W/\mathrm{d}F$ in Eq. (19) (which constitute the interdependence) cancel when the above limits are taken. It is fundamental to point out that in reality no steady-state will be reached, the interactions between the resources are very dynamic. For the management purpose the steady-state conditions will demonstrate the tendency of the system. Only with economic balance (when one activity does not completely dominates the other) the ecological–economic interdependence can be achieved.

2.2. Dynamic simulation model for the allocation of workers between forestry and fishery

The model was compiled in the software STELLA II® for windows. Due to the simplicity of the modelling procedures in STELLA it was possible to manipulate and test some of the variables used in the optimization model. The basic assumptions of the simulation followed the optimization model but now other variables and also

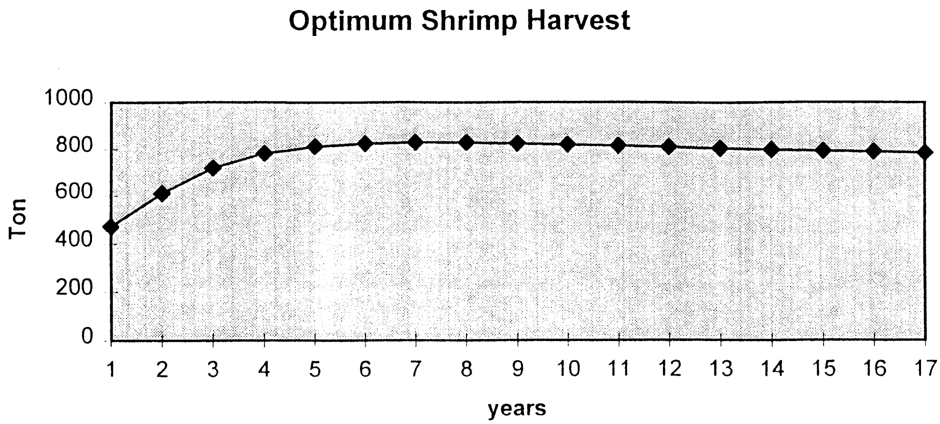


Fig. 12. Shrimp harvest given by the simulation model.

empirical data, from a small fishing community in the south coast of Brazil, were added.

2.2.1. Area of empirical study

Cananéia is a city located in the south coast of the state of São Paulo, 25°S (Brazil), with an approximate area of 10000 ha (Fig. 3) (Besnard 1950a). The mangrove area is $\approx$ 55886 m^2, corresponding to one third (37.64%) of the state of São Paulo mangroves, with 28665 m^2 considered high forests and 27231 m^2 low forest (Herz, 1990).

The typical mangrove species on the area are: *Rhizophora mangle*, *Laguncularia racemosa* and *Avicennia schaueriana*. From the ecological point of view, mangroves are the dominant ecosystem of the lagoon. They are part of the estuarine environment in which they play an essential role in the high productivity of the system, from both an ecological and economic point of view.

This region is considered to be reasonably preserved, being classified by the IUCN (International Union for the Nature Conservation) as the third estuary of the world in terms of primary productivity (Adaime, 1985). It has only 51 m^2 of altered mangroves and 215 m^2 of degraded mangroves (Herz, 1990).

The population of Cananéia is $\approx$ 7.726 people, living primarily on subsistence fishery and agricultural activities with an increasing share of the local economy being due to tourism (Grasso, 1994). It is estimated that there are $\approx$ 1000 fishermen, most of them being artisanal fishermen. This region is considered one of the poorest coastal areas in the state of São Paulo, the mangrove plays an important role in the subsistence of those people. Local residents use mangroves as sources of energy and building materials as well as for fishing purposes. More than 80% of the fisheries activity is made in inland waters due to the abundance of the fluvial and lagoon species such as Mugilidae and Clupeidae. The most common harvested products are fish and shellfish. This ecosystem also presents interest for tourism, developers have recognized the recreational potentials of the area.

2.2.2. Description of the model sectors

Fig. 4 presents the main sectors of the model and how they connect with each other.

2.2.2.1. Fisheries. The fisheries sector was divided into three main fishing categories: shrimp fisheries, miscellaneous fish species and weir fisheries. This represents the main fisheries activities in the chosen area. For shrimp fisheries only one species was considered, the White shrimp (*Penaeus schimitii*) due to its importance in local fisheries. The miscellaneous fisheries category is represented by species such as catfish (*Bagre* sp., *Genidens genidens* and *Netuma barba*); Southern King Croaker (*Menticirrhus americanus*); Atlantic

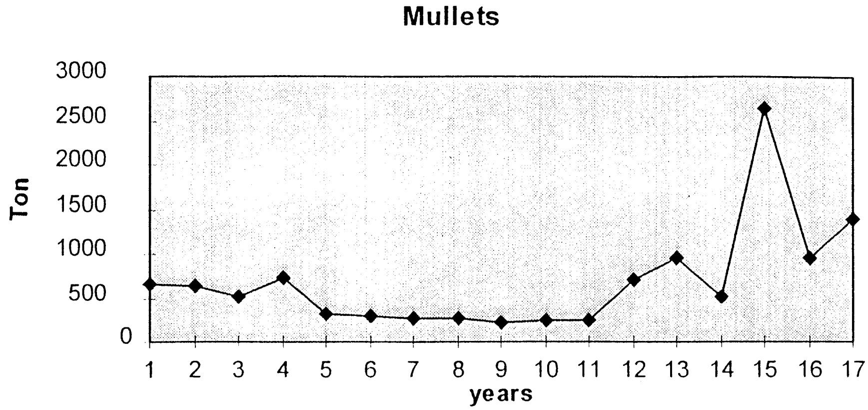


Fig. 13. Actual data of Mullets (Weir stock) harvest in Cananéia (Brazil).

Croaker (*Micropogonias furnieri*); Robalo (*Centropomus* spp.). Finally, the weir fisheries depend mainly on the and Mullets Nei species (*Mugil platanus* and *M. curema*).

The basic growth function Eq. (4) was used for all categories, which in the simulation case became:

```
Growth_Function_F=rate_of
    -increase*Fish
    -Stock*(1-(Fish_Stock/K_F)) .
```
(22)

The main difference between the growth functions is the individual rate of increase for each species. The rate of increase is dependent on the relationship between area of mangrove and natural death rate of each species. The mangrove area is assumed to protect the young from predation by bigger fish, so as the mangrove area decreases, the death rates increases. In this case, it was assumed that the relationship follows an exponential decay curve. The death rates for fish stock and for weir stock are the same. A sensitive analysis of this relationship was performed and showed that the model is not very sensitive to small changes on the relationship.

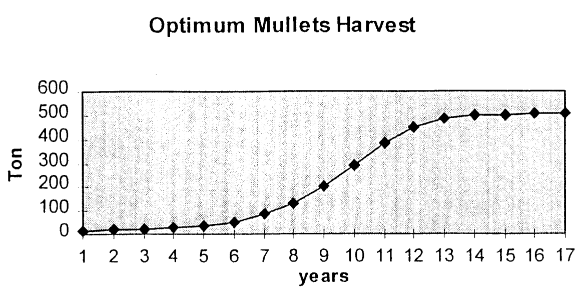


Fig. 14. Data of mullet harvest given by the simulation model.

The rate of increase was then defined as:

```
rate_of_increase=Reproduction
    -Rate-Natural_Death_Rate.
```
(23)

The carrying capacity (K) is also specific to each category and is assumed to be 30 times the initial stock of fish and two times the initial shrimp stock (for more details of the variable values and names see Appendix A).

The net revenue from the fisheries activity is given by:

```
Revenue_F
    =(Harvest_F*Price_F)-Costs
    -of_Shrimp_Fisheries.
```
(24)

Costs are assumed to be constant and are described on the fisheries costs sector. The general equation for harvesting, is the following:

$$\text{HARVEST} = Q.\ \text{STOCK.}\ \text{EFFORT} \quad (25)$$

where Q = catchability coefficient. The catchability coefficient is constant and it is measured by vessels/day (Clark, 1976). The effort is also a function of fleet capacity and number of workers in the activity. The marginal changes in the fleet capacity are given by $dFc/dt = I(t) - D^*Fc(t)$ and effort is constraint by fleet capacity at time $t - Fc(t)$, where $0 < E(t) < Fc(t)$. Fleets capacity depreciates at rate D, and may be increased by investment at rate $I(t)$.

2.2.2.2. Fishing revenue. The fishing revenue sector has a simple description of the revenues in the different categories. The weir fisheries is considered for all fishermen in the area, i.e. since it does not exclude the worker from other activity, due to the fact of it being fixed to the fringe areas of the mangrove. So the total revenue from weir activity is divided equally between workers in the shrimp and miscellaneous category.

2.2.2.3. Ecosystem. This sector contains all the major environmental factors that determine the mangrove growth and development described previously. Based on the differences growth rates of different types of mangroves, it will combine the following values for hydrological energy (adapted from Twilley, 1988):

1. basin = 0.176 − 0.184;
2. fringe = 0.192 − 0.4;
3. riverine = 0.408 − 0.56.

The dbh (diameter at breast height) is a important variable for the establishment of the growth rate. Table 1 gives the average values for the different mangrove areas (Mitsch and Gosselink, 1993), the data is based on mangroves sites in Florida, Mexico, Puerto Rico, Brazil, Costa Rica, Panama and Ecuador.

The equation for the forest increment is based on a gap model. The growth equation is developed by assuming that tree volume is a function of a tree's diameter (D) squared times the trees height (H), and that tree growth is based on the annual volume increment (Shugart, 1984). The volume increment is:

$$\frac{d(D^2H)}{dt} = r \cdot La \cdot \left[1 - \left(\frac{DH}{D_{max}H_{max}}\right)\right] \qquad (26)$$

2.2.2.4. Forestry. The forestry sector contains all the economic variables related to the activity and subjected to the rate of increment in trees given by

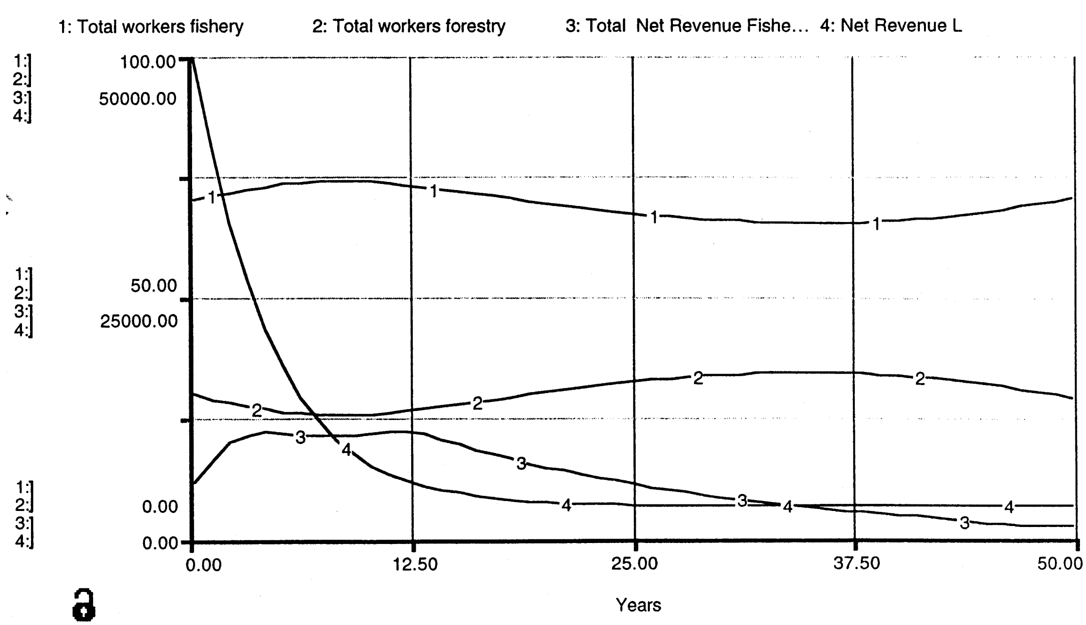


Fig. 15. Graph showing the allocation of workers between activities and their respective revenue (Scenario 2).

Table 1
Structural characteristics of canopy vegetation for major mangrove types[a] (Mitsch and Gosselink, 1993)

Vegetation type	Number of trees (#/ha)		Stand height (m)
	>2.5 cm dbh	>10 cm dbh	
Fringe mangroves	4005 ± 642 (33)	852 ± 115 (31)	13.3 ± 2.6 (32)
Riverine mangroves	1979 ± 209 (28)	661 ± 71 (32)	21.2 ± 4.8 (26)
Basin mangroves	3599 ± 400 (31)	573 ± 102 (21)	9.0 ± 0.7 (31)

[a] The values are average ± standard error (number of observations).

the ecosystem sector. The forestry logging will be represented by the function:

LOGGING

= f(EFFORT, NUMBER OF TREES)

Assuming that a man can cut up to a 100 trees a year, the profit will be:

```
Net_Revenue_L
    =(Logging*Price_L)-Costs_L.   (27)
```

2.2.2.5. Human activities. The functions represented in this sector are the same as those described in the optimization model by Eqs. (5)–(10). So the decision of which activity the workers should take in a certain time period is established by:

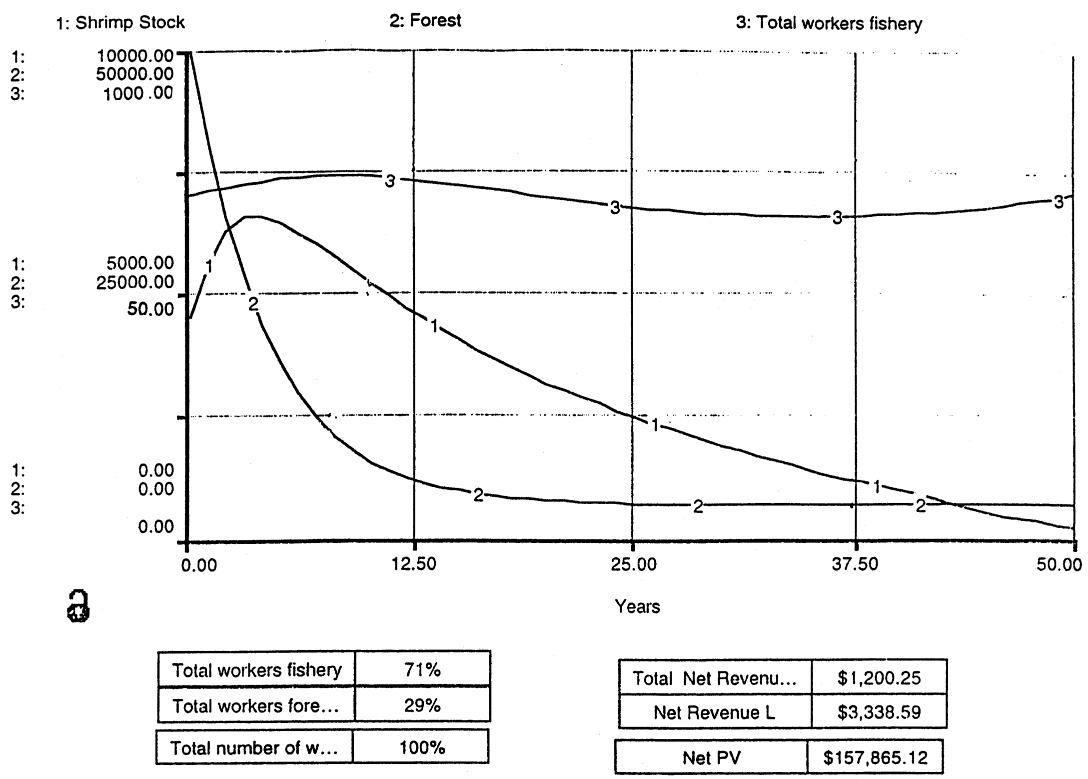
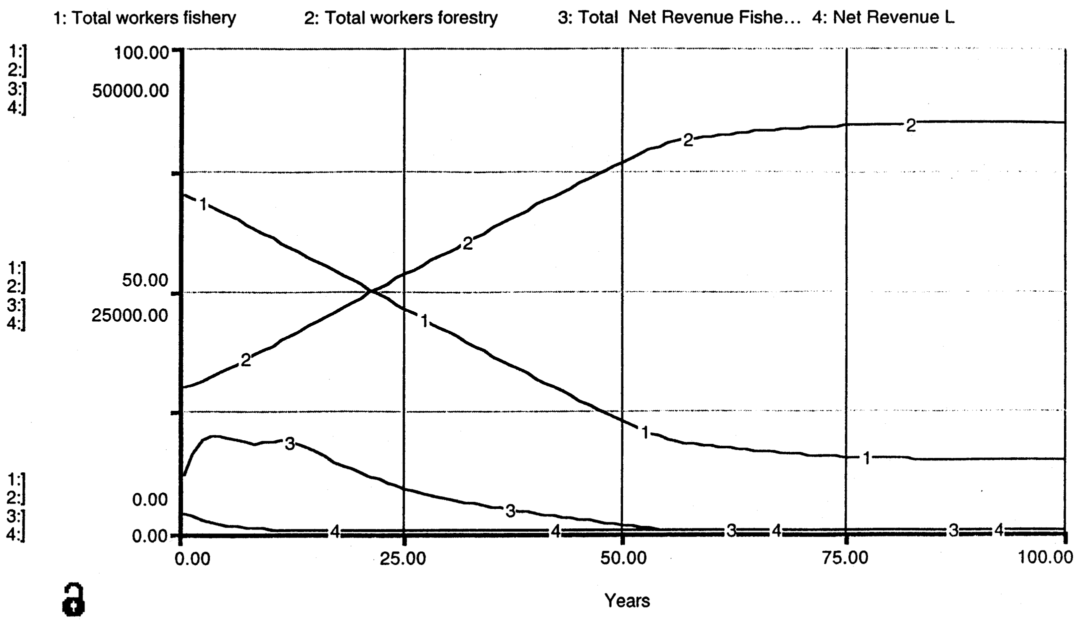


Fig. 16. Graph showing number of workers in fishery and the behavior of the shrimp and forest stocks (Scenario 1).



Total workers fishery	15%
Total workers fore...	85%
Total number of w...	100%

Total Net Revenu...	$123.58
Net Revenue L	$122.00
Net PV	$9,717.32

Fig. 17. Graph showing the allocation of workers between activities and their respective revenue (Scenario 3).

```
Indice_activity_benefits
        =EXP(-Advantage_of_fishing
        -over_logging)
                -EXP(1/Advantage_of
        -fishing_over_logging).          (28)
```

The advantage of fishing over logging is represented by Eq. (7) described in the previous model and is a function of the total revenue in fisheries activity and the net revenue in logging activity.

Assuming that the total number of workers does not change over time, i.e. there is no possibility for new workers to enter the system or for the actual workers to leave it.

2.2.2.6. Present value. This sector presents the total net revenue for both activities being discounted at an initial rate of 5% a year.

2.2.3. Simulation results and discussion

2.2.3.1. Scenario 1. The first scenario started with the same number of workers in both activities (for more details of initial conditions see Appendix A). The allocation of workers between activities will tend to change according to their respective net revenues, but it will stay close to the mean (Fig. 5). The system has a dynamic equilibrium due to the mobility of workers between activities. In a first moment the workers will tend to over-exploit the mangrove forest stock, so for the first 10 years the loggers will experience a great decrease on their revenue due to the increase in the cost and effort of cutting another unit of forest. Both revenues will to converge after this period, getting to the economic equilibrium after ≈ 25 years. It was decided not to run the model for over 50 years, because it would not incorporate any important changes that could happen in the area, as e.g. the emergence of an alternative economic activity, tourism. This assumes that the prices are constant for all items in the model[1].

The main goal of this model is to observe whether the economic and the ecological optima could both be achieved at the same time. Fig. 6 presents the behavior of the resources stocks during the 50 year period. It is possible to see that all stocks get to a constant level after ≈ 13 years. The forest stock will drop dramatically for the first 12 years, but it seems that it will still support the fishery activity and the forestry workers will feel this effect through their net revenue, so they will start moving towards the fishery activity. The model shows an ecological–economic equilibrium after 13 years. The optimum of the allocation is found when the natural capital stock is kept constant, meaning that its use has been carried out on a sustainable level. It is important to say that this equilibrium will only be achieved due to the fact that the workers can interchange between activity and assuming that there is no costs for them to change economic activity.

Figs. 7–9 present the shrimp and fish stocks and their respective harvesting rates, recruitment and net revenue. The net revenues for fish stocks 2 and 3 will be negative in the first moment due to the over-fishing. The demand and the market price for those type of fish are not high, so a great effort in catching them will not be profitable. The recruitment of stocks 2 and 3 will also suffer a great decay in the first 13 years, but it will still be able to recover. The environmental variables are not constant, but they do not undergo any extreme changes. The climatic data are based on reports from the Instituto Oceangrafico, Universidade de São Paulo (1993). Fig. 10 presents the behavior of the growth rate of mangrove and the variables that are considered as being the most relevant for the characterization of the mangrove forest. There is no environmental disturbance added to the system in order to be able first to identify the most important factors for the ecological equilibrium.

2.2.3.1.1. Validation. For the calibration purposes, the data generated by the model and the real data of the fisheries harvest in Cananéia (CEAGESP, 1993) were compared. It is possible to see that the actual situation does not indicate a sustainable level of exploitation in the area. If the general shape of the curves are considered, it is possible to see a relationship between the real data and the model simulation. Also, it is necessary to consider the fact that the real data can have biases that were not controlled. The peaks found on the *Peneaus schimitti* real data graph could not be explained by any climatic change or increase on the catch effort (Figs. 11–14).

Unfortunately there is no data related to the amount of forest harvested due to the fact that this is considered an illegal activity, but as there is no enforcement in the area, the activity is done freely.

2.2.3.2. Scenario 2. A second run is made with the same parameters established previously, but now the proportion of workers between activities are not the same. If the model is run with only 30% of the workers in the forestry activity, it is possible to see that the equilibrium will be found but the workers will tend to remain in the same proportion as was initially established (Fig. 15). The net revenue from fishery will be smaller in this case than in Scenario 1; this happens because the net revenue of forestry activity will increase due to the fact that there will be less competition for the use and commercialization of this resource. Actually in this case the forestry revenue will be (in general) similar to the previous case. The shrimp stock will be most affected by having an increase in the number of fishermen, this resource will be extinct at the end of the 50-year period (Fig. 16).

2.2.3.3. Scenario 3. If 70% of the workers are initially allocated to forestry activity, there will be a fast crash of the fishery activity due to the lack of protection for the juvenile fish (Fig. 17). Also, the net revenues will be smaller than the previous

[1] The average prices taken from 20 years of data (1972–1992) are used.

scenarios, indicating a future crash of the whole system.

2.2.3.4. Combination between the dynamic optimization and simulation models. Using our simulation results and substituting Eqs. (16) and (17), it is possible to find the shadow values for the fish (μ_x) and forest stocks (μ_F), being 187 and 0.007, respectively. For the analysis of these values it is necessary to use the units that have been applied. In the fisheries stock, the unit is tons, so the increase of one more ton in the fisheries stock would increase the total benefit of fishing in 187. Due to the fact that forestry is dealing with units of trees, an increase of one unit in the stock would increase the total benefit of logging in 0.007.

3. Conclusions

The scenarios indicate that the model is sensitive to the initial number of workers in each activity. As a result for both models (simulation and optimization) it was possible to observe that the equilibrium will be found when initial conditions of an equal distribution of workers between activities are established. Nevertheless, the best management option would be to have significantly more workers in the fishery activity than in forestry. Thus, in this case, policies of taxation and law enforcement against clear cutting the mangroves should be implemented. If working in a developing country where those policies are not possible to be implemented, some participative management techniques should be used to demonstrate to the local people the advantages of rationally using the resources from the mangrove ecosystem.

In terms of using one of the modelling processes as a management and consensus building tool, the simulation model proved to be more appropriate. The simulation model defines more than one equilibrium situation, showing its usefulness for real world management cases. The optimization model is difficult to deal with due to the problem of the increase in complexity when a new variable is added, resulting, sometimes in an over-simplification of the model.

Data availability has always been a problem for modelling ecosystems in general. It was possible to find some information for only a few variables used in the simulation model, but still it is possible to run the model and get some outputs to discuss and even compare with some of the real data. It means that the initial condition can change, even though it is still possible to find another equilibrium. It is important to emphasize that no steady-state will be achieved and therefore, the simulation model seems to better represent the changes over time in the study area.

The combination of both models give us more possibilities of exploiting different situations. Both models prove that there is a long term gain from the sustainable use of the natural resource and therefore there is a close connection between the different economic activities that an ecosystem can support. They give us tools for decisions about the optimal degree of the economic activity, as well as about maintenance requirements of the ecosystem, since fishery will be possible only when one keeps a minimum of safety standards in the ecosystem. It would be interesting to test whether the allocation of workers is more effective than taxes and subsidies in this case, for the preservation of the ecosystem's characteristics.

The models presented in this paper are based on simple interactions between ecological services and the economic activities depending on them, and the benefits that could be gained when planners have an overview of how the ecosystem works. Knowledge of the interactions of a physical system gives a wide range of options for using policy tools for the preservation of the area and consequently, for the economic benefit of local workers.

The development of models will often lead to many new questions; to answer these, the management analysis team must return to the field, laboratory, or library to gather more information and restructure the models. This results in more questions, and so the cycle continues (Swartzman and Van Dyne, 1972).

Appendix A

Variables	
F_t	total volume of timber
X_t	amount of fisheries stock present at time t
C	unit cost of timber harvest
C_x	cost of unit harvest of fish
P	unit timber price
P_x	average unit price of fish
B	$[f_t \cdot P] - C_t$ net benefit of forestry harvest at time t
B_x	$[h_t \cdot P_x] - C_x$, net benefits from fish harvest at time t
λ	shadow value of the growth in respective capital stock
δ	social discount rate
t	year
Control variables	
h_t	harvest rate of fish per unit boat-net-men effort at time t
f_t	forestry harvest at time t

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