Indira Gandhi
National Open University
School of Social Sciences

# MEC-108
# Economics of Social Sector and Environment

Block

# 4

## ECONOMICS OF ENVIRONMENT

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# BLOCK INTRODUCTION

The present block deals with Natural and Environmental Resource economics. The scope includes marketed and non marketed 'renewable' and 'non-renewable' resources and environmental resources. Under renewable resources, we consider in particular natural resources like fish and forests. Such resources can be harvested with due regard to their regenerative capacity whereby their usage becomes sustainable. Non-renewable resources include resources like minerals which are limited in their quantity and are available within a given time period. They are useful for human activity and are therefore capable of being exhausted due to over exploitative use. Their regeneration sometimes take very long time running up to millions of years. The usage of such non-renewable resources can however be made sustainable within the human activity horizon only in the sense of alternative resource development (i.e. development of substitutes) for which technological innovation becomes crucial. Such resources are treated in literature as 'scarce resources'. Such non-renewable resources can only be subjected to more economic and judicial usage by employing economic instruments like price, rent, substitutes and public policy and to that extent, the inter generational efficiency and equity can then be ensured. Policies have to be therefore designed so that extraction of non-renewable resources are made with due regard to their exhaustible nature.

**Unit 10** deals with the theme of Demand for Natural and Environmental Resources. Using the theory of Dynamic Optimisation and Control, the unit deals with the economics of non-renewable (i.e. exhaustible) resources for two timeframes viz. discrete timeframe and continuous time frame. Under these, various alternative scenarios like: monopoly mine, competitive mining, extraction with constant marginal cost, extraction with stock effect, extraction with technical change, etc. are considered. Under each, conditions of optimal extraction are derived/explained.

Given that for environmental resources, there is almost a non-existent market mechanism for a well defined allocation, we need to pay special attention for their protection. In view of this, **Unit 11** deals with the issue of Valuation of Environment. The concept of 'Total Economic Value' of environment is first explained. Different valuation tools like: market prices, shadow prices, hedonic pricing, travel cost, constructed market techniques, etc. are subsequently described. In a manner of overall generalisation, the issue of Valuation of Biodiversity is discussed in conclusion.

**Unit 12** focuses on the theme of Determinants of Renewable Resources. Like in Unit 10, this unit also employs the approach of 'dynamic optimization'. Two cases of fishery and forestry are elaborated for economic analysis. Under the former, the bio-economics of fishery is explained by a reference to conditions like open access and common property solution so as to arrive at an optimal biomass. Under the latter, concepts like rotation age and optimal rotation are explained. The unit concludes with a discussion on the topic of 'investment under uncertainty'.

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# UNIT 10 DEMAND FOR NATURAL AND ENVIRONMENTAL RESOURCES

**Structure**

## 10.0 OBJECTIVES

After going through this unit, you will be able to:

- specify the fundamental challenges of using the non-renewable resources optimally;
- state the basis of a resource taxonomy (classification system) that is used to distinguish various categories/measures of resource availability and scarcity;
- explain the relevance of dynamic optimization in natural resource economics and the basic concept of Optimal Control Theory;
- state the fundamental principle of exhaustible resources under Discrete and Continuous Time Frameworks;
- derive the Hotelling rule (for different market structures and different assumptions on the cost of extraction) for optimal rate of extraction of non-renewable resources; and
- discuss the concept of resource scarcity and the various dimensions of economic rent.

## 10.1 INTRODUCTION

This unit mostly deals with the economics of exhaustible resources. Hence in dealing with the economics of natural resource use in particular, the main focus of this unit is to analyze how society should optimally extract such resources over time? It revolves around the basic questions like: are we as a society using them too fast? Are there sufficient non-renewable resources to maintain our economic wellbeing for the foreseeable future? Thus, much of the unit examines the dynamics of the extraction costs and mineral prices under various assumptions. We will see that the presence of user cost or opportunity cost is central to the economics of exhaustible resources.

Traditional usage of natural resources confines the term to the environmental and ecological systems that are useful to mankind or could be useful under feasible technological, economic, and social circumstances. Examples of such natural resources are forest land and its flow of multiple products and services (e.g. timber, wild-life habitat, etc.), natural land areas preserved for aesthetic, recreational, or scientific purposes (e.g. silent valley of Kerala, wet lands of eastern Kolkata, etc.), the fresh and salt water fisheries, mineral resources that include mineral fuels and non-fuels (e.g. coal, aluminium, etc.), other energy sources such as solar, tidal, wind, and geo-thermal systems, water resources, and the waste-assimilative capacity of the environment and ecological systems. These examples make it clear that what we perceive as natural resources depend on the conditions we have inherited from the past, current or foreseen technologies, economic conditions, and tastes. For instance, a century ago, not much was known about benefits of wetlands or about uranium. Hence, in dealing with the economics of natural resource use, we analyze in particular how society should use a resource efficiently and for this what is the rate at which a rational agent should extract such resource through time. A distinction is made between resource and environmental economics, where the latter is focused here only on the ways in which the wastes are to be disposed of (as it results in the quality of air, water, soil, etc. which together serve as waste receptors), for the conservation of natural environment and biodiversity.

## 10.2 TAXONOMY OF RESOURCES

Three separate concepts are normally used to classify the stock of exhaustible/depletable resource. They are (1) *current resources*, (2) *potential resources*, and (3) *resource endowment*. **Current reserves** are defined as known resources that can profitably be extracted at current prices. Their magnitude can be expressed as a number. The amount of **potential reserves**, on the other hand, depends upon the price people are willing to pay for those resources – the higher the price, the larger the amount of reserves potentially available. For instance, techniques, more expensive than conventional ones, generally allow greater amount of a resource to be recovered. As the price of extraction per unit increases, the amount of a resource that can be economically recovered also increases. Thus, potential reserves can be defined as a function rather than a number. The natural occurrence of resources in the earth's crust represents **resource endowment**. It represents the upper limit on the availability of terrestrial resources. Since the size of the resource endowment does not, in any way, depend on the price, it is a geological rather than an economic concept.

Natural resources, include *renewable resources* such as fish population and forests and *non-renewable exhaustible resources* such as oil reserves and mineral deposits. Here, we adopt the convention that classifies natural resources as renewable and exhaustible depending on their rates of regeneration. Oil is exhaustible because its formation requires millions of years which is not an economically meaningful time frame. Trees and fishes are renewable because they can grow to maturity within a reasonably short span of time. Thus, it is possible, though not inevitable, that a flow of these resources could be maintained over time. It needs to be remembered, however, that for some renewable resources, the continuation and volume of their flow depend crucially on human interventions. Overharvesting reduces the stock of fish, which in turn reduces the rate of natural regeneration of the fish population. This may even lead to extinction of the otherwise renewable resource. For other renewable resources, such as solar energy, the amount consumed by one generation does not reduce the amount available to the generations that follow. Managing natural resources of either kind has its own challenge. The challenge for exhaustible resources involves allocating dwindling stocks among generations. In contrast, the challenge for managing renewable resources involves the maintenance of an efficient and sustainable flow over time. At an analytical level, however, both the resource categories may be thought of to have a common foundation. The stock of natural resources (e.g. the population of fish in a lake or the number of tons of coal remaining in a coal field) measures the state of a resource. Stocks of renewable resources like fish, grow through regeneration; while exhaustible resources like coal are available in fixed quantities. During a particular time period, the stock depletes at the rate of harvesting or extraction per period. These attributes of natural resources have much in common with man-made capital. Just as investment increases and depreciation reduces the stock of man-made capital, growth through regeneration increases and harvesting or extraction depletes the stock of natural resources. The central issue in the allocation of natural resources is therefore how much of the resources should be harvested (extracted) today? Finding a best allocation of natural resources over time can be regarded as a problem 'dynamic optimization'.

## 10.3 DYNAMIC OPTIMIZATION

All natural systems are dynamic in the sense that their stock change over time. The important point is that while there is obvious direct dependence between human wellbeing and natural resources, the functioning of the economic system itself is interrelated with, and threatened by, natural resource depletion. The difficulty is that many of these 'external costs' will be displaced in both space and time as they are inter-temporal and lateral external costs. Therefore, looking at the direct and immediate cost of resource use will almost certainly understate the true costs of resource depletion. The supply of non-renewable resources can be viewed as a three stage process with complicated dynamic relationship. First, current decisions are related to past decisions as well as to expectations of the future prices and the costs. Second, it is assumed that producers take these inter-temporal cost decisions into account in planning their decision at each stage of the process. Thus, the current rate of extraction affects the amount that may be extracted in future periods. Consequently, costs of extracting a unit of, say, mineral today depends not only on the current level of mineral usage and necessary inputs and their prices, but also on the level of input usage in the past as well as on the impact of current extraction on the profitability of the deposit. For instance, for a given inventory of discovered sites, a decision to develop relatively low cost sites today leaves only higher cost sites for the future. In view of this, third, any reduction in the total stock of resource bearing sites and the tendency for the earlier discovery of large and more accessible sites, leads to increased exploration costs over time.

Dynamic optimization is an important method of analysis in environmental and resource economics. In such problems, it is common to try to maximize some measures of net economic value, over some future horizon, subject to the dynamics of the harvested resource and any other relevant constraints. The solution of the dynamic optimization of a natural resource would be a schedule of 'time path' indicating the optimal amount of harvest (or extraction) in each period.

For continuous time problems, a frequently used method is *optimal control*. The optimization problem requires an understanding of what variables are under control. The choice of such variables, called *control variables,* determines the size of the *state variables* that are determined within the dynamic optimization model. The constraint to the problem include both dynamic constraints that represent how the state variables change over time and *boundary conditions* that specify the initial or starting values of the state variables, and possibly their value at the end of the programme. If the objective function is differentiable and strictly concave in the control variable, no direct constraints are imposed on the value of the control variable and the functions that govern how the state variables change over time. Such dynamic constraints in optimal control are both differentiable and concave.

### 10.3.1 Optimal Control Theory

Optimal control provides a set of necessary conditions, sometime called the maximization principle, used to solve for optimal paths or trajectories for the control and state variables. Consider an inter-temporal objective functional – V (i.e. objective function set across the time period 0 to T) without discounting as follows:

$$\text{Max V} = \int_0^T f[a(t), x(t)]dt \text{ ……….. (1),}$$

$$\text{Subject to } \frac{da}{dt} = \text{g[a(t), x(t), t] …………(2),}$$

where x(t) = Control Variable, a(t) = State Variable and

$$\text{a(o)} = a_o \text{ …………… (3)}$$

1. The **dynamic constraint** $\frac{da}{dt}$ of equation (2) says how the state variables change over time.

2. The **boundary constraint** of equation (3) represents the initial value of the state variable where the terminal value of the state variable may also be specified as boundary constraint in some problem.

The solution to this optimization problem involves setting up a **Hamiltonian** function consisting of the objective functional plus the dynamic constraint, multiplied by the *co-state variables*[or *adjoint variables* ($\lambda_t$)] – a function of time. The co-state variables can be interpreted as the *shadow or imputed price* of the state variable at a given instant of time (analogous to the notion of lagrangian multiplier in static optimization). At the end of the terminal period T, it must be the case that λ(t) = 0, if a(t) $>$ 0, for otherwise, we would not have optimal path and we would not be maximizing the objective functional subject to the constraint. In case both a(t) and λ(t) are positive ($i.e.$>0), it represents a sub-optimal situation. This implies that although the state variable has positive value [since λ(t) >0], we have yet chosen to leave some of it at the end of the programme. The reason being that decreasing the amount of state variable a(t) at the terminal period would simultaneously increase the objective functional (V).

Therefore the Hamiltonian functional is:

$$H[\mathrm{a(t), x(t), \lambda(t), t}] = f[[\mathrm{a(t), x(t), t}] + \lambda(\mathrm{t})[\mathrm{g\{a(t), x(t), t\}}] \text{ ……….. (4)}$$

The assumptions we make are:

(i) no constraint on the control variable; and (ii) objective functional is differentiable in control variable.

The necessary condition, therefore, is given by:

$$\frac{\partial H}{\partial x(t)} = 0 \text{ ………… (5)}$$

$$\frac{\partial \lambda(\mathrm{t})}{\partial t} = -\frac{\partial H}{\partial a(t)} > 0 \text{ , … … .. (6), } \quad \left(\text{since} \frac{\partial H}{\partial a(t)} < 0\right)$$

$$\frac{da}{dt} = \mathrm{g\{\, a(t), x(t), t\}} \text{ ………… (7)}$$

$$\text{a(o)} = a_o \text{ … … … … … (8)}$$

$$\lambda(\mathrm{t}) = 0 \text{ if a(t)} > 0 \text{ , … … … … … …. (9)}$$

**Interpretation:**

1. Equation (5) implies that the optimal path requires the partial derivative of the Hamiltonian w.r.t. the control variable x(t) must be zero at each point of time.

2. Equation (6) implies that the partial change in the co-state variable w.r.t time must be the negative of the partial derivative of the Hamiltonian function w.r.t. the state variable.

3. Equation (7) and (8) recover the dynamic constraints of equation (2) and boundary condition of equation (3) in the original problem.

4. Equation (9) is called the *Transversality Condition* which ensures the trajectories are optimal at the terminal time T.

Since the conditions (5 – 9) are using the variables that are functions of 't', finding the optimal path for the control, state and co-state variables involve solving the differential equations. Quantitative analysis of optimal paths are done through phase diagrams, which trace out the points where $\frac{dx(t)}{dt} = \frac{da(t)}{dt} = 0$. Phase diagram helps to analyse the steady state of the dynamic system and the potential trajectories to the steady state.

## 10.4 ECONOMICS OF NON-RENEWABLE RESOURCES

Non-renewable/exhaustible resources form the basis of modern economy. Without metal or fossil fuels, modern industrial society would not have sustained. The fundamental difference between the economics of mine and that of renewable resources such as fisheries or forests is that a mineral is a *sterile asset,* for which the natural replenishment feedback loop can be safely ignored. Or the rate of replenishment of these resources is so low that it does not offer a potential for augmenting the stock in any reasonable time frame. Thus, an exhaustible (depletable) resource has a limited stock, constrained by geological processes, but whose current reserves can be augmented by new exploration/discovery, economic replenishment and recycling. Stimulant of economic replenishment includes: price and technological progress. Another side of the depletable resources is that their potential reserves can be exhausted owing to demand for and durability of the products built within the resource. In most of the cases, the size of potential reserves of depletable resources depend explicitly on our ability to store the resource (e.g. helium). Not all depletable resources permit recycling or reuse (e.g. coal, oil and gas) which once combusted turns into heat energy. The heat dissipated into the atmosphere becomes non-recoverable. Even if most of them are recyclable (e.g. copper) the theoretical upper limit on recycling is less than 100 percent.

In the following section, we examine the economics of extracting a non-renewable resource. In particular, we derive the extraction path that maximizes the present value rents from a mine. As we know, the natural resource economics treats resources in the ground as capital assets. By leaving resources in the ground (preserving them), the resource owner can expect capital gain, as the resource price rises through time. In case of zero extraction cost, the owner will be indifferent between holding the resources in the ground and extracting it, if the rate of capital gain ($\frac{\dot{P}}{P} = \frac{dp}{dt}$/P) equals the rate of discount (approximated by market rate of interest).

### 10.4.1 Exhaustible Resource Use: Discrete Time Frame

Various techniques and approaches have been used to model the dynamics of the environment and natural resources. Difference equations are used in modelling systems where change occurs at discrete points of time.

#### 10.4.1.1 Single Period Extraction

Recall the equilibrium condition for a price taking firm, producing reproducible goods: P = MC, for each period. If P > MC, the firm will increase production to maximize profit. But in the case of the firm extracting exhaustible resources such behaviour of equating P = MC implies extraction of more stocks than what is profitable. The equilibrium condition of extraction or sale of a unit of exhaustible resource needs some modification over this standard approach of reproducible goods because it involves *opportunity costs*[usually called the *user cost (UC)*]. User cost does not exist for the conventional reproducible goods because the production of a unit today does not reduce the quantity that can be produced in the future. Given the limitations of physical stock, there is a trade-off between the present and the future profits. Thus, the implication for a producer extracting or selling a unit of exhaustible resource today is equivalent to foregoing the value or profit that might have been obtained in the future date. For instance, a barrel of oil extracted today is equivalent to a barrel unavailable for extraction in the future. Therefore, in deciding whether to extract and sell an extra barrel today, the extractor must consider not only the cost of pumping the barrel but also the cost of foregoing the higher return that could be earned if the oil is extracted and sold in the future. Thus, instead of the usual efficiency condition P = MC, we need to define the condition for optimal extraction at each period of time for a competitive resource owner firm as: P = AMC = **MC + UC,** where AMC is the **Augmented Marginal Cost.** This may be treated as the ***first condition of optimal depletion of resources***. As Figure 10.1 shows, given the demand function P = P(y), only $Y^*$ units (rather than $Y^{**}$, where P = MC) will be extracted by the price taking firm, seeking to allocate extraction efficiently over time. This leaves positive difference AB (the opportunity cost/user cost) between P and MC. Thus, the current extraction rate of a private owner of a natural resource depends not only on the current price (as in standard theory), but also on the expected future prices, which determines the opportunity cost of additional current extraction. Hence, a competitive supplier that

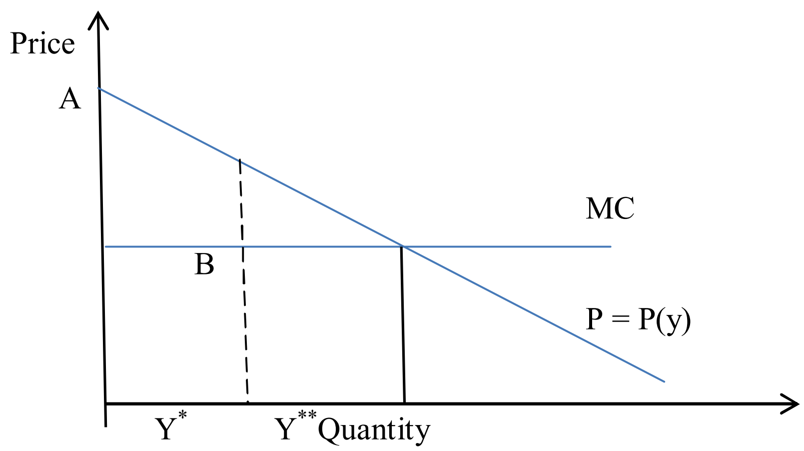


**Figure 10.1: Optimal Extraction of Exhaustible Resources**

**Note**: Here AB = User Cost/Opportunity Cost; $Y^{**}$ = Competitive equilibrium at P = MC expects future prices to be sufficiently low compared to the current price (i.e. the opportunity cost of extraction is small) may extract and sale intensively in the current period. But if future price are expected to be sufficiently high, the same current price may induce no extraction today.

### 10.4.1.2 Two Period Extraction

Consider a scenario where the resource owner may extract and sale the resource in current period (t = 0) or retain it till next period t = 1. Let $p_o$ and the $p_1$ be the unit prices in the current period (t = 0) and next period (t = 1) respectively. Let 'c' be the constant unit cost of extraction (i.e. it does not vary in the two periods). The stock being fixed, any unit sold in period t=0 will reduce the quantity that can be sold in period t = 1.Hence, net revenue in current period (t = 0) is ($p_o$ – c), but in that case there will be a foregone revenue: ($p_1$ – c) in the period t = 1. Thus, the present value of the net revenue foregone in period 1 is: $\frac{(p_1-c)}{(1+\delta)}$ , where $\delta$ is the discount rate (approximated as the market rate of interest).Hence, the O*pportunity cost/User cost* of selling a unit today being$\frac{(p_1-c)}{(1+\delta)}$,the return from selling a unit at the current period, will be:$(p_o$- c) - $\frac{(p_1-c)}{(1+\delta)}$.

*[If extended for T periods, then the present value of the stream of benefits ($B_o$, $B_1$, $B_2$ ……… $B_T$, received in period 0, 1, 2, ……, $T^{th}$ periods) over a period of T years is:*

*PV ($B_o$, $B_1$, $B_2$ …… $B_T$)* = $\sum_{t=0}^{t=1} B_t/(1+\delta^t)$ *]*

1. If $(p_o$- c) > $\frac{(p_1-c)}{(1+\delta)}$,the resource owners would be better off by selling and extracting the resources at the current period.

2. If $(p_o$- c) < $\frac{(p_1-c)}{(1+\delta)}$,the resource owners would be better off by foregoing extraction for the future period.

3. If $(p_o$- c) = $\frac{(p_1-c)}{(1+\delta)}$, $then\ p_o = c + \frac{(p_1-c)}{(1+\delta)} = MC + UC$ . The resource owners would be indifferent between extracting today or foregoing it in the current period for the future extraction. Optimal extraction will take place at this point where the current price of the resource extraction is equal to the marginal cost (MC) plus the user cost (UC).

Thus, the condition$\frac{(p_1-c)}{(p_o-\text{c})} = (1+\delta)\ or\ (p_1-c) = (p_o-\text{c})(1+\delta)$is the **Second Condition for the optimal depletion of resources** in which the net future resource price is growing at the rate $\delta$.This is the famous **Hotelling condition**, after an important demonstration by *Harold Hotelling in 1931 (*which will be re-examined in the next section in the continuous time framework).*Hotelling condition states that along the optimum extraction path, where the resource owner is indifferent as to the options of extracting or leaving the resource in ground, the price of the resource, net of marginal extraction costs (i.e., the user cost) has to rise at a rate equal to the discount rate.*

If the MC of extraction is small relative to the price of the resource (i.e. c = 0, for simplicity) then, $\frac{p_1}{p_o} = (1+\delta)$ or $p_1 = p_o(1+\delta)$. Thus, along the optimal path, resource price grows at the discount rate and higher the discount rate faster will be the price of the resource rise along the optimal path. And higher the value of $\delta$, lower is the user cost of resources. UC = $\frac{(p_1 - c)}{(1+\delta)}$ implies depletion will take place at a faster rate. Similarly, smaller the value of $\delta$, higher is the value of UC and the resource owner will postpone extraction for the future period rather than satisfying the current demand.

Consider a situation of two countries having approximately same underground reserves as also the same costs of extraction and the selling price of the resources in the global market. If credit is rationed more tightly in one country [i.e. higher rate of interest $\Rightarrow$ higher discount rate $\Rightarrow$ lower user cost of resources],the current price would reflect more extraction in the short run so as to maximize national wealth. Since both the countries are facing same sequence of initial current price in the world market, assuming countries are small i.e. they are both price taker in the world market.

Consider a situation when the mine operator is asked to shut down a highly valued or polluting mine (with some grace period permitted to mitigate the dislocation caused by the closure). During the grace period, premature closing lowers the user cost of an additional unit. Thus, it lowers the AMC in each period before the date of closure as compared to the preceding periods of policy announcement. If the sequence of world price is unchanged, the mine operator will find it profitable to intensify mining throughout the grace period.

#### 10.4.1.3 Availability of a Substitute (Backstop)

The above discussion of optimal depletion of exhaustible resource was based on the absence of available substitutes (or backstop as it is sometimes called). However, it may happen that some substitute renewable resource is available at a constant MC. For instance, one may consider an optimal depletion problem of oil or natural gas with solar substitute. Society would opt for the switch-over by renewable resources whenever it is cheaper to do so. Hence, the Augmented Marginal Cost (AMC) cannot exceed the MC of the backstop. Suppose p = a – cq is the inverse demand faced by the resource owner. Hence, p + cq = a is the maximum willingness to pay (called the **Choke price**) for a unit resource, which sets the upper limit on AMC when no substitute is available. We know that the resource price:

for t = 1 is: $p_1$ = MC + $(p_o - MC)\ (1 + r)$,

for t = 2, it is $p_2$ = MC + $(p_1 - MC)\ (1 + r)$

$$= MC + [\{\text{MC} + (p_o - MC)(1 + r)\} - MC)]\ (1 + r)$$

$$= MC + (p_o - MC)(1 + r)^2 \text{ \& so on.}$$

Hence the resource price for t = n is: $p_n = MC + (p_o - MC)(1 + r)^n$

With time, $p_t$ moves away from MC, rising at a rate that approaches the rate of interest 'r', as the user cost (UC) component dominates the fixed MC of extraction.

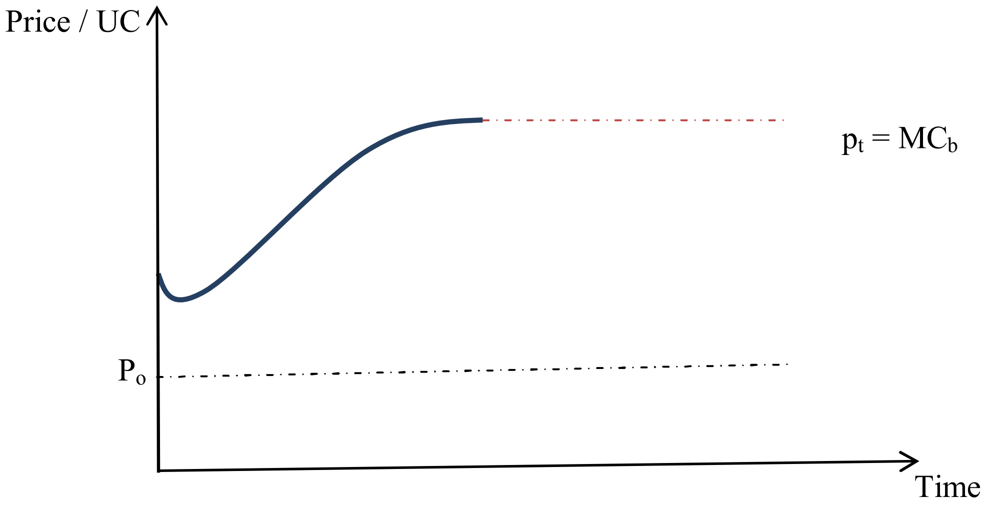


**Figure 10.2: Time Path of Price and AMC**

Does the price rise continue indefinitely when a substitute is available? A limit on the rise of AMC and price will be set by the cost of a substitute or backstop (See Figure 10.2). Consider the example of solar energy whose marginal cost is $MC_b$. If p = AMC = $MC_b$ (since unlimited solar resource stock cannot have any user cost),suppose the switch or transition from oil to backstop takes place at time T. Price at time T is given by $p_T$ = MC + $(p_o - MC)(1+r)^T$. But unlimited solar energy without any UC implies $p_t$ = $MC_b$. Therefore, $(p_o - MC) = \frac{(MC_b - \text{MC})}{(1+r)^T}$. This implies that at the initial user cost at t = 0, $(p_o - \text{MC})$ is the difference between the cost of the backstop and the cost of oil, discounted back from the date of transition T. Substituting the expression for $(p_o - \text{MC})$ into the equation $p_t$ = MC + $(p_o - MC)(1+r)^t$, we get

$$p_t = MC + \frac{(MC_b - \text{MC})}{(1+r)^T}(1+r)^t p_t$$

$$= MC + \frac{(MC_b - \text{MC})}{(1+r)^{T-t}} \; \forall \; \text{T} < \text{t}.$$

The above equation gives the expression for the price of oil in terms of the cost of backstop (and the cost of oil) at any time t < T. It moderates the increase in AMC and price due to the presence of backstop technology.

### 10.4.1.4 Technological Progress

In principle, the extraction cost would rise over time as initial lower cost of extraction would deplete the reserves faster and higher cost of extraction would leave the reserves to be exploited in future. Since the search for newer resources involves costs, the more easily accessible resources are first exhausted and then the extraction activity moves to less accessible areas (such as bottom of the ocean or high slopes of the mountain). This suggests that the marginal cost of exploration would rise over time. Rising AMC of a resource induces the society towards exploration activities where technological progress would yield reductions in the cost of extraction. If the MC of extraction of newly explored field is sufficiently low, this could lower or at least moderate the increase in AMC and price. However, with a finite amount of a particular exhaustible resource, a fall in AMC would not last indefinitely. Technical progress would thus reduce the cost of extraction initially, thereby reducing the AMC for a transition period, but ultimately it would have to increase.

**Check Your Progress 1** (answer the question in about 100 words within the space given)

1. In the taxonomy of natural resources, distinguish between the terms 'current reserves' and 'potential reserves'.

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2. State the dynamic three stage process involved in the supply of non-renewable natural resources.

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3. State the objective functional set across the time period '0 to T' defining in particular the dynamic and boundary constraints.

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4. Do you think that the stock of an exhaustible/depletable resource can be augmented? How? What factors acts as 'stimulants' in this regard?

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5. State the first condition of 'optimal depletion of resources'. In what way the usual efficiency condition P = MC is different in the case of a competitive resource owner firm?

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6. Given that the rate of depletion is $\delta$, state the Hotelling condition for the optimal depletion of resources in a discrete two period extraction model.

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### 10.4.2 Exhaustible Resource Use: Continuous Time Frame

Another way to model the dynamics of natural resource optimisation is to assume that the change occurs continuously rather than at discrete points in time. We will first examine this problem from the perspective of an individual mine operating in a competitive market with costless extraction and then proceed to study the variants of the situation.

#### 10.4.2.1 Individual Competitive Mine

Consider a single price taking owner of natural resources (having an insignificant market share to influence the market price). In its simplest framework, we assume zero extraction cost, a competitive market for the mineral, perfect information in terms of resource stock and prices, and that the extracted mineral will be completely sold in the period it is mined. Let x be the extraction rate chosen to maximize the present value of rents from extraction, as given by the equations:

$$Max\ V = \int_{t=0}^{T} e^{-\delta t} Px\, dt\ , \ldots\ldots\ldots\ (10), \text{ subject to,}$$

$$\frac{db}{dt} = -\,x \ldots\ldots\ldots\ldots\ (11)$$

$$b_o \geq \int_{t=0}^{T} xdt \ldots\ldots\ldots\ (12)$$

In this case, the *choice* or *control variable* is the rate of extraction (x) defined as some quantity per time period (t). P is the unit resource (mineral) price, $\delta$ is the discount rate by the firm, $b_o$ is the initial reserve, which is a known quantity. The rate of extraction on the right hand side of equation (11) determines the rate at which the remaining reserves (b) given on the left hand side of equation changes with respect to time. The greater is the extraction rate, the faster will be the decline in the remaining reserves (b). Equation (12) ensures that the cumulative extraction can never exceed the quantity available. We assume here that the time horizon for the mine is given i.e. T is known.

To determine the optimal extraction path we can set up a function that incorporates the objective functional in (10) with the dynamic constraint given by (11) using the present value Hamiltonian (H):

$$H = e^{-\delta t} Px + \lambda(-x)\ \text{--------}\ (13)$$

where P, x and λ are the functions of time and λ is the present value of the shadow price of the resource stock. Since the firm is maximizing the present value of its rent over time, at any instant of time we must have:

$$\frac{\partial H}{\partial x} = e^{-\delta t} P - \lambda = 0 \text{ or } \lambda = Pe^{-\delta t}\ \ldots\ldots\ldots\ldots\ (14)$$

The cost of extraction being zero, and as there is no benefit on the *cost side* from delaying extraction, the shadow price of the resource at any period t is equal to the present value of the resource price. The owner of the resource would therefore be indifferent between a unit of resource at price P now and the same unit at $Pe^{-\delta t}$ in t years. Since the price it receives for its production is given, the optimal rate of extraction is determined solely by the rate at which the resource price changes over time and the discount rate $\delta$. If the resource price is constant, it would be optimal to extract all the remaining reserves of the mineral at the earliest possible moment (provided $\delta > 0$)as any delay in extraction would lower the present value of the rents from the mine.

If the resource price was increasing over time such that $P = e^{\gamma t} P(0)$, $P(0)$being the price at t = 0, there are three possibilities:

1. $\gamma < \delta$: it would be optimal to extract all the minerals at the earliest possible moment because any delay in extraction would reduce the present value of the returns from extraction (with the present value of the resource price declining over time).

2. $\gamma > \delta$: the present value of the resource price being increasing over time, it would be optimal to wait to the last possible moment (just before T) to extract the remaining reserves of mineral. In this case, although the mineral is a sterile asset, it would pay to keep it in the ground for as long as possible, because delaying extraction allows the firm to sell the mineral at the highest possible price.

3. $\gamma = \delta$: the present value of the resource price being the same at any point of time, the firm would be indifferent between extracting now or later provided all the resource would be extracted by time T. In this case, the rate of increase in the mineral price would be exactly equal to the discount rate i.e.

$$\frac{dp}{dt}/\text{P} = \delta \quad \ldots\ldots\ldots\ldots\ldots \quad (15)$$

Equation (15) is similar to the one derived in the discrete time case i.e. the **Hotelling rule.** *Hotelling rule* is thus the equilibrium condition, when at each point in time the demand for mineral at the prevailing price exactly equals the amount extracted. Hotelling rule can come in different forms, as we shall see, depending on the assumption on the cost of extraction

For non-renewable resources, the terminal time or *transversality conditions* also play an important role in determining the optimal rate of extraction. In the above problem, it will always pay to extract and sell the mineral reserves because the extraction costs are zero. In reality the costs of extraction being always positive, it is possible for some of the mineral at the terminal time T to be left in the mine because it is not profitable to extract it. The other possibility is that at the terminal time T, the mineral is completely exhausted. In this case, the transversality condition given by (16) and (17) below helps to ensure optimal extraction and determine whether the mine is completely exhausted or not at T.

$$H = Pxe^{-\delta t} + \lambda(-\text{x}) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

$$e^{-\delta t}\,\lambda\text{b}(\text{T}) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

Condition (16) can be called a *performance test* and requires that at the terminal time T, it is no longer profitable to extract the mineral. If this were not the case (H > 0) it would imply that some mineral had been left in the ground while it was still profitable to extract it. In other words, the extraction path would not be optimal. Condition (17) is the so called *asset test* and requires that the product of the current value of the shadow price ($e^{-\delta t}\,\lambda$) of the resource and the remaining reserves denoted by b(T) be zero at T. This can be satisfied if either the current value of the shadow price is zero, or the mineral has been completely exhausted (b = 0). In the first case, it is no longer worth while to extract the mineral, and in the second, the mine has been exhausted and there is no more mineral left to extract.

### 10.4.2.2 Competitive Mining Industry

Here we assume that the industry's inverse demand for the mineral is given by (18) below, where the time subscripts on the market price (p) and the industry level of extraction (x) have been dropped for convenience and a and g are parameters.

$$p = a - gx \text{ , ................. (18)}$$

At the terminal time T, when the mineral from all the mines has been extracted, it has to be the case that p = a, where a is called the *choke price* i.e. the price at which the quantity demanded is zero (which may be explained by the existence of readily available substitutes at the choke price). Such substitutes may exist from a readily available technology, often called a *back-stop technology*, that can supply a perfect substitute at a choke price. If the value to the society from the mineral after its extraction is equal to the present value of the area under the inverse demand curve, then the rate of extraction that maximizes this value is the solution to the problem:

$$Max\ V = \int_{t=0}^{T}\{\int_{0}^{x(0)}(a - gx)dx\}e^{-\delta t}dt \text{ ............. (19)} \quad \text{subject to}$$

$$db/_{dt} = -x \text{ .................. (20)}$$

$$b_o \geq \int_{t=0}^{T} xdt \text{ .............. (21)}$$

The expression in the curly bracket in (19) represents the area under the industry inverse demand curve. The lower limit of integration is the industry demand at the choke price and

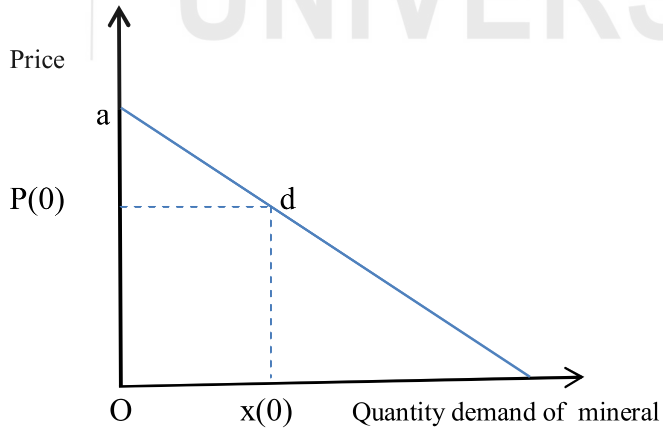


**Figure 10.3: Area Under the Inverse Demand Curve**

the upper limit of integration x(0) is the industry demand at the initial price of the mineral p(0) (Figure 10.3). Here, the area under the inverse demand curve is defined by the area bounded by the vertices 0, a, d and x(0).

The present value Hamiltonian for the problem defined in (19) – (21) is:

$$H = \{\int_{0}^{x(0)}(a - gx)dx\}\, e^{-\delta t} + \lambda(-x) \text{ ................. (22)}$$

Since the optimal rate of extraction must ensure that the present value Hamiltonian is maximized at each point in time we have:

$$\frac{\partial H}{\partial x} = (a - gx)e^{-\delta t} - \lambda = 0 \Rightarrow \lambda = (a - gx)e^{-\delta t} \Rightarrow \lambda = \mathrm{p}e^{-\delta t}$$

$$\therefore \mathrm{p} = \lambda\, e^{\delta t} \text{ ...... (23)}$$

Condition (23) must be satisfied at each moment in time and is identical to the optimal rate of extraction for the individual mine in (14), with the exception that x now refers to the industry demand for the mineral supplied by all the mines. Unlike the individual mine problem, however, we cannot treat the price of the mineral as given because it is determined by the amount extracted by all the mines. To understand how the price of the mineral must change to maximize (19), we can examine a number of possible price paths. Suppose the industry price path is:

$$p = e^{-\gamma t}\mathrm{p}(0) \text{ ................ (24)}$$

Consider the three situations:

1. $\Upsilon < \delta$ i.e. $e^{-\gamma t}\mathrm{p}(0) < \lambda\, e^{\delta t}$. This implies that the growth rate of the resource price is rising at a rate less than the discount rate. It will be possible to increase the present value of the consumer surplus by increasing the extraction rate of the industry since extracting more today gives greater return than leaving the marginal unit in the ground.
2. $\Upsilon > \delta$ i.e. $\mathrm{p}(0) > \lambda\, e^{\delta t}$. This implies that the growth rate of the resource price is rising at a rate more than the discount rate. It will be possible to increase the present value of the consumer surplus by decreasing the industry level of extraction because extracting marginally less of mineral would generate a greater return.
3. $\Upsilon = \delta$ i.e. $\mathrm{e}^{-\gamma t}\mathrm{p}(0) = \lambda\, e^{\delta t}$. This implies that the growth rate of resource price is rising at the same rate as the discount rate. This will ensure the maximization of the present value of consumer surplus. All the mine owners are indifferent between extracting today and that in the future period.

$$\text{Hence,} \frac{dp}{dt} = -\gamma e^{-\gamma t}\ \mathrm{p}(0)$$

$$or\ \ \frac{dp}{dt} / \mathrm{p} = \frac{-\gamma e^{-\gamma t}\ \mathrm{p}(0)}{e^{-\gamma t}\ \mathrm{p}(0)} \Rightarrow -\gamma = \delta\ (say)$$

$$\text{i.e. } \frac{dp}{dt} / \mathrm{p} = \delta \quad \text{.......... (25)}$$

To determine the industry rate of extraction at each point of time we can substitute (24) i.e., $p = e^{-\gamma t}\mathrm{p}(0)$ into the demand equation (18) $p = a - gx \Rightarrow e^{-\gamma t}\ \mathrm{p}(0) = a - gx \Rightarrow x = \{a - e^{-\gamma t}\ \mathrm{p}(0)\}/\ \mathrm{g}$. Industry rate of extraction at the optimal path ($\gamma = \delta$) is:

$$x = \{a - e^{-\delta t}\mathrm{p}(0)\}/\ \mathrm{g} \text{ ........... (26)}$$

Since the extraction is costless, the mineral reserve will be totally extracted by the terminal time T$\Rightarrow \int_0^T x\, dt = b_o$ ........... (27).

Given the Hotelling rule: $\frac{dp/dt}{p} = \delta$ and differentiating the inverse demand function w.r.t. t :

$$\Rightarrow \frac{dp}{dt} = \text{-g} \frac{dx}{dt} \text{ i.e. } \mathrm{p}\delta = -\mathrm{g}\frac{dx}{dt} \text{ or}$$

$$\frac{dx}{dt} = -p\,\delta/g \text{ ............... (28)}$$

To derive the optimal extraction path for x we have to solve for the initial and terminal conditions given by initial price p(0) and terminal time T. Substituting equation (26) into (27) :

$$\int_0^T \frac{a - e^{-\delta t}\,\mathrm{p}(0)}{g}\,dt = b_o \Rightarrow \int_0^T \frac{a}{g}\mathrm{dt} - \frac{\mathrm{p}(0)}{g}\int_0^T e^{-\delta t}\ dt = b_o$$

$$\Rightarrow \frac{a}{g}\mathrm{T} - \frac{\mathrm{p}(0)}{g\delta}\left[e^{\delta t}\right]_0^T = b_o \Rightarrow \frac{a}{g}\mathrm{T} - \frac{\mathrm{p}(0)}{g\delta}\left[e^{\delta T} - 1\right] = b_o \text{ ----------------} \quad (29)$$

We know that the price of the mineral at the terminal time is equal to the choke price i.e.$e^{\delta t}\ \mathrm{p}(0) = q$ …….. (30).

Thus, equation (29) and (30) can be solved for 2 unknowns $\mathrm{p}(0)$and T for specific values of δ, $b_o, a, g$.

Sensitivity analysis shows a rise in initial reserves $(b_o)$, increases T, but decreases $\mathrm{p}(0)$. While a rise in the discount rate δ lowers both T and $\mathrm{p}(0)$,under a perfectly competitive situation with price taker firms, perfect information about $\mathrm{p}(0)$, $p = e^{-\gamma t}$ p(0), and mineral reserves, and absence of externality (in both production and consumption), the Hotelling rule suggests that the rate of extraction will raise the mineral price.

### 10.4.2.3 Monopoly Mine and the Rate of Extraction

Observation on mining industry indicates that market structure is mostly non-competitive. For many minerals like bauxite, nickel, iron, manganese, copper, molybdenum, etc. the industry is captured by small number of large mine owners that are either state owned enterprises or large MNCs. So we need to understand the effect of market structure on the rate of extraction. In the case of monopoly mine owner, the rate of extraction affects the resource price it receives for the mineral it sells. Thus, the problem of the Monopolist is:

$$\text{Max V} = \int_{t=0}^{T} e^{-\delta t}\, xp(x)dt \text{, subject to the conditions:}$$

$$\text{(i)}\ \frac{db}{dt} = -\text{x} \quad \text{and} \quad \text{(ii)}\quad b_o \geq \int_{t=0}^{T} xdt.$$

Present value Hamiltonian for the monopolist’s problem is:

$$H = x\,P(x)e^{-\delta t} + \lambda(-\mathrm{x}) = 0 \text{ …………….. } (30)$$

The optimal rate of extraction for a monopolist must ensure that the present value of the rent in the Hamiltonian is maximized at each point in time i.e.

$$\frac{\partial H}{\partial x} = \left[P(x) + \frac{dp}{dx}\,x\right]e^{-\delta t} - \lambda = 0 \qquad \Rightarrow \qquad \lambda = \left[P(x) + \frac{dp}{dx}\,x\right]e^{-\delta t}$$

where, $\left[P(x) + \frac{dp}{dx}\,x\right]$ *is the marginal revenue* $(MR)$ *of the monopolist.*

$$\text{Thus, } \lambda = \mathrm{MR}\, e^{-\delta t} \text{ or } \mathrm{MR} = \lambda\, e^{+\delta t}.$$

Therefore, $\frac{dMR}{dt} = \lambda\,\delta e^{+\delta t} \Rightarrow \frac{dMR}{dt}\ /MR = \frac{\lambda\,\delta e^{+\delta t}}{\lambda\ e^{+\delta t}} = \delta$

The result is similar to that of the competitive mine except that the growth rate of the marginal revenue of the monopolist must rise at the rate of discount, if the present value of the return from extraction are to be maximized. In the case of the monopolist, he practices inter-temporal price discrimination to ensure that the present value of his marginal revenue is the same at each point of time. By contrast, the competitive industry in equilibrium ensures that the present value of its resource price is the same at any point of time. The effect of the market structure on the rate of extraction depends on the industry demand for the mineral. For a standard inverse demand function: $p = a - gx,$ price elasticity of demand varies with the rate of extraction. It pays the monopolist to set the extraction profile so as to maximize the MR he receives. Hence, there is a tendency to lengthen the extraction profile and reduce the initial rate of extraction at t = 0 (as compared with the competitive industry).

We know that MR = p[1-$\frac{1}{Ed}$], where $Ed = \frac{dx}{dp}\frac{P}{x}$ *is the Price Elasticity of demand.* Since the monopolist will never operate at the inelastic part of the Ed ( $|Ed| < 1$ ) ⇒ $\frac{1}{Ed} > 1$ ⇒ MR < 0. This implies that a marginal increase in the rate of extraction will reduce total revenue. Thus, for a linear demand where the absolute value of the price elasticity of demand varies from 0 when p = 0 to ∞ when p = a, the monopolist can increase the present value of the rents, by establishing a different extraction profile to the competitive industry. In particular, the monopolist will supply relatively less on the least elastic portion of the demand curve and supply relatively more on the more elastic part of the demand (thus receiving a higher price) in comparison to a competitive industry (Figure 10.4: p-23). Thus, in the face of more elastic demand, the monopolist *stretches out* the extraction profile by supplying a very small amount of mineral over a larger period of time when the demand is more elastic. As a result, for the same linear inverse demand function and initial reserves, a monopolist will exhaust the mine at a later date than a competitive industry. However, extraction profile of the competitive industry and monopoly will not always be different as it depends critically on industry inverse demand. If the industry demand is *iso-elastic* like an inverse demand (i.e. p = $ax^{-g}$), the price elasticity being the same, the extraction profile of the monopolist and competitive industry will be identical for whatever the price. Thus, the monopolist is unable to practice price discrimination by changing the rate of extraction.

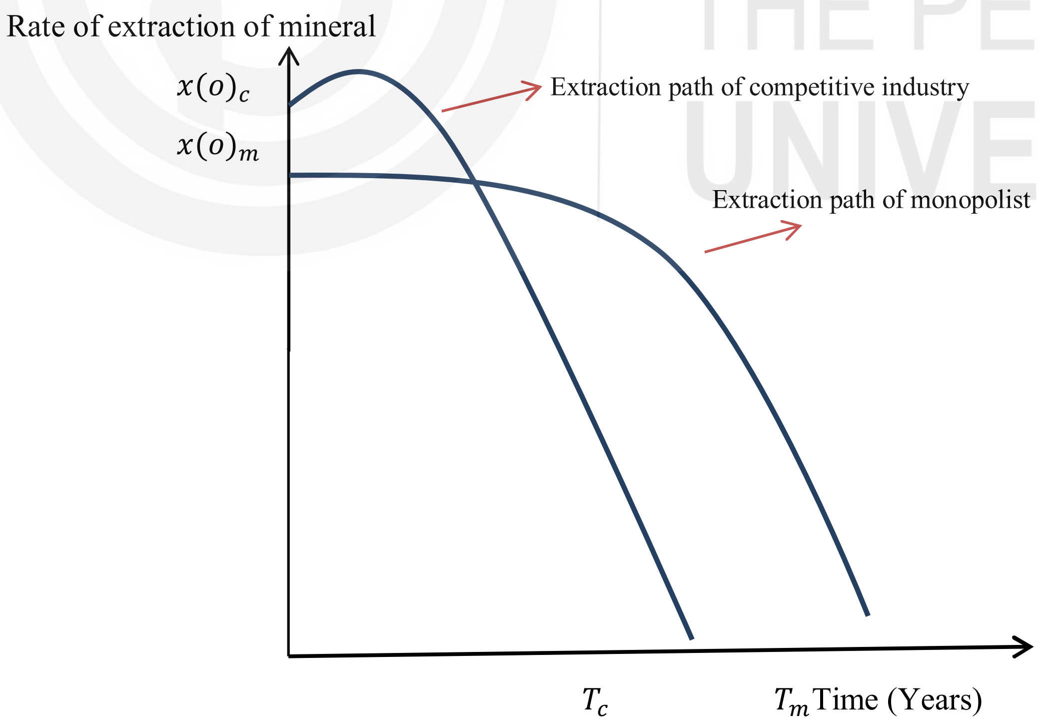


**Figure 10.4: Optimal Extraction Path of Competitive Industry**

***Note***: $x(o)_c$ and $x(o)_m$ are initial rate of extraction of a competitive and a monopolist industry. $T_c$and $T_m$ are terminal point and the shut down point of the competitive industry and a monopoly.

### 10.4.2.4 Extraction with Constant Marginal Cost

In reality, the total cost of extraction will increase with the rate of extraction (i.e. increasing the marginal costs of extraction). As a result, for a given level of extraction, not only the cost of extraction will be higher, there will be a depletion effect reducing the stock of remaining reserves. One factor which can offset this effect is technical change that could reduce the costs of production in the future for a given level of extraction and remaining reserves. Together, these factors have important implications for the optimal extraction of non-renewable resources. In the earlier instances considered above, we have seen that the present value of the shadow price equals the price of the mineral as positive marginal extraction costs place a wedge between the two prices. In the present case, the shadow price (more precisely the current value of the shadow price or $\lambda\, e^{-\delta t}$) is called the net price or rent or marginal *user cost.* It represents the marginal value of the mineral in situ i.e. in the ground.

In the current instance, we assume that the marginal cost of extraction is constant (say c), so that the stock effect is zero, and that there is no technological change. Hence, the maximization problem for a competitive mine will be:

$$Max\, V = \int_{t=0}^{T} e^{-\delta t}\,(P(x) - cx)\, dt\,, \ldots\ldots\ldots\ldots \quad (31)$$

$$\text{subject to} \frac{db}{dt} = -\,x \ldots\ldots\ldots\ldots\ldots \quad (31)$$

$$b_o \geq \int_{t=0}^{T} x dt \ldots\ldots\ldots\ldots \quad (32)$$

The present value Hamiltonian (H) for this problem is:

$$H = e^{-\delta t}(p - c)x + \lambda\,(-x) \text{ -------- } (33),$$

λ being the present value of the shadow price of the resource stock. If the firm is maximizing the present value of its rent over time, then at any instant of time it must have:

$$\frac{\partial H}{\partial x} = e^{-\delta t}(p - c) - \lambda = 0 \text{ or}$$

$$\lambda = (p - c)e^{-\delta t} \ \ldots\ldots\ldots\ldots \quad (34)$$

Multiplying both sides of the equations of (34) by $e^{\delta t}$:

$$\lambda e^{\delta t} = (p - c) = q \ \ldots\ldots\ldots\ldots\ldots \quad (35)$$

Where q is the net price of the resource. For the firm to be indifferent between extracting the mineral now versus the future, equation (35) implies that the growth rate in the net price must increase at the discount rate i.e.:

$$\left(\frac{dq}{dt}\right) / q = \delta \ \ldots\ldots\ldots\ldots\ldots\ldots \ (36)$$

Equation (36) is equivalent to the *Hotelling rule* we previously found in equation (15) (in 10.4.2.1) except that the growth rate of *net price* equals the discount rate. Indeed, in this special case, where the marginal costs of extraction is unaffected by either the rate of extraction or the remaining reserves or technological progress, the growth rate in the resource price will also be equal to the discount rate. This is illustrated in the Figure 10.5 for an inverse linear demand as can also be seen from (35) where by differentiating w.r.t. time (t) we have:

$$\frac{dp}{dt} = \frac{dq}{dt} + \frac{dc}{dt}, \text{ with } \frac{dc}{dt} = 0$$

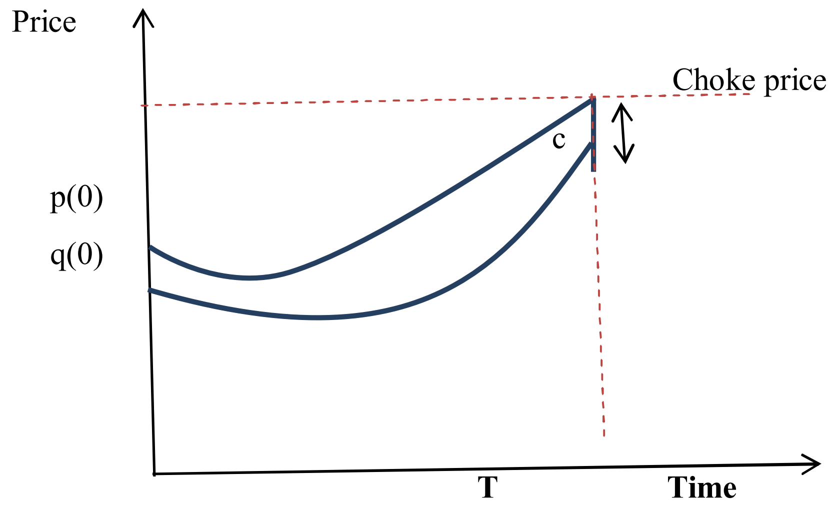


**Figure 10.5: Resource and Net Price Path with Linear Inverse Demand**

With the initial and net resource prices defined as q(0) and p(0) and the terminal time T as A, the resource price equals the choke price and the net price equals the choke price less the constant marginal cost of extraction 'c'. Assuming that all markets are competitive, all mines have the same private rate of discount (equal to the social rate of discount) and all mine owners have perfect information about current and future prices and reserves. Then, (36) is an *equilibrium condition*. In other words, the growth rate of the net price equals the discount rate ensuring that supply of the minerals exactly equals the demand for the mineral at all points in time. The assumption critical to this result is therefore that the mine owners have perfect information regarding reserves and future prices. However, in reality there is a whole lot of uncertainty with future markets, long term mineral supply contracts and prices. Thus, the expectation about the future prices has an important effect on current and future supply of non-renewable resources. If extraction is costly, it is possible that the reserve is still not exhausted by the time T. Equation (36) can then be rewritten as:

$$\frac{dq}{dt} = q\,\delta \ldots\ldots\ldots\ldots \quad (37)$$

The LHS represents the instantaneous return from leaving a marginal amount of the mineral in the ground – which is the increase in the net price of the resource. The RHS represents the instantaneous return from extracting a marginal amount of the mineral, the return put in a bank earning an interest equal to the rate of discount. Thus, if the LHS (the instantaneous return from investing in the resource) equals the RHS (the instantaneous return from disinvesting or extracting the resource), the firm's extraction rate maximizes the present value of rents from the mine.

### 10.4.2.5 Extraction (with Stock Effect)

If the cost of extraction rise with a decline in the remaining stock of reserves, the *stock effect* represents an additional return from investing (or not extracting) a marginal amount of the resource. The extra return represents the cost of savings from having a larger amount of the resource in the future, resulting in a lower marginal extraction cost. Thus, if we have to write the total cost of extraction as $c(x,b)$ then the marginal cost (MC) of extraction would be $\frac{\partial c(x,b)}{\partial x}$, or equivalently written as $c_x(x,b)$. Further, given that extraction cost is increasing with the decline in the remaining stock of reserves we have $\frac{\partial c(x,b)}{\partial x} < 0 \ or \ c_x(x,b) < 0$. This represents the *stock effect* or the additional return (due to lower extraction costs in the future) from not extracting a marginal unit of the resource. It can be shown that, if the stock effect for a firm were to be indifferent from extracting (or not extracting) a marginal amount of the resource, the following condition must hold:

$$\frac{\partial q}{\partial t} + \frac{\partial c(x,b)}{\partial b} = q\delta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (38)$$

Equation (38) is called the *modified Hotelling Rule.* In the presence of stock effect, it is possible to have the mine shut down before all the remaining reserves are exhausted. To understand this, note that as the reserves of stock b approaches 0, the marginal cost of extraction may become so high that the net price q also approaches 0. When the net price is zero, it is no longer profitable to extract the resource. This is the so called *shut down point*. Thus, whether or not the mine shuts down depends on the characteristics of the cost function $c(x,b)$. If the mine does shut down with incomplete extraction, the net price must be decreasing over time. Moreover, the rate of extraction is also declining over time until the shut down point. To show this, we can use two necessary conditions that must be satisfied along the optimal extraction path: the *performance test* at the terminal time and the partial derivative of the current value Hamiltonian with respect to the rate of extraction set equal to zero. That is:

$$\big(px - c(x,b)\big) + q(-x) = 0 \ \ at\ T \ldots\ldots\ldots\ldots \quad (39)$$

$$\big(p - c_x(x,b)\big) = q \ , \ \forall\ t \quad \ldots\ldots\ldots\ldots\ldots \quad (40)$$

At the shutdown point q = 0 (and b > 0), from (39) we have $p = c(x,b)/x$. This implies that the average cost (AC) of extraction equals the resource price. From (40), at q = 0, we have $p = c_x(x,b)$. This means the marginal cost of production equals the resource price. Thus (39) and (40) taken together imply that AC = MC. Prior to the shut down point, however, $\big(px - c(x,b)\big) + q(-x) > 0$, so that AC is not at its minimum point and therefore MC > AC. For well behaved cost functions with monotonically increasing marginal costs, this implies that the rate of extraction is higher when recovery of the mines begins, and as q declines, MC converges to AC, thus implying the rate of extraction declines.

### 10.4.2.6 Extraction with Stock Effect and Technical Change

Here we examine what may happen to the net price and the resource price if there is both technological progress (that tends to reduce costs over time) and an offsetting stock effect. In this case, we assume the extraction cost function: $c(x,b,t)$, where $c_x(x,b,t) > 0$, $c_{xx}(x,b,t) > 0$, $c_{xb}(x,b,t) < 0$, and $c_{xt}(x,b,t) < 0$. The associated present value Hamiltonian for a competitive firm with such a cost function will be:

$$H = e^{-\delta t}\big(Px - c(x,b,t)\big) + \lambda(-x).$$

A necessary condition for the firm to maximize the present value of the rent from extraction is therefore:

$$\frac{\partial H}{\partial x} = e^{-\delta t}\big(p - c_x(x,b,t)\big) - \lambda = 0 \Rightarrow \big(p - c_x(x,b,t)\big) = q \ (= \lambda e^{+\delta t}) \quad \ldots\ldots\ldots\ldots \quad (41)$$

where $c_x(x, b, t) =$ MC. Differentiating (41) w. r. t. time we get,

$$\frac{dp}{dt} = \frac{dq}{dt} + \frac{dMC}{dt} \quad \text{............ (42)}$$

where, $\frac{dMC}{dt} = c_{xx}(x, b, t)\frac{dx}{dt} + c_{xb}(x, b, t)\frac{db}{dt} + c_{xt}(x, b, t)$

Rewriting (38), the modified Hotelling Rule, which must also hold true along the optimal extraction path in terms of $\frac{dq}{dt}$ and substituting into (42) we obtain:

$$\frac{dp}{dt} = \delta q - c_b(x, b, t) + \frac{dMC}{dt} \ \ or \ \ \frac{dp}{dt} + c_b(x, b, t) - \frac{dMC}{dt} = \delta q \quad \text{............ (43)}$$

Equation (43) is a portfolio balance equation called the **fundamental equation of non-renewable resources.** The LHS of (43) is the instantaneous return from investing in the resource or not extracting a marginal amount of the resource. It consists of any rise in the resource price, lower marginal costs of extraction in the future from having marginally greater remaining reserves and lower marginal costs in the future associated with technological progress. The RHS is the instantaneous return from extracting a marginal amount of the resource and putting it in a bank to receive a rate of return equal to the discount rate. Depending on the relative magnitude of $c_b(x, b, t)$and $\frac{dMC}{dt}$, the resource and the net price may be rising or falling over time. Thus, depending on the form of technical change, the resource price, the extraction cost and the user cost may move in different direction.

### 10.4.2.7 Variable Quality of Reserves

So far we have assumed that all the mines have same quality of ore. However in reality, the quality of mines differ across and over time for any given mine. Moreover, in many cases the quality or the grade of the ore extracted at any point in time is partly determined by the mine owner. Thus, when choosing an optimal extraction path the mine owner faces two decisions: (i) the rate of extraction (how much of the resources to be removed); and (ii) the quality of the ore to be extracted.

We would expect the highest-grade ore with the highest user costs to be extracted first and the more marginal deposit be extracted later, if the present value of the resource price is rising over time. This is because the rising resource price will eventually make the marginal deposit profitable to extract (as compared to the preceding period) – an insight first made by David Ricardo around two hundred years ago. Indeed, as we expect, the trend for most of the mineral is for the quality of ore to decline over time.

**Check Your Progress 2** (answer the question in about 100 words within the space given)

1. State the transversality conditions for the 'performance test' and the 'asset test' in the case of a individual competitive mine. When are these conditions satisfied and what are its implication to the miner?

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2. What is 'choke price'? To what factor, does the existence of choke price may be explained?

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3. State the equilibrium condition for the case of 'extraction with constant marginal cost'. What is the basic assumption critical to this result?

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4. Write the equation for modified Hotelling Rule? What is meant by the 'shut down point'?

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5. Write the equation known as a portfolio balance equation. Specify the implication of its two sides, in terms of the respective rate of return.

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## 10.5 RESOURCE SCARCITY

In ancient Greece, when tin became scarce, its price rose so high that the Greeks had to switch over from bronze to iron. The same happened with timber; its scarcity changed shipbuilding techniques from the frame-first to the hull-first method in order to save timber. Such physical limits to natural resources are still one of the main concerns of economic theory. The economics of mining indicates a potential relationship between costs of extraction, the resource price, net price of non-renewable resources and the level of remaining reserves. These and other variables have been used to provide measures of scarcity of non-renewable resources. Such indexes of scarcity have generated a very large literature, motivated by the concern that the world may soon *run out* of key resources that have very few or very expensive substitutes. These concerns have been labelled as *'scarcity controversies'*, as many have argued that the availability of key non-renewable resources (such as oil) will impose limits to growth (Meadows et al., 1974). There are also others who have argued that few, if any, limits exist (Simon 1995). While comparing various notions of scarcity, it should be clear that the absolute scarcity is increasing as the reserves of non-renewable resources are finite. Thus, any scarcity index that we use is a relative measure of scarcity. The indexes can be separated into physical or resource indexes and price or economic measures.

### 10.5.1 Theories of Resource Scarcity

In simple economic terms, adequacy or scarcity of a good is reflected by its costs and relative prices. It is a fact that both material resources and man-made goods having positive prices, reflects this scarcity. However, scarcity is not the only influence on price and prices also often do not fully reflect scarcity specially if natural resources encompass the full range of environmental functions, amenity provision, waste assimilation and life support and raw materials supply. In economics, natural resource scarcity is therefore a relative concept. From the *Malthusian perspective*, it is the absolute physical limit to non-renewable resources that is predicted to become binding in the near/medium term future. Forecast in this tradition is based on the static stock index calculations. They utilize only supply data, covering only the proved reserves, and assume an exponential trend rate of growth in resource demand. This approach is epitomized by the publication of *Limits to Growth (Meadows et al., 1972).* A related *Neo Malthusian position* emphasizes the importance of 'environmental limits to resource exploitation' (e.g. mineralogical thresholds in terms of required energy inputs for extraction and other pollution costs).

According to the Ricardian perspective, the 'depletion effect' of resource exploitation is felt in terms of rising costs and material prices over time as the quality of available resources decline. Resource adequacy forecasts in this tradition typically assume an expansion of recoverable resource stock (which is greater than the proved reserves) via increased exploration effort and success and rapid technological progress (in particular the establishment of backstop energy technology). Thus, advances in processing technology enable extractors to bypass costly mineral beneficiation processes. This has led to the recovery of precious metals and copper from relatively low grade ores. Thus, Ricardian analyses indicate no scarcity dilemma within atleast the next hundred years or so. The depletion effect is further mitigated by compensatory processes stimulated by the market. These processes include material and function substitute, industrial process changes, and scrap recycling.

Are resources getting scarce? We will consider two economic measures of resource scarcity, namely cost and price to confront the question raised. As already indicated, David Ricardo viewed the increasing costs associated with depletion as a limit to growth. In principle, extraction costs may rise over time as lower-cost reserves are depleted and higher-cost reserves remain to be exploited. Certainly resources have been extensively depleted over the last century and more. How have costs behaved? The predictions of Ricardian scarcity were examined empirically for the USA in a famous study by Barnett (1979). The authors considered two versions of the ***scarcity hypothesis***: a strong version, that unit costs of extractive (exhaustible material) industries should rise through time; and a weak version, that costs in extractive industries should rise relative to non-extractive industries. The latter version recognizes the impact of technical progress in lowering the costs of production in modern economies.

For all true extractive industries, costs over the long term have declined relative to the costs in non-extractive industries. Many studies have examined the proposition that because of the influence of user cost, prices of exhaustible resources should rise relative to those of reproducible resources. This proposition was rejected owing to four basic reasons cited for supporting the rejection of the scarcity hypothesis (Bowers, 1997).

1. As higher grade resources are exhausted, lower grade resources are found in greater abundance. Furthermore, the difference in grades diminishes as the known stock expands.

2. As a particular resource becomes scarce, price rises are offset by switches in demand to substitutes (backstop). That is, scarcity is offset by decline in demand.

3. Increases in prices stimulate exploration for new deposits and induce increased recycling.

4. Technical progress influences supply by reducing extraction costs and by making possible the exploitation of previously uneconomic deposits. It also reduces demand by encouraging efficiency in resource use.

### 10.5.2 Resource Measure

Mere existence of a non-renewable resource in the earth's crust does not imply that it is available for extraction. This is because for the vast majority of the earth's minerals (excluding the hydrocarbons) there exists a hypothesized *mineralogical barrier*. Extraction of mineral beyond the barrier is technically possible, but at a several magnitudes of higher costs than the current method of extraction cost. Thus, physical indices of minerals in terms of their abundance in absolute in the earth's crust are worthless as a measure of relative scarcity. An alternative physical measure is the economically extractable part of mineral resource reserves. Such measures include *reserve-to-use ratios* and have frequently been used as indicators of scarcity of non-renewable resources. Although appealing, reserve-to-use ratios could be misleading. First, reserve do not include measured, indicated or inferred resources that will provide a potential source of supply, should the net price or user cost of the resource rise sufficiently. Second, if the increasing relative scarcity increases beyond the resource price, it provides an incentive to explore for new mineral sources that are undiscovered. Third, an increasing resource price stimulates the development and search for substitutes that may be renewable. For instance, rising energy prices of hydrocarbons have stimulated research and development into photovoltaic cells that generate electricity from solar radiation. Fourth, a rising real price of resource, will (all other things being equal), tend to reduce the demand thus extending the remaining life of the reserve. For instance, the world reserve-to-use ratio for petroleum in 1950 was 20 years, but rose to 29 years in 1980(Randall 1987) despite the fact that the annual world consumption increased almost six fold over the intervening 30 years. Moreover, reserve-to-use ratios are based simply on current estimates of resource use and do not consider any trends in production (increasing or decreasing) over time.

### 10.5.3 Price Measures

Three broad price measures have been employed to assess the relative scarcity of non-renewable resources: the real price of the resource, the real extraction costs, and the user cost or net price. However, these three price measures are not independent (as seen above in the Hotelling rule and in the modified Hotelling rule) and with the interplay of changes in demand, stock effects, and technological change, the real prices may be rising over some period and then declining over others. One of the most cited studies of real non-renewable resource prices [by Barnett and Morse, 1963(since updated)] indicates that based on the evidence for the period 1870 to 1973, an index of mineral prices, relative to non-extractive commodities, has varied considerably, although there has been no discernible long term upward trend. In fact, looking back, the real price of major minerals and energy sources (aluminium, coal, copper, iron, lead, petroleum, natural gas, nickel, silver, tin, zinc) tended to rise during the 1970s, but many declined in price during the 1980s and 1990s (Krautkramer, 1998). An alternative price measure is the marginal user cost or net price of non-renewable resources. The higher the user cost, or the *in situ* value of the resource, the greater is the relative scarcity. Whether the user cost is rising or falling depends on the interplay of stock effects, demand (existence of substitutes) and technological change. Thus, it is possible to have declining user cost and decreasing relative scarcity due to stock effects, but the absolute level of abundance of the resource may decline over time as the remaining reserves are extracted.

## 10.5.4 Economic Scarcity Indices

Three measures are generally used in the literature of economics in this respect.

1. Real unit costs of production of the resource – the real quantity of homogenous inputs required to provide a unit of constant quality of extractive output.

2. Real price of resource intensive goods –

3. Rental rate of the resource (i.e. true user costs) – which is unobservable, and hence for some non-renewable resources, the user cost is equal to the shadow price of a unit of its stock. The shadow price reflects the present value of benefits of shifting the production of a unit of the resource to the future. The price is the value of an additional unit of proven reserves equal to the cost of the producing that additional unit (known as the marginal replacement cost or discovery cost).

Hall and Hall (1984) suggest a four-fold scarcity typology.

1. Malthusian stock scarcity (MSS) – Here the resource is fixed in absolute size and extraction costs are constant.

2. Malthusian flow scarcity (MFS) – Here the resource is fixed in absolute size but extraction costs rise with the rate of extraction.

3. Ricardian Stock Scarcity (RSS) – No absolute size constraint exists but the extraction costs rise with the rate of extraction and how much is the quantity of resource extracted to date.

4. Ricardian Flow Scarcity (RFS) – No absolute size constraint exists but the extraction costs rise with the rate of extraction.

Hall and Hall (1984) have shown that the price of the resource output (P) is related to the three costs [viz. Average Cost (AC), User Cost (UC) and Present Value of Future Cost (PV (FC)]. For the four type of scarcities mentioned above, the relationship between P and the three types of costs are respectively as follows:

1. MSS: P = AC + UC

2. MFS: P = AC + PV(FC) + UC

3. RSS: P = AC + PV(FC)

4. RFS: P = AC

The 'limits to growth' analysis was essentially Malthusian stock in which the absolute limits to resource stock were assumed. The backstop technology follows Ricardian stock, because although we were concerned to find a price path which exhausted the stock at a point of time (when the resource price equals the backstop price), the implication is that some resources will be left over when the backstop technology takes over.

Thus, only for the RFS case, a unit cost measure alone will appropriately measure the output since the price captures both the user cost element and the factor reflecting the impact of current extraction on future cost.

### 10.5.5 Prices, Substitutes and Public Policy

While the prices (resource price, user cost and extraction costs) may be declining over time, the implication is that the measure of relative scarcity may move in the opposite direction of the measures of absolute scarcity. But the lack of discernible upward trend in prices may be a cause of concern because, in its absence, the market will not give appropriate signal or incentives to the firm to develop substitutes. Prices will eventually rise due to a stock effect and it may suddenly cause a major negative economic shock – a scenario sometimes called *Malthusian perspective.* However, unlike the oil supply shock of 1973 and 1979, a rapidly rising price due to cumulative extraction will almost certainly be anticipated. Consequently, the expectation of rapidly rising prices should, in turn, spur research and development for substitutes. Concerns over running out of non-renewable resources have led some policy makers to provide public incentives for developing substitutes and exploring for undiscovered resources. Following the first oil shock, various government also offered research and development support to develop alternative energy sources, such as solar energy and wind power. For instance, wind power in specially windy locations and close to areas of electricity demand is now price competitive with some non-renewable source (like coal) in terms of electricity generation.

Another set of government policy is to levy rental charges (called royalties) on non-renewable resource extraction. Investing all the rents from non-renewable resources to create a stream of benefits today and into the future [called **Hartwick's rule** (Hartwick, 1977)] is an important mechanism of attaining sustainable development by ensuring that the future generation also can benefit from the resources. Alternative methods of rent capturing, suggested by Garnaut and Clunies Ross (1975), levies a charge on mines in excess of extraction and exploration costs, including a return on the capital employed. Other methods of rent capturing is auction of mineral leases and charges imposed in excess of a return to capital employed by mines.

### 10.5.6 Resources and Rents

Rents provide the principal incentive for the extraction of non-renewable resources. Thus, an understanding of the factors that contribute to rents, provides insights into the extraction of non-renewable resources. The term economic rent refers to those returns that exceeds the value required to ensure the supply of a factor of production. In the case of non-renewable resources, economic rents exist whenever user cost is positive. The user cost multiplied by the volume of mineral extraction, sometimes defined as *scarcity rent*, indicates that it is a return to the owner of the resources (hence also called as resource rent) arising from its limited supply. In this case, although the marginal extraction of resources would generate positive return (user cost is positive), additional supply is constrained because miners are inter-temporally tempted to satisfy themselves with the instantaneous rate of return (i.e. from not extracting exactly equal to the rate of return of competing assets).

Another rent that may be enjoyed by the owners of non-renewable resources is a *differential rent,* also called Ricardian rent. Differential rent arises from the fact that for a factor of production fixed in supply (like mineral reserve), the marginal output from the addition of successive units of variable factors (such as labour and capital) eventually falls. If the marginal costs of extraction were constant, there would be no differential rent. The returns from the sale of units of outputs (such as mineral) that exceeds both the variable cost of production and the return to the fixed factor in an alternative use is differential rent.

The concepts of resource rent and differential rent are illustrated in Figure 10.6 for an individual mine supplying $x^*$ at time point t for a price $p^*$. The scarcity rent is the difference between the resource price and the marginal costs of extraction multiplied by the amount of mineral extracted. The units of mineral extracted at a cost less than the marginal cost of extraction ($MC^*$) associated with $x^*$, enjoy a differential rent (or Ricardian rent) arising from the quality of resource, such as its accessibility or location or other factors. The combination of the resource and differential rent constitutes the firm's economic rent from selling $x^*$ units of resources at price $P^*$.

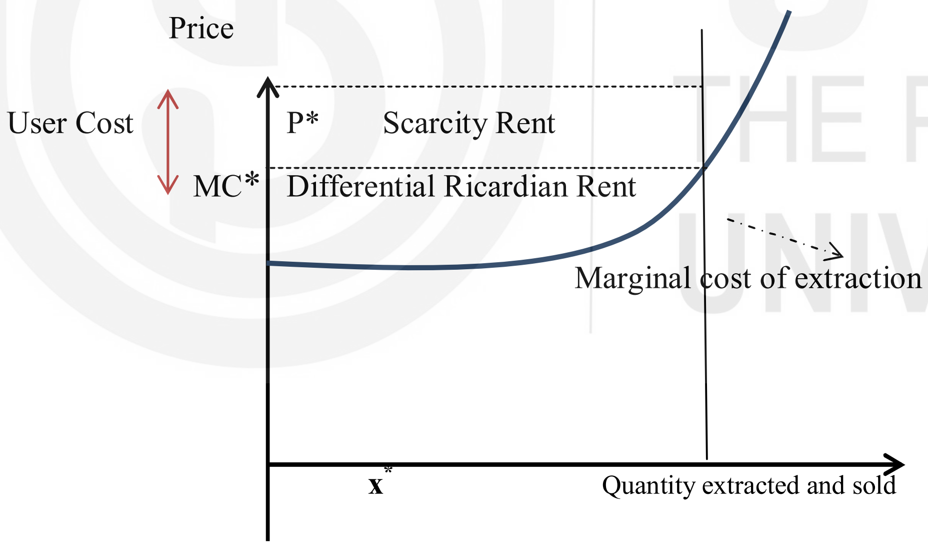


**Figure 10.6: Rents and Non-renewable Resources**

**Check Your Progress 3** (answer the question in about 100 words within the space given)

1. Distinguish between the Malthusian and the Neo-Malthusian perspectives on the limits to resources. How is the Ricardian perspective different from these?

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2. On what empirical evidence, the contention on 'limits to resources' been rejected?

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3. What is meant by 'hypothesized mineralogical barrier'?

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4. Why are reserve-to-use ratios considered misleading?

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5. What evidence is there to suggest that it is possible to have 'declining user cost' and 'decreasing relative scarcity' in spite of the absolute level of the availability of a resource coming down with extraction?

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6. State the four-fold economic scarcity typology suggested by Hall & Hall. Which of these more appropriately measures the value of output and why?

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7. What is the scenario referred to as the Malthusian Perspective?

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8. Illustrate the policy options available to ensure the sustainable use of resources under the approach of 'levying of rental charges'?

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9. How is 'differential rent' defined? How is it different from the 'resource rent'?

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## 10.6 LET US SUM UP

The unit has analysed the optimal rule of resource extraction through time for resources which are of non-renewable nature. It provides the specifications of optimal extraction path and the conditions underlying it. Since this involves inter-temporal choice, the problem has to be solved using the dynamic optimization approach. In discussing both the discrete and continuous time frame analysis, alternative models with no stock effect, with stock effect and technological progress are discussed. An exhaustible resource with a backstop technology will be extracted until the resource price hits the choke-price at which the backstop is profitable to operate. Thus, the unit examines the basic Hotelling rule along with its various modified versions under different assumptions. Starting with the baseline model of competitive mining firm without stock effect, there is a natural extension to include the market imperfection through monopoly mining, highlighting the basic difference in optimal extraction rule under these two different market structures. The concluding part deals with the elements of resource scarcity, its measures and indices and the various concepts of economic rents.

## 10.7 KEY WORDS

**Choke Price** — Specifies the price corresponding to the maximum willingness to pay. So it is the price corresponding to which demand is zero.

**Concave Function** — A function of a single variable is concave if every line segment joining two points on its graph does not lie above the graph at any point.

**Discount Rate:** — Is the extent to which future benefit flows are devalued. This is because, for an individual, money today is more valuable as he can invest in bank and earn interest income.

**Non-renewable Resource :** — These are natural resources whose reserves/stock in the earth's crust is fixed.

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| | The rate of regeneration is negligibly small, so the stock depletes with every unit of extraction and finally gets exhausted. |
| **Opportunity Cost:** | Is the resource rent or the royalty for the owner of the resource. It is given by the price over and above the marginal cost at the equilibrium. |
| **Intergenerational Equity** | Is equity in terms of distribution of resources and justice between present and future generations. |
| **Iso-elastic Function** | In mathematical economics, an isoelastic function, sometimes called constant elasticity function, is a function that exhibits a constant elasticity, i.e. has a constant elasticity coefficient. The elasticity is the ratio of the percentage change in the dependent variable to the percentage causative change in the independent variable, in the limit as the changes approach zero in magnitude. |
| **Renewable Resource:** | The essential feature of renewable resource is that the stock is not fixed and therefore can increase naturally if the stock is allowed to regenerate. However, there is a threshold point defined by the maximum stock, beyond which no renewable resource can regenerate, which is further decided by the carrying capacity of the ecosystem in which it exists. |
| **Stock Variable** | Represent a quantity/volume at a particular point of time. It has no time dimension as against the flow which has time dimension. |
| **Flow Variable** | A variable whose value depends on a period of time rather than an instant, example being the gross domestic product. |

## 10.8 SUGGESTED REFERENCES FOR FURTHER READING

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## 10.9 ANSWERS/HINTS TO CYP QUESTIONS

**Check Your Progress 1**

1) See 10.2 and answer.
2) See 10.3 and answer.
3) See 10.3.1 and answer.
4) See 10.4 and answer.
5) See 10.4.1 and answer.
6) See 10.4.1.2 and answer.

**Check Your Progress 2**

1) See 10.4.2.1 and answer.
2) See 10.4.2.2 and answer.
3) See 10.4.2.4 and answer.
4) See 10.4.2.5 and answer.
5) See 10.4.2.6 and answer.

**Check Your Progress 3**

1) See 10.5.1 and answer.
2) See 10.5.1 and answer.
3) See 10.5.2 and answer.
4) See 10.5.2 and answer.
5) See 10.5.3 and answer.
6) See 10.5.4 and answer.
7) See 10.5.5 and answer.
8) See 10.5.5 and answer.
9) See 10.5.6 and answer.

# UNIT 11 SUPPLY OF ENVIRONMENTAL SERVICES

**Structure**



## 11.0 OBJECTIVES

After going through this unit, you would be in a position to:

- indicate the importance of valuation of environment and ecosystem services;
- explain the concept of total economic value of environment;
- distinguish between use value and non-use value of environment;
- explain various methods of estimation of the value of environment;
- discuss the issues in valuation of biodiversity; and
- explain the fact that environment is under-valued.

## 11.1 INTRODUCTION

There could be several services supplied by the environment. According to Millennium Ecosystem Assessment Report (2005), there are four major ecosystem services, viz. i) provisioning services, ii) regulating services, iii) cultural services, and iv) supporting services. Provisioning services relate to the goods and services provided by the environment that have a direct benefit to people. This includes food and fibre, fuel, genetic resources, biochemical and fresh water. Regulating services, as the name suggests, includes several functions of the environment that regulates our environment. Under this category, we can include air quality maintenance, climate regulation, regulation of human diseases, pollination, protection from storm, etc. Under cultural services, we include the non-material benefits that people receive from the environment such as spiritual and religious values, traditional and formal knowledge systems, and recreation and ecotourism. Supporting services refer to the services that help in production of ecosystem services. They differ from provisioning, regulating and cultural services in the sense that their impact on people are either indirect or occur over a long period of time. Examples under this category could be solid formation services, production of primary oxygen, nutrient cycling and provision of habitat.

Over time, there has been depletion of natural resources and degradation of environment, which have adversely affected quality of life. As pointed out in Units 2 and 3 of this course, environmental concerns has a tendency to differ across geographical regions, level of economic development and cultural factors. The problem of environmental degradation has thus been witnessed at all levels. A major reason behind environmental degradation is the fact that we presume many environmental services to be freely available and thus assign zero economic value to it. A proper understanding of the value of environment would help in creation of awareness among stakeholders, efficient allocation of resources in production process, and policy formulation for improvement in the quality of environment.

## 11.2 IMPORTANCE OF VALUATION OF ENVIRONMENT

Environment retains the capacity to regenerate itself in certain aspects and to some extent. If extraction from the environment is less than its regeneration capacity, there is no depletion to the stock of natural capital. For example, if harvesting of forest products from forests is more than its regeneration capacity, the quality of forests as well as the area under forests will be adversely affected. Moreover, excessive withdrawal of forest resources would result in a decline in supply of forest resources available to the economy in the long run. In a similar manner, depletion in the stock of natural capital in general would adversely affect the flow of environmental services.

It is often argued that over-exploitation takes place because stakeholders do not take into account the social costs and benefits in individual decision-making. In the presence of externalities, market forces cannot take care of environmental conservation because costs and benefits of certain individual motive driven economic activities that result in environmental degradation are incident on different economic agents. For example, in order to cut costs a cement factory does not install pollution abatement technology and pollutes the air in the locality. Thus, the benefits accrue to the owner of the factory but the cost of pollution is borne by inhabitants in the locality in terms of increased health expenditure. Beneficiaries of environment such as households and firms often have short-term parochial interest where only private costs and benefits are taken into account. Valuation of environment in a social and long term perspective would help policy formulation to make the polluters pay for environmental degradation. Thus, it would help in internalization of externalities.

In recent years attempts have been made to extend the product boundaries. Environmental functions which were ignored earlier on the ground of being freely available have been given due recognition. It is difficult to assign proper value to environmental functions as they are intangible in nature and do not have a formal market. It has been emphasized in numerous studies that proper accounting for environmental resources used up in economic activities is a difficult task. Lack of a market for these resources, inappropriate policy measures to internalize the externalities, and inadequate standards of measurement invariably results in under-valuation of environmental resources. However, proper valuation of environmental resources by extending the traditional product boundary provides a better tool for policy formulation and decision-making. Moreover, it allows comparison of advantages and disadvantages of alternative scenarios of the environment [Lettee and de Boo, 2002].

In order to give due importance to environment, the stock of natural capital and its quality is included while estimating the environment-adjusted GDP (usually called EDP, which is equivalent to GDP plus the value of environment vide Unit 14). Whenever there is depletion to the stock of natural capital or there is deterioration in its quality, estimated EDP declines accordingly. In order to estimate EDP it is important to find out the total economic value (TEV) of environment. Valuation of the resources provided by environment is considered to be a complex issue. The problem comes up at two levels: identification of environmental functions and assigning value to these functions. The problem of identification comes up as it is difficult to ascertain the uses to which the environment is subjected. While some of the environmental functions are tangible in nature others are intangible. The problem of valuation arises as it is difficult to assign values to the environmental functions in the absence of market. In many cases, the market for these functions are incomplete while in others the market does not exist at all. The literature on total economic value of environment is still blurred with ambiguity. However, in recent years many studies have been undertaken to find out empirical methods of valuing environment. Nonetheless, it is still in a nascent stage and much abstraction and subjectivity remains in the methodology, as we will see below.

## 11.3 TOTAL ECONOMIC VALUE OF ENVIRONMENT

As mentioned above, it is difficult to identify and compile an inventory (or a complete list) of environmental functions. The identification problem comes up because a large array of functions emanating from environment is not marketed and thus omitted in decision-making. Traditionally, as these goods and services do not enter into formal markets, it is assumed to be either free or of little value. We can explain the problem by an example viz. the value of quality air. Oxygen contained in the air helps in sustenance of life for human beings and animals in addition to being used in production of many commodities such as chemicals. We breathe the air available to us in the atmosphere for which no market exists in the sense that there are no sellers and buyers and we do not have to pay for the air we breathe. Moreover, there is little choice before us regarding the quality of air we breathe i.e. as individuals we cannot buy better quality air for a higher price. The reason for such a situation is the non-excludability feature of air i.e. once it is available in the atmosphere no one can be excluded from breathing it. However, the quality of air deteriorates due to gaseous emissions from industries, transport vehicles and sewage. The quality of air concerns us as there is a cost associated with the deterioration in its quality such as the loss of productivity due to ill health, increase in health expenditure and increase in the probability of falling ill. Air pollution is an externality to the production process in an industry or running a vehicle or household wastes as the cost of pollution is not borne by the polluter. Pure air has an important function in the sense that it helps us stay fit. However, we presume air to be a free good and ignore its value in decision-making. A question therefore arises: what is the value of pure air? As no market for air exists, it is difficult to find out. An indirect method of ascertaining the value of quality air could be the total cost involved in the loss of productivity and health expenditure. You can find out numerous examples similar to the above and appreciate the value of various environmental functions.

Figure 11.1 presents a detailed list of various aspects of environmental functions and values ascribed to these functions. The total economic value of environment arises because of its 'use values' and 'non-use values'. As its name suggests the use value pertains to different uses to which the environment is subjected to. On the other hand, the non-use value relates to the psychological and ethical aspects associated with the environment (for example, protection of endangered species, maintenance of habitat). The use values are of three types: direct use value, indirect use value and option value. The direct use value of environment is further sub-divided into two groups viz. i) consumptive or extractive use value (e.g. commercial and domestic goods derived from

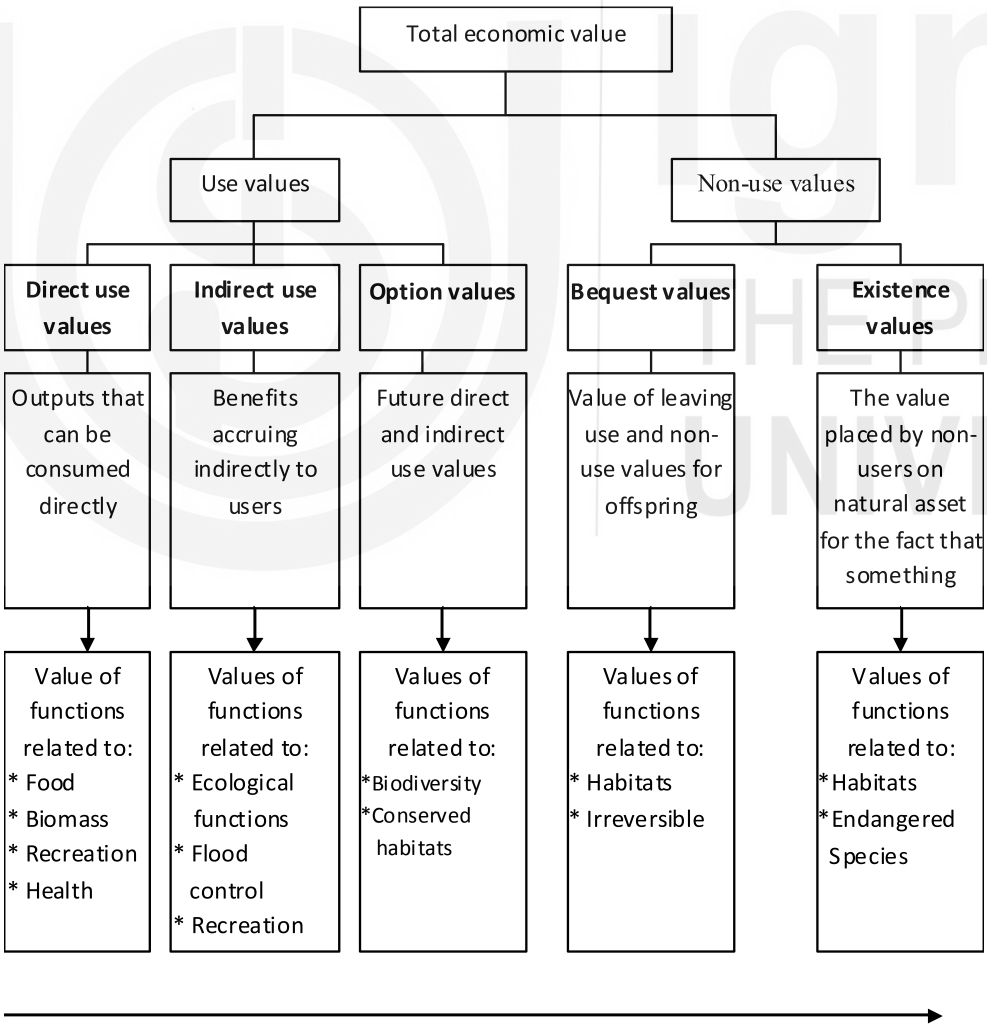


**Figure 11.1: Total Economic Value of Nature**

(Source: Lette and de Boo, 2002; Munasinghe, 1991) environment), and ii) non-consumptive use value (e.g. recreation, science and education). Let us explain the distinction between the three categories viz. direct use, indirect use and option values with an example, say the TEV of forests. As we know, forests provide us with timber and other minor forest products (such as seeds, leaves, etc.) which are of direct economic use value. Thus, it is easy to correlate certain environmental functions which are of direct economic use to economic activities. However, it is difficult to correlate certain environmental services with economic activities, typically in the case of

those pertaining to indirect use values. Here the relationship between environmental services and economic activity is round about. Continuing with the same example of forests, we can say that it helps in maintaining moisture in the surrounding atmosphere which may not be of any direct use to us. The moisture in the environment in turn helps in plant growth and thus agricultural production is higher if moisture is maintained within a particular range.

The third category of use values i.e. option values of environment pertain to the possible use of the resources in future. Environment holds innumerable possibilities in the sense that certain resources may not be useful now but may increase production in future. For example, current research in biotechnology and genetic engineering has combined strains of different species to produce high yielding variety (HYV) seeds which are resistant to pests. Another example of option value could be the use of silicon chips in computer, a technology unknown to us a few decades ago. Thus, we do not know the value of certain functions of environment, which only time can unfold.

The non-use value of the environment is divided into two categories: bequest value and existence value. Bequest value of the environment relates to the idea that the environment should be passed on to future generations so that they can derive both use and non-use values from it. It is important since many ecological changes taking place due to technological progress and economic development are irreversible. Many species, both animals and plants (e.g. indigenous varieties of rice and other crops) have got extinguished from earth in the course of time. It is therefore desirable that biodiversity be maintained on earth. The second category i.e. existence values depict the fact that individuals assign importance to the existence of natural beauty even though it may not be of any economic use to them. The very existence of forests, water streams, sea coasts, parks, etc. are important to individuals even though they may never use it in their lifetime.

A list of environmental functions under different categories is presented in Figure 11.1. From this list, you can appreciate the importance of each of these functions and provide concrete examples under each head. Note that the categories mentioned in the figure are arranged in such a manner that as we move from left to right, the tangibility of the services decline. Thus, indirect use value is less tangible in nature than direct use value, while option value is less tangible than indirect use value.

The impact of certain environmental functions is local in nature while others can percolate to national and international levels both in geographical terms and future generations over time. For instance, moisture regulation due to a watershed is local in nature. But the benefits of carbon sequestration cross local boundaries as it reduces global warming. Thus, forest areas in a country is valuable not only for the country itself but for other countries also. Similarly the benefits of forests as a habitat for genetic resources could be of immense value for future, much beyond the comprehension of current generation. Thus, the question of stakeholders to environment comes up here. Usually, it is the local government which pays for the maintenance of forests while its benefit is shared, although to a limited extent, at the national and international levels. Should not the international organizations pay for the maintenance of forest areas in developing countries? This partly explains (apart from humanitarian reasons) the interest afforestation programmes generates globally and grants/soft-term-loans the developing countries receive from developed ones and international organisations.

Environment is undervalued as we usually take into account those functions of the environment which enter into formal markets such as raw materials. This results in gross under-estimation of the value of environment as many environmental and ecological services are not taken into account. We should appreciate that the indirect use values, option values and non-use values, although intangible in nature, are also important.

**Check Your Progress 1** [answer the questions in about 100 words within the space given]

1. Why is environment undervalued?

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2. Explain the concept of total economic value (TEV) of environment?

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3. Illustrate the difference between direct use value and indirect use value of environment with an example.

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## 11.4 VALUATION TOOLS

Existing literature suggests a number of valuation tools for environmental services and there is need on our part to identify the appropriate valuation tool. Here, following Lette and de Boo (2002), we present eight commonly used valuation tools. These are: (i) market prices, (ii) efficiency or shadow prices, (iii) hedonic pricing, (iv) travel cost, (v) production function approach, (vi) related goods approaches (e.g. barter exchange, direct substitutes and indirect substitutes), (vii) constructed market techniques (e.g. contingent valuation and contingent ranking), and (viii) cost based valuation methods (such as indirect opportunity cost, restoration cost, replacement cost, relocation cost and preventive expenditure). Of these methods, market prices and shadow prices deal with natural resources which are marketed while the remaining methods are used in cases where no formal market exists.

**Table 11.1: Forest Functions and Relevant Valuation Tools**

| **Use Value** | | **Non-Use Value** | | |
|---|---|---|---|---|
| **1. Direct Use Value** | **2. Indirect Use Value** | **3. Option Value** | **4. Bequest Value** | **5. Existence Value** |
| Wood products (timber, fuel)<br><br>Non-wood products (food, medicine, genetic material)<br><br>Educational, recreational and cultural uses<br><br>Human habitat | Watershed protection<br><br>Nutrient cycling<br><br>Air pollution reduction<br><br>Micro-climatic regulation<br><br>Carbon storage | Possible future uses of goods and services mentioned in 1 and 2 (use values) by actual stakeholders | Possible future uses of goods and services mentioned in 1 and 2 (use values) by the offspring of actual stakeholders | Bio-diversity<br><br>Culture, heritage<br><br>Benefits to stakeholders of only knowing on the existence of goods and services without using them |
| **Valuation Tools** | | | | |
| Marketing analysis<br><br>Related goods approach<br><br>Travel cost method<br><br>Contingent valuation method<br><br>Hedonic pricing | Restoration cost<br><br>Preventive expenditure<br><br>Production function approach<br><br>Replacement cost | Contingent valuation method | Contingent valuation method | Contingent valuation method |

<u>**Source**</u>: Lette and de Boo, 2002; Barbier, 1991

For the different environmental services mentioned in Fig. 11.1, suggested valuation tools are indicated in Table 11.1. You may note that valuation of environment requires meticulous planning on the geographical area to be covered, type of environmental products and services to be included, and the valuation tool to be applied. There is a vast literature available on valuation of various environmental services. A brief discussion on various valuation tools is presented below.

### 11.4.1 Market Prices

Valuation at market prices can be applied to natural resources which are marketed. Market price, as we know, is realized when demand for a product equals its supply. Since it is determined as a result of interaction between numerous buyers and sellers, it is considered to be a kind of equilibrium price. The advantage with market price is that it reflects the willingness to pay by the consumers. Thus, it could be a acceptable method for valuation (of environmental resources) if there is no market failure or policy failure. However, in many instances there are distortions to the market price and it does not reflect true economic value of a commodity. Thus, allocation of resources on the basis of market prices does not represent economic efficiency in the utilisation of resources. The distorting factors could be taxes imposed and subsidies provided by the government. For instance, subsidies on fertiliser reduce its price than what it would otherwise have been. Thus, the market price of fertiliser is less than its true economic value inducing farmers to buy more of it. A second source of distortion to market price could arise due to fixation of exchange rate, particularly for commodities traded internationally.

Many of the environmental resources do not enter the market in the sense that they are not traded at all. In such cases, valuation of the resources at market prices is not possible and we have to look for alternative valuation tools. Secondly, property rights for natural resources in most of the cases lie with the government. But unauthorised selling of minerals, forest products, hide and horns of animals, etc. is rampant in many countries including India. In such cases, the seller does not bear the cost of production of the product and therefore can afford to sell it much cheaper.

### 11.4.2 Shadow Prices

As mentioned above, market prices do not represent the true economic value of a product due to market failure and policy failure. Market failure means the inability of the market mechanism, under certain circumstances, to reflect accurately the value of the environmental goods and services. Policy failure occurs when a particular government policy has unintended side effects or cause inefficient resource use. For instance, some of the state governments in India in the past have followed a policy of subsidising minor irrigation through tube wells in order to increase food grains production. The concessions offered to farmers in terms of lower interest rate and cash subsidies, provided the right incentives for farmers to go for more and more number of deep tube wells which increased irrigation facility. The unintended environmental impact, however, was the change in cropping pattern in favour of water-intensive crops, excessive depletion of underground water resources and the consequent lowering of water table which eventually dried up the shallow tube wells resulting in overall water shortage.

A limitation of the use of market prices is that although it reflects the unit cost of production of the goods or services to the individuals, it does not take into account the social cost and benefit. Use of shadow prices rectifies this shortcoming by taking into account the societal impact of the production of the commodity or services. However, a limitation of the shadow prices method is that it may be biased, as the estimation procedure may be imperfect. Moreover, it may suffer from personal bias of the researcher or the decision-maker.

### 11.4.3 Hedonic Pricing Method

This method is used for valuation of non-marketed goods and services. In this method, we decompose the price of a commodity into the prices of its components or attributes. This can be explained by an example of housing prices. It is observed that the price of a house in an urban setting is ascribed to availability of various amenities such as open space, lower noise and congestion, and proximity to parks apart from the structure and size of the house itself. A house with better environmental amenities (where we assume that facilities like proximity to public school, availability of public transport, police protection, decent neighbourhood, etc. remain similar) usually fetches a higher price than the one located in a polluted environment. Thus, the difference in the price of the two houses can be considered as the willingness to pay for better quality environment.

This method needs to be used with caution as it is difficult to keep certain variables unchanged (for instance, in the above example, size of house and similarity of non-environmental factors) while allowing for changes in environmental attributes. Secondly, much subjectivity is involved in the decomposition of the attributes, measurement of these attributes, and precise valuation these attributes. Thirdly, data requirement is enormous in the case of hedonic pricing method hindering its application.

### 11.4.4 Travel Cost Method

This method assumes that the consumer has a willingness-to-pay (WTP) to procure certain environmental goods or services. You would have noticed from Table 11.1 that travel cost method can be applied to estimate only the direct use value of environment. Though still not fully perfected (Kolstad, 2011), it has been widely applied to measure the use value of recreational facilities. The basic idea behind travel cost method is that the cost incurred on travel and time spent to visit a recreational site can be taken as a representative of their WTP for marketed goods (recreational services, in this case). Wide application of travel cost method is made in areas of: (i) determination of access fee for recreational sites, and (ii) evaluation of changes in the environmental quality of recreational sites. There are three approaches to travel cost method: (i) zonal approach, (ii) individual approach, and (iii) random utility approach.

In the zonal approach, we divide the area surrounding the recreational site into various zones, usually in concentric circles. We then gather data on the number of visitors from each zone in a year (expressed as number of visitors per 1000 population in the zone). We then calculate the 'average travel cost on a round trip' (to and fro journey) for each zone taken as the 'average distance travelled by a visitor multiplied by the standard per kilometre cost'. This is then used to estimate the 'standard cost of time spent per visitor'. Finally, the total travel cost is obtained by adding up the cost of time spent and the travel cost. The individual approach is similar to the zonal approach except for the fact that it relies on a statistical analysis of the data obtained from individuals rather than the zones. Regression analysis is used to estimate the demand function for the average visitor to the site.

In the random utility approach we make use of the 'constrained utility maximization problem'. This is different from the zonal and individual approaches in the sense that it does not predict the actual number of trips a person will take to a recreational site. Rather, it estimates the probability that a person will visit a particular site, given the amenities it provides vis-à-vis other recreational sites. The underlying idea is to estimate the consumer surplus derived by visitors to a recreational site. If a number of recreational sites are available as close substitutes to one another, and a visitor has to make a choice, she is assumed to prefer the recreational site that offers maximum consumer surplus. The data requirement for the random utility model is much higher as compared to the zonal and individual approaches.

The travel cost method is thus based on the revealed preferences in the sense that in this method the behaviour of the respondents are observed or revealed. A major limitation of the travel cost method is that persons living nearer to a recreational site have lower travel cost and therefore lower value of the environmental services provided by the site.

### 11.4.5 Production Function Approach

The production function approach is applied to estimate the indirect use value of the environment. It consists of two steps: first, establish a relationship between the environmental input/service and the output, and second, estimate the monetary value of the environmental function. For instance, soil erosion upstream causes siltation in canals, reducing the flow of irrigation water. As a result of decreased water supply, there is a decline in crop production downstream. In order to measure the cost of soil erosion, we estimate the crop loss due to siltation and find out its value in money terms. This estimate is then considered as an estimate of the cost of soil erosion.

### 11.4.6 Related Goods Approaches

There are three similar methods under this category viz. barter exchange approach, direct substitute approach and indirect substitute approach (Lette and de Boo 2002). Here, a non-marketed environmental good or service is related to a marketed good or service.

**<u>Barter Exchange Approach</u>**: Some of the forest products such as wild fruits and vegetables are not sold in formal markets. However, some of these goods may be exchanged on a non-commercial basis for goods which are available in the market. The unit of exchange between the two can be used to evaluate the forest product. For instance, leafy vegetables are collected from forest by villagers residing in fringe areas which are quite often used for self–consumption. Since these vegetables are not marketed, it is not possible to find out their market prices. However, if these vegetables are regularly exchanged for some other commodity, like paddy, then the unit of exchange between leafy vegetable and paddy can be considered to determine the market price of leafy vegetables. In other words, the price of paddy used as a barter exchange, could be used to find out the value of the non-marketed leafy vegetables under consideration.

**Direct Substitute Approach**: In this case, the value of a similar good is used for the valuation of a natural resource. For instance, for the value of fuel wood collected by villagers from the nearby forests, a close substitute could be either the fuel wood bought from the market (by those who need to buy them) or the value of kerosene or charcoal used as an alternative resource to serve the need for fuel. The accuracy of this method, however, depends on the extent to which the non-marketed natural resource used and the marketed product are substitutes to each other. The limitations of market prices discussed earlier in Sub-Section 11.4.1 apply in this case also.

**Indirect Substitute Approach**: In many cases, it is difficult to find a direct substitute of a feely obtainable resource like fuel wood which is also traded in the formal market. In such cases, we combine the production function approach with the direct substitute approach. We first find out a direct substitute of the environmental function performed by the non-marketed product and then proceed to find out the value of this direct substitute through the production function approach. In other words, we find out the value of the environmental function indirectly through the production function approach. The indirect substitute approach is once again based on the stringent assumptions about the substitutability between the two goods, the role of the substitute good as an input in the production of the output and the value of the output.

### 11.4.7 Constructed Market Techniques

In many cases where environmental goods and services do not enter formal markets we construct a hypothetical market for the purpose of valuation of the environmental function. There are two methods under this category as discussed below.

**Contingent Valuation Method**: In this method, we construct a hypothetical market for a particular environmental function. This is an interview-based method where respondents are asked to place a value on certain environmental function or their willingness-to-pay (in monetary terms) for continuation of the environmental function. Alternatively, some studies measure the willingness-to-accept for foregoing the environmental function. Here, the consumers are hypothetically compensated for the change in the environmental service.

**Contingent Ranking Method**: This is also an interview-based method but differs from the contingent valuation method in that it does not ask the respondents to place a monetary value on an environmental function. It rather asks the respondents to rank a few amenities. Of these amenities, one is viewed as benchmark against which others are compared.

The constructed market techniques are put under the category of 'stated preference method' as the respondents 'state' their views on the issue not 'revealed' in their behaviour. There are certain advantages as well as limitations of the stated preference methods. The major advantage is its flexibility i.e. it can be used in the valuation of a wide variety of non-marketed environmental goods and services. In fact, it is the only method available for valuation of non-use value of environment. There are certain conceptual problems associated with the stated preference methods. First, the estimated value of the willingness-to-pay is often found to be different from the estimated value of the willingness-to-accept with the latter being usually higher than the former. Moreover, both these terms do not imply the same property rights. Secondly, the persons interviewed are hypothetical consumers who may not be aware of the benefits of the environmental function. If they were actually asked to make payment, their behaviour would be different. Thus, it is sensitive to numerous biases in survey design and implementation.

### 11.4.8 Cost Based Methods

There are five cost-based valuation tools. These tools take the cost of maintenance of the environmental function as its value.

**Indirect Opportunity Cost**: This method is used when more of individual labour, as compared to capital requirement, is involved in harvesting or collecting the natural resource. A basic assumption of this method is therefore that the requirement of capital for such a job is minimal. For instance, for gathering fuel wood in forests individuals need to spend time and do not need much capital. The opportunity cost of such time spent could be considered as the value of the environmental resource under consideration. The pitfall of this method is that the value of environment obtained bears no relationship with its cost of production. In the example of fuel wood, if the value of fuel wood is taken to be only its gathering cost, then it assumes that the cost of production of fuel wood is zero which is not true. Secondly, in many cases fuel wood gathering is a subsidiary activity i.e. farmers on their way back home from their main job may collect some fuel wood. In such cases it involves joint production (e.g. farm output and fuel wood) and separating the labour cost of fuel wood is arbitrary.

**Restoration Cost**: The restoration cost technique takes into account the cost of recreating the ecosystem. For instance, degradation of forests results in a reduced flow of forest products and its other functions. In order to restore the flow of functions of the forest, government intervention (in terms of policy implementation for afforestation) is necessary. Thus, according to the restoration cost method, the value of forest functions is its restoration or re-creation cost.

**Replacement Cost**: This method takes the value of ecological functions as the re-creation cost (of ecological functions) through man-made production processes. It assumes that the benefits provided by an intact ecosystem can be measured and there are alternatives available to provide such benefits.

**Relocation Cost**: This method is applicable in situations where natural environment in a particular area is put to some alternative use. For instance, the cost of establishing a new protected forest area. In this method, the flow of ecological functions is maintained as in restoration cost and replacement cost techniques. However, the difference is that instead of recreating ecological functions in the vicinity, the inhabitants are moved to a different locality.

**Defensive Expenditure**: This could be considered as a revealed preference method where the value of environmental benefit is taken to be the cost of averting the adverse impact of environmental degradation. We can cite the following two examples to explain this method: (i) farmers can increase the use of inputs (fertilizer, pesticides, seed, etc.) to neutralize the effect of falling land productivity; (ii) in order to avoid cough, breathlessness or irritation in the eyes, residents in an industrial area may take regular medicines. The expenditure on such heads can be added to obtain the total preventive or defensive cost, which will then provide a better estimate of the value of environment.

From the above discussion , you would have noticed that the valuation tools are to be applied to specific environmental services and that too in a limited geographical area. For valuation of a particular function, there could be more than one valuation tool. The use of a technique (or a combination of these techniques) therefore depends upon the nature of the problem – apart from the objectives of the study and the convenience of the researcher. Given the nature of problems encountered and the enormous task involved, most studies are local in their approach with few researchers having attempted to consider a comprehensive study on total economic value of environment.

## 11.6 VALUATION OF BIODIVERSITY

Biological diversity (or biodiversity in short) refers to the presence of a large variety of biological resources. A biological resource is a gene or species or ecosystem (OECD 2002). Diversity in biological resources implies that a habitat is richer or more diverse if the number of species available is larger. Thus, there is concern for 'evenness' of species in the sense that all the species serve to coexist when they are in adequate numbers. In other words, if one species is available in large number, while another is almost extinct, it does not indicate a sustainable position. Thus, two important characteristics of an ecosystem are 'richness' and 'evenness' of species. For this, two dimensions of biodiversity are important viz. species composition (i.e. the variety of species that are present) and species interaction (i.e. how different species interact – particularly *trophic* interaction in a food chain). These characteristics taken together imply that a change in the species composition on earth or in a region could have severe environmental implications from the point of view of sustainability.

Valuation of biodiversity is a complex issue as biodiversity is not an object; it is a set of characteristics or attributes which are intangible and incomprehensible as it is. Thus, many of the valuation tools discussed above will be irrelevant for valuation of biodiversity. As you can observe from Table 11.1, biodiversity has both 'use value' and 'non-use value'. Its use value pertains to option value which is yet to unfold (i.e. certain genetic resource may be of immense value in future) and its non-use value refers to bequest value and existence value (i.e. passing on the environment to the next generation and value derived by non-users from the fact that something exists, respectively). The most suitable methods for valuation of biodiversity are 'stated preference methods' like contingent valuation and contingent ranking. In fact, contingent valuation method is widely applied for evaluation of 'willingness to pay' for conservation of endangered species. This is evidenced by several studies which have attempted to estimate the willingness to pay of individuals for conservation of specific species (Table 11.3). A major problem that comes up in using the stated preference method for valuation of environment is that a large number of people do not have adequate and correct information on the concept of biodiversity and its importance. Because of this, when they are asked to assign a value on biodiversity or rank alternative scenarios, their preferences do not describe reality. Secondly, the value assigned by individuals to biodiversity may be lexicographic rather than utilitarian. An implication of this is that individuals do not visualize the possibility of compensating for the loss through an increase in the availability of another good or service (Salles, 2011).

The valuation of biodiversity is thus a contentious and debatable issue but the valuation methods are getting refined over the years. In this context, a statement by an eminent ecologist, Robert Scholes, is worth noting: “the total value of biodiversity is infinite so having a debate about what is the value of nature is actually pointless because we can’t exist without it”. The issue is not to put an economic value on nature, but to translate the value of losses from destruction of some ecosystems in terms that allow comparison with other societal issues (Salles, 2011).

Table 11.3

Willingness-to-pay for diverse charismatic vertebrate species (in dollars per household and per year)

| Group | Species | Place | WTP ($) | Reference |
|---|---|---|---|---|
| Mammals | Rhinoceros | UK for Namibia | 54-65 | OCDE, 2001 |
| | Wolf | Sweden | 126 | Loomis et White, 1996 |
| | Grizzly bear | USA | 46 | Id |
| | Sea otter | USA | 29 | Id |
| | Grey whale | USA | 26 | Id |
| | Bighorn Sheep | USA | 21 | Id |
| | Caribou | Canada | 14-98 | Anielski et Wilson, 2005 |
| Birds | Northern spotted owl | USA | 70 | Loomis et White, 1996 |
| | Whooping cranes | USA | 35 | Id |
| | Red cockaded woodpecker | USA | 13 | Id |
| | Bald eagles | USA | 24 | Id |
| Reptiles | Sea turtle | USA | 13 | Loomis et White, 1996 |
| Fishes | Pacific salmon | USA | 63 | Loomis et White, 1996 |
| | Cutthroat trout | USA | 13 | Id |
| | Atlantic salmon | USA | 8 | Id |
| | Squawfish | USA | 8 | Id |
| | Stripped shiner | USA | 6 | Id |

Source: Salles (2011)

## 11.5 VALUATION OF ENVIRONMENT IN INDIA

In recent years a large number of studies have come up on valuation of environment in India. Most of these studies have a limited coverage in terms of geographical area and environmental functions. However, a few studies have attempted to take a broader view of the environmental aspects. A brief overview of some of these studies is presented in this section. We first begin by making a reference to the official recognition accorded by the central statistical organisation (CSO), the principle data publishing source in India on GDP and other macroeconomic aggregates, in taking initiatives to account for natural resources depletion while assessing their true economic value to the country’s GDP estimates.

As we know, environment provides a wide range of functions many of which are intangible in nature. Only some of these are tangible and are therefore traditionally included in the estimation of gross domestic product (GDP). Two sectors which are important from the point of view of natural resources depletion with its impact on environmental sustainability that has received the attention of the Indian statistical system are: (i) mining and quarrying and (ii) forestry. The former deals with the extraction of raw materials where the GDP originating from the mining sector is assessed as the gross value added to the resources available naturally. Although it contributes about 2.5 percent of

GDP, it still seems to be an underestimate of its true economic value as only the extraction cost is taken into account. A similar scenario is observed in the case of forestry sector which contributes about 2 percent of GDP of India. The estimation procedure of the contribution of forestry and logging sector to GDP is given in the publication 'National Account Statistics: Sources and Methods' (2012) brought out by the Central Statistical Organisation (CSO). According to National Industrial Classification (NIC) the activities that are covered in the forestry sector are: (i) growing of standing timber (planting, replanting, transplanting, thinning, etc.); (ii) logging (e.g. felling timber and producing wood in the rough); (iii) gathering tendu leaves; (iv) gathering of other wild growing forest materials (cork, lac, resins, etc.) including fuel wood; and (v) logging service activities (such as transportation of logs within the forest). The GDP from forestry sector is estimated by the production approach where the value of output is estimated at factor cost.

According to the CSO (2012) data on major forest products are available but quality of data on minor forest products is generally not satisfactory. It is primarily due to substantial unrecorded exploitation of forest resources apart from authorized production by the right holders. The unrecorded production comprises: (i) authorised (but unrecorded) and unauthorised removals of timber and firewood from reserved/protected forest land; and (ii) unrecorded production from privately owned forests and non-traditional forest areas (e.g. trees in village commons, field ridges, canal sides, road sides, fruit trees no longer productive, etc.). The CSO estimates the unrecorded production as a percentage of recorded production.

Observing that many of the services provided by forests are not included in the GDP, many researchers have attempted to do so by expanding the product boundary of forest goods and services and then estimate the value of these services. For instance, Chopra (1993) includes forest services such as soil conservation, nutrient recycling, and tourism and recreation apart from supply of fuel wood and fodder. She takes into account some of the use, non-use and option values of forests and estimates that the value of forests ranges between \$4034 and \$6662 per hectare. Of this, the use-value is estimated to be about 45 percent.

The estimation of goods and services originating from nature is limited to marketable and tangible products only. Keeping in view the fact that such a definition of the value of environment is too narrow, some studies have attempted to extend the product boundary. For instance, in a micro-study Hadker (et al., 1997) the recreational and educational value of a local park in Mumbai is estimated by contingent valuation method. At the state level, Haripriya (2000) has estimated the carbon sequestration function of forests in Maharashtra.

The stated preference method is quite popular and applied in a large number of studies. In the Indian situation, this method has been applied by Hadker et al. (1997) for measurement of recreational and educational value of Borivli National Park in Mumbai, James and Murty (1998) for the cost of water pollution of the river Ganga and Murty and Menkhaus (1994) for valuation of ecotourism in Koladeo national park.

**Check Your Progress 2** [answer in about 100 words in the space given]

1. Explain the contingent valuation method of valuing environment.

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2. Suppose you have to estimate the total economic value of a watershed near your village. What are the functions of the watershed that you would include? How would you measure the value of these functions?

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3. What are the problems encountered in estimating the total economic value of environment in India?

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## 11.5 LET US SUM UP

Environment has a vast array of functions out of which some are assumed to have a zero economic value as these are available free to us. Some of these functions are non-tangible in nature and not marketable. However, these functions have important role in our production and consumption activities. As the value of all the environmental services are not taken into account in decision-making environment is always undervalued. In recent years, researchers have attempted to expand the product boundary of environment by considering the value of more and more functions of the environment. The problem however lies at two stages: identification of environmental functions and valuation of these functions. Existing literature on environmental valuation provides a wide range of valuation tools all of which are discussed in this unit. The measurement procedures are quite different and are suitable for different functions and circumstances. While applying these techniques the appropriateness of these tools should be carefully judged. In India, in recent years, a lot of studies have been undertaken on valuation of different aspects of environment. Most of these studies are microscopic in the sense that they consider a small geographical area. However, a few studies have extended the product boundary and considered the economic value of certain environmental aspects of the whole country.

## 11.6 KEY WORDS

**Carbon Sequestration**: The value of carbon sequestration function of forests is estimated by going through the following steps: (i) estimate the bio-mass stocked in a forest area, (ii) estimate the change in stock (= regeneration – depletion) over a year, (iii) estimate the carbon stock in such wood mass, (iv) assume a standard price of carbon per ton of weight and (v) estimate the value of the annual change in carbon stock in the forest area.

**Market Failure**: The price determined by interaction of supply and demand does not reflect true economic value of a product. Apart from externalities, there are certain factors such as taxes, subsidies and other regulations that hinder realisation of a market price based on economic efficiency.

**Policy Failure**: It refers to the unintended adverse effects of government policy. For instance, a policy to promote minor irrigation may result in depletion of water table. Similarly, a policy to promote industry may adversely affect the environment.

**Stakeholders**: It implies interests groups which can be divided into various categories such as local, national and international. Also, stakeholders can be seen as intergenerational groups such as current generation and future generation. As natural capital is limited, interests of various stakeholders often conflict with one another.

**Social Capital**: It refers to the stock of community resources. It is reflected in religious, ethical, social and cultural interactions in a community which contributes to the collective social well-being.

**Human Capital**: It is the collective human knowledge, skill and intellect. Together with social capital, human capital forms the interface between man-made capital and natural capital.

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## 8.7 ANSWERS/HINTS TO CYP EXERCISES

**Check Your Progress 1**

1. Environment is undervalued as we consider only those functions which enter into formal markets; as we have a short-term goal; and as we consider only private costs and benefits.
2. We need to widen the product boundary by considering all the environmental functions. Thus we include both use and non-use values to obtain TEV.
3. Use value involves some human interaction with the resource. Direct use value is tangible in nature while indirect use value is intangible. The indirect use value is difficult to quantify as it is intangible. You can consider an example of your choice. The difference can be explained through an example of a watershed in a village. Examples of direct use values are: supply of irrigation water to nearby land, drinking water supply to households and animals, fishery, etc. An example of indirect use values is microclimatic stabilisation.

**Check Your Progress 2**

1. You can go through Sub-section 8.4.7 to answer this question. As additional material, you can go through some case studies that have used this method, for example, Hadker et al (1997).
2. In order to find out the TEV of the watershed you need to consider both use and non-use values of watershed. Prepare a figure similar to Fig. 8.1 and cite at least one function under each head. For each function, point out the valuation method you will use.

# UNIT 12 DETERMINANTS OF RENEWABLE RESOURCES

**Structure**



## 12.0 OBJECTIVES

After going through this unit, you will be able to:

- state the basic features of renewable resources;
- specify the characteristics of renewable resources under dynamic system and dynamic optimization;
- derive the results for the optimal use of renewable resources under the discrete and continuous time frames;
- discuss the biological model for optimal harvest of fishing resources;
- discuss the economic approach to optimal forestry in terms of the Faustmann Result;
- bring out the influence of different exogenous variables upon the optimal rotation length in forestry;

- state the factors that keeps the optimum rotation age in forestry under private markets different from the social optimum; and
- outline the new dimensions to forestry under the contemporary challenges.

## 12.1 INTRODUCTION

The essential feature of renewable resources is that the stock is not fixed i.e. it can increase naturally if the stock is allowed to regenerate. Examples of renewable resources are fishery, forest, marine resource, water, etc. However, there is a threshold point defined by the maximum stock, beyond which no renewable resource can regenerate. This is further decided by the carrying capacity of the ecosystem in which it exists. The potential for increase is important because man can harvest the incremental stock and, provided certain conditions are met, the harvesting of the incremental stock and its growth can go on for successive time points in a sustainable manner. Other things being equal (i.e. conditions within the relevant ecosystem not adversely affected) there is reason to suppose that this process of harvesting can carry on for very long period. Thus, although the natural growth process can replenish the loss of biomass due to the harvest within a relatively short period, if the harvesting rate far exceeds the natural regeneration rate, it may lead to a situation where the stock might go below the threshold level so that further regeneration is not possible. In such cases, further harvesting could lead to extinction of the renewable resources. The line dividing the exhaustible resources and renewable resources is not always clearly drawn. In view of this, just as exhaustible resources in a sense can be renewed (through exploration and technology), renewable resources can suffer the opposite effect of being exhausted. In fact, much of the current concern about resource exhaustion involves renewable resources.

In the case of biological resources, the size of the resource stock (population) is determined jointly by biological factors and human interference. The size of the population, in turn, determines the availability of resources for the future. As the flow of these resources over time is not purely a natural phenomenon, a crucial issue is the optimum (efficient) rate of resource use over time and over generations. A related question is: can the market be relied upon to achieve and sustain this rate? However, the framework used in this Unit is focused on single species, without considering the fact that species are *interdependent*. This approach acknowledges the fact that the optimal use of interdependent species might be exceedingly complex. Two important renewable resources viz. fishery and forestry are only considered in this unit.

## 12.2 DYNAMIC OPTIMIZATION

All natural systems are dynamic in the sense that they change over time. They are also able to sustain life despite shocks. One important feature of the dynamic system is whether the variables within the system tend to converge to a fixed point (called steady state) over time. The existence of such steady state points and whether we can ever reach them is of particular importance for managing natural resources. The fixed point is globally stable because whatever be the initial value of the variable (i.e. greater or lesser than the steady state point) the variable will converge itself over time. The transition of a variable (or system) from one value to another over time is called *trajectory*. Since a steady state point is an optimum of a given objective function, we wish the optimum to be globally stable in the sense that whatever the initial value of the system the trajectory should always converge to the optimum. The more able is a system to return to a former state, the larger is the magnitude of stock and greater is its resilience. But some untimely shocks may upset the system so seriously that it may flip to an entirely different state.

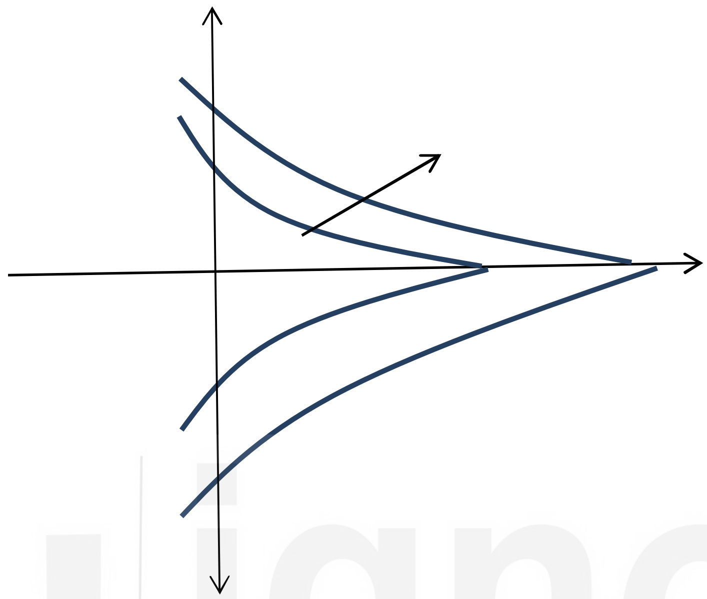

**Figure 12.1: Trajectories to a Fixed Point**

In a dynamic optimization problem, the stock and flow relationships are characterized by dynamic constraints that defines how the stock changes over time. For analysing this, in this unit, we first consider a fishery population, where the optimization is to maximize the present value of the net profits, governed by the dynamic constraint specified as:

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

where, x is the stock of fish, $\frac{dx}{dt}$ is the change in the stock of fish over time, F(x) is the natural growth of the fish stock determined by mortality and fertility and h(t) is the harvest for time period t.

### 12.2.1 Discrete Time Model

When changes occur at discrete points of time, the difference equation describing the dynamic path is specified as:

$$x_{t+1} = f(x_t) .$$

If, $x_{t+1}$ = a + b$x_t$ is the first order difference equation, then the general solution is derived by solving the complementary function and the particular integral. Thus, steady state value is the particular integral: $x_t = x_{t+1} = x_p = \frac{a}{1-b}$, b≠ 1.

Then for the Complementary Solution ($x_C$), let $x_t$ = A$b^t$, so that, $x_{t+1}$ = A$b^{t+1}$

Thus the Solution: $x_t = x_C + x_p = \text{A}b^t + \frac{a}{1-b} = (x_0 - \frac{a}{1-b})b^t + \frac{a}{1-b}$, 0 < b< 1

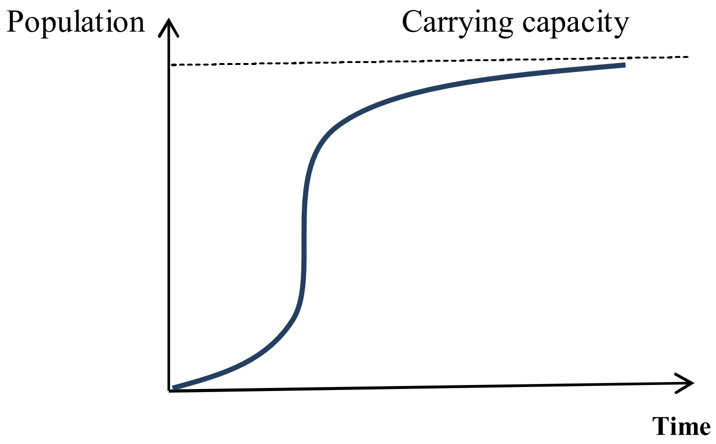


**Figure 12.2: Sigmoid or S shaped Growth Curve**

Since $0 < b < 1,\ as\ t \to \infty,\ x_t \to x_p$.

Thus, $x_t$ *converges towards the fixed point* $\frac{a}{1-b}$, *if* $0 < b < 1$ .

Difference equations can be used to model seemingly very complex system behaviour. A commonly used model of population dynamics of some animal population growth is captured by *logistic growth* curve: $x_{t+1} = a\, x_t(1 - x_t)$. It exhibits a lower growth at the lower population level and when it is large, it has its highest rate of growth at intermediate level of stock. Such behaviour is called *density dependent growth*.

## 12.2.2 Continuous Time Model

When changes occur at a continuous point of time differential equations are used. For the logistic growth curve $ax_t\,(1\text{-}x_t)$, we have:

$$\frac{dx}{dt} = ax(1 - x) = \dot{x}$$

$$\frac{d\dot{x}}{dt} = a(1 - x) - ax = a - 2ax$$

$$\frac{d\dot{x}}{dt} = 0 \implies a - 2ax = 0 \text{ or } x = 1/2$$

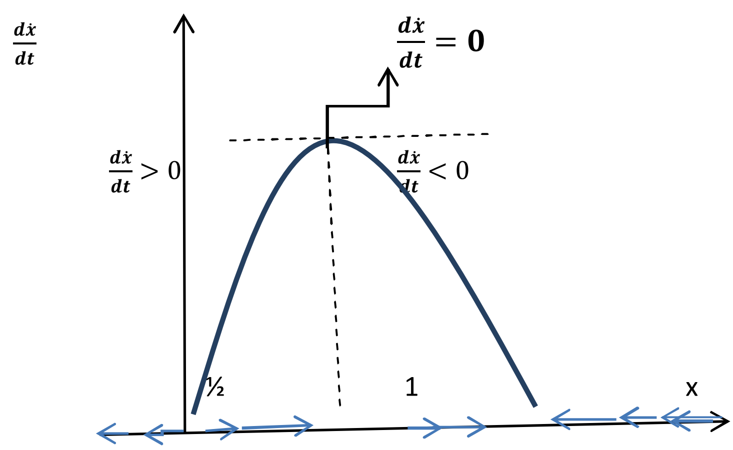


**Figure 12.3: Logistic Growth Curve**

$$\frac{dx}{dt} = 0 \; when \;\; either \; ax = 0, or \; (1 - x) = 0$$

$$i\,e. \; when \; either \; x = 0 \; or \; x = 1$$

Hence, the growth of the population or biomass has three fixed points:

$$x = 0 \; or \; x = 1, x = 1/2$$

1. $x = 0 \;\Longrightarrow \frac{dx}{dt} = 0 \Longrightarrow Population \; is \; extinct$

2. $x = 1 \Longrightarrow \frac{\boldsymbol{d\dot{x}}}{\boldsymbol{dt}} = 0 \Longrightarrow \frac{\frac{dx}{dt}}{dt} = 0$
$\Longrightarrow \; x^* = 1/2 \Longrightarrow Growth \; of \; population \; is \; maximum$

3. $x = 1 \Longrightarrow \frac{dx}{dt} = 0 \Longrightarrow Population \; is \; at \; the \; carrying \; capacity$

Differential equation can be used to model a wide range of dynamic behaviour. For instance, a variable in a system may exhibit exponential growth.

$$\frac{dx}{dt} = (a - b)x \Longrightarrow \frac{1}{x}dx = (a - b)dt \;\; \Longrightarrow \int \frac{1}{x}dx = (a - b)\int dt \;\; \Longrightarrow or$$

$$lnx = (a - b)t + c$$

Or $x(t) = \; e^{(a-b)t+c} \; = \; e^{(a-b)t}e^c$ , for t = 0 , $x(0) = \; e^{(a-b)0}e^c$. Thus, $x(0) = \; e^c$

Therefore $x(t) = \; x(0)e^{(a-b)t}$

Where, a is birth rate, b is death rate, (a –b) is net growth rate,
$x(t) \; is \; the \; population \; in \; time \; t \; and \; x(0)$is the initial population.

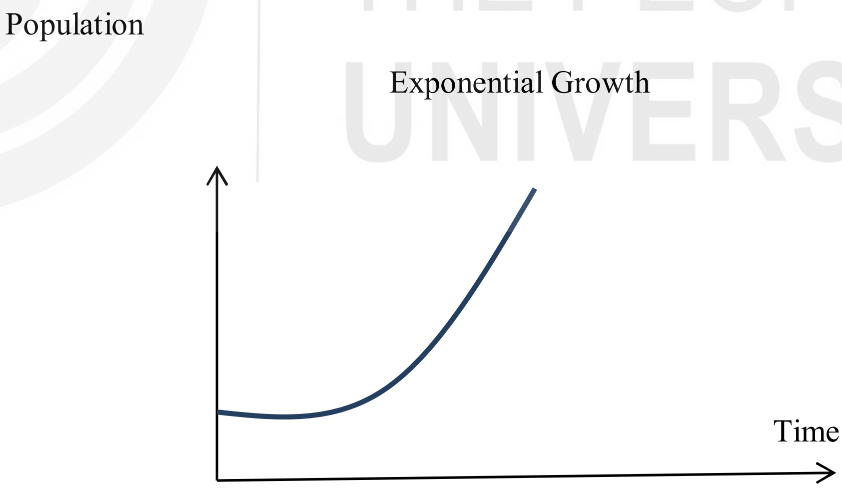


**Figure 12.4:Exponential Growth**

The system has only one fixed point, where $\frac{dx}{dt} = 0,$ when $x(t) = 0.$ However, no natural system can have exponential growth in the long run. There exists some finite limit on the ultimate size of the variable.

**Check Your Progress 1 [answer within the space provided in about 100 words]**

1. What is meant by a 'fixed point' in a dynamic system? By what alternative name is this fixed point also called as?

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2. In a standard fishery population optimization problem, explaining the usual notation followed, state how the dynamic constraint is specified?

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3. In a dynamic optimisation problem under continuous time framework, in which two steady state points the growth of the population is optimum? Why?

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## 12.3 BIO-ECONOMICS OF FISHERY

The basic economic choice to be made with respect to living resources such as fish stock is 'how intensively they should be exploited'. Fishing requires application of fuel, labour and implements, all of which could be used for some other purpose. The question therefore is whether we are getting as much value in return for our efforts from fishing as we could get otherwise. The reason why most of the fish in the sea are not farmed is that, unlike land resources, most fishes are highly mobile, cannot be domesticated in a terrestrial sense and inhabit a world where boundaries are difficult and expensive to enforce and therefore property rights cannot be enforced. As a result, only selected pockets of fish stocks are over exploited from both biological and economic perspectives. The consequence of over-exploitation has a profound impact on the poor world (especially in Asia) where fish represents a major source of animal protein.

Many examples exist on how over fishing has brought about the collapse of fisheries (e.g. Canada's northern Cod fishery, important sardine and herring fisheries, innumerable salmon fisheries) or to a situation of extreme vulnerability to environmental shocks. Degradation of habitats, especially important spawning grounds, by fishing and other activities also have negative impacts on several important stocks. According to one estimate, a substantial part of the world's fisheries are biologically over-exploited in the sense that if stocks were allowed to recover they would generate a higher yield or catch (Hilborn and Walters 1992). Despite this observation, the world's catch has continued to increase and therefore the existing and previously under-exploited stocks are coming under increased fishing pressure. Increased fishing effort and decline in catch and stocks of some important fisheries can be analysed by using both biological and economic models.

### 12.3.1 Surplus Yield Model/Schaefer Model

An important class of biological model, that are widely applied in fisheries and elsewhere are *surplus yield or production* model. Surplus yield model ignores the issues of differences in cohorts and mortalities. It simply analyses the interaction effects of the biomass and growth in the biomass on the fishery. Such kind of models can take various functional forms, but all assume density dependent growth. This assumption means that the biomass has a tendency (in the absence of fishing) to approach its maximum level or carrying capacity at the rate that depends on the size of the biomass. The fastest growth is when the biomass is at the intermediate level and its slowest growth is when the biomass is either close to zero or close to its carrying capacity. A commonly estimated model that assumes the logistic growth equation, called the Schaefer model, is as follows:

$$\frac{dx}{dt} = rx(1 - x/k) \ldots\ldots\ldots\ldots\ldots\ldots \text{(12.1)}$$

Where, x is the biomass, r is the intrinsic growth rate, and k is the maximum carrying capacity for the fishery.

Consider a population dynamics of a stock of fish (or biomass) of a single species which is supposed to follow growth through time 't'. If it follows a logistic function, then the stock of fish multiplies at low levels, but as they begin to compete for food supply, their rate of growth slows down and eventually the stock converges to some maximum level just equal to the carrying capacity ($X_{max} = k$) of the ecosystem for that species (in the absence of human intervention). The growth curve (Figure 12.5) starts from the critical minimum level of population $X_{min}$. If the bio mass goes below this critical level, the species is driven to extinction $X_{zero}$. The growth of biomass ($\frac{dx}{dt}$) or $\dot{X}$ (i.e. the rate of change in stock X with respect to time) is represented on the vertical axis and the level of stock or biomass X on the horizontal axis. For the ease of exposition, we assume that there is no critical minimum size of population and therefore the segment between $X_{min}$ and $X_{zero}$ is omitted. The Figure thus reflects that the rate of growth of resource stock is first positive, then reaches a maximum and then declines as the stock gets bigger. If we let the resource alone, it will grow and grow in size, in terms of the total biomass, until it reaches the carrying capacity of the environment at $X_{max}$. The growth rate of the resource reaches a maximum at the point $X^*$ [called the *maximum sustainable yield* (MSY) which is to be derived by maximising equation 12.1 w.r.t.

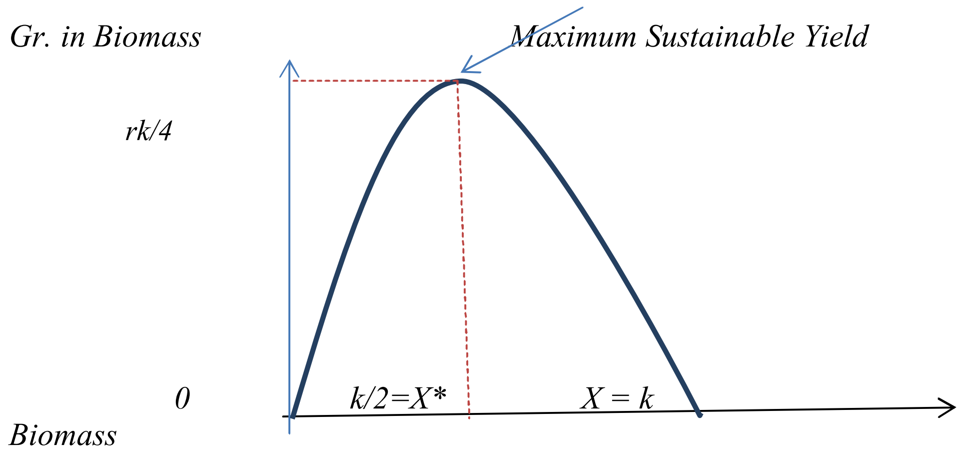


**Figure 12.5: Schaefer Model of a Fishery**

x]. Thus, if fishers are only concerned about the quantum of optimum fish they should catch, $X_{MSY}$ is the optimum level of biomass as it corresponds to the greatest surplus yield or sustainable harvest. The harvest level is called the *surplus yield* because if it is taken from the stock, it will regenerate itself without changing the level of biomass. Hence, MSY is the most we can take from the resource on a sustainable basis i.e. without reducing its long term stock. In the absence of fishing, the biomass should converge to its carrying capacity at k which generates a zero surplus yield.

Algebraically, differentiating the growth in biomass given in equation 12.1, and setting the result equal to zero, we can determine the biomass level that maximizes the growth. Thus:

$$\frac{\frac{dx}{dt}}{dx} = r\left(1-\frac{x}{k}\right) + rx\left(-\frac{1}{k}\right) = r - \frac{2xr}{k} = 0 = 2x = k \Longrightarrow x^* = {}^{k}/_{2}$$

…………… (12.2)

$x^*$ being the *maximum sustainable yield,* ${}^{k}/_{2}$ is the level of biomass that yields the highest yield or harvest of fish, without reducing the biomass. Substituting for $x^*$ from equation 12.2 into 12.1, the yield at this level of biomass can be shown equal to ${}^{rk}/_{4}$. The biomass that coincides with the maximum sustainable yield or MSY is commonly referred to as $X_{MSY}$. However, such an approach to fishery management is problematic for several reasons. First, fisheries like any natural population, are subject to random shocks, and trying to manage fishery to be always at a given biomass level will almost certainly fail. Moreover, in the face of uncertainty, an important management goal is likely to include a lower variance in the catch from year to year which may not coincide at a biomass level $X_{MSY}$. Second, measuring the parameters of the surplus yield model is prone to both error and bias since for obtaining the estimates of both ‘r’ and ‘k’, with any reasonable degree of precision, requirement of data on the biomass (at, or near to, the point of growth in the biomass) is close to zero. Third, as we will soon see the biomass that maximizes the total harvest will, in general, not maximize the net economic return from fishery.

### 12.3.2 Gordon Schaefer Model

The maximization of harvest or a yield from a renewable resource does not coincide with the maximization of the resource rent. This is because neither costs nor revenue are proportional to the harvests. One of the first to show this result in a formal way by using a biological and economic (bioeconomic) model for fishery was Scott Gordon (1954) for which he adopted the surplus yield model of Schaefer. In light of this, Gordon's analysis on fishery has commonly come to be referred as the *Gordon Schaefer Model.* In this, it is assumed that the harvests of fishers (h) is proportional to both the levels of biomass (q) and the fishing effort (E). That is:

$$h = qEx \quad \ldots\ldots\ldots\ldots\ldots \quad (12.3)$$

where q is the catchability coefficient that is independent of either fishing effort or the biomass. Using equations 12.1 and 12.3, the effort required to harvest the surplus yield ($\frac{dx}{dt}$) (which leaves 'x' unchanged) can be calculated as:

$$h = qEx = rx\left(1-\frac{x}{k}\right) \quad \Rightarrow \quad E = \frac{r\,(1-\frac{x}{k})}{q} \quad \ldots\ldots\ldots\ldots\ldots \quad (12.4)$$

The maximization problem that will solve for the optimal biomass level [which will give the highest net return (revenue minus costs) from the fishery on a sustained yield basis] is, therefore:

$$Max\,\pi = ph - cE \quad \ldots\ldots\ldots\ldots \quad (12.5)$$

where '*p'* is the competitive price and '*c'* is the competitive cost of fishing effort. Given that the harvest should equal the surplus yield, we can substitute (12.4) in (12.5) to obtain:

$$Max\,\pi = pqEx - cE = prx\left(1-\frac{x}{k}\right) - c\frac{r}{q}\left(1-\frac{x}{k}\right); \text{ [using (12.4) for E]}\ldots\ldots\ldots\ldots(12.5_a)$$

$$= r\left(1-\frac{x}{k}\right)[px - \frac{c}{q}] \quad \ldots\ldots\ldots\ldots\ldots \quad (12.5_b)$$

Differentiating w.r.t. 'x' and setting the first order condition equal to 'zero', we get:

$$\frac{d\pi}{dx} = \frac{d}{dx}\left[r\left(1-\frac{x}{k}\right)px - r\frac{\left(1-\frac{x}{k}\right)c}{q}\right] = \frac{d}{dx}\left[rpx - \frac{rp}{k}x^2 - \frac{rc}{q} + \frac{rc}{kq}x\right]\ldots\ldots\ldots\ldots\ldots\ldots(12.5_c)$$

$$= rp-2(rp/k)x+(rc/kq)=rp[1-(2/k)x]+(rc/kq)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12.5_d)$$

$$= pr\left(1-\frac{2x}{k}\right) + \frac{cr}{qk} = 0 \Rightarrow pr + \frac{cr}{qk} = \frac{2pr}{k}x$$

$$\therefore \quad x^* = \frac{k}{2pr}[pr + \frac{cr}{qk}] = \frac{c}{2qp} + k/2 \quad \ldots\ldots\ldots\ldots \quad (12.6)$$

If (12.6) is positive then fishers are earning resource rents or *super normal profits* (where if total revenue equals total costs, fishers earns normal profit). The biomass that maximizes the resource rent or sustainable economic yield, $x^*$, is commonly called $x_{MEY}$ or the biomass that gives the *maximum economic yield*. Provided that *q, c* and *p* are greater than zero, it follows from (12.2) and

(12.6) that the biomass that maximizes the sustainable economic yield is greater than the maximum sustainable yield i.e. $x_{MEY} > x_{MSY}$. This is shown in Figure 12.6, where the net revenue curve and $x_{MEY}$ represents the point where the marginal revenue from a change in the biomass exactly equals the marginal cost of harvesting this quantity of fish. The maximum economic yield gives higher level of the biomass than $x_{MSY}$, because the total cost of harvesting is decreasing in the biomass. In this sense, the biomass is like an input into the harvesting function where more fish can be caught for the same level of fishing effort.

Although $x_{MEY}$ is the biomass level that maximizes the resource rents, in the absence of any control on entry into the fishery, positive rents would attract further fishing effort reducing the biomass below $x_{MEY}$. In fact, so long as fishers can only earn normal profit in alternative employment, with resource rent being positive in fishery, additional fishing effort will continue to increase until eventually the resource rents are levelled to the point of profit in alternative employment. If such a point is represented by $x_{INF}$ (x infinity) and refers to the point of *bionomic equilibrium* (because if the biomass is greater than $x_{INF}$, additional fishing effort and entry would move it towards $x_{INF}$), exploitation with a biomass less than $x_{INF}$ generates a negative return reducing the effort and inducing exit. The time it would take to reach the bionomic equilibrium in an open access fishery depends on the rate of entry, the

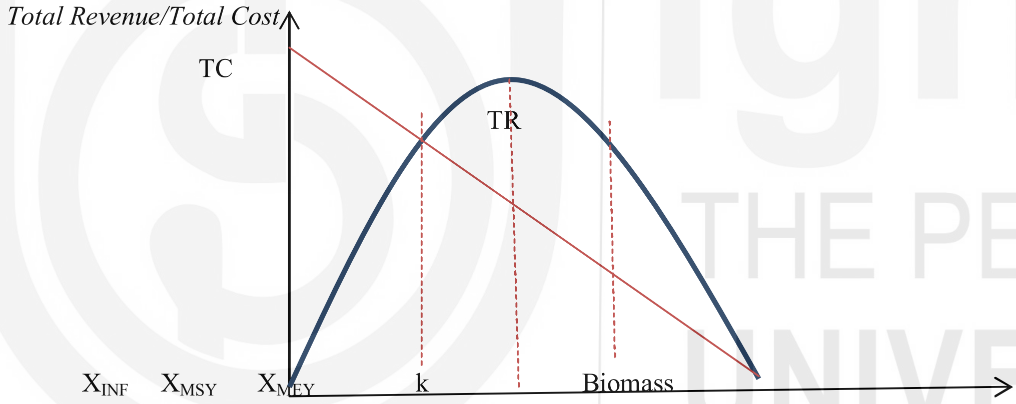


**Figure 12.6: The Gordon-Schaefer Model (Sustained Yield Biomass)**

size of the resource rents, the initial rate of exploitation, and other factors. The tendency for a common pool resource where yields are rivulrous and exclusion is difficult to move towards $x_{INF}$ has been called the *tragedy of commons* (Hardin, 1968). The tragedy arises because the resource is overexploited economically because no property rights exist. Thus, although fishers would be better off if the fishery were at $x_{MEY}$, the lack of property rights precludes the possibility of staying at such a point, or at any other biomass with positive resource rents. This is because positive resource rents attract additional fishing effort that reduces the biomass and move it towards bionomic equilibrium.

The Gordon-Schaefer model may also be represented directly in terms of the level of fishing effort rather than the level of biomass. This can be done by solving equation 12.5, but substituting for x rather than E. Thus, the maximization problem becomes:

$$Max\ \pi = \frac{pqEk(r-qE)}{r} - cE \quad \ldots\ldots\ldots\ldots \quad (12.7), \text{ so that,}$$

$$\frac{d\pi}{dE} = pqk - \frac{2pq^2Ek}{r} - c = 0 \quad \Rightarrow \quad E^* = r\left(\frac{1}{2q} - c/2q^2pk\right) \ldots\ldots\ldots\ldots \quad (12.8)$$

The level of fishing effort that corresponds to $x_{MEY}, x_{MSY}, and\ x_{INF}$, are $E_{MEY}, E_{MSY}, and\ E_{INF}$. These are indicated in Figure 12.7. From equation 12.3, we note that a higher X implies a lower level of fishing effort. Thus, if $x_{MEY} > x_{MSY} > x_{INF}$, it follows that $E_{MEY} < E_{MSY} < E_{INF}$. In other words, the level of fishing efforts that gives the maximum economic yield is less than the level of fishing effort that ensures the maximum sustainable yield. Thus,

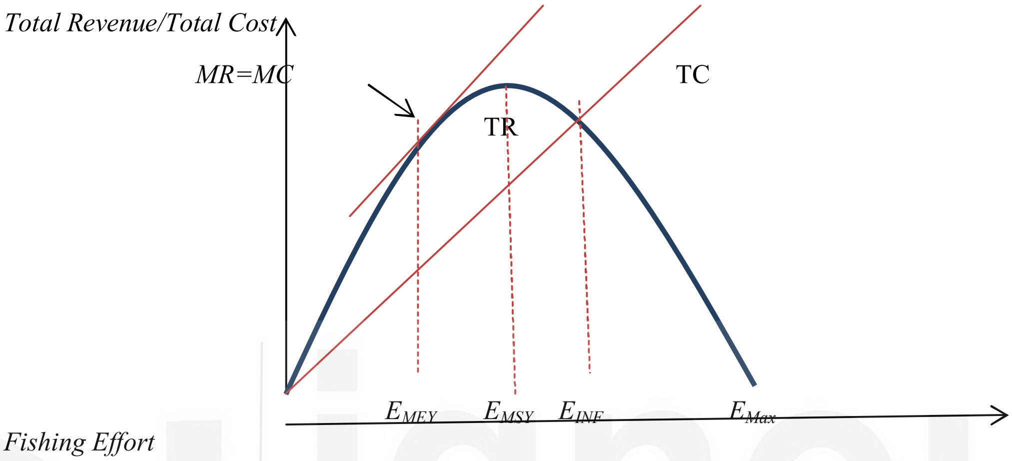


**Figure 12.7: The Gordon-Schaefer Model (Sustained Yield Effort)**

in the Gordon Schaefer or static economic model of the fishery, rent maximization is more conservative with lower fishing effort than the maximization of the sustained yield from the fishery. The implication is that if fishing effort could be controlled at $E_{MEY}$ (or at the point less than $E_{INF}$), then complete rent dissipation can be avoided. The first step is to restrict access to the fishery or limit entry in terms of the number of fishers or vessels. The second step is to control the fishing effort of fishers who have access to the fishery. The former has proved much easier than the latter. Although the results from the Gordon Schaefer model has proved insightful, it fails to consider what is the optimal path to get to the rent maximizing level of the biomass [a point recognized by Gordon himself (1956)]. The model also does not consider the consequences of discounting on the optimum harvest and biomass level.

## 12.3.3 Open Access and Common Property Solution

As we know, private ownership is not that common in the case of major fishery or forestry. Instead, we mostly observe government territorial ownership as with territorial waters with free access by the relevant country. Similarly, for some species of interest like whales, there may be no territorial rights either: the sea may simply be internationally common property. In either case, if there is excess profit above the normal level (i.e. TR > TC) new entrants will come in and the solution will be $E_{INF}$ (i.e. where TR = TC as in the Figure 12.7). The equilibrium is where profits are dissipated to the point where each resource exploiter secures only normal profit. Such open access equilibrium with the fishing effort of $E_{INF}$ at the point of equality of TR = TC may occur under certain common situations like:

1. The stock is less than that associated with profit maximization and the harvest rate is lower.

2. Open access does not coincide with MSY, unless TC cuts TR at the latter's maximum.

3. Open access does not generally lead to the extinction of the species – as argued by some environmentalists that open access resources are inevitably doomed. The conditions under which extinction will occur are: (a) effort is costless i.e. effort is at $E_{max}$ as in Figure 12.7 and the stock goes to zero and (b) harvesting takes place at levels persistently above the natural rate of regeneration i.e. the harvest is *non sustainable*.

In the case of open access, since no one owns the resource, there is no limit to the new entrants. However, there is some well defined group or community who enjoys the user right in the case of common property fishery. Hence, in terms of Figure 12.7, we may expect a common property solution somewhere between the profit maximizing solution and the open access solution. Since the profit maximizing solution involves least effort, in case of a larger stock, the risk of extinction is low. The open access solution, although is more likely to risk extinction, is not inevitable. This is because effort is much greater and stocks are consequently lower. The common property solution therefore lies somewhere in between.

### 12.3.4 Optimal Biomass

Discounting has important implications in terms of both the optimal level of harvest and biomass. The greater the discount rate, the less valuable are returns in the future relative to the present and greater the incentive not to invest in the resource reducing the current harvest. To show this result formally, we first need to determine the optimal level of biomass given a positive discount rate.

Let '*h*' be the *control variable* (i.e. the level of harvest) for determining the present and future values of the resource stock. Let $x$ be the *state variable* denoting the stock of biomass and $F(x)$ the growth in the biomass in the absence of fishing. Let $p$ be the given price of the resource with the cost of harvest defined by $c(x)h$ where $c'(x) < 0$ indicates that an increase in the biomass for a given harvest level reduces the costs of fishing. The instantaneous resource rent or net returns in the fishery is $[p - c(x)h]$ with time entering the problem through the discount factor $e^{-\delta t}$, $\delta$ being the discount rate. The dynamic problem of the fishery is to maximize the present discounted value of the resource rent (V) with the objective functional given as:

$$Max\ V = \int_{t=0}^{\infty} e^{-\delta t}\{(p - c(x)h\}dt \quad \ldots\ldots\ldots\ldots\ldots \quad (12.9)$$ subject to the

$$Dynamic\ Constraint\ \dot{x} = \frac{dx}{dt} = F(x) - h \quad \ldots\ldots\ldots\ldots.. \quad (12.10)$$

$$and\ the\ boundary\ constraint\ \ x_o = x(0) \ \ldots\ldots\ldots\ldots. (12.11)$$

Equation (12.10) is the *dynamic or the biological constraint*, which states that the change in the biomass over time must equal the growth in the biomass less the harvest. If $\frac{dx}{dt} = 0$, the resource is being harvested sustainably, if $\frac{dx}{dt} > 0$, the harvest is less than the growth in the biomass which amounts to '*investing*' or increasing the resource stock and if $\frac{dx}{dt} < 0$, the harvest exceeds the growth in the biomass amounting to '*disinvesting*' or reducing the resource stock. Equation (12.11) is the initial value of the *state variable* i.e. the resource stock or biomass describing 'the state of the system' in terms of the fishery.

The solution comes from the *Optimal Control Theory* where the present value Hamiltonian (H) is:

$$H = e^{-\delta t}\{p - c(x_t)\}h + \lambda_t\{F(x) - h\} \text{ ................ (12.12)}$$

The total current value Hamiltonian ($\bar{H}$) which captures all possible benefit from the fish stock, including both the present and the future benefits is obtained by multiplying (12.12) by $e^{\delta t}$ and denoting $He^{\delta t} = \bar{H}$ and $\lambda_t e^{\delta t} = \mu_t$:

$$\bar{H} = \{p - c(x_t)\}h + \mu_t\{F(x) - h\} \text{ ................ (12.12a)}$$

Where, $\{p - c(x_t)\}h$ is the current benefit and $\mu_t\{F(x) - h\}$ is the net future benefit with $\mu_t = e^{\delta t}$ as the *co-state variable* or the *shadow price* of the resource stock for the remaining period. We have two necessary conditions of which the first is:

1. $\frac{\partial H}{\partial h_t} = 0 \Rightarrow \frac{\partial \bar{H}}{\partial h_t} = 0$

i.e. $\frac{\partial \bar{H}}{\partial h_t} = p_t - c(x) - \mu_t = 0 \Rightarrow \mu_t = p_t - c(x) \Rightarrow p_t = \mu_t + c(x)$ ......... (12.13)

i.e. the price of the resource at the current period is equal to the marginal cost plus the user cost (shadow price).

2. The second necessary condition is: $\frac{\partial \lambda_t}{\partial t} = \frac{\partial H}{\partial x_t}$ .......... (12.14)

Note that $\bar{H} = e^{\delta t} H.\ Hence,\ e^{-\delta t}\bar{H} = H.\ That\ is,\ e^{-\delta t}\frac{\partial \bar{H}}{\partial x} = \frac{\partial H}{\partial x}$ .......... (A)

Similarly since $\mu_t = e^{\delta t}\lambda_t,\ \lambda_t = e^{-\delta t}\mu_t.\ Hence,\ \frac{d\lambda_t}{dt} = -\delta e^{-\delta t}\mu_t + e^{-\delta t}\frac{d\mu_t}{dt}$ ...... (B)

Substituting (A) and (B) in equation (12.14):

$$\frac{d\lambda_t}{dt} = \frac{\partial H}{\partial x} \Rightarrow -\delta e^{-\delta t}\mu_t + e^{-\delta t}\frac{d\mu_t}{dt} = e^{-\delta t}\frac{\partial \bar{H}}{\partial x}.$$

That is, $\frac{d\mu_t}{dt} - \delta\mu_t = \frac{\partial \bar{H}}{\partial x} \Rightarrow \frac{d\mu_t}{dt} = \delta\mu_t + \frac{\partial \bar{H}}{\partial x} \Rightarrow \frac{d\mu_t}{dt} = \delta\mu_t + \frac{\partial c(x)}{\partial x_t}h - \mu_t F'(x)$ ... ... ... (12.15)

[since from (12.12a) differentiating with respect to x $\Rightarrow \frac{\partial \bar{H}}{\partial x} = \frac{\partial c(x)}{\partial x_t}h - \mu_t F'(x)$].

Now from (12.13), $\mu_t = p_t - c(x) \Rightarrow \frac{d\mu_t}{dt} = -c'(x)\frac{dx}{dt} \Rightarrow \dot{\mu} = -c'(x)\dot{x}$

$i.e.\ \dot{\mu} = -c'(x)\{F(x) - h\}$ ...... [from the dynamic constraint equation (12.10)]

For the steady state $\dot{\mu} = 0,\ F(x) = h$. Hence, from (12.15) $we\ get,$

$$\frac{d\mu_t}{dt} = \delta\mu_t + \frac{\partial c(x)}{\partial x_t}h - \mu_t F'(x) = 0$$

$\delta\mu_t = -\frac{\partial c(x)}{\partial x_t} h + \{p_t - c(x)\}F'(x)$ [i.e. by substituting $\mu_t$ from (12.13)]

$\therefore \mu_t = \frac{1}{\delta} \quad \{-\frac{\partial c(x)}{\partial x_t} h + \{p_t - c(x)\}F'(x)\} \Longrightarrow \mu_t = \frac{1}{\delta}\frac{d}{dx}\{\{p_t - c(x)\}F(x)$ ……. (from the steady state condition $F(x) = h \Longrightarrow \mu_t = \frac{1}{\delta}\frac{dR(x)}{dx}$………….. (12.16)

$$\Longrightarrow p_t - c(x) = \mu_t = \frac{1}{\delta}\frac{dR(x)}{dx} \text{ ……… (12.16 a)}$$

Equation (12.16 a) is the Fundamental rule of optimal use of Renewable Resources. It implies that, if we reduce the stock of resource by harvesting a small amount there will be an immediate gain of $\big(p - c(x)\big)$, which is the instantaneous marginal return from harvest. But there will be a loss of future sustainable amount $\frac{dR(x)}{dx}$. The present value of the future sustainable amount (over an infinite time horizon) is $\frac{1}{\delta}\frac{dR(x)}{dx}$. This is due to the loss of stock of offspring of the marginal stock of harvest. Immediate marginal gain from an increase in current harvest of resource must be equal to the present value of future losses in rental brought about by that change. Equation (12.16a) solved for unknown 'x', provides the *singular solution* of the control problem. If $x^* > 0$ , it is the unique solution with $x^*$ representing the optimal equilibrium stock level.

Given $\mu_t = \big(p - c(x)\big)$ , from equation (12.13), rewriting equation (12.15) we get:

$$\dot{\mu} = \frac{d\mu_t}{dt} = \delta\mu_t + \frac{\partial c(x)}{\partial x_t} h - F'(x)\mu_t$$

$$i.e. \dot{\mu} = \delta\mu_t + \frac{\partial c(x)}{\partial x_t} F(x) - F'(x)\mu_t$$

Dividing both sides by $\mu_t$ we get: $\frac{\dot{\mu}}{\mu_t} = \delta + \frac{\partial c(x)}{\partial x_t}\frac{F(x)}{\mu_t} - F'(x)$ ………….. (12.17)

1. If the resource is a non Renewable resource (no intrinsic growth) then, $F'(x) = 0$

2. If the stock has no impact on cost then, $\frac{\partial c(x)}{\partial x_t} = 0$

Therefore equation (12.17) becomes: $\frac{\dot{\mu}}{\mu} = \delta$ ……………. (12.18)

As per the *Hotelling formulation* for Non Renewable resources, growth rate of the user price or the internal rate of return of the resource stock is equal to the discount rate. If $F'(x) = 0$ but the stock effect i.e. $\frac{\partial c(x)}{\partial x_t} \neq 0$ then extraction cost increases as long as $\frac{\partial c(x)}{\partial x_t} < 0$. Therefore, from (12.17) we get:

$$\frac{\dot{\mu}}{\mu} = \delta + \frac{\partial c(x)}{\partial x_t}\frac{F(x)}{\mu}. \text{ Thus, } \frac{\dot{\mu}}{\mu} < \delta, \text{if } \frac{\partial c(x)}{\partial x_t} < 0 \; and \; \frac{F(x)}{\mu} > 0. \quad (12.19)$$

The above (called as the Modified Hotelling Rule) implies that the *Shadow price* (or the future price of resources) will grow at a rate less than the rate of interest (or the discount rate).

**Check Your Progress 2 [answer within the space provided in about 100 words]**

1. State the form of the Schaefer Model. In this, show that the biomass level which maximises the growth of a single specie fishery population can be obtained as: $x^* = {}^{k}/_{2}$.

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2. Using the Schaefer Model [stated as: $\frac{dx}{dt} = \frac{rx(1-x)}{k}$], show that in the Gordon Schaefer Model stated as h = qEx (with known explanations for h, q and x), where the 'effort (E)' required to harvest the surplus yield is calculated by: $E = \frac{r}{q(1-\frac{x}{k})}$ .

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3. Is it true that open access always leads to extinction of resource accessed? State the two conditions under which extinction of a natural resource can occur due to open access.

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4. State the dynamic problem of fishery for maximising the present discounted value of the resource rent.

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5. State the 'fundamental rule of optimal use of renewable resources' with its implication.

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6. With explanation of notations employed, state the Modified Hotelling Rule and its implication.

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## 12.4 ECONOMICS OF FORESTRY

Forests are integral part of human civilization. They provide multiple benefits (i.e. wide spectrum of goods and services) including fuel, foodstuffs, building materials. It is an important source of environmental and amenity services. Forests protect us from flood, soil erosion, helps in carbon sequestration and thereby cleanse the air, attract rain, maintain the pool of genetic resources, protects bio diversity by acting as a natural habitat of wild life, etc. They thus play a crucial role in the ecology of watersheds that supply much of our useful water. Moreover, forests have great value in providing amenity services by adding to the scenic beauty, recreation and aesthetic motivation. Forestry economics has therefore broadened its focus from the study of the production of timber, or forest products, to more complex problems involving the environmental amenities, the critical role they play in sustaining ecosystem and consumption smoothening of the poor rural community. Forests, besides protecting many attributes of renewable resources, also exhibit some unique features. Trees are commercially valuable when they are cut and sold. However, if not cut, like capital assets, standing forests provide a stream of non-timber environmental services. Most of the environmental benefits provided by the forests have positive externalities which normally cannot be captured by the resource managers leading to inefficient management. Hence, the present section on forestry aims at covering how economics can be combined with forest ecology to arrive at an efficient management of this important natural resource.

One of the main issues involved in modelling the issues of forestry is that of choosing the appropriate scale. A forest may be small private forest or can be as large as covering a span of two continents or it may contain a diverse mix of tree species or a mono-specie 'timber stand' distinguished only by age. The most common unit of analysis used in forestry issues is 'timber stand'. In general, timber stand consists of trees within a contiguous area sharing similar characteristics such as age species, composition, etc. A forest can then be made up of a number of stands that are commonly managed as individual units. The fact that trees are fixed in location has several important implications. In general, a stand becomes more valuable with age as the standing volume increases. It is also assumed that the value of per unit volume of trees increases with age, reflecting the higher prices associated with older and larger trees. The flow of the benefits like forage for both domestic grazing stock and wild life, wild life habitat, water flow and recreational opportunities, changes over time as trees mature. The ability of the trees to sequester carbon is also dependent upon the size and age of the trees. Within a forest, the costs may be such that standing timber has no commercial value (as the price of the forest product that can be derived from the wood net of all processing costs, may just equal their transportation and harvesting costs). This limit marks the *extensive margin* beyond which trees have no commercial value. Other land uses such as agriculture, may also compete with forest land. Where economic return to forest land equal those of competing land uses, it delineates the '*intensive margin'*. The intensive margin is also used to sometimes describe the level of economic utilization within a timber stand. Certain species or smaller trees may be uneconomic and therefore be left behind depending upon the harvesting policies.

### 12.4.1 Biological Approach

The timber value of a tree is determined by the volume of a saleable timber a tree can produce. The volume of a timber in a uniform forest depends on the age of the trees represented by its *logistic growth function f(t)*. Since saleable timber is produced only after a tree has reached a minimum age $t^*$, the Logistic growth function demonstrates that the growth of a tree may continue to increase over time to a maximum (when the volume of a timber reaches a plateau) and then declines as the tree ceases to grow further after attaining its maturity. In fact, it may actually become negative when it starts decaying and eventually die. The typical relationship between the age of a timber stand (or tree) and volume is shown in Figure 12.8. The average annual increase in timber stand volume is known as the **Mean Annual Increment (MAI),** while the annual increase in timber volume (i.e. the change in volume from year to year) is known as **Current Annual Increment (CAI).** The biological approach to commercial forestry management is to choose the harvest age at which MAI of the trees in the timber stand is maximized (sometimes called the Culmination of the MAI). In a forest where the number of even aged stand equals the rotation age, harvesting a stand each year and replanting that stand will yield the maximum harvest by volume that can be sustained over time (since each stand advances in age and trees that are $T_{m-1}$ mature will become available for harvest in the succeeding year). The problem is therefore formulated as choosing the time of harvesting, T, that maximizes harvest volume over time. That is:

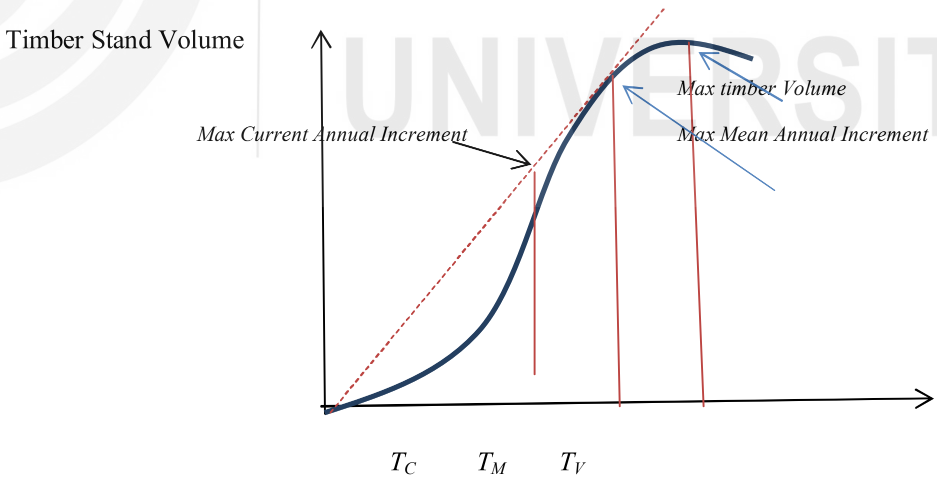


**Figure 12.8: Timber Stand Age (Years)**

$$\text{Maximize } W(T) = \frac{V(T)}{T} = MAI$$

First order condition gives:

$$\frac{dW}{dT} = \frac{V'(T)}{T} - \frac{V(T)}{T^2} \; i.e. \; \frac{V(T)}{T} = V'(T) = CAI \; \ldots\ldots\ldots\ldots\ldots \; (12.20)$$

Figure 12.9 shows the MAI which corresponds to the average product curve and the CAI (the marginal product curve or $V'(T)$ based on the growth function depicted in Figure 12.8. The 'culmination of mean annual increment' (CMAI) is reached where CAI crosses the MAI curve i.e. at $T_m$. This is equivalent to choosing the stock and harvesting effort that will maximize the sustained yield in fisheries (MSY). Under this approach, each year $1/T_m$ of the forest would be harvested (assuming all stands are identical).

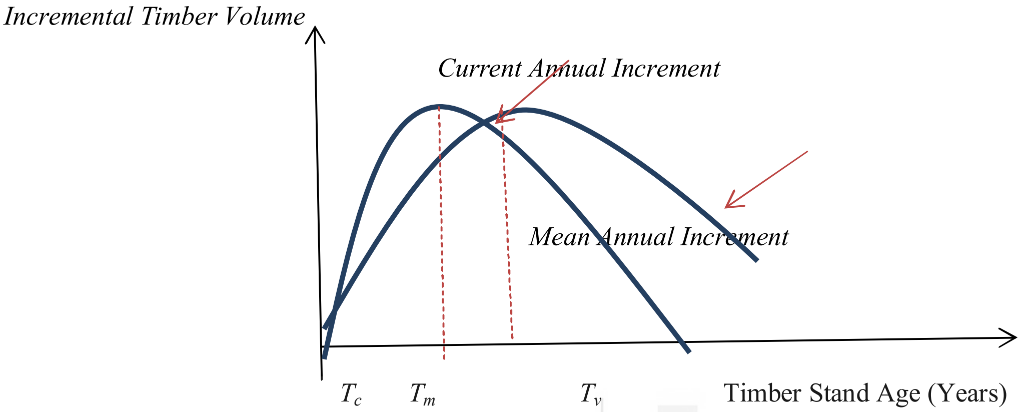


**Figure 12.9: Mean Value Increment and Current Annual Increment**

### 12.4.2 Economic Approach

The approach based on biological criteria is criticized on the ground that it does not take into account the economic criteria. Economic efficiency of timber management implies choosing the optimal age of harvesting a tree that would maximize the present value of the net benefit from wood. This in turn implies determining the optimal rotation age for a forest stand given a set of exogenous variables (like growth of a tree, output they produce, discount rate, etc.) that would maximize the present value from harvesting a tree.

#### 12.4.2.1 The Single Stand One Rotation Problem

The approach here assumes that the stands have been established with no costs involved in tending the stands. It further assumes that a new stand will not be established after harvest. Thus, the value of the tree at time 't' is the constant price P times the volume V(t) net of harvesting. Therefore, the net present value of a harvest at time T is given by:

$$\pi = [(P)V(T)]e^{-\delta T} \quad \ldots\ldots\ldots\ldots \quad (12.21)$$

The one period optimal rotation problem can be written as choosing the optimal harvest age $T_s$ that maximizes the net present value:

$$\frac{d\pi}{dT} = \big((P)V(T)\big)e^{-\delta T}(-\delta) + (P)V'(T)e^{-\delta T} = 0 \quad \ldots\ldots\ldots \quad (12.22)$$

The above first order condition can be rewritten as:

$$(P)V'(T) = \delta PV(T) \;\; or \;\; \frac{V'(T)}{V(T)} = \delta \ldots\ldots\ldots (12.23)$$

The LHS of (12.23) is the instantaneous increase in the value of standing timber i.e. the net revenue accruing from the increase in growth from waiting to harvest the trees. The RHS is the return if all the trees were harvested and the money is invested to earn a rate of interest equal to the discount rate. Since the net price P is constant, this is equivalent to choosing the rotation length where the growth rate (expressed in percentage term) is equal to the discount rate.

### 12.4.2.2 Single Stand Continuous Forestry Problem (the Faustmann Result)

If we assume that land will be dedicated to forestry, we then need to incorporate the effect of growing subsequent crops of tree on the same site. *Martin Faustmann (1849)* was the first to identify the problem as choosing the harvest period to maximize the net present value of a series of future harvest or the optimal rotation age T, for a series of sequential harvests of a timber stand on the same site. Considering *'c'* as the replanting cost associated with establishing the next stand of trees, immediately following harvest but again assuming that the first stand has already been established, we have:

$$\pi = (PV(T) - c)e^{-\delta T}\{1 + e^{-\delta T} + e^{-\delta 2T} + e^{-\delta 3T} + \cdots \dots \dots\} \dots\dots\dots\dots \quad (12.24)$$

$$= \frac{(PV(T)-c)e^{-\delta T}}{1- e^{-\delta T}} = \frac{PV(T)-c}{e^{\delta T}-1} \dots\dots\dots\dots \quad (12.25)$$

$$\frac{d\pi}{dT} = 0 \Longrightarrow \frac{d\pi}{dT} = \frac{(PV(T)-c)(-e^{-\delta T}\delta)}{(e^{\delta T}-1)^2} + \frac{PV'(T)}{e^{\delta T}-1} = 0 \dots\dots\dots \quad (12.26)$$

Rewriting the above equation as: $PV'(T) = \frac{(PV(T)-c)(e^{\delta T}\delta)}{e^{\delta T}-1}$ ..........(12.27)

$$\frac{PV'(T)}{(\boldsymbol{PV(T)- c})} = \frac{((\boldsymbol{e^{\delta T}\delta})e^{-\delta T}}{(e^{\delta T}-1)e^{-\delta T}} = \frac{\delta}{(1- e^{-\delta T})}$$

$$\Longrightarrow \frac{PV'(T)}{(\boldsymbol{PV(T)- c})} = \frac{\delta}{(1- e^{-\delta T})} \dots\dots\dots\dots \quad (12.27a)$$

Thus the term in the RHS of (12.27a) means, if all the trees were harvested and money put in the bank (with the discount rate approximated at the market rate of interest $\delta = r$), the term in the RHS is the opportunity cost of postponing the harvest or the interest income foregone. The LHS is the instantaneous increase in value of standing timber from waiting to harvest the trees (net revenue accruing from increasing growth). For the equality to be re-established the forest must be harvested sooner when $V'(T)$ is greater at an earlier age.

Equation (12.27a) can be rewritten as :

$$PV'(T) = (PV(T) - c)(\delta) + PV'(T)e^{-\delta T} \dots\dots\dots\dots\dots\dots \quad (12.27b)$$

Equation (12.27b) again equates the marginal benefit of harvesting against the marginal costs of waiting. The first term in the RHS is the opportunity cost of postponing the harvest or the interest income foregone. The second term in the RHS is the cost incurred due to postponing harvest leading to loss of growth of replanting. It reflects the opportunity cost in delaying the establishment of new trees that can grow faster. The additional increase in costs is attributed to waiting reduces the optimum rotation age compared to the single stand case which can also be seen by setting c = 0. For the equality to be re-established the forest must be harvested sooner when $V'(T)$ is greater at an earlier age.

The second term of RHS in (12.27a) can be rewritten, where $T_f$ or $T^*$ has been chosen to optimize the problem, as follows:

$$\frac{PV'(T^*)}{(\boldsymbol{PV}(T^*) - \boldsymbol{c})} = \frac{\delta}{(1 - e^{-\delta T^*})}$$

$$PV'(T^*) = (\boldsymbol{PV}(T^*) - \boldsymbol{c})\frac{\delta}{(1 - e^{-\delta T^*})}$$

$$PV'(T^*)e^{-\delta T} = (\boldsymbol{PV}(T^*) - \boldsymbol{c})\frac{e^{-\delta T^*}\delta}{(1 - e^{-\delta T^*})}$$

$$PV'(T^*)e^{-\delta T} = \frac{(PV(T^*) - c)\delta}{(1 - e^{-\delta T^*})/e^{-\delta T^*}}$$

Thus, $PV'(T^*)(e^{-\delta T}) = \delta\left\{\frac{(PV(T^*)-c)\}}{(e^{\delta T^*}-1)}\right\} = \delta\pi^*$ ........... (12.28)

since from (12.25), we can write, $\pi^* = \left\{\frac{(PV(T^*)-c)\}}{(e^{\delta T^*}-1)}\right\}$

The term $\pi^*$is the capitalized value of land from growing trees in perpetuity on the site. RHS of 12.28, $\delta\pi^*$, is the *land rent* captured by the flow of the value per period of time associated with the piece of land dedicated to the forestry. It can also be thought of as the opportunity cost associated with using the land to grow trees.

### 12.4.3 Rotation Age

We can compare how the optimal harvest age changes when we use economic criteria rather than the biological criteria. We do this by deriving the optimal rotation age under the two different formulations. As we have seen in Figure 12.9, the average annual growth V(T)/T and the incremental annual growth of timber $V'(T)$ are expressed as functions of the timber age T. We can similarly express both V(T)/T and $V'(T)$ as functions of the volume V(T) since timber volume increases directly with age (Figure 12.10). The only difference is that the horizontal axis captures timber volume and not age. The rotation length that maximizes the average timber volume over time is when the mean annual growth rate equals the average

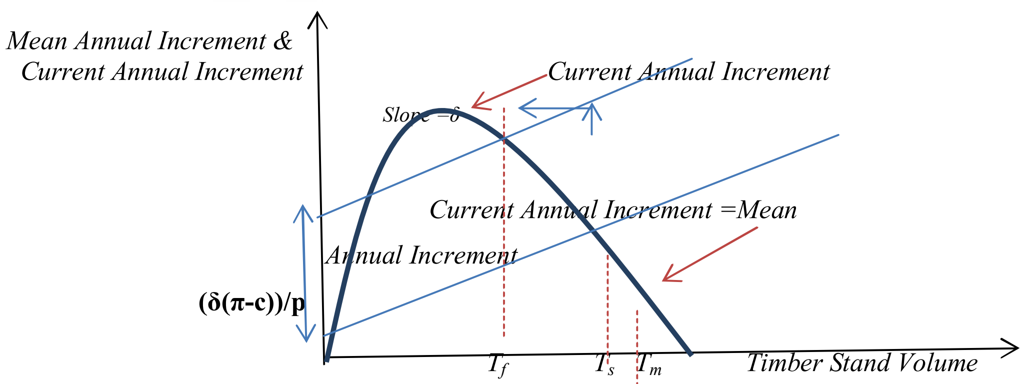


**Figure 12.10: Comparison of Optimal Rotation Age**

annual growth rate (given by $T_m$ in Figure 12.9). The optimal rotation length under the single stand, one time harvest problem (as given by equation 12.23) can be rewritten as $V'(T) = \delta\, V(T)$ which gives a line with a slope $\delta$, through the origin. The optimal harvest age is then given by $T_s$ where the line intersects the $V'(T)$. In this case, trees are harvested earlier when we use economic criteria rather than biological criteria. In the case of continuous forestry, under the Faustmann formulation, from equation 12.27 we have:

$$PV'(T) = (PV(T) - c)(\delta) + PV'(T)e^{-\delta T}$$

By substituting $\delta\pi \; for \; PV'(T)e^{-\delta T}$, from equation 12.28 and dividing by P we get:

$$V'(T) = \frac{(PV(T) - c)(\delta)}{p} + \delta\pi / \text{p}$$

$$Thus, V'(T) = \delta V(T) + \frac{\delta}{P}(\pi - c) \text{ ……….. (12.29)}$$

This yields a line with a slope $\delta$ and an intercept $\frac{\delta(\pi - c)}{p}$ that can be plotted against the volume V(T).

1. If $\pi > c,$ the capitalized value of the land exceeds the replanting costs thereby yielding a positive economic value to the forestry. This implies an upward shift of the $\delta V(T)$ curve yielding an optimal rotation length of $T_f < T_s$ (for the one period rotation case).

2. If $\pi = c,$ then the cost of replanting exactly offsets the value expected from future harvests (which also takes into account the cost of replanting in the future). In this case, the solution is same as single stand case as there is no value associated with the future harvests.

3. For $\pi < c,$ then the expected value of the land is negative, suggesting that the land will not remain in forestry since after harvests the replanting costs exceeds the value of the reforested land.

### 12.4.4 Comparative Static/Changes in Exogenous Factors

Both the single stand and the Faustmann models can be used to investigate the influence of different exogenous variables on the optimal rotation length. Examples include changes in the discount rate ($\delta$), changes in the net price ($P$), changes in the cost of replanting ($c$). From the first order condition one can show that an increase in the discount rate will shorten the optimal harvest, while a decrease in the net price will lengthen the optimal rotation. This can be seen in Figure 12.10 where an increase in $\delta$ will steepen the slope and shift the intercept up, while the increase in net price P will shift the intercept up (as intuitively the land will now be worth more). However, one cannot establish a general rule regarding the optimal rotation if more than one variable changes, unless one specifies the relationship between the parameters. For instance, if the discount rate increases but the price decreases, the change in rotation depends upon the relative magnitude of the two opposing effects. If c increases, then [V(t) – c] will fall. Thus, the length of rotation increases as replanting cost increases. The increase in cost reduces the value of the forest and increases the rate of return on the existing land.

### 12.4.5 Optimal Rotation and Social Optimum

The optimum rotation age achieved through private markets may significantly differ from the socially optimum age for several reasons. First, there may be environmental benefits associated with the timber stand that are not taken into account by the decision maker. These externalities can lead to rotation ages that are too short or may even lead a private manager to harvest where a public manager would not. Second, where the private discount rate is higher than the social discount rate, this will lead to shorter rotation ages. Third, imperfect markets may also yield incorrect prices leading to incorrect rotation ages.



### 12.4.6 New Dimensions to Forestry Issues

How countries manage their forests is not confined to the boundaries of the nation state but increasingly includes international aspects. First, many of the important environmental characteristics associated with forests (such as biodiversity and their potential to sequester carbon) have an international dimension. These are recognised in two international environmental agreements viz. the Convention on Biodiversity and the Framework Convention on Climate Change (Kyoto Protocol). Second, as the shift towards sustainable development was adopted by many developed countries, trade in the forest products also grew and the environmental aspects of how the goods are produced became increasingly important. This means the impact from changes in one country's policies, designed to satisfy broader environmental objectives, cannot be examined by excluding the indirect effect such changes might have elsewhere. For instance, a country's change in policy towards more protected forest may reduce domestic production but may shift demand to other regions or countries where forests are managed in an unsustainable manner. Similarly, efforts to combat deforestation through measures such as export bans on logs may be counter-productive. Maestad (2001) argues that timber trade restrictions, designed to reduce deforestation, may not reduce but may actually increase and induce the conversion of forest land to other uses by depressing the value of timber. Efforts to develop international consensus through an environmental agreement on forest management have so far failed. Some critical questions raised on multiple uses are: (i) how do policy makers reconcile environmental, economic and social objectives? (ii) when do some of these objectives compete with one another? (iii) how are the public values recognised under systems of private ownership? and (iv) how can policy makers create incentives for sustainable forestry? One attempt to answer some of these questions has been through forest product certification, which identifies forest products produced in a sustainable manner. This is the first major attempt to use private markets to provide public goods and was initiated by NGOs that has developed international label based on the manner in which timber is produced. The aim was to create new markets that would provide a premium over traditional markets providing incentives to the firms to practice sustainable forestry. Developing countries, however, have voiced concerns that certification may emerge as a trade barrier meant to protect domestic industries in developed countries. The increasing attention paid towards certification will link countries' domestic forest management policies even more firmly to the international market place.

**Check Your Progress 3 [answer within the space provided in about 100 words]**

1. Distinguish between the terms 'extensive margin' and 'intensive margin'.

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2. Suppose the relationship between the growth of fish stock and the stock of fish is expressed as $\dot{x} = 4x - 0.1x^2$, where the growth is expressed in tons and the stock $x$ is expressed in thousand tons. Compute maximum sustainable yield (MSY), and stock corresponding to the MSY.

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3. If the demand for fish is given by $P = 400 - 3h$, h being the harvest with $h = 0.6E$, where, E is the effort level. Marginal costs and average costs are constant and equal to 200 per unit of effort. Find the bio-economic and private competitive equilibrium levels of effort and harvest.

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4. Specify the optimal rotation problem which maximises the net present value of forestry in a single stand one rotation problem.

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5. State three reasons as to why the optimum rotation age achieved through private market may significantly differ from the socially optimum age.

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## 12.5 INVESTMENT UNDER UNCERTAINTY

Much of the early literature on the economics of renewable resources was cast in a decision environment of perfect certainty. However, both biological parameters (such as growth rates and carrying capacity) and economic parameters (such as price and marginal costs) are more likely to exhibit stochastic change over time. In addition, the goal of simple net present value maximization (the pre-cursor to equations related to the steady-state condition of renewable resource) may be replaced when economic activity can be characterized by irreversibility and flexibility in timing. In such applications, a framework of investment under uncertainty is more suitable. This framework for natural resource valuation and management has generally emerged from theories of capital investment, and more specifically from the *options value* literature of corporate and public finance. Most decisions to invest exhibit some degree of *irreversibility*; where initial capital outlays can never be recovered or externalities associated with economic activity cannot be reversed. The timing of many investments can also be flexible. Both irreversibility and the ability to wait for new information introduce a positive value of delay to many investments. Known as an option value, this additional opportunity cost of investment can push optimal rates of return well-above discount rates common to the traditional net present value framework. When uncertainty is explicitly considered, stochastic trigger values can be developed which indicate when an investment should be undertaken. Such stochastic optimal timing problems have become an important part of the renewable resource economics literature.

## 12.6 LET US SUM UP

Renewable natural resources include those resources (like stocks of fish, forests, or freshwater) useful to human economies. They exhibit growth and therefore requires sustainable maintenance and protection from exploitation over an economic planning horizon. Renewable resources across the world are experiencing a discernible decline along both socioeconomic and ecological gradients. Statistics on ocean fishery depletion, forest land conversion, top-soil loss, desertification, species extinction and freshwater diminution, overwhelmingly point to the consequences of human domination of the planet's resources. The size of the resource stock (population) of these biological resources is determined jointly by biological factors and human interference. The size of the population, in turn, determines the availability of resources for the future. As the flow of these resources over time is not purely a natural phenomenon, a crucial issue is the optimum (efficient) rate of resource use over time and over generations. At the heart of nearly all economic models of renewable resources (relevant to market-based decisions), is the goal of efficiency, where marginal benefits of the next resource put to economic use is exactly equal to its marginal cost of production and/or benefits to society. Discounting the economic value has important implications in terms of both the optimal level of harvest and biomass. The greater the discount rate, the less valuable are returns in the future relative to the present, and the greater the incentive not to invest in the resource by reducing the current harvest. The question of when and how much to harvest (present vs. future time periods), has been posed as a balancing act between current and future benefits and costs. Method of dynamic optimization (i.e. the best allocation over time) is used to strike this balance. Thus, a renewable resource problem is typically framed as a maximization of some single measure of net economic value over some future time horizon, subject to the natural dynamics of the harvested resource, an initial stock size, a target for the end of the planning horizon (or a limit in the case of an infinite-time horizon), a measure of time preference, and other relevant market, price, and technology constraints. This unit provides an elaboration of fundamental equation of renewable resources, highlighting the essence of an efficient, market-based approach to management. Two sections on *fishery* and *forestry economics* deal with the type of decision rules depicted in this framework. Thus, in case of fishery resources the fundamental principal is that the immediate marginal gain from an increase in current harvest of resource must be equal to the present value of future losses in rental brought about by that change. This is in fact the modified extension of *Hotelling formulation* for non renewable resources. *Shadow price* (or the future price of resources) will grow at a rate less than the rate of interest (or the discount rate) due to the non-zero stock effect. The *Faustmann rotation* is the optimal solution to the infinite-horizon timber harvest, where the marginal benefits of waiting are equated to the marginal opportunity costs of delaying both the current stand and all future stands.

## 12.7 KEY WORDS

**Biodiversity** : Is the variety of different types of life found on Earth and their variations within species. It is a measure of the variety of organisms present in different ecosystems. This can refer to genetic variation, ecosystem variation, or species variation (number of species) within an area, biomass, or planet. Biodiversity is not distributed evenly on Earth. It is richest in the tropics.

**Biomass** : Is measured as the total weight of all fish species in the sea or all tree species in the forest.

**Carrying Capacity** : It determines the maximum limit of the stock of any biomass beyond which it cannot grow. This is the maximum bearable by the given habitat.

**Discount Rate** : Is a measurement of human preference for near term over longer term benefits or reduced costs.

**Dynamic Optimization** : Is a method of economic analysis used to determine the most efficient allocation of resources over time.

**Exponential Growth** : Occurs when the growth rate of the value of a mathematical function is proportional to the function's current value, resulting in its growth with time being an exponential function. The formula for exponential growth of a variable x at the (positive or negative) growth rate r, as time t goes on in discrete intervals (that is, at integer times 0, 1, 2, 3, ...), is $x_t = x_o (1 + r)^t$, where $x_o$ is the value of x at time 0. For instance, with a growth rate of r = 5% = 0.05, going from any integer value of time to the next integer causes x at the second time to be 5% larger than what it was at the previous time. Since the time variable, which is the input to this function, occurs as the exponent, this is an exponential function.

**Externality** : Is the activity of one agent which affects (positively or negatively) the utility or costs of other agent/agents for which it is not compensated.

| | |
|---|---|
| **Forest Rotation** | A forest rotation starts with planting and finishes with felling. It varies from species to species (like it may take 100 years for an oak tree). |
| **Faustmann Rotation** | Is the optimal solution to the infinite-horizon timber harvest, where the marginal benefits of waiting are equated to the marginal opportunity costs of delaying both the current stand and all future stands. |
| **Marginal Value** | Is the net benefit of an incremental change in the level of a resource stock or harvest. |
| **Open Access** | Open-access property is not managed by anyone, and access to it is not controlled. It is non-excludable (no one can exclude anyone else from using it) but may be rival (one person's use of it reduces the quantity available to other users). There is no constraint on anyone using open-access property (excluding people is either impossible or prohibitively costly). Examples of open-access property are the upper atmosphere (navigable airspace) or ocean fisheries (navigable waterways). |
| **Option Value** | Is the economic value of delaying an investment decision. |
| **Rotation Age** | It reflects the harvesting age of a tree in a sequence of harvesting. |
| **Resilience** | Is the ability to maintain a given state when subject to disturbance. |
| **Sustainable Yield** | It reflects the harvesting which is equal to natural growth rate so that the stock is kept intact. |
| **Particular Integral** | Consider the differential equation: dy/dt = b. Its straight integration i.e. its general solution is: y (t) = bt + c. The LHS of this equation is the complementary function (i.e. integral with is but the complement of the differential equation dy/dt) and RHS is the 'particular integral' of the differential equation. |

## 12.8 SUGGESTED REFERENCES FOR FURTHER READING

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## 12.9 ANSWERS/HINTS TO CYP QUESTIONS

**Check Your Progress 1**

1) See 12.1 and answer.

2) See 12.1 and answer.

3) See 12.2.2 and answer.

**Check Your Progress 2**

1) See 12.3. 1 and answer.

2) See 12.3.2 and answer.

3) See 12.3.3 and answer.

4) See 12.3.4 and answer.

5) See 12.3.4 and answer.

6) See 12.3.4 and answer.

**Check Your Progress 3**

1) See 12.4 and answer.

2) We know the stock attains the maximum growth at :$\frac{d\dot{x}}{x} = 0 \Longrightarrow \frac{d\dot{x}}{x} = 4 - 0.2\,x = 0$, which gives $x = 20$ thousand tons. Hence this is the stock compatible with MSY. Now, MSY $=4\,x - 0.1x^2 = 4(20) - 0.1(20)^2 = 40\ tons.$

3) To find the bio-economic equilibrium, set total revenue equal to total costs.

$$\text{TR} = \text{ph} = TR = ph = \{400 - 3(0.6E)h\} = TC = 200E$$

$$(400 - 1.8E)(0.6) = 200.\ \ i.e. 240 - 1.08E = 200 \Longrightarrow E = 37.\ Hence, h = 0.6E = 22$$

To find the competitive equilibrium equate MR and MC $\Longrightarrow 240E - 1.08E^2 \Longrightarrow MR = 240 - 2.16E$ & $MC = 200. \Longrightarrow \; 240 - 2.16E = 200 \; \Longrightarrow E = 18.5, \; h = 0.6E = 11.$

4) See 12.4.2.1 and answer.

5) See 12.4.5 and answer.