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"Fifth Course on Mathematical Ecology
including and introduction to Ecological Economics"

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AN INTRODUCTION TO THE OVER EXPLOITATION OF RENEWABLE RESOURCES

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MANAGEMENT PROBLEMS

One resource

Analysis at equilibrium

- Maximum sustainable yield
- Bionomic equilibrium

Dynamic analysis

- Discount rates
- Optimal control
- Maximum principle

Several interacting species

Several age classes

potuto evitare una maggiore conoscenza dell'ecosistema che veniva perturbato dagli uomini.

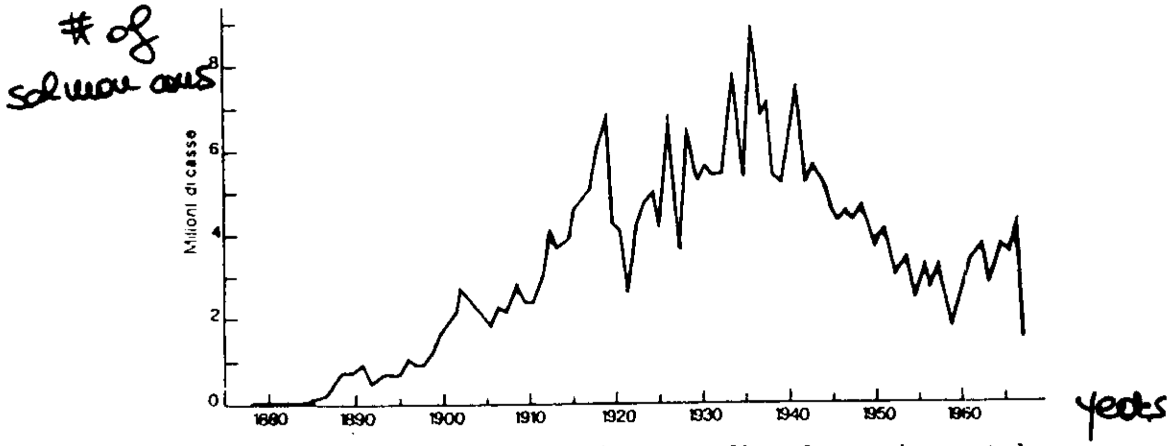


Fig. 1.1 - Numero totale di casse di salmone in scatola prodotte in Alaska tra il 1878 e il 1967 (da Fishery Statistics of the United States).

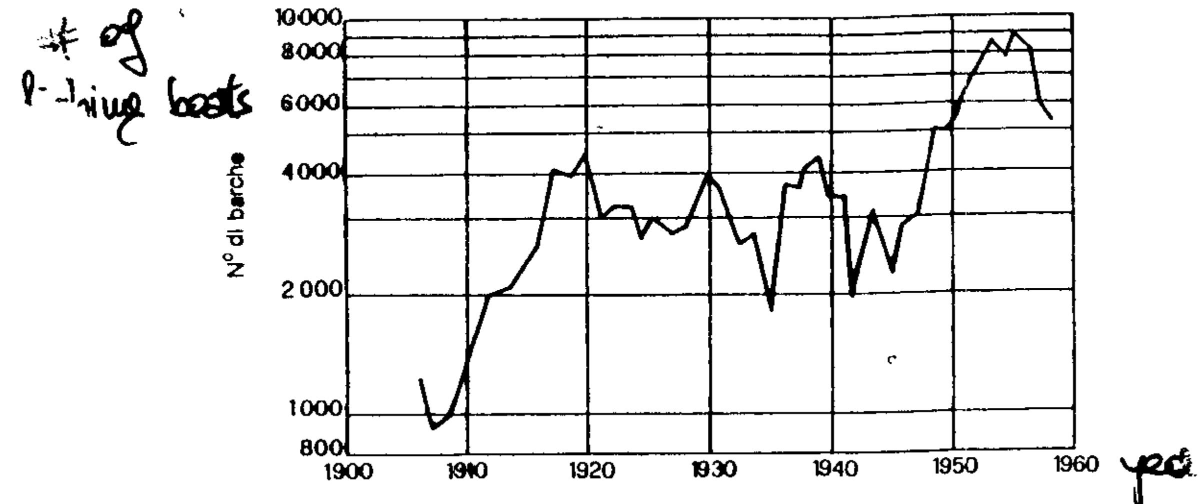


Fig. 1.2 - Numero di barche da pesca usate per la cattura del salmone in Alaska tra il 1906 e il 1959 (da Cooley, 1963).

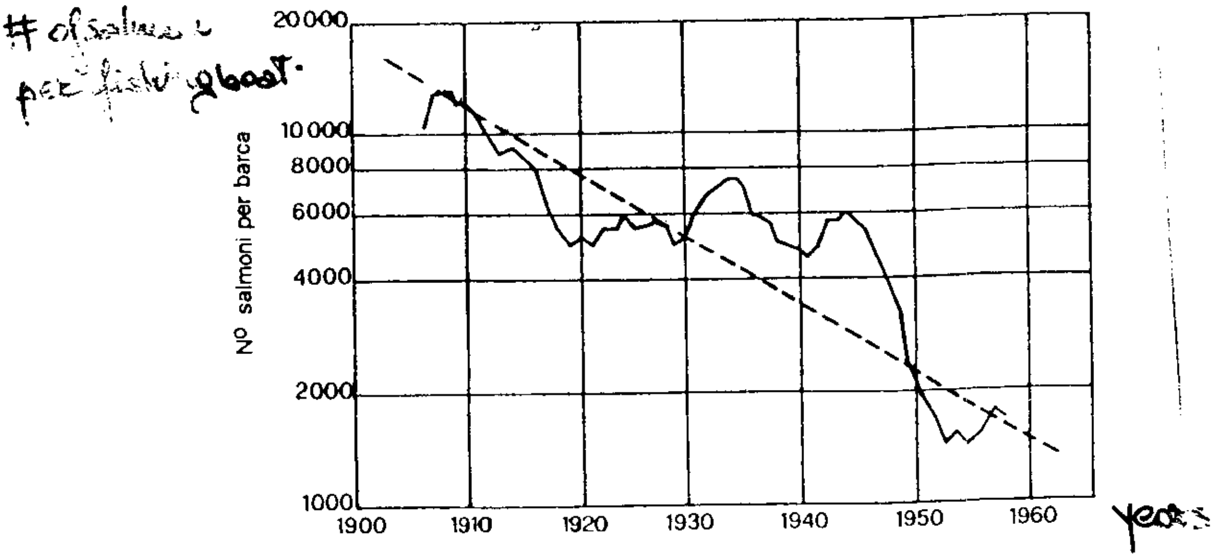
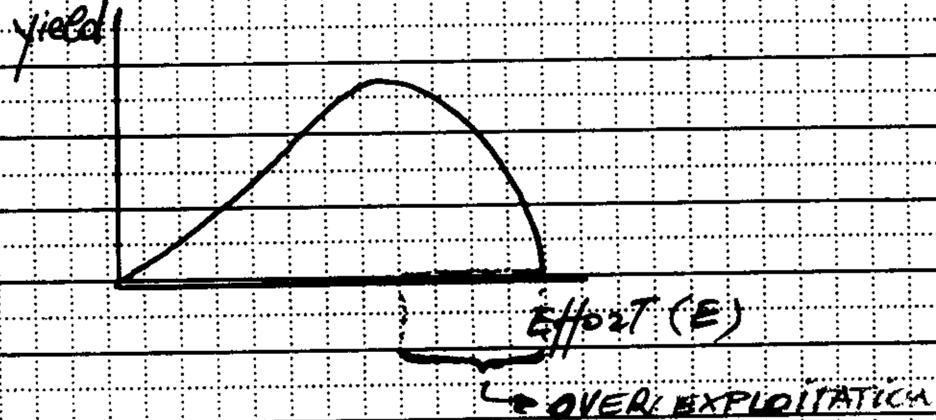


Fig. 1.3 - Numero medio di salmoni catturati da una barca da pesca in Alaska tra il 1906 e il 1959 (da Cooley, 1963).

Why is it difficult to manage renewable resources?

- Increasing exploitation effort does not necessarily increases yield



- They are often open access resources

⇓

OVER-EXPLOITATION

THE FISHERMEN DILEMMA

Fishermen A \ Fishermen B	Small harvesting effort	High harvesting effort
small harvesting effort	3, 3	1, 4
high harvesting effort	4, 1	2, 2

Non-cooperative policies

$\Downarrow$

- overexploitation
- bioeconomic inefficiency.

Harding : "The Tragedy of the commons"
Science

NEED FOR REGULATION

Question:

What do we want to achieve?

- To maximize yield in the long run (MSY)
- To maximize net economic benefit in the long run
- To reduce the risk of extinction in the long run

How can we achieve it ?

Non exclusive tools :

- restrictions on quotas
- " on fish age, size, gender ...
- " on net type, number, size, ...
- " on type of fishing boats, engine power, ...
- ...

Exclusive tools

- restrictions on number of licences, i.e., number of fishermen, hunters, # of boats
- " " on time
- " on space (nursery areas)

Economic and Market Tools

- Taxes
- subsidies
- Transferable quotas (Kyoto mechanism)

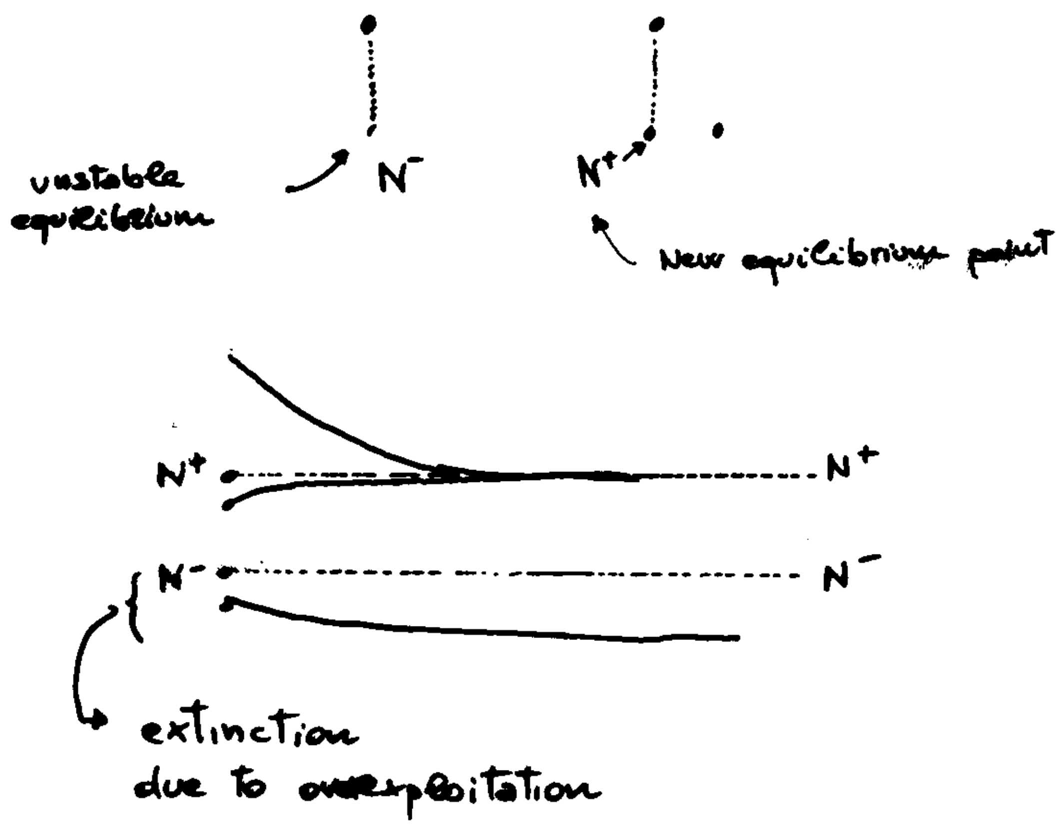
ONE RESOURCE- CONTINUOUS MODELS

$$\frac{dx}{dt} = \dot{x} = F(x) - h$$

x = resource biomass

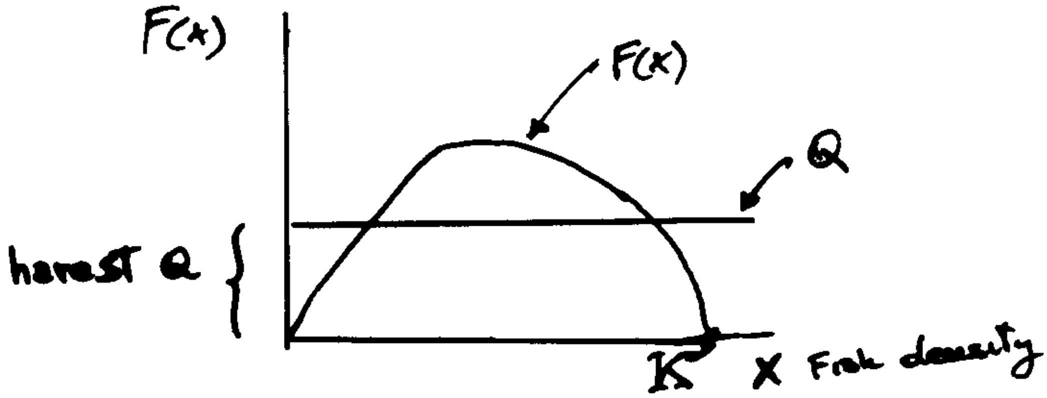
$F(x)$ = net growth rate

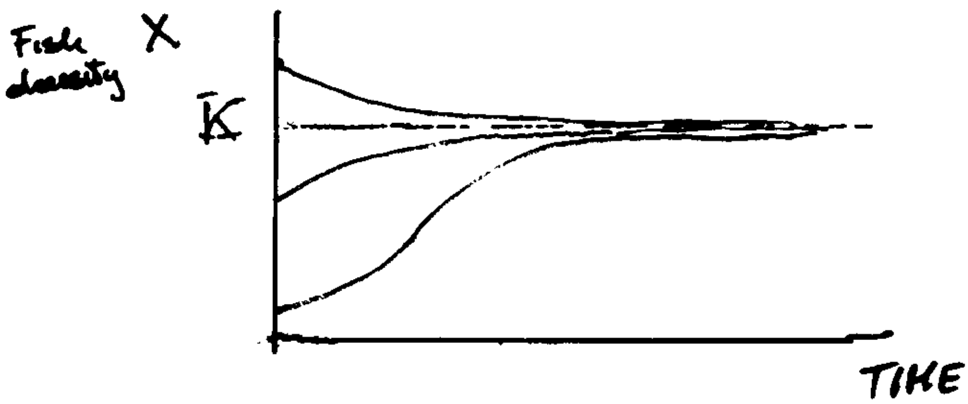
h = harvesting rate


unstable equilibrium
N⁻
N⁺
New equilibrium point
N⁺
N⁺
N⁻
N⁻
extinction due to overexploitation

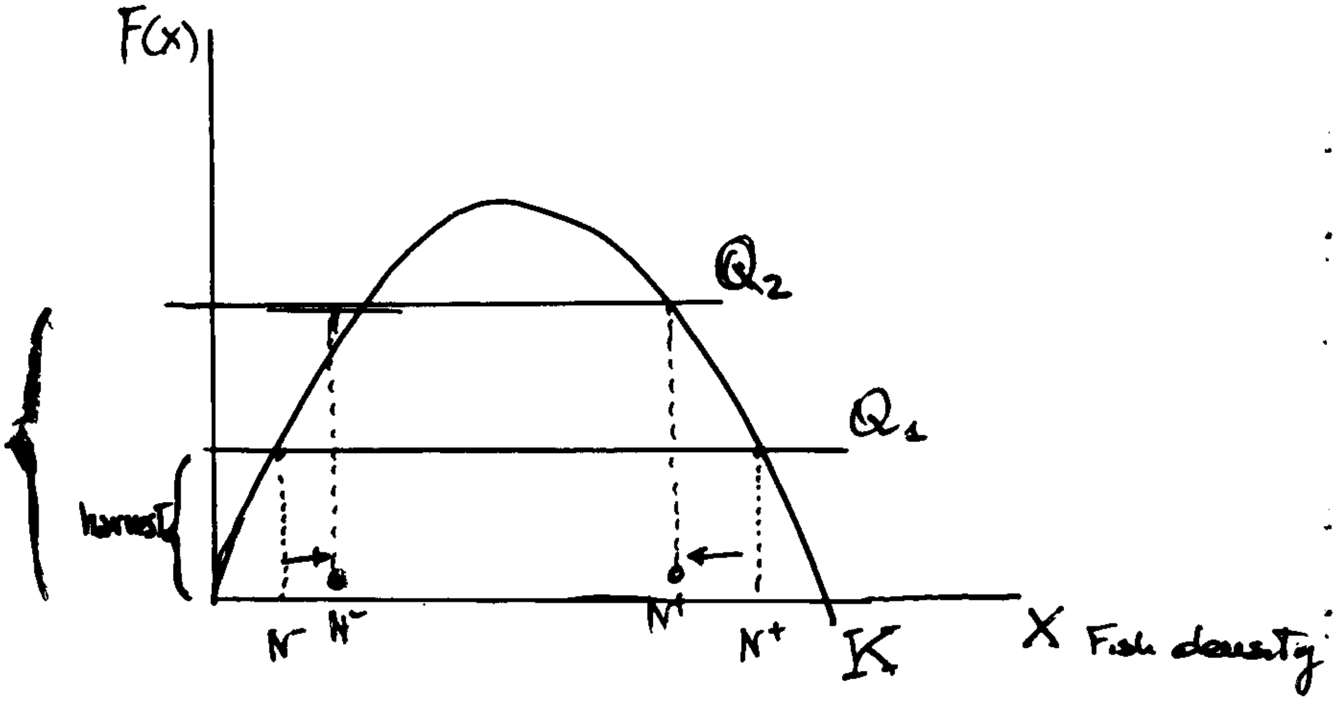
Fixed harvesting-quota Policy

$$\mathring{X} = F(x) - Q$$





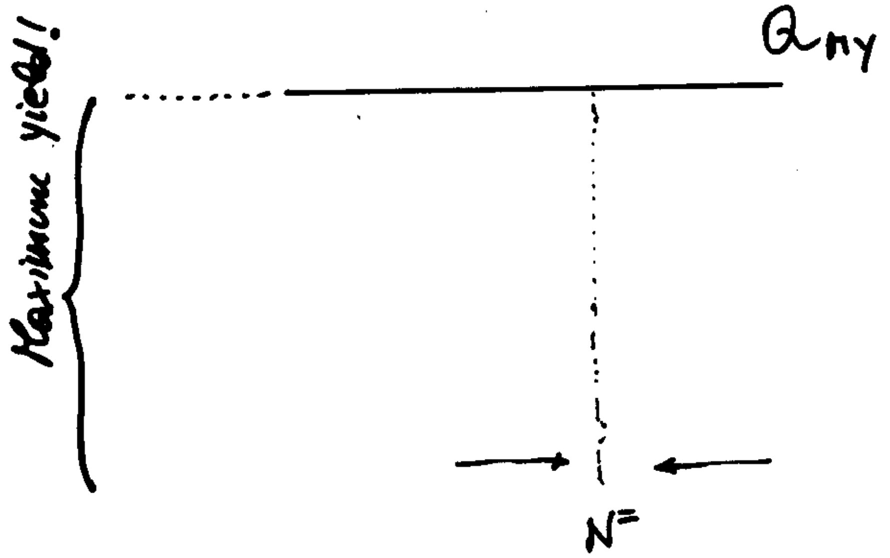
What happens if we want to maximize yield by using a fixed-quota policy?

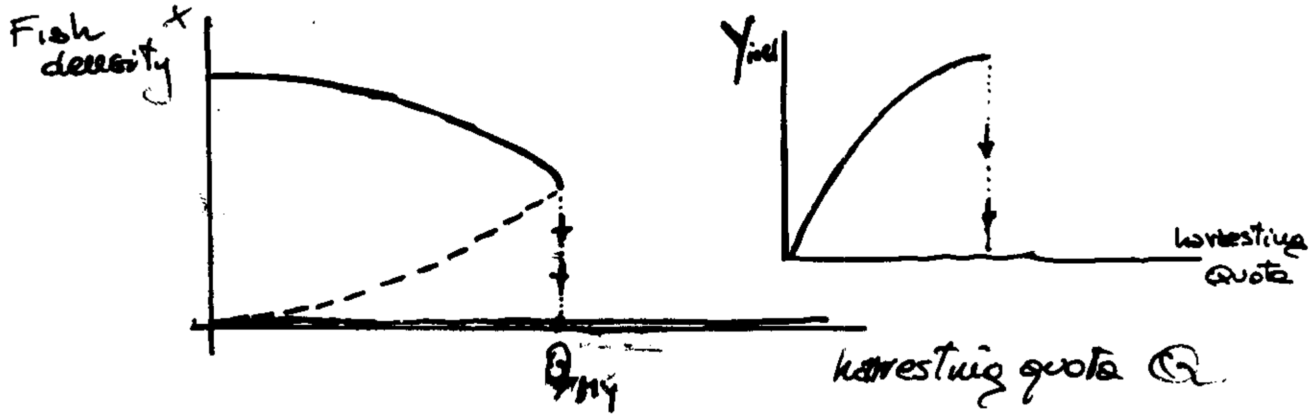


Tab. 8.2 - Catture mondiali di balene e relative quote ne anni recenti (in unità di balenottere azzurre)

WORLD CATCH of WHALES and TARGET QUOTAS (IN BLUE-WHALE UNITS)

Anno YEAR	Cattura totale WORLD CATCH	Quota TARGET QUOTA
1947-48	16.364	16.000
1952-53	14.866	16.000
1957-58	14.850	14.500
1958-59	15.300	15.000
1959-60	15.511	15.000
1960-61	16.433	
1961-62	15.252	
1962-63	11.306	15.000
1963-64	8.429	10.000
1964-65	6.987	8.000
1965-66	4.091	4.500
1966-67		3.500





⇒ extremely dangerous policy

- requires huge monitoring effort
- the public authority has to pay for monitoring.

Harvesting rate h and effort E

The effort E is some suitably defined measure of the harvesting stress on the resource being exploited

- Number of boat-days
- Capital invested in the harvesting activity
- Number of working hours of harvesting people

Obviously

$$h = g(E, x)$$

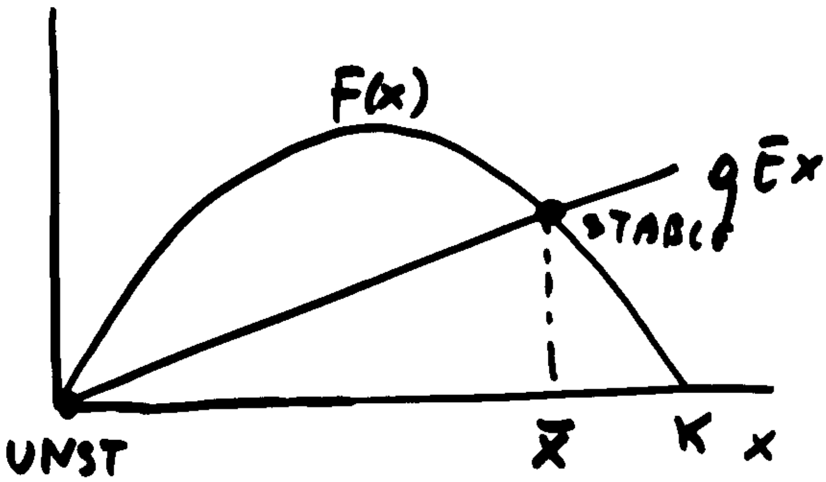
Usually one assumes

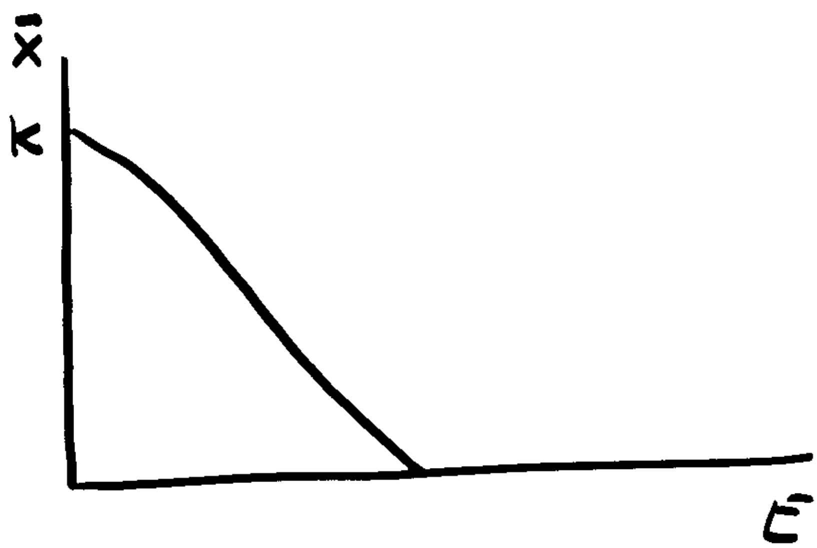
$$h = qEx$$

catchability coefficient

ANALYSIS AT EQUILIBRIUM

$$\dot{x} = F(x) - qEx = 0$$



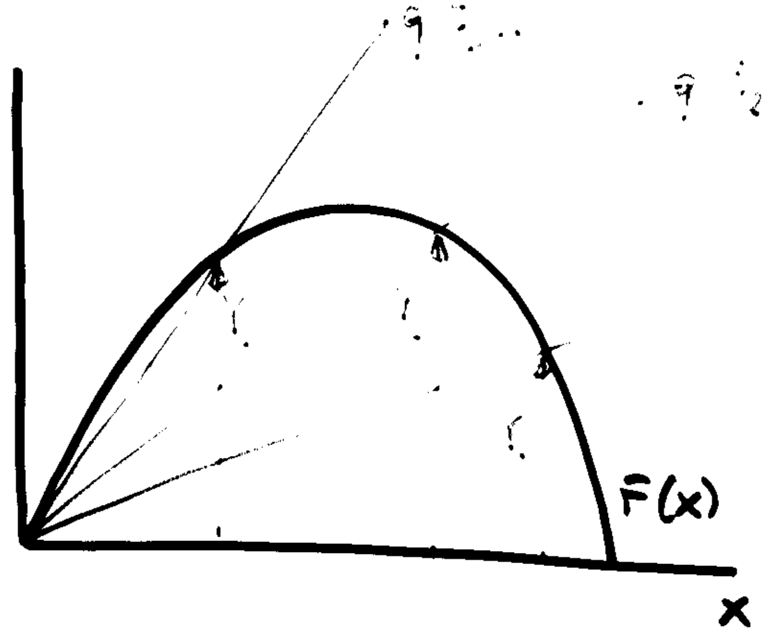


YIELD - EFFORT CURVES

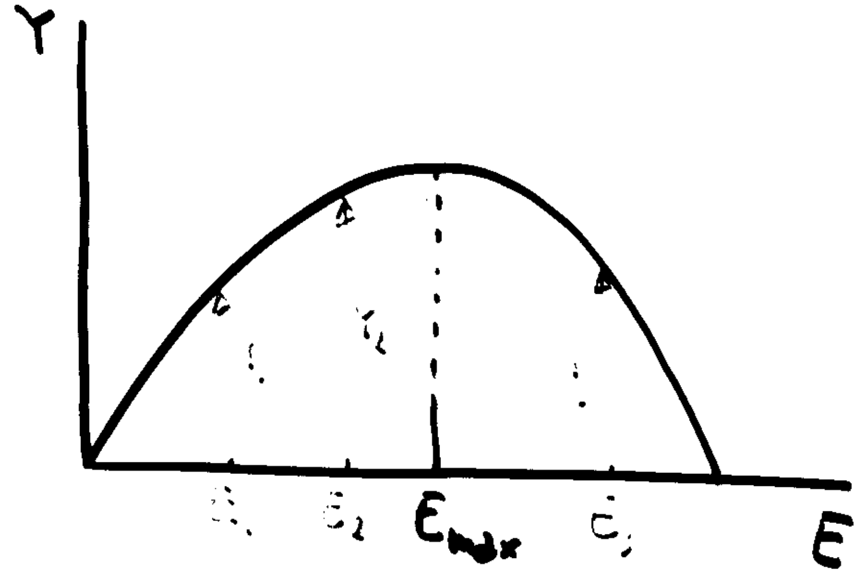
We define <u>sustainable yield</u> the constant harvesting rate which is obtained at equilibrium by applying a certain constant effort

$$Y = qE\bar{x}$$

where $\bar{x}$ is the equilibrium corresponding to effort E



$E_1 < E_2 < E_3$

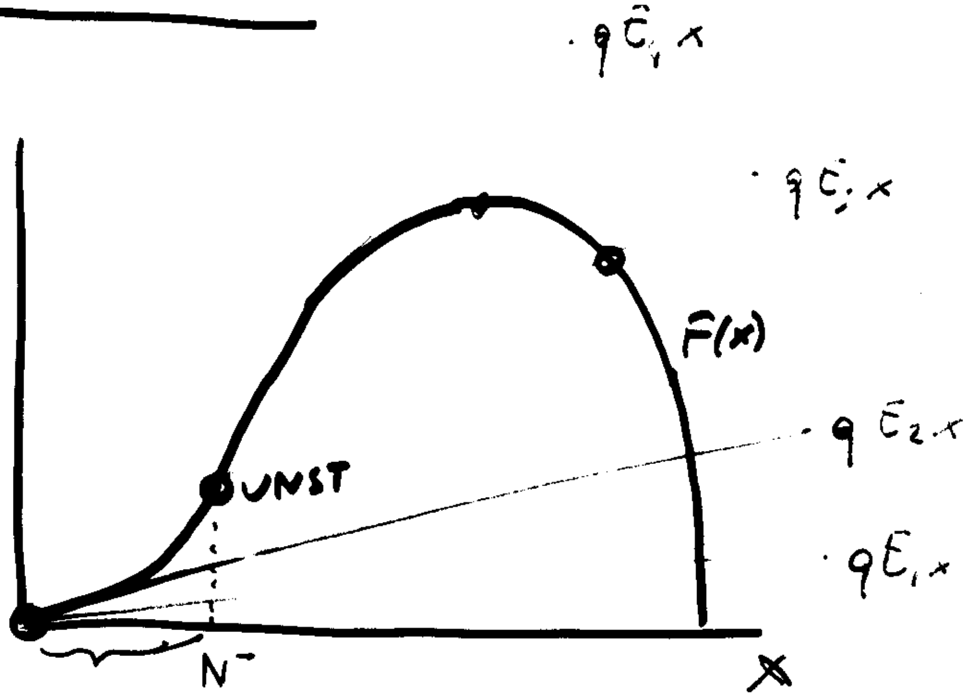


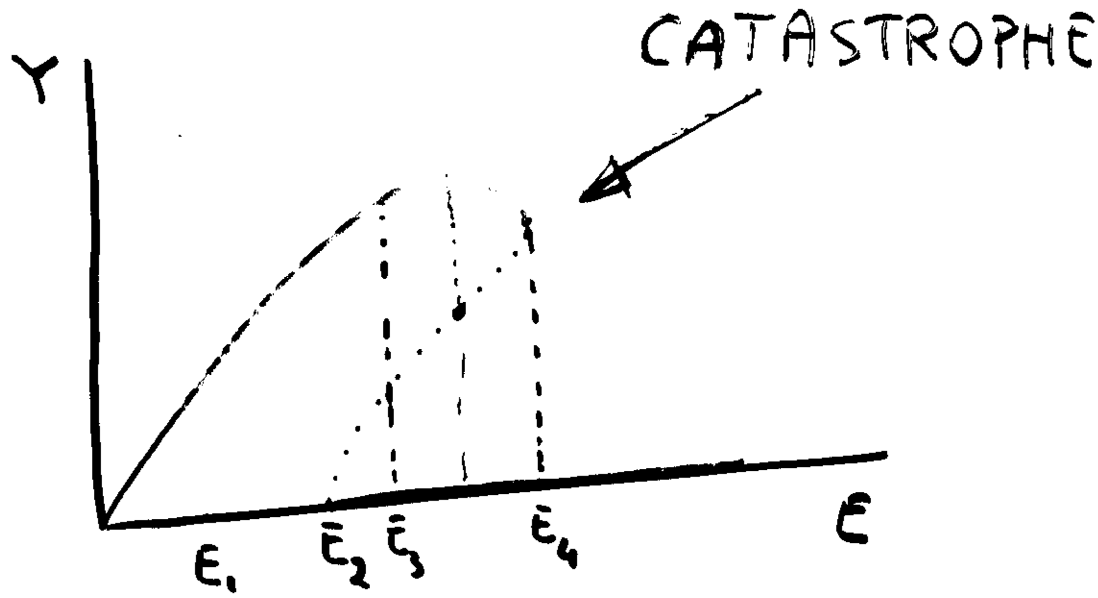
The effort E_{max} gives the Maximum Sustainable Yield (MSY)

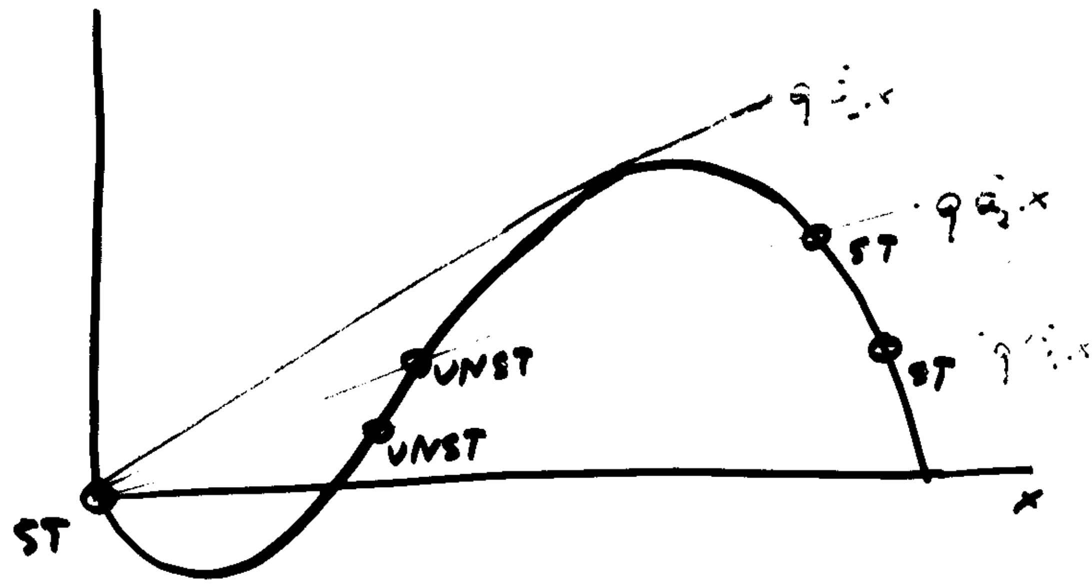
$E < E_{max}$ → biological underexploitation

$E > E_{max}$ → biological overexploitation

DE PENSATION






ST
UNST
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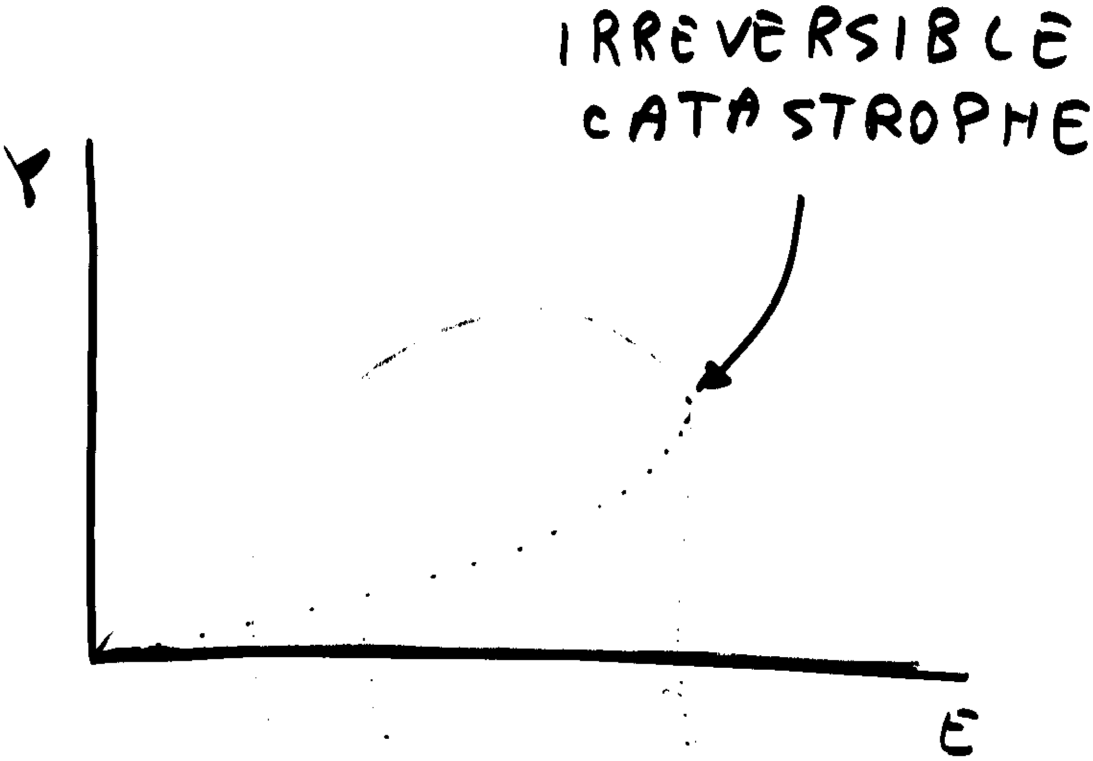
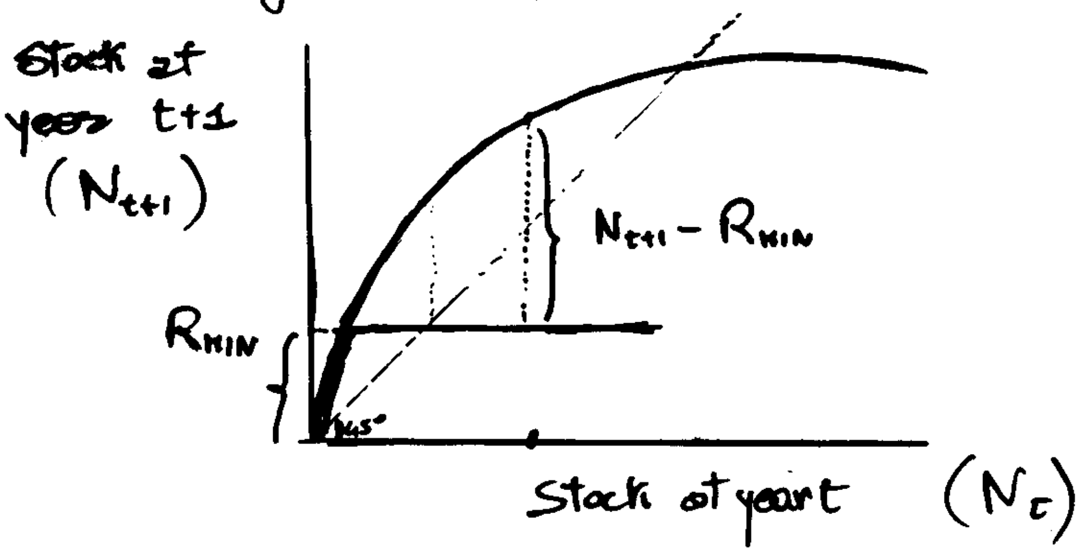
ST
x


IRREVERSIBLE
CATASTROPHE
Y
E

Reducing the risk of extinction

⇒ harvest only what exceeds a given quota of the reproductive stock



$$\text{Harvest } H_{t+1} = \begin{cases} 0 & \text{if } N_{t+1} \leq R_{MIN} \\ \alpha\left(N_{t+1} - R_{MIN}\right) & \text{if } N_{t+1} > R_{MIN} \end{cases}$$

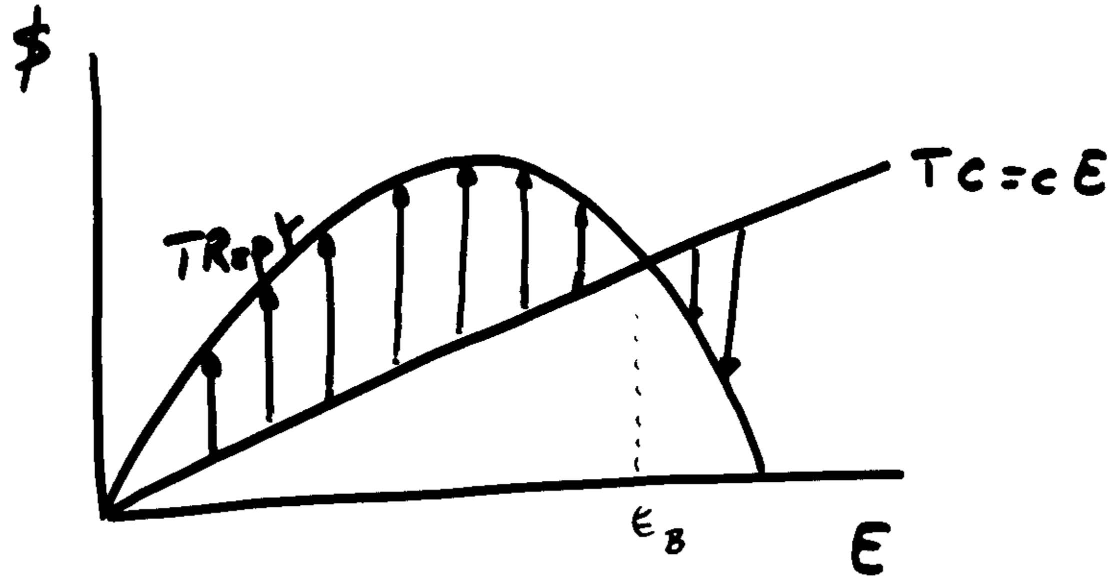
OPEN ACCESS RESOURCE

H. S. Gordon (1954)

The analysis is still performed at equilibrium, but economics is taken into account

$$TR = \text{Total Revenue} = \underbrace{p}_{\text{price}} \; \underbrace{Y(E)}_{\text{sustainable yield}}$$

$$TC = \text{Total Cost} = \underbrace{c}_{\text{cost}} \; \underbrace{E}_{\text{effort}}$$



TP = Total Profit = TR - TC

<u>Example</u> (Schaefer model)

$$\dot{x} = rx\left(1-\frac{x}{k}\right) - h \qquad h = qEx$$

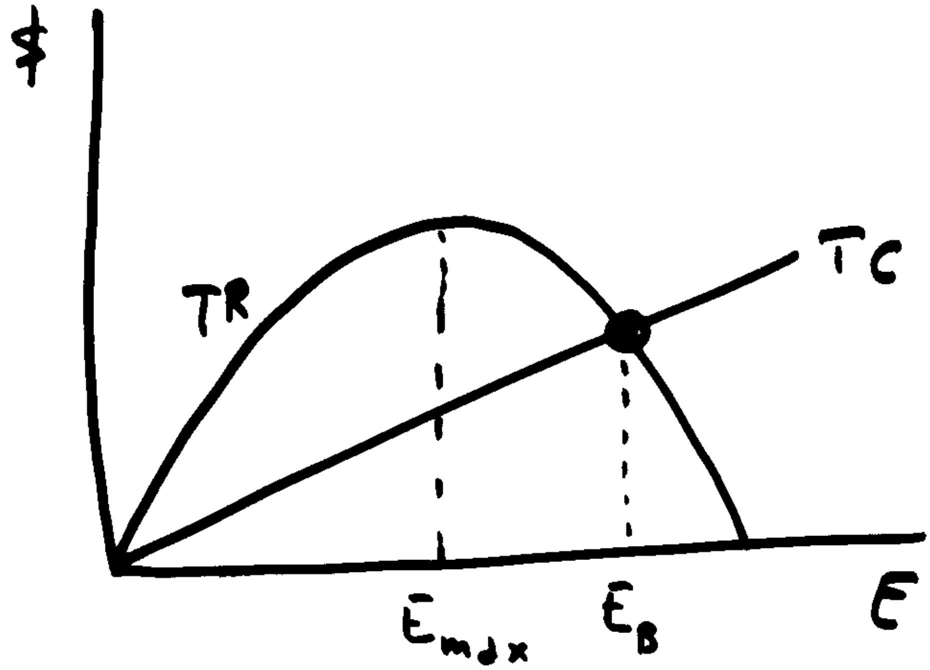
Equilibrium

$$r\bar{x}\left(1-\frac{\bar{x}}{k}\right) - qE\bar{x} = 0 \longrightarrow \bar{x} = k\left(1-\frac{qE}{r}\right)$$

$$Y = qkE\left(1-\frac{q}{r}E\right)$$

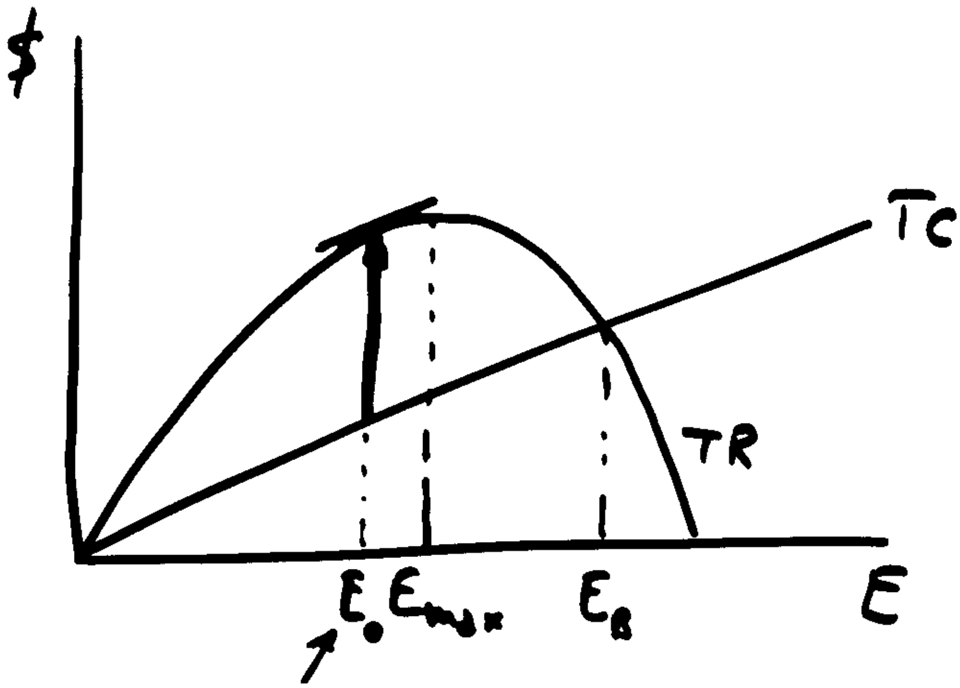
$$TP = TR - TC = pqkE\left(1-\frac{qE}{r}\right) - cE$$

Bionomic Equilibrium



In an open access resource an equilibrium (bionomic equilibrium) is attained corresponding to the effort E_B where total revenue equals total cost

ECONOMIC EFFICIENCY



E_B is inefficient

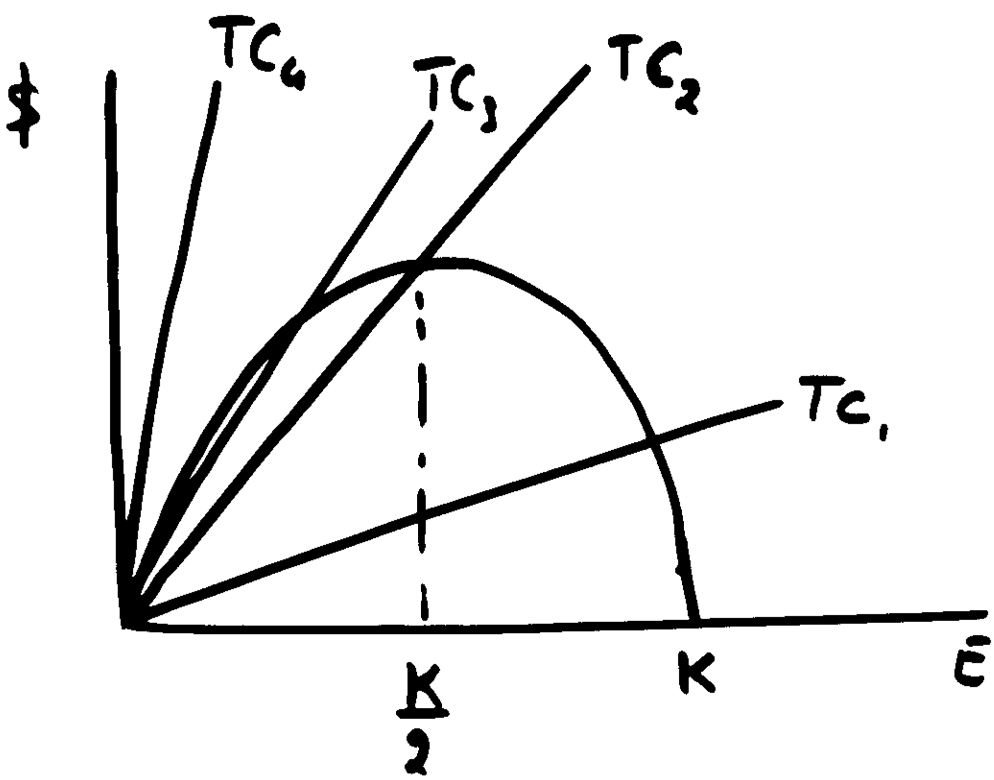
E_0 maximizes the sustainable profit and is economically efficient

Example (Schaefer model)

$$TR = pqkE_B\left(1 - q\frac{E_B}{r}\right) - cE_B = 0$$

$$E_B = \frac{r}{q}\left(1 - \frac{c}{pqK}\right)$$

$$\bar{x}_B = \frac{c}{pq}$$



$$\frac{c_1}{p_1} < \frac{c_2}{p_2} < \frac{c_3}{p_3} < \frac{c_4}{p_4}$$

overexploitation   MSY   underexploitation   no exploitation

Introducing the discount factor

$$\delta = \log (1+i)$$

one gets

$$(1+i)^k = e^{\delta k}$$

and

$$PP = \sum_{k=0}^{\infty} e^{-\delta k} P_k$$

In the case of a continuos flow $P(t)$ of revenues

$$PP = \int_0^{\infty} e^{-\delta t} P(t)\, dt$$

OPTIMAL CONTROL PROBLEMS

So far we have considered only the case

$$E(t) = \text{constant}$$
$$x(t) = \text{constant}$$

searching for values E° and x° optimal according predetermined criteria.

2 questions

1) Why should a constant effort give better results than a time-varying one?
2) What to do if the resource initial biomass $x(0)$ is different than x°?

POSITION OF THE PROBLEM

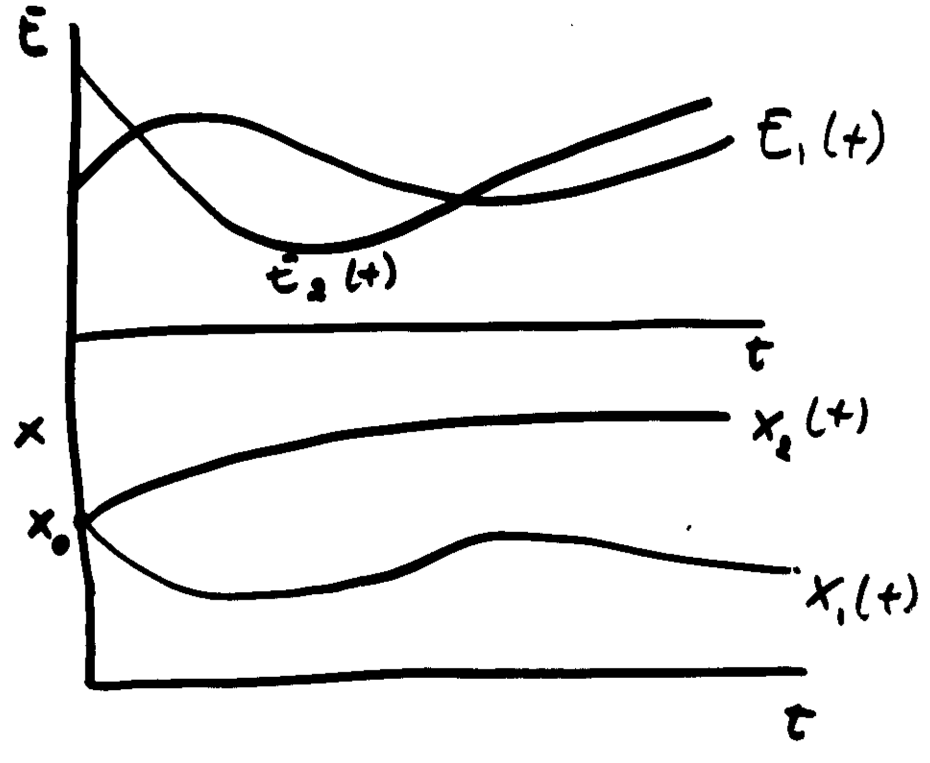
$\dot{x} = F(x) - qEx$

$x(0) = x_0$

$0 \leq E \leq E_{sup}$

The objective is to find the strategy $E(t)$ which maximizes the present value of the profit, i.e.

$$PP = \int_0^{\infty} e^{-\delta t} \left(pqE(t)x(t) - cE(t) \right) dt$$



PROBLEM HARD TO BE SOLVED

$$\Downarrow$$

MAXIMUM PRINCIPLE

(Pontryagin, 1958)

$$\dot{x} = F(x) - qEx$$

$$PP = \int_0^\infty e^{-\delta t}(pqEx - cE)\,dt$$

$$\mathcal{H} = e^{-\delta t}(pq\,x(t) - c)E(t) + \lambda(t)(F(x) - qEx).$$

= Hamiltonian

Adjoint variable
Shadow price
Costate

If $E^{0}(t)$ is an optimal effort strategy and $x^{0}(t)$ the corresponding resource dynamics, then there exists a shadow price $\lambda^{0}(t)$ such that

$$\frac{d\lambda^{0}(t)}{dt} = -\frac{\partial \mathcal{H}}{\partial x}$$

and the Hamiltonian is maximized at any instant by $E^{0}(t)$, i.e.

$$\mathcal{H}\left(x^{0}(t), t, E^{0}(t), \lambda^{0}(t)\right) \geq \mathcal{H}(x^{0}(t), t, E, \lambda^{0}(t))$$

$$\mathcal{H} = e^{-\delta t}(pqx - c)E + \lambda\left(F(x) - qEx\right) =$$

$$= \underbrace{\left[e^{-\delta t}(pqx - c) - \lambda q x\right]}_{\sigma(t)} E + \lambda F(x)$$

$\sigma(t)$: switching function

1. If $\sigma(t) > 0 \longrightarrow E^{\circ}(t) = E_{sup}$

2. If $\sigma(t) < 0 \longrightarrow E^{\circ}(t) = 0$

3. If $\sigma(t) = 0 \longrightarrow$ singular solution

SINGULAR ARC

a. $\sigma(t) = e^{-\delta t}(pqx - c) - \lambda q x = 0$

b. $\dot{\lambda} = -\dfrac{\partial \mathcal{H}}{\partial x} = -e^{-\delta t} pq\hat{E} + \lambda q E - \lambda F'(x)$

From a.

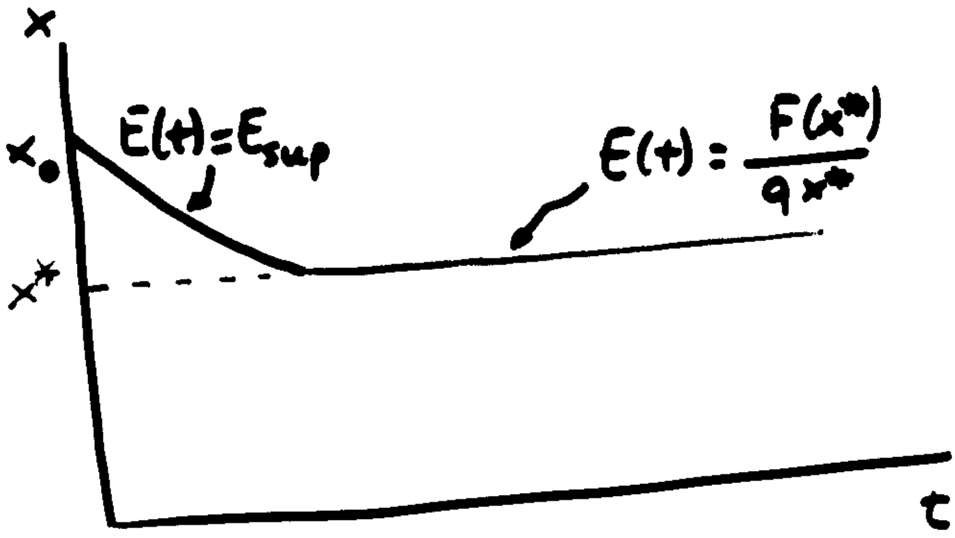
$$\lambda = e^{-\delta t} p - e^{-\delta t} \frac{c}{qx}$$

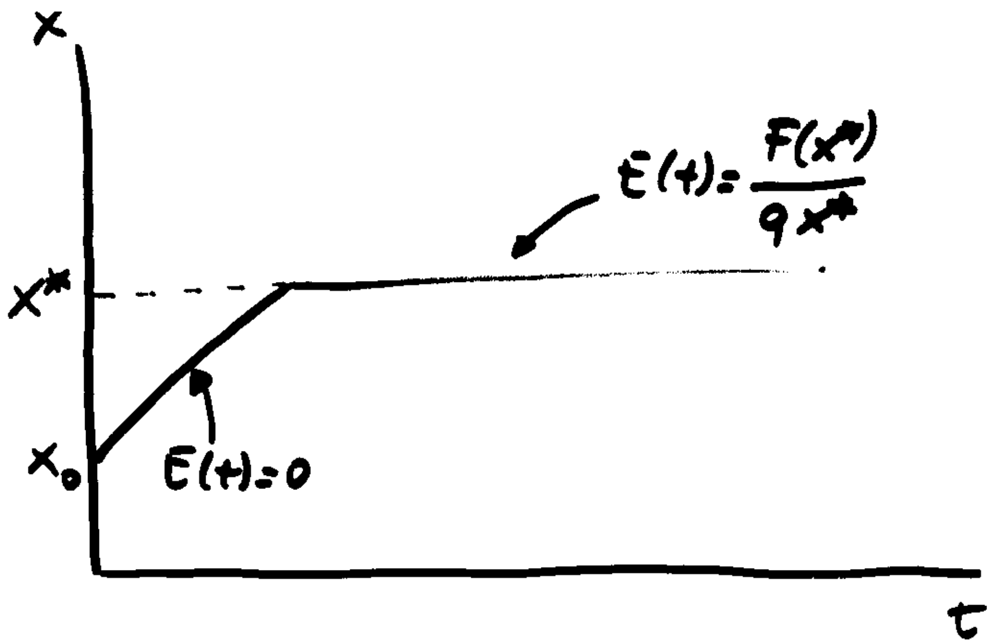
Differentiating and substituting into b. one gets

$$F'(x) + \frac{\frac{c}{qx^2} F(x)}{p - \frac{c}{qx}} = \delta$$

This is an equation in x.
Suppose there is a unique solution x^*

OPTIMAL SOLUTION





$$F'(x) + \frac{\frac{c}{q x^2} F(x)}{p - \frac{c}{qx}} = \delta$$

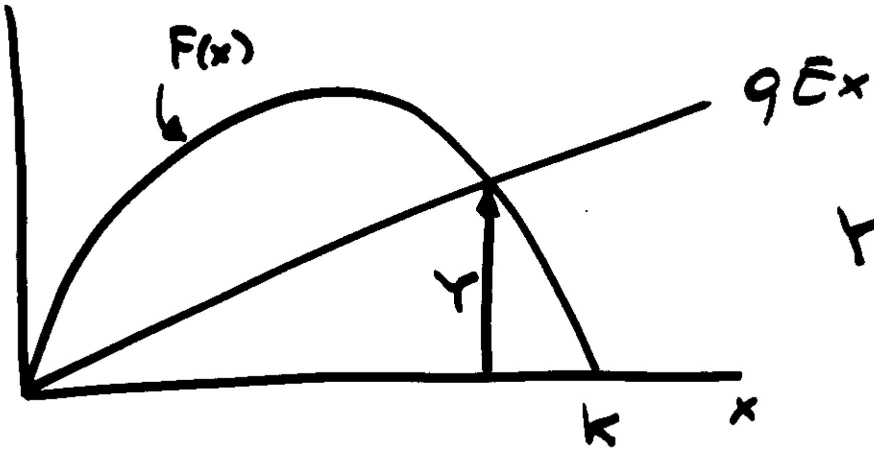
Introduce the cost per unit harvest

$$\gamma(x) = \frac{c}{qx} \qquad \left(\text{Hint: } \gamma(x)\, h = \frac{c}{qx} q E x = cE\right)$$

$$F'(x) - \frac{\gamma'(x) F(x)}{p - \gamma(x)} = \delta$$

$$F'(x)(p - \gamma(x)) - \gamma'(x) F(x) = \delta (p - \gamma(x))$$

$$\frac{d}{dx}\left[(p - \gamma(x)) F(x)\right] = \delta (p - \gamma(x))$$



$Y = F(x)$

$(p - \gamma(x))F(x) = \Pi_s(x) =$ sustainable profit when resource is at equilibrium x

Let

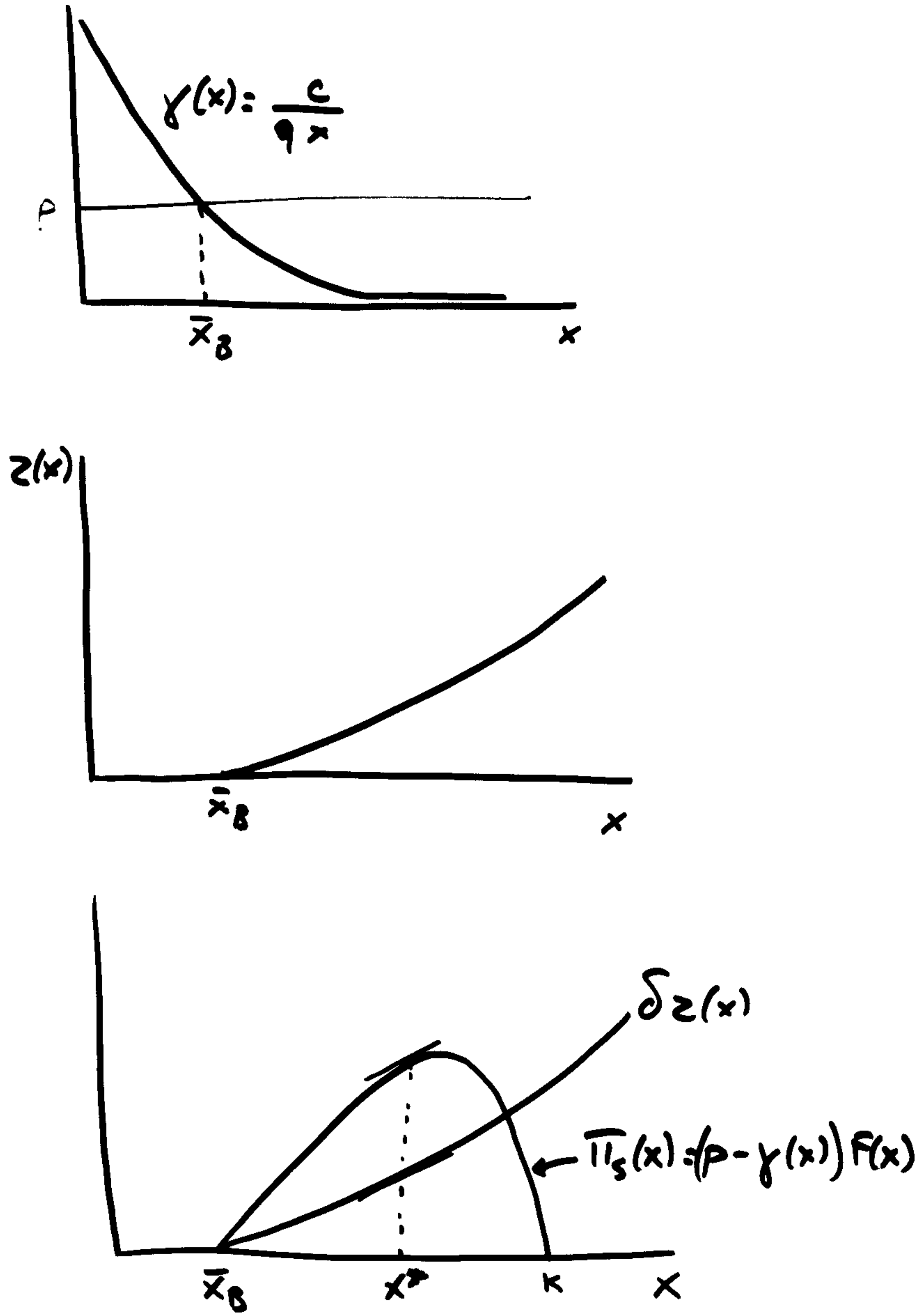
$$z(x) = \int_{\bar{x}_B}^{x} (p - \gamma(\sigma))\, d\sigma = \text{cash value of resource } x$$

where $\bar{x}_B = \dfrac{c}{pq}$ = bionomic equilibrium

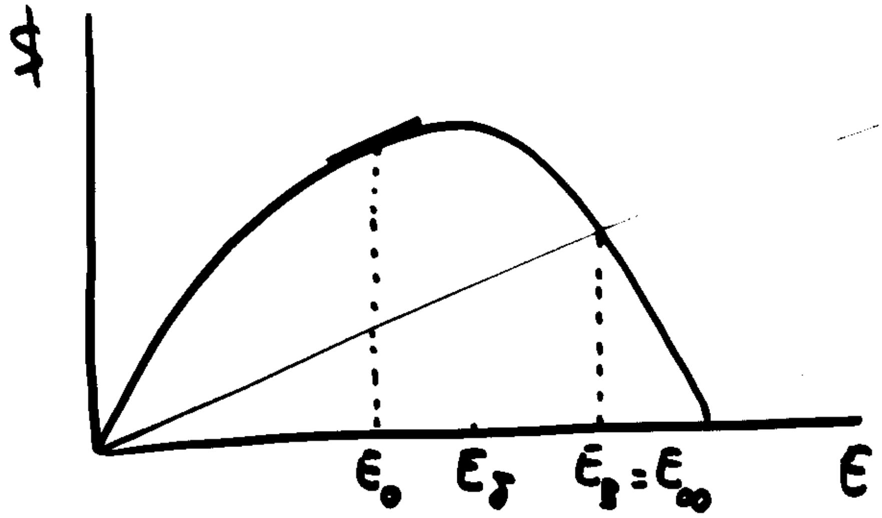
and $p - \gamma(\bar{x}_B) = 0$.

Then the equation for x^* is

$$\frac{d}{dx}\left(\Pi_s(x) - \delta z(x)\right) = 0$$



$\delta z(x)$ = opportunity cost of capital



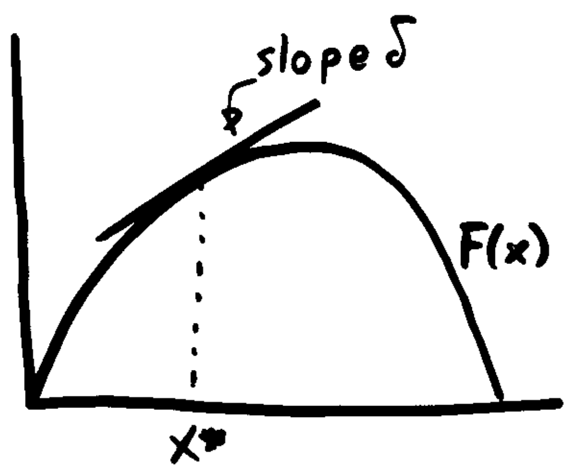
$\delta \to \infty$ $x^* \to \bar{x}_B$ = bionomic equilibrium

$E \to E_B$

$\delta \to 0$ $x^*, E \to$ most efficient solution without discount

CASE WITH VANISHING COSTS

$F'(x) = \delta$



If $\delta > F'(0)$

$\Downarrow$

EXTINCTION

CRITIQUES

1. Prices and costs are not constant but vary in time
2. Price p depends upon harvest h
3. Prices and costs are subject to supply and demand mechanisms
4. Biology is elementary
5. Effort E is not always a realistic control variable. Alternatives are: taxes, fishing period control, subsidies, catch quotas

INTEREST- DISCOUNT FACTORS

$\underline{i}$ = annual interest

If a present return is invested at interest $\underline{i}$, after n years the value of the return becomes

$$FP = PP\,(1+i)^n$$

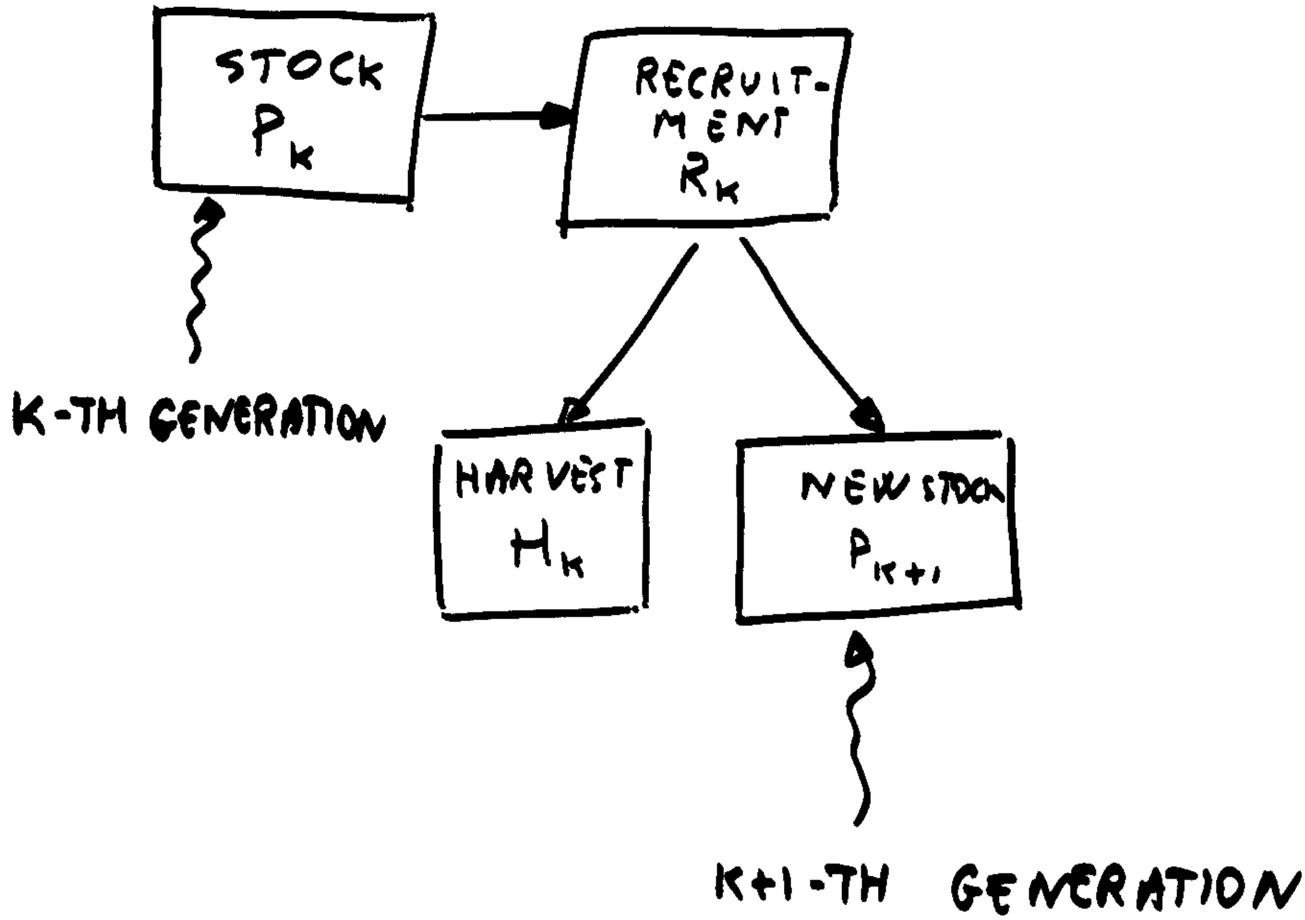
Thus the present value of a future return is

$$PP = \frac{FP}{(1+i)^n}$$

When considering a sequence of profits $P_0, P_1, P_2 \ldots$ in years 0, 1, 2 ...

$$PP = \sum_{k=0}^{\infty} \frac{P_k}{(1+i)^k} = \sum_{k=0}^{\infty} \gamma^k P_k$$

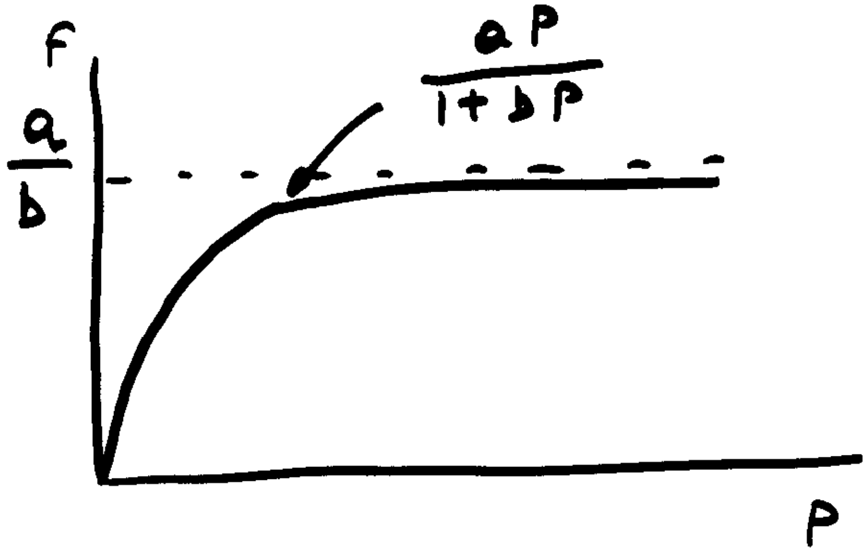
ONE RESOURCE - DISCRETE MODELS



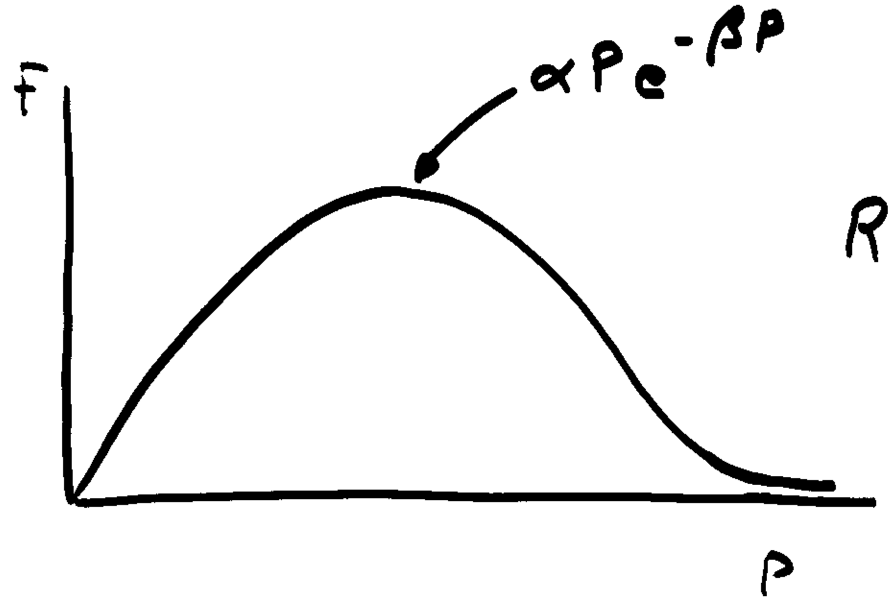
$$P_{k+1} = F(P_k) - H_k$$

STOCK-RECRUITMENT RELATIONSHIP

EXAMPLES OF STOCK-RECRUITMENT CURVES

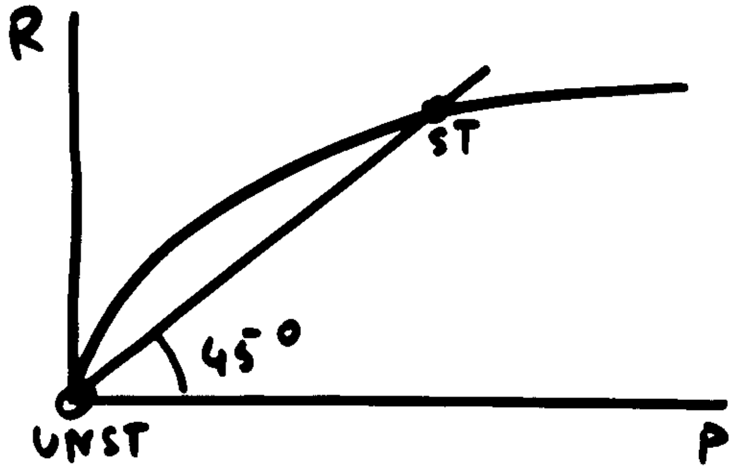


Beverton-Holt Model

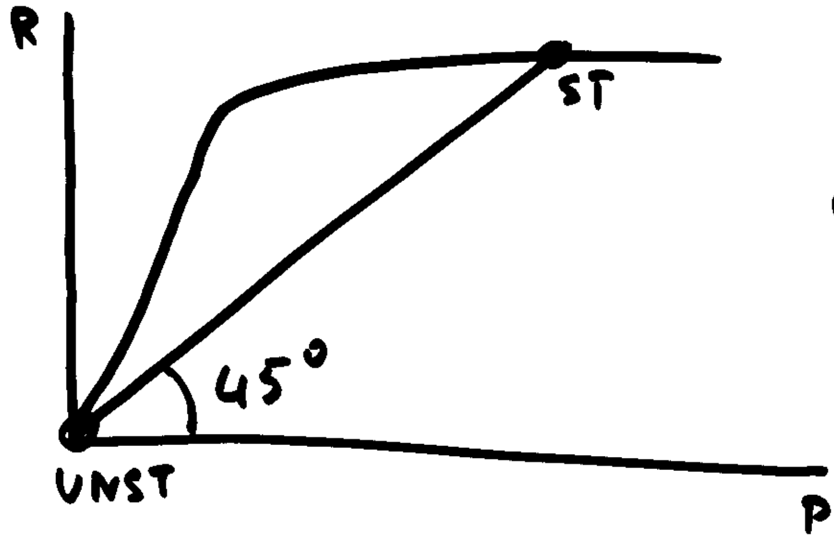


Ricker Model

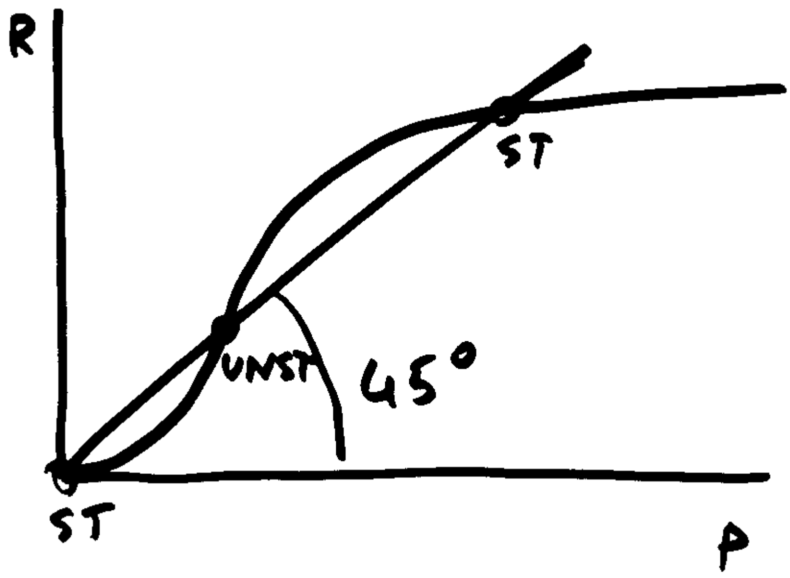
CLASSIFICATION OF S.-R. CURVES



COMPENSATION



DEPENSATION



CRITICAL DEPENSATION

RELATIONSHIP BETWEEN HARVEST AND EFFORT

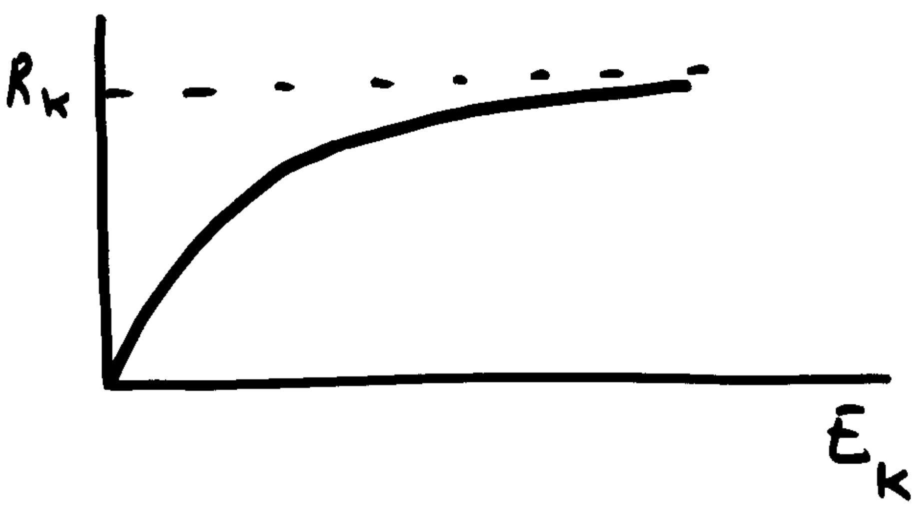
$$H_k = g(R_k, E_k)$$

Obviously a constraint is that

$H_k \le R_k$

A usual choice of function g is

$$H_k = R_k\left(1 - e^{-\alpha E_k}\right)$$

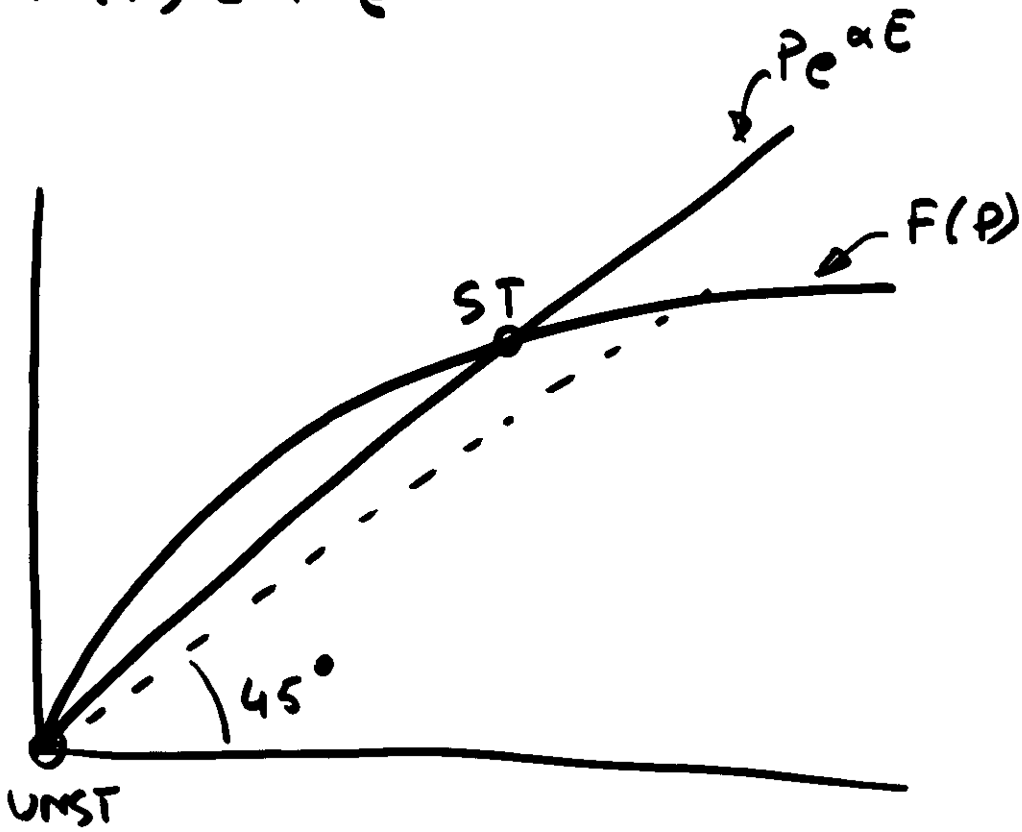


ANALYSIS AT EQUILIBRIUM

$$P_{k+1} = F(P_k) - R_k\left(1 - e^{-\alpha E_k}\right) =$$
$$= F(P_k)\, e^{-\alpha E_k}$$

At equilibrium

$$F(\bar{P}) = \bar{P}\, e^{\alpha E}$$

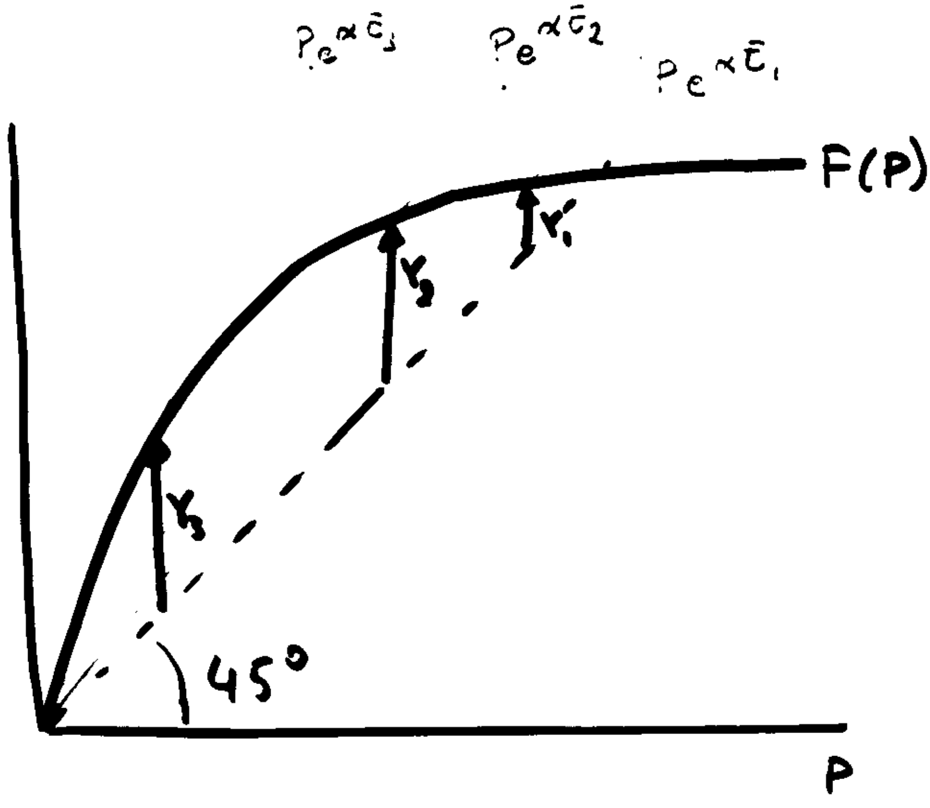


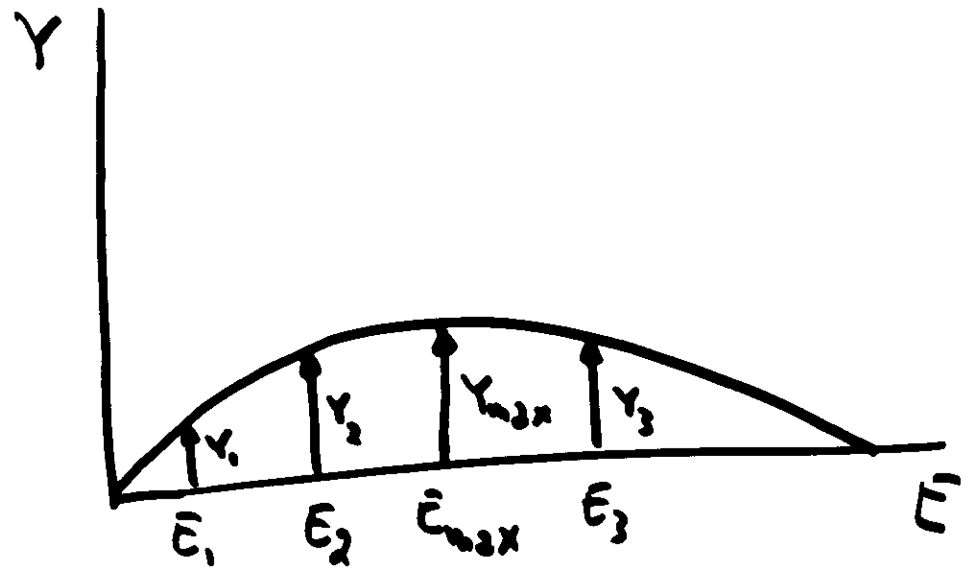
YIELD-EFFORT CURVES

The <u>sustainable yield</u> is

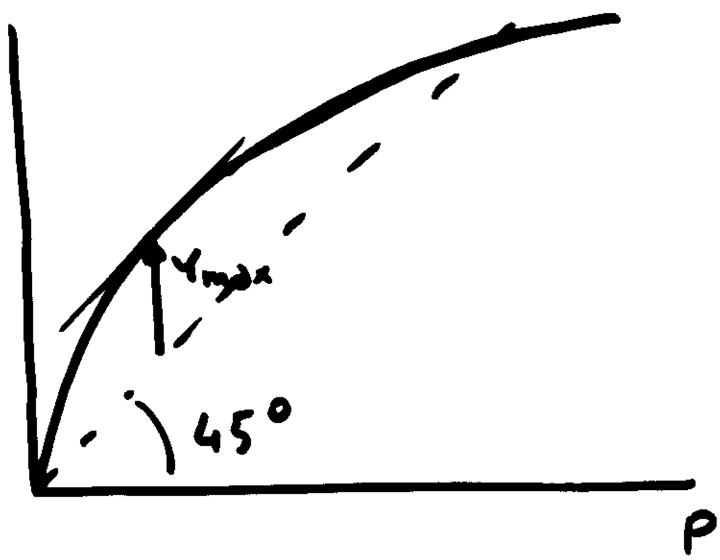
$$Y = F(\bar{P})(1-e^{-\alpha E}) = F(\bar{P}) - \bar{P}$$

where $\bar{P}$ is the equilibrium stock corresponding to effort E

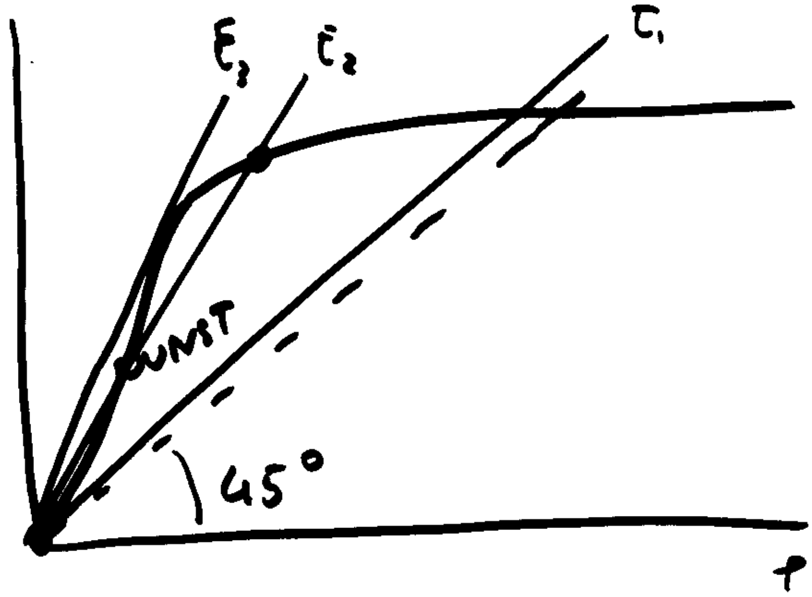


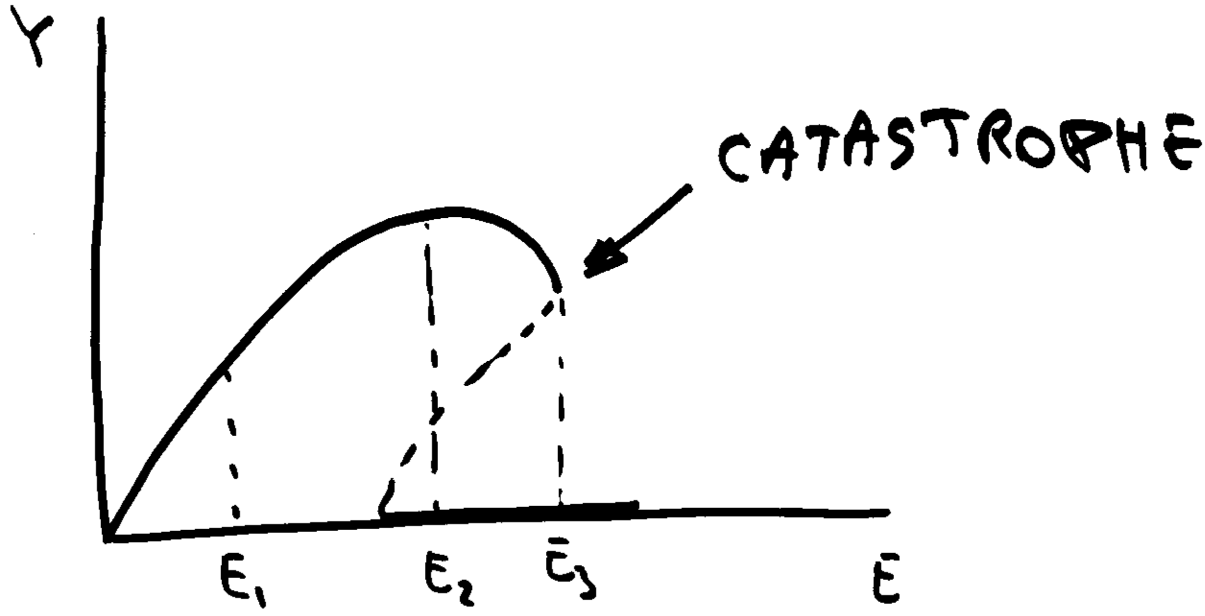


Y_{max} is the MSY



DEPENSATION





CRITICAL DEPENSATION