Renewable Resources

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1. Introduction

This is an introduction to some basic concepts in the analysis of biological resources, with special focus on fisheries management.

2. Biological Resources

1. Definitions

- A resource is renewable if its stock can be replenished.
- A biological resource, also called an interactive resource, is a class of renewable resources for which the size of the resource stock, (resource population, resource biomass) is determined jointly by biological considerations and by actions taken by the society.
- In biological resources the size of the population now determines the availability of the resource in the future. Thus, biological factors and human actions jointly determine resource flow.
- Management problem: What is the optimal use of the resource across time and generations?

Two dimensions are relevant in the management of biological resources:

- ♦ The biological dimension
- ♦ The economic dimension

2. The biological dimension

A central concept in the analysis of the biological dimension for management purposes is the *rate of growth* of the resource biomass (population).

Let $x(t)$ be a variable that depends on time t. The rate of growth of x is defined as:

$$r_x = \frac{dx/dt}{x} = \frac{\dot{x}}{x}$$

In exponential population growth we have: $r_x = r$, *or* $x(t) = x_0 e^{rt}$. The rate of growth is constant. Environmental limitations could, however, cause growth to decline as a function of population. This implies that the rate of growth is defined as: $r(x)$ with $r'(x) < 0$ which is the case of *compensation.* One of most commonly used formulations for the compensation case is the logistic equation for which $r(x) = r\left(1 - \frac{x}{K}\right)$, and the rate of change of the biomass per unit time is defined as:

$$\frac{dx}{dt} = \dot{x} = rx\left(1 - \frac{x}{k}\right) = F(x) \qquad (1)$$

for which r is intrinsic rate of growth, and k is environmental carrying capacity. Population is in equilibrium when $\dot{x} = 0$. The logistic growth has two equilibria:

$x = 0$ which is *unstable* and $x = k$ which is stable (see figure 2.1). The evolution of the population is determined by the solution of the differential equation (1) as (see figure 2.2):

$$x(t) = \frac{k}{1 + ce^{-rt}}, \; c = \frac{k - x_0}{x_0}$$

The maximum rate of change for the biomass is defined at the population level that maximizes *F*(*x*), or $x^* = \arg\max_x F(x)$. This value is determined by:

$$F'(x) = 0 \; or \; r - \frac{2rx}{k} = 0 \Rightarrow x^* = \frac{k}{2}$$

3. **Population growth under constant harvesting**

We assume that a constant amount *h* of the biomass is harvested per unit time. Then the change of the population per unit time is determined as:

$$\frac{dp}{dt} = F(x) - h = rx\left(1 - \frac{x}{k}\right) - h$$

When $h = \max F(x) = h_{MSY}$, we have harvesting at the *maximum sustainable yield* (MSY). If $h < h_{MSY}$ then we have two equilibria, $(x_1, x_2): \dot{x} = 0$, with $x_1 < x_2$ shown in figure 2.3a. The lower equilibrium is unstable and the higher one is stable. If $h > h_{MSY}$ then the population declines to zero, we have extinction of the species and *x* = 0 is a stable equilibrium (figure 2.3b). If $h = h_{MSY}$, then there is only one *semi-stable* equilibrium (figure 2.3c).

4. **Fishing effort and production functions**

Let:

- *h*: catch rate or yield (tons/day)
- *t*: time (days)
- *E*: effort measured in standardized vessels
- *x*: fish biomass (stock) in tons

The harvesting or catch is defined though a harvesting production function

$$h(t) = f(E(t), x(t))$$

Assume that:

i. Catch per unit effort $\left(\frac{h}{E}\right)$ is proportional to fish density

ii. The density of the fish is proportional to the fish abundance, biomass.

Then the harvesting function can be specified as:

$$h(t) = qE(t)x(t)$$

where *q* is the catchability coefficient. A more general production function can be written as: $h = qE^{\alpha}x^{\beta}$.

Sustained yield function

Sustained yield is an equilibrium concept where *h,E,x* are constant.

Let $F(x) = rx\left(1 - \frac{x}{k}\right)$, $h = qEx$, $\dot{x} = F(x) - h$. In equilibrium $F(x) = h$, or $rx\left(1 - \frac{x}{k}\right) = qEx \Rightarrow x^e = k\left(1 - \frac{qE}{r}\right)$ then $h^e = qEx^e$ and the sustained yield function is defined as:

$$h^e = qEk\left(1 - \frac{qE}{r}\right) \qquad (2)$$

Sustained harvesting is shown in figure 2.4a for different effort levels. The inverse relationship between effort and biomass is shown in figure 2.4b. The sustained yield function (2) is shown in figure 2.5. The effort corresponding to MSY is obtained by the solution of the maximization problem $\max_E h^e = \max_E qEk\left(1 - \frac{qE}{r}\right)$ which yields, after taking the first derivative and equating with zero:

$$E_{MSY} = \frac{r}{2q} \qquad (3)$$

Then by substituting into (2)

$$h_{MSY} = \frac{kr}{4} \qquad (4)$$

The x_{MSY} is defined as the solution with respect to *x* of $rx\left(1 - \frac{x}{k}\right) = qE_{MSY}x$ or

$$x_{MSY} = \frac{k}{2} \qquad (5)$$

Major problems with the concept of the MSY as an operational harvesting rule are:

- MSY is unstable (semi-stable)
- Natural fluctuations may lead to resource depletion
- Ignores social and economic considerations of renewable resource management
- Ignores “non market” preservation or existence values.

When the resource growth function is characterized by depensation (figure 2.6a), then excess-harvesting leads to extinction and the system exhibits hysteretic effects (figure 2.6b).

3. Static Economic Models of Fisheries

1. Open access fisheries

In open access or common property fisheries exploitation of the resource is unregulated. Therefore everyone can potentially harvest the resource.

Equilibrium fishery (Gordon-Schaefer)

Let p be the price per unit of harvested biomass. Fishermen are price takers, that is, they take price p as given. Revenue from harvesting is defined as:

$$R = ph = pqEx\,,\ h = qEx$$

with $\dot{x} = rx\left(1 - \frac{x}{k}\right)$ and sustainable yield function $h = qEk\left(1 - \frac{qE}{r}\right)$.

Assume fixed cost per unit effort c. Then total costs are defined as

$$TC = cE$$

In open access rents are dissipated or $R = TC$, or $ph = cE$. Then the following equilibrium values are defined:

$$pqEx = cE \Rightarrow x^{\infty} = \frac{c}{pq} \text{ bionomic equilibrium}$$

$$ph = cE, \text{ or}$$

$$pqEk\left(1 - \frac{qE}{r}\right) = cE \Rightarrow E^{\infty} = \frac{r}{q}\left(1 - \frac{c}{pqk}\right)$$

$$h^{\infty} = qE^{\infty}x^{\infty} = \frac{cr}{pq}\left(1 - \frac{c}{pqk}\right)$$

Bionomic equilibrium is shown in figure 3.1.

2. **Regulated fisheries**

Suppose a regulatory agency owns the fishery. The objective is to maximize economic profit, by choosing the optimal (profit maximizing effort). The problem is:

$$\max_E\ ph(E) - cE,\ or$$

$$\max_E\ pqEk\left(1 - \frac{qE}{r}\right) - cE$$

The optimality (first order) condition is: $ph'(E) = c$. So in profit maximizing equilibrium the slope of the sustainable yield function equals the cost per unit of effort. Using this condition the equilibrium values for *E, h,* and *x* are defined as:

$$pqk - \frac{2pq^2kE}{r} = c,\ or$$

$$E^* = \frac{r(pqk - c)}{2pq^2k}$$

$$h^* = qkE^*\left(1 - \frac{qE^*}{r}\right)$$

In equilibrium $F(x) = h$, thus equilibrium biomass under regulation is determined by the solution with respect to *x* of:

$$rx\left(1 - \frac{x}{k}\right) = qxE^*$$

As shown in figure 3.1, equilibrium effort and harvesting is less and equilibrium biomass more in profit maximizing equilibrium as compared to the open access equilibrium.

3. Supply curve for an open access fishery

Equilibrium effort and biomass in an open-access fishery is defined as:

$$E^\infty = \frac{r}{q}\left(1 - \frac{c}{pqk}\right),\ x^\infty = \frac{c}{pq}$$

Then

$$h^\infty = qE^\infty x^\infty = \frac{rc}{pq}\left(1 - \frac{c}{pqk}\right) = S(p)$$

The function $h^\infty = S(p)$ is a supply function for an equilibrium open access fishery. The supply function has the following characteristics:

- $h^\infty = 0$ if $p < \frac{c}{qk}$
- $S(p)$ is increasing in *p*, for $\frac{c}{qk} \leq p < \frac{2c}{qk}$
- $h^\infty = h_{MSY}$ if $p = \frac{2c}{qk}$
- $S(p)$ is decreasing in *p*, for $p > \frac{2c}{qk}$

The shape of the supply function and the market equilibrium is shown in figure 3.2. According to this model, small harvesting, *h*, and high price, *p* is an indication of over fishing. Figure 3.3 shows the possibility of bionomic instability.

4. Dynamic Economic Models of Fisheries

1. The dynamic problem

The models described above are equilibrium fishery models since it is explicitly assumed that the fish population is in equilibrium. This is not, however, the case in most situations, so there is a need to take into account resource dynamics.

Let $h = qEx$ and $TC = cE$. The net revenues when the effort over a time interval Δt is $E\delta t$, is defined as $NR = (qx - c)E\Delta t$. When the objective is to maximize the present value of net revenue over an infinite time horizon, the objective function is defined as:

$$PV = \int_0^\infty e^{-it}(qx - c)Edt$$

or for a more general net revenue function $R(x, E)$

$$PV = \int_0^\infty e^{-it}R(x, E)dt$$

where i is the rate of interest indicating continuous discounting.

Definitions for future and present values

The future value of an amount V compounded for n periods at a rate of interest ρ is defined as:

$$FV = V(1 + \rho)^n$$

Conversely the present value of an amount V received n periods from now is:

$$PV = \frac{V}{(1 + \rho)^n}$$

The present value of a cash flow R_t from $t = 0$ to $t = T$ is defined as:

$$PV = \sum_{t=1}^{T} \frac{R_t}{(1 + \rho)^t}$$

It is possible that $t \to \infty$.

When the time is continuous the present value is defined as:

$$PV = \int_0^\infty e^{-it}R(t)dt$$

2. **Dynamic fishery management**

In a dynamic context the fishery management problem can be written as:

$$\max_{\{E(t)\}} \int_0^\infty e^{-it}R(x(t), E(t))dt$$

$$\text{subject to} \qquad (6)$$

$$\dot{x}(t) = F(x(t)) - h(x(t), E(t)),\ x(0) = x_0 > 0$$

This is an infinite horizon optimal control problem. The solutions for this type of problem are presented in chapter 7.

For the fishery problem, the optimal control problem (6) can be further specified by considering the revenue function, $ph - cE, h = qEx$. Writing $E = \frac{h}{qx}$, the control problem can be written as:

$$\begin{gathered}\max_{\{E(t)\}} \int_0^\infty e^{-it}\left(ph - \frac{ch}{qx}\right)dt \\ \text{subject to} \\ \dot{x} = F(x) - h,\ x(0) = x_0 > 0,\ 0 \le h \le h_{\max}\end{gathered} \tag{7}$$

The current value Hamiltonian for this problem is defined as:

$$\begin{aligned}H(x,h,\lambda) &= ph - \frac{ch}{qx} + \lambda[F(x) - h] \\ &= \left(p - \frac{c}{qx} - \lambda\right)h + \lambda F(x)\end{aligned} \tag{8}$$

The necessary conditions for optimality require that *h* maximizes the Hamiltonian function for every *t*, or:

$$h(t) = \begin{cases} 0 \ \text{if}\ \lambda(t) > p - \dfrac{c}{qx} \\ h_{\max}\ \text{if}\ \lambda(t) < p - \dfrac{c}{qx} \end{cases} \tag{9}$$

and

$$\dot{\lambda} = i\lambda - \frac{\partial H}{\partial x} = [i + F'(x)]\lambda - \frac{ch}{qx^2} \tag{10}$$

For

$$\lambda(t) = p - \frac{c}{qx} \tag{11}$$

we have by taking the derivative with respect to time:

$$\dot{\lambda} = \frac{c}{qx^2}\dot{x} = \frac{c}{qx^2}(F(x) - h) \tag{12}$$

Substituting λ from (11) into (10) we have:

$$\dot{\lambda} = [i + F'(x)]\left(p - \frac{c}{qx}\right) - \frac{ch}{qx^2} \tag{13}$$

Equating (12) and (13) we obtain:

$$F'(x) + \frac{cF(x)}{x(pqx - c)} = i \tag{14}$$

Condition (14) determines the optimal equilibrium biomass x^*. If we use the logistic growth equation $F(x) = xr\left(1 - \frac{x}{k}\right)$, then x^* is defined as:

$$x^* = \frac{1}{4}\left[x^\infty + k\left(1 - \frac{i}{r}\right) + \sqrt{\left(x^\infty + k\left(1 - \frac{i}{r}\right)\right)^2 + 8kx^\infty \frac{i}{r}}\right] \qquad (15)$$

where $x^\infty = \frac{c}{pq}$ is the bionomic equilibrium. It holds that $x^* < x^\infty$. Optimal harvesting is defined as:

$$h(t) = \begin{cases} 0 \ \mathit{if} \ \ x(t) < x^* \\ h_{\max} \ \ \mathit{if} \ \ x(t) > x^* \\ h^* = F(x^*) \mathit{if} \ \ x(t) = x^* \ \ \mathit{or} \ h^* = rx^*\left(1 - \frac{x^*}{k}\right) \end{cases} \qquad (16)$$

The optimal harvesting rule follows the most rapid approach path (figure 4.1). When the observed biomass is above the optimal equilibrium level, then harvesting is at the technical maximum. When the observed biomass is below the optimal equilibrium level, then harvesting is at zero. If the observed biomass is at the optimal equilibrium level, then harvesting is determined at the level that keeps the population in equilibrium or $h^* = rx^*\left(1 - \frac{x^*}{k}\right)$.

5. Optimal Investment in Dynamic Models of Fisheries and Game Theoretic Concepts

1. **Dynamic Investment Strategy**

In the model of the previous unit effort was defined as a one-dimensional index of economic inputs in harvesting. It is more realistic however to assume that the variable input "effort" is combined with physical capital, like vessels, which determines fishing capacity. Capital accumulates through non-reversible investment and depreciates at a constant rate.

Let $K(t)$ denote capital stock or equivalently capacity in fishing, $I(t)$ gross investment in fishing capacity, and δ the depreciation rate. Then the accumulation of fishing capacity is defined as:

$$\dot{K}(t) = I(t) - \delta K(t),\ K(0) = K_0 > 0$$

If c_f is the cost per unit of gross investment, then the optimal control problem that corresponds to (7) is defined as:

$$\begin{aligned}
&\max_{\{E(t)\}} \int_0^\infty e^{-it}\left[(pqx - c)E - c_f I\right]dt \\
&\text{subject to} \\
&\dot{x} = F(x) - h,\ x(0) = x_0 > 0 \qquad\qquad (17) \\
&0 \le E(t) \le K(t) \\
&\dot{K} = I - \delta K
\end{aligned}$$

A graphical solution to this problem is shown in figure 5.1 for two possible initial biomass values x_0, $x_0^{'}$.

The optimal path has the following characteristics:

1. Starting from x_0 capacity is built up to $K(x_0)$
2. Harvesting takes place at full capacity following a MRAP to drive biomass down to x_1^*. Capital depreciates at a rate δ.
3. Stock is low, capacity is excessive and fishing effort is below full capacity, or $E^* < \left\lfloor K(t) \middle| x_1^* \right\rfloor$.
4. Capacity is fully used, but is still going down. The stock starts recovering.
5. Stock reaches equilibrium at x_2^*. Additional investment is undertaken to increase capacity to K_2^*.
6. Long run equilibrium: $K = K_2^*$, $x = x_2^*$, $E = K_2^*$, $I = \delta K_2^*$

2. Tragedy of the Commons

We show that for a common property resource, like for example an open access fishery, noncooperative exploitation can lead to the depletion of the resource (tragedy of the commons).

Consider the open access fishery with:

$$TR = ph \text{ , } h = qEx \text{ , } TC = cE$$

Open access implies that exploitation takes place up to the point where rents dissipate or $TC = TR$. Then bionomic equilibrium is obtained as $x^{\infty} = \frac{c}{pq}$.

Consider the following payoff matrix of the noncooperative game regarding the exploitation of the resource.

		Exploiter A	
		Conserve	Deplete
Exploiter B	Conserve	(3,3)	(1,4)
	Deplete	(4,1)	(2,2)

The above game corresponds to the *prisoners' dilemma*. The dominant strategy is (Deplete, Deplete) and although both exploiters would have been better off by cooperation [that is, following (Conserve, Conserve)], by the nature of the non-cooperative game they deplete the common property resource.

The (Conserve, Conserve) outcome can be obtained only as a trigger strategy equilibrium in the context of a dynamic game.

6. Policy Issues

1. Principles of resource regulation

In common property resources the basic externality is the "stock externality". The individual exploiters ignore the effects that their action might have on the stock of the resource and the future productivity of the stock.

Let there be $i = 1,...,n$ exploiters with harvesting functions:

$$h_i = \phi(E_i, x),\ \frac{\partial \phi}{\partial x} < 0,\ \frac{\partial \phi}{\partial E_i} > 0,\ \frac{\partial^2 \phi}{\partial E_i^{\ 2}} < 0$$

and cost functions $c_i(E_i),\ c_i' > 0,\ c_i'' > 0$. Assume that the resource price is exogenous at the level p. Then the individual exploiter solves the problem:

$$\max_{E_i \geq 0} p\phi(E_i, x) - c_i(E_i) \qquad (18)$$

with optimality condition:

$$p\frac{\partial \phi}{\partial E_i} = c_i'(E_i),\ for\ E_i = E_i^0 \qquad (19)$$

Condition (19) characterizes resource exploitation at the private optimum, with privately-optimal effort at the level E_i^0.

Assume that the resource is managed either cooperatively or by a social planner. The objective is the maximization of the net present value of profits subject to the constraint imposed by the growth of the resources biomass. Thus the cooperative or social optimum can be obtained as the solution of the following problem:

$$\begin{aligned} &\max_{\{E_1(t),...E_i(t)\}} \int_0^\infty e^{-it} \sum_{i=1}^n \left[p\phi(E_i, x) - c_i(E_i)\right] dt \\ &s.t.\ \dot{x} = F(x) - \sum_{i=1}^n \phi(E_i, x) \end{aligned} \qquad (20)$$

The current value Hamiltonian for this problem is defined as:

$$\begin{aligned} H(x, E_1, ..., E_n, \lambda) = &\sum_{i=1}^n \left[p\phi(E_i, x) - c_i(E_i)\right] + \\ &\lambda\left[F(x) - \sum_{i=1}^n \phi(E_i, x)\right] \end{aligned} \qquad (21)$$

with optimality conditions

$$(p - \lambda)\frac{\partial \phi}{\partial E_i} = c_i'(E_i),\ for\ E_i = E_i^* \qquad (22)$$

Condition (22) characterizes resource exploitation at the social or cooperative optimum, with socially-optimal effort at the level E_i^*.

Since $\lambda > 0$, because it is the shadow value of the resource, it can be seen by comparing (19) with (22) that $E_i^0 > E_i^*$, for all *i*. Therefore excess effort is exercised at the private optimum relative to the social optimum and the resource is overexploited.

Instrument for resource regulation

The deviation in the exploitation of the resource under the private and the social optimums implies that there is a need for economic policy so that private profit-maximizing exploiters will be induced to behave according to the cooperative or social optimum, by reducing their effort. The following instruments can be used to regulate the private producers which exploit the resource.

i. Taxes on resource harvest

Let there be a tax τ per unit harvest. The individual exploiter pays this tax per unit harvest of the resource. Thus the private exploiter solves the problem:

$$\max_{E_i \geq 0} p\phi(E_i, x) - c_i(E_i) - \tau\phi(E_i, x) \tag{23}$$

with optimality condition

$$(p - \tau)\frac{\partial \phi}{\partial E_i} = c_i'(E_i), \; for \; E_i = E_i^0 \tag{24}$$

If we set $\tau = \lambda$, then it is clear by comparing (22) or (24) that $E_i^0 = E_i^*$.

Therefore a regulator can obtain the socially-optimal effort and resource harvesting by imposing a tax on harvesting equal to the shadow value of the exploited resource. The intuition behind the result is clear. At the private optimum the resource is over-exploited because its shadow value is not taken into account. Therefore by introducing this shadow value in the form of the tax, the social optimum can be achieved.

Taxes on harvesting are not common in practice. Methods that have been used in practice to reduce effort are:

ii. Reduction of the harvesting season

Shortening the harvesting season can reduce annual effort. This measure can create excess capacity as exploiters try to maximize harvest over a short time interval and require more capacity to do so.

iii. Limits on harvesting

Each individual exploiter can not harvest more than a certain amount $\bar{h}$. The exploiter solves the problem

$$\begin{gathered} \max_{E_i \geq 0} p\phi(E_i, x) - c_i(E_i) \\ s.t. \; \phi(E_i, x) \leq \bar{h} \end{gathered} \tag{25}$$

with optimality condition:

$$(p - z)\frac{\partial \phi}{\partial E_i} = c_i'(E_i), \; for \; E_i = E_i^0 \tag{26}$$

where z is the Lagrangean multiplier associated with the constraint of problem (25). If the harvesting limit is set such that $\bar{h} = \phi(E_i^*, x)$, then the social optimum can be achieved. The use of harvesting limits requires an extensive monitoring system.

iv. Tradable catch quotas

Each exploiter (fisherman) is allocated a catch quota. Quotas can be traded. If one fisherman wants to catch more than his quota, he should buy more quotas from fishermen willing to sell. To achieve the social optimum the total amount of quotas should be set at the level $\sum_{i=1}^{n} \phi(E_i^*, x)$. In this case the equilibrium quota price tends to λ, the shadow value of the resource, and equilibrium is achieved.

2. Specialization in mechanistic resource-based models of species competition (Tilman)

Specialization at the private optimum

Let $B_i(t)$, $i = 1,...n$ denote the biomasses of n species at each point in time. The species are competing for a single limiting resource R. The rate of growth for each species i is defined as:

$$\frac{\dot{B}_i}{B_i} = g_i(R) - d_i \tag{27}$$

with $g_i' > 0$, $g_i'' < 0$, and d_I the natural mortality rate for species i. The limiting resource evolves according to

$$\dot{R} = S - \sum_{i=1}^{n} w_i g_i(R) B_i \tag{28}$$

where S is the constant resources supply per unit time, and w_i is the concentration of the resource in the tissues of species i.

Let h_i be harvesting of species i by a profit-maximizing exploiter and let $p_i = P_i - c_i$ be the net profit per unit harvest. In equilibrium $\dot{B}_i = \dot{R} = 0 \ \forall i$, and the profit-maximizing exploiter solves the following problem assuming zero discount rate:

$$\begin{aligned} &\max_{(h_1,...,h_n)\geq 0} \sum_{i=1}^{n} p_i h_i \\ s.t.\ & 0 = B_i[g_i(R) - d_i] - h_i \\ & 0 = S - \sum_{i=1}^{n} w_i g_i(R) B_i \end{aligned} \tag{29}$$

By writing $h_i = B_i[g_i(R) - d_i]$, the problem can be restated as:

$$\begin{aligned} &\max_{(h_1,...,h_n)\geq 0} \sum_{i=1}^{n} p_i B_i[g_i(R) - d_i] \\ s.t.\ & \sum_{i=1}^{n} w_i g_i(R) B_i = S \end{aligned} \tag{30}$$

The Lagrangean function for this problem is defined as:

$$L = \sum_{i=1}^{n} p_i B_i [g_i(R) - d_i] + \mu\left[S - \sum_{i=1}^{n} w_i g_i(R) B_i\right] \qquad (31)$$

with optimality conditions:

$$\begin{aligned} & g_i(R)[p_i - \mu w_i] \le p_i d_i \ \text{ with equality if } B_i > 0 \\ & g_i(R)[p_i - \mu w_i] < p_i d_i \ \text{ then } B_i = 0 \end{aligned} \qquad (32)$$

$$\sum_{i=1}^{n} g_i'(R) B_i [p_i - \mu w_i] = 0,\ R > 0 \qquad (33)$$

Assume:

a. $\frac{p_1}{w_1} = \arg\max\left\{\frac{p_i}{w_i}\right\}$

b. $g_1(R) - d_1 = \arg\max\{g_i(R) - d_i\}$

From assumption (a), species one ($i = 1$) is a candidate for optimal specialization. The objective function with only one species ($i = 1$) harvested becomes

$$\pi_1 = p_1 B_1 [g_1(R) - d_1]$$

Substituting for B_1 from $S = w_1 g_1(R) B_1$, the profit function becomes:

$$\pi_1 = \frac{p_1}{w_1} \frac{S}{g_1(R)} [g_1(R) - d_1]$$

Under assumptions (a) and (b), $\pi_1 = \arg\max\{\pi_i\}$. Therefore at the private optimum, specialization in species one takes place and the system tends into a monoculture.

Social optimum and preservation of biodiversity

It has been well established that monocultures create negative externalities. These externalities are not taken into account at the private optimum. Assume that these externalities can be captured by the function $U(\mathbf{B})$, $\mathbf{B} = (B_1, ..., B_n)$, with the following properties:

$$\frac{\partial U}{\partial B_i} > 0,\ \frac{\partial^2 U}{\partial B_i^{\ 2}} < 0,\ \lim_{B_1 \to 0} \frac{\partial U}{\partial B_i} = +\infty$$

These properties imply that all species are useful and that when a species is close to extinction, its marginal usefulness becomes very large. The problem for the social planner becomes:

$$\begin{aligned} & \max_{(h_1,...,h_n) \ge 0} \sum_{i=1}^{n} p_i h_i + U(\mathbf{B}) \\ & s.t.\ 0 = B_i [g_i(R) - d_i] - h_i \\ & \qquad 0 = S - \sum_{i=1}^{n} w_i g_i(R) B_i \end{aligned} \qquad (33)$$

with optimality conditions:

$$\frac{\partial U}{\partial B_i} + g_i(R)[p_i - \mu w_i] \leq p_i d_i \text{ with equality if } B_i > 0$$
$$if \ \frac{\partial U}{\partial B_i} + g_i(R)[p_i - \mu w_i] < p_i d_i \text{ then } B_i = 0 \quad (34)$$

$$\frac{\partial U}{\partial B_i} + \sum_{i=1}^{n} g_i'(R) B_i [p_i - \mu w_i] = 0,\ R > 0 \quad (35)$$

Since $\lim_{B_1 \to 0} \frac{\partial U}{\partial B_i} = +\infty$, $B_i = 0$ can not be a solution of (34). Therefore at the solution , $B_i > 0$, and all species are preserved at the social optimum.

Environmental policy

Since there is a deviation between the private and the social optimums, environmental policy can be introduced in order to induce the private markets *not to* create a monoculture but to achieve the social optimum and preserve biodiversity.

Introduce biomass and resource taxes per unit deviation between observed biomass, B_i , and desired biomass, B_i^*, and observed resource level, R, and desired resource level, R^*. Total tax payments are:

$$\tau(B_i - B_i^*) + \tau(R - R^*)$$

The profit-maximizing explorer solves:

$$\begin{aligned} &\max_{(h_1,\ldots,h_n)\geq 0} \sum_{i=1}^{n} p_i h_i + \tau(B_i - B_i^*) + \tau(R - R^*) \\ &s.t.\ 0 = B_i[g_i(R) - d_i] - h_i \\ &\quad\ \ 0 = S - \sum_{i=1}^{n} w_i g_i(R) B_i \end{aligned} \quad (36)$$

If the tax is set such that $\tau = \frac{\partial U}{\partial B_i}$, it is clear by comparing the optimality conditions of problem (33) with those implied by problem (36) that the private optimum under taxes coincides with the social optimum. Therefore environmental policy in this form can preserve the socially optimal biodiversity.

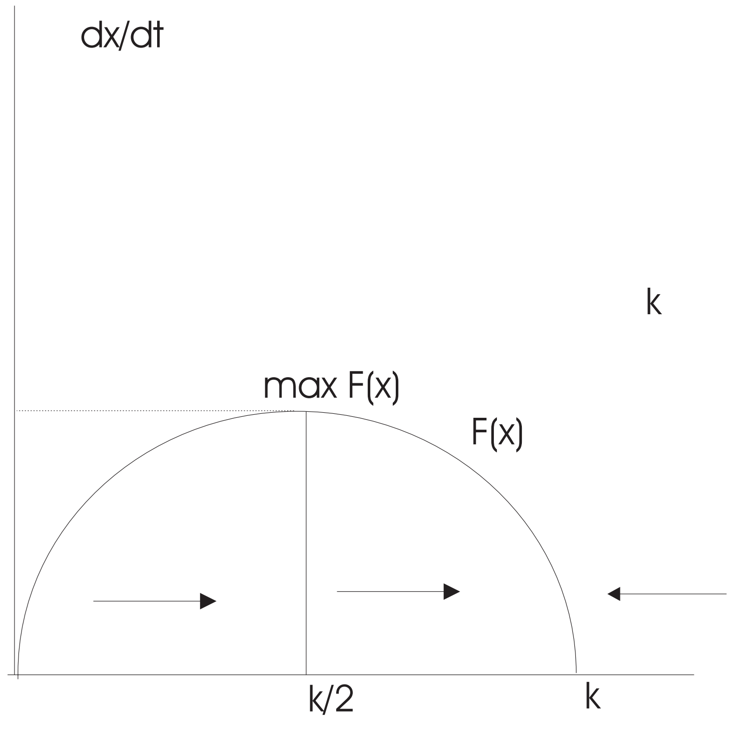

Figure 2.1 Logistic growth

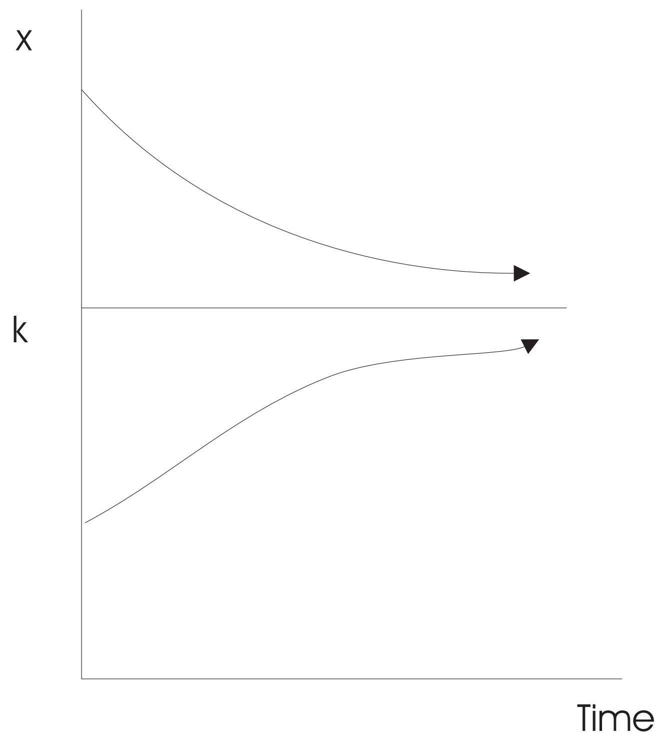

Figure 2.2 Evolution under logistic growth

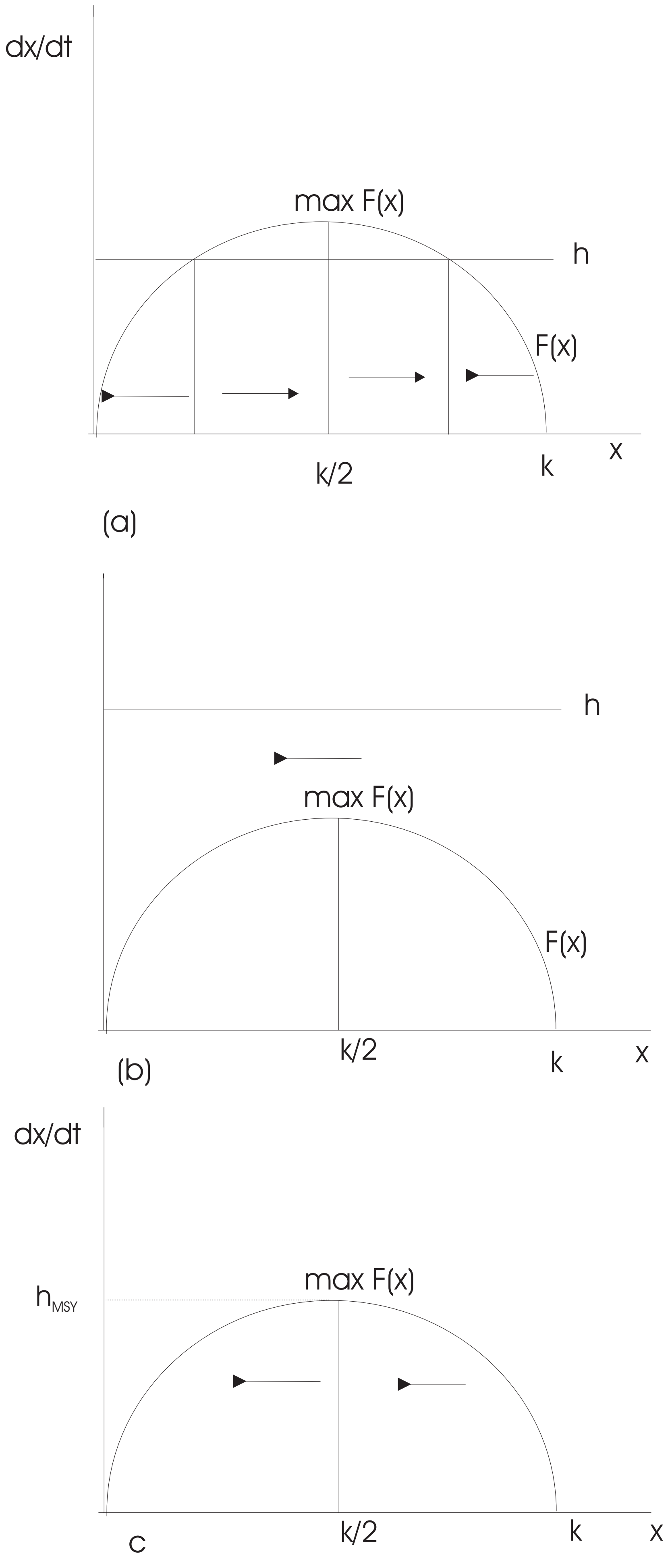

Figure 2.3: Constant harvesting

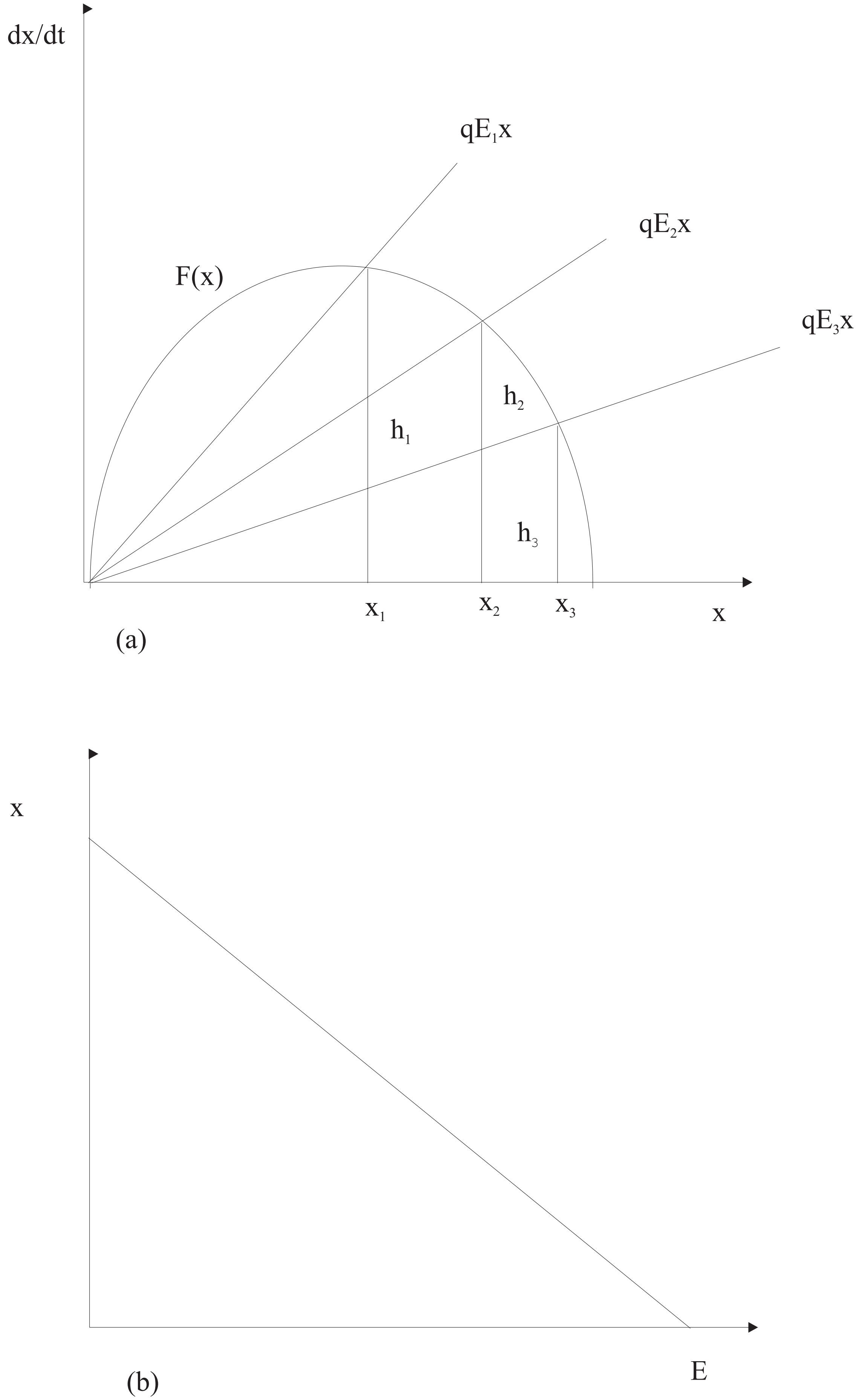

Figure 2.4: Sustained yield

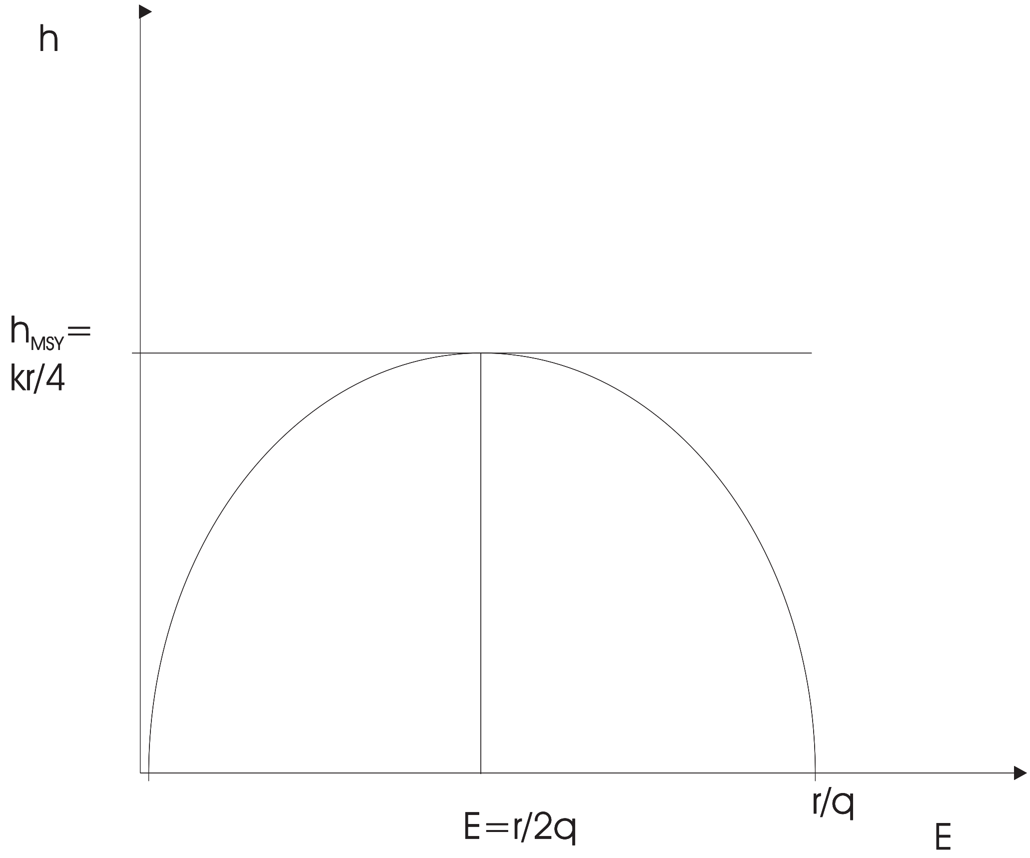

Figure 2.5: Sustained yield

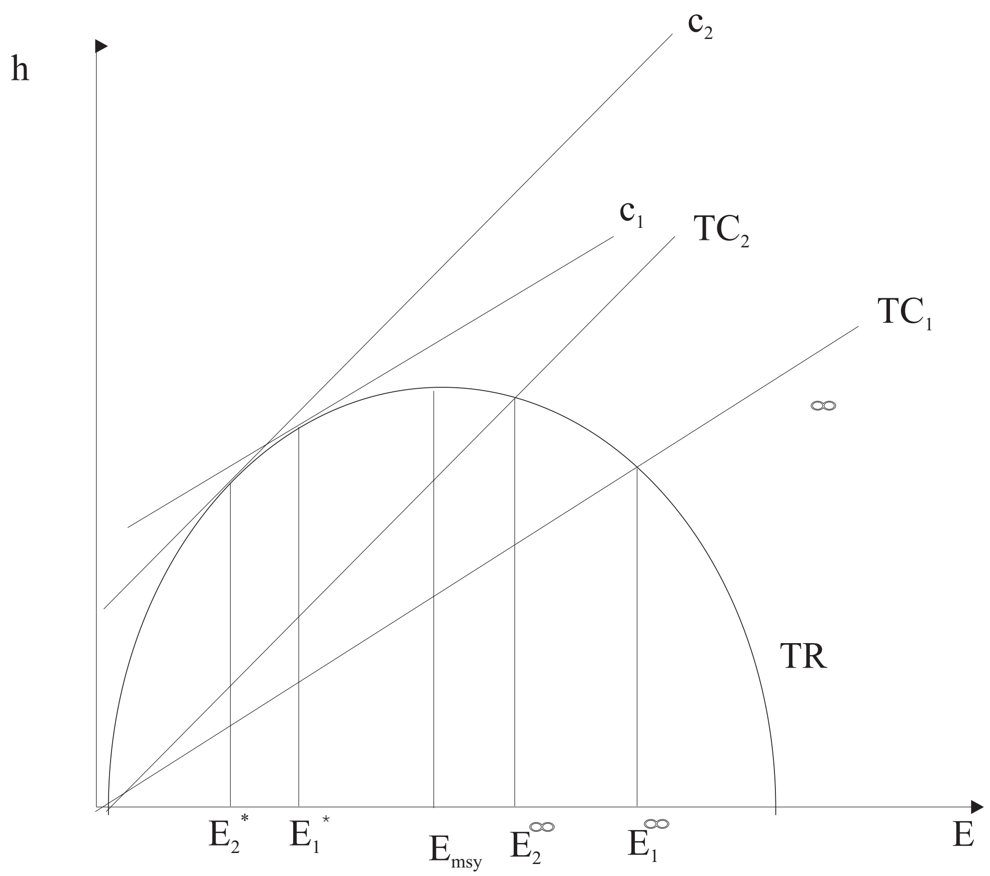

Figure 3.1: Bionomic equilibrium and profit maximizing equilibrium

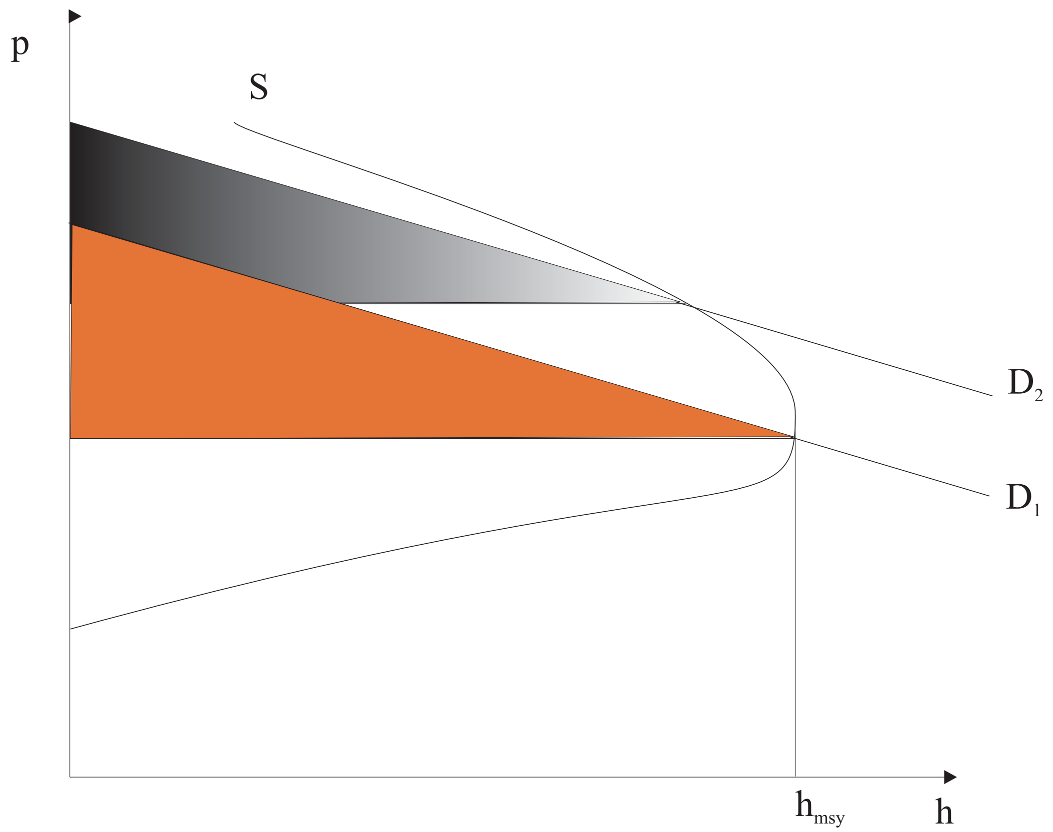

Figure 3.2: Supply curve and market equilibrium for an open access fishery

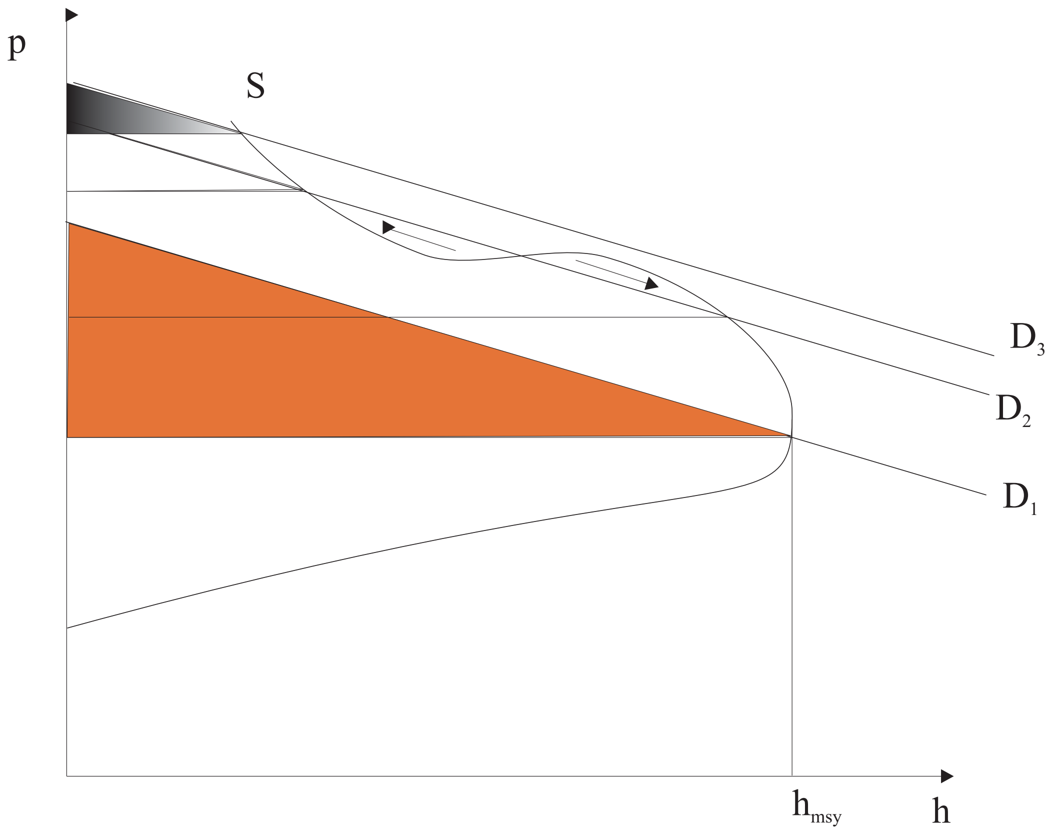

Figure 3.3: Bionomic instability and market equilibrium for an open access fishery

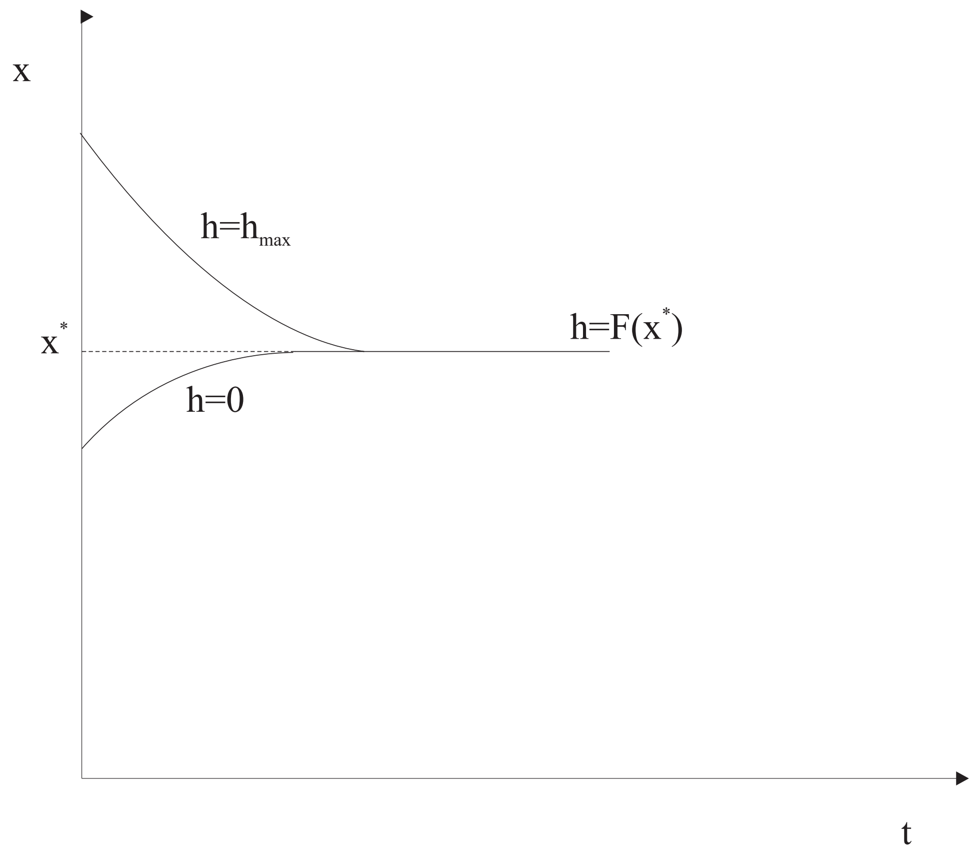

Figure 4.1: Most rapid approach path

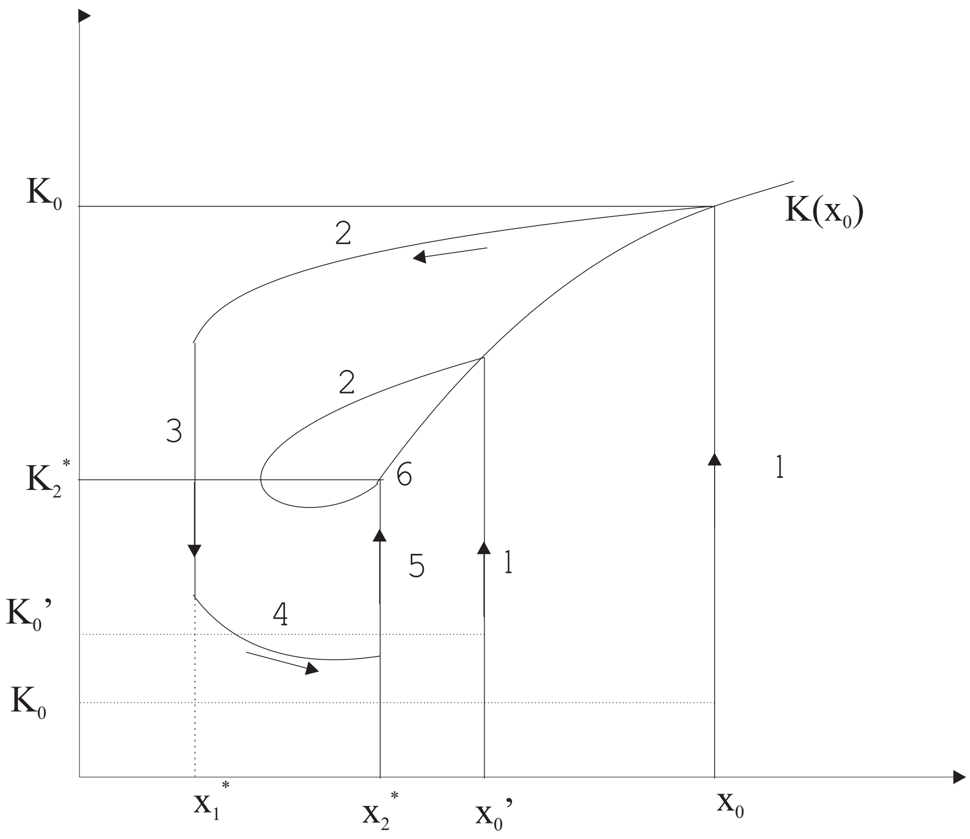

Figure 5.1: Optimal investment