Economics of Natural Resources

1. INTRODUCTION

Traditional usage confines the term natural resources to naturally occurring resources and environmental and ecological systems that are useful to mankind or could be useful under feasible technological, economic, and social circumstances. Examples of natural resources are forest land and its 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, aluminum etc.); non-mineral energy sources of solar, tidal, wind, and geothermal systems; water resources; and also 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, and uranium was not known.

Here we deal with the economics of natural resource use. In particular we analyse how society should exploit a resource efficiently and the rate at which a rational agents should exploit such resource through time. The rest of the paper is organized as follows: In Section 2 we adopt a resource taxonomy (classification system) that is used to distinguish various categories/measures of resource availability. Section 3 deals with the question of how to allocate exhaustible resources efficiently over time. It also discusses certain related aspects of exhaustible resources. Section 3 analyses the basic issues of economics of renewable resources taking fishery and forestry as examples. Section 5 discusses certain aspects of water resource management and concludes.

2. RESOURCE TAXONOMY

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 example, techniques, more expensive than conventional ones, generally allow greater amount of a resource to be recovered. As the price 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.

These distinctions among the three concepts are important. Failing to take note of them may lead to erroneous conclusions. We need to remember that data on current reserves does not represent the maximum potential reserves. We also need to remember that the entire resource endowment cannot be made available as potential reserves at some price people will be willing to pay. Certain mineral resources are prohibitively costly to extract. It is not likely that any society, current or future, would be willing to pay the price necessary to extract them. This, then, would imply that the maximum feasible size of the potential reserves is likely to be smaller than the resource endowment. Box 1 gives us some ideas about the state of a exhaustible resource in India.

Box 1: Exploration and Production of Petroleum in India

India continues to be one of the least explored regions. of the 26 sedimentary basins, only 6 have so far been explored, accounting for only 30 per cent of the country's prognosticated reserves. India's balance recoverable crude oil reserves are declining continuously after peaking at 806 million metric tons in 1992. This indicates the need for greater exploration efforts.

Source: Parikh (1999)

Natural resources, as we have said before, include renewable resources such as fish population and forests and non-renewable exhaustible resources such as oil reserves and mineral deposits. Thus for another useful classification of natural resources, 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 yearswhich 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 humans. 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 to have a common foundation. The stock of natural resources (for example, 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, so growth through regeneration increases and harvesting or extraction depletes the stock of natural resources.

We will take up next the economics of exhaustible resources. Analytics of both exhaustible and renewable resources involve some mathematics. However, we will attempt to explain the basic ideas without developing the mathematics (other than some simple algebra) that underlies them.

3. MANAGING EXHAUSTIBLE RESOURCES

Exhaustible resources will be depleted so long as the extraction rate is positive. Are our exhaustible resources being depleted too rapidly? To answer questions like this we need to know the optimal rate at which to extract/deplete exhaustible resources. With that in view we will present here some simple and intuitive results involved in the theory of depletion.

What are the conditions that must hold while depleting an exhaustible resource over time, that is, along an optimal depletion path? The supply (and extraction) behavior of a price-taking owner[1] of an exhaustible resource such as oil differs from that of an ordinary good or resource. An exhaustible resource is limited in quantity and is not producible like an ordinary good. Ordinary goods produced in the economy using available methods of production can be replicated. Since exhaustible resources are created by geological processes with geological time spans, they can be regarded as fixed in quantity, although the total quantity available may not be known.

A price-taking firm supplying ordinary goods will adjust production in all periods so that the incremental cost of production of an extra unit of output, i.e., its marginal cost (*mc*) of production in each period equals price (*p*) in that period. If the *mc* is less than *p*, the supplier can raise current profits by increasing production. However, when the firm is the extractor of an exhaustible resource, such behavior might require extraction of more stocks than is available to the firm.

Cases like this, then, require some modifications of the standard theory. Since an exhaustible resource is limited in quantity and is not producible, extraction and sales of a unit today, involves an *opportunity cost*; the value that might have been obtained for that time at some future date. This opportunity cost is

[1] Competitive owner who sells his natural resource in a market where he does not have a large enough market share to be able to influence market prices.

usually given the name *user cost* (*uc*). The presence of user cost is central to the economics of exhaustible resources. User cost does not exist for conventional reproducible goods since the consumption of an amount now does not reduce the quantity that can be consumed in the future; additional quantities can always be produced. However, a barrel of oil extracted today is a barrel unavailable for extraction in the future. In deciding whether to extract and sell an additional barrel today, the extractor must consider not only the cost of pumping the barrel, but also the cost of foregoing the highest return that could have been earned if the oil had instead been pumped and sold in the future. Hence, it is necessary to have a more inclusive definition of marginal cost and we call it *augmented marginal cost* (Salant, 1995). The augmented marginal cost (*amc*) is, then, defined as the marginal cost of extraction (*mc*) plus the user cost (*uc*).

When *mc* is redefined in this way, it is optimal for a competitive resource owner (firm) to extract the resource in each period to the point where its *amc* equals the market price (p). Instead of the usual efficiency condition, price (p) = marginal extraction cost (*mc*), we have:

$$p = mc + uc.$$

This is the first condition of optimal depletion. As shown in Figure 1, it implies that less of the resource will be extracted today than if it were a producible ordinary good or a resource. Given the relation between demand and price $p = p(y)$, where p is the price and y is the quantity demanded and extracted, only y^* units (rather than y^{**} where $p = mc$) will be extracted by a resource planner or a price-taking firm seeking to allocate extraction efficiently over time. This leaves a positive difference AB (the opportunity cost/user cost) between p and mc.

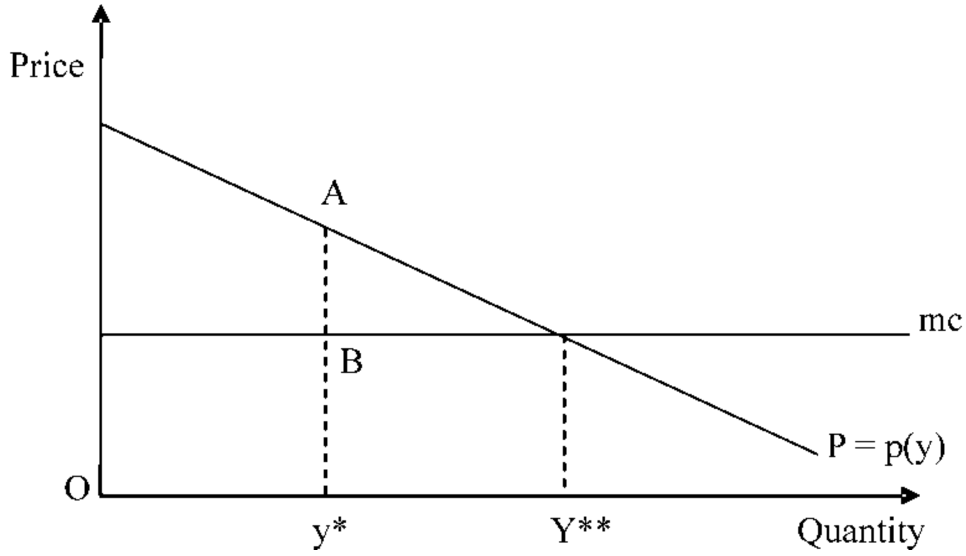

Figure 1:Optimum Extraction of an Exhaustible Resource.

Beneath the apparent simplicity of this rule lies a wealth of subtlely (Salant, 1995). The rule implies, for example, that the current extraction rate by a private owner of a natural resource depends not only on the current price, as in the standard theory, but also on expectation about future prices. These price expectations determine the opportunity cost of additional current extraction. A competitive supplier that expects future prices to be sufficiently low compared with the current price may extract and sell intensively in the current period, judging the opportunity cost of additional extraction to be small. But if future prices are expected to be sufficiently high, the same current price may induce no extraction whatsoever today.

For some further results let us, for simplicity, assume just two periods: the resource owner either extracts and sells the resource today, in period 0, or retains it in the ground until the next period 1. Let the price he can obtain for a unit of the resource today be *p0* and the price he expects to prevail for a unit in the next period be *p1*. The cost per unit of extracting the resource and delivering it to the buyer is *C*, which is not expected to vary between periods 0 and 1, that is $C = mc$ remains constant.

Because the owner has a fixed stock (to be supplied from) of the resource, any unit sold in period 0 will reduce the quantity that can be sold in period 1. If he sells the unit in period 0 he will receive net revenue of *p0–C* but forgo revenue of *p1-C* in the following period. The value in period 0 of the net revenue foregone is its present value *(p1-C)/(1 + r)* where *r* is his discount rate[2].

Hence his return from selling a unit today will be:

(p0 – C) – (p1 – C) / (1 + r)

(p1-C)/(1+r) is the opportunity cost of his decision to sell a unit today. It is the user cost of his decision. It arises because he is faced with the alternative of selling it in the following period. If

(po – C) > (p1 – C) / (1 + r)

he will be better off selling his resources in the current period. If, on the other hand,

(po-C) < (p1-C) / (1 + r)

he will be better off by leaving it in the ground. His optimum amount of current extraction is given where

$$po\text{-}C = (p1\text{-}C) / (1 + r) \tag{1}$$

This implies that $po = C + (p1 – C) / (1 + r)$ (1a)

Equation (1a) states our earlier result that the current price of the resource when it is extracted optimally, should be equal to the *mc* plus the user cost (*uc*).

With reproducible resources there is no element of user cost since resources are produced in each period to satisfy the demand in that period and there is no carry over from period to period. Hence, as we have seen earlier, for a reproducible resource the optimum output is given where *po = C*.

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[2] The present value (PV) of a stream of net benefits B_o …., B_T received over a period of *T* years is computed as $PV\ (B_o \ldots\ldots B_t) = \sum_{t=0}^{T} B_t / (1+r)^t$ where Σ is the summation, *r* is the appropriate interest rate, B_o is the amount of net benefits receivers immediately, and B_t is the amount of net benefits received t years from now. The process of calculating the present value is called discounting and the rate r is referred to as the discount rate. One rupee received in period *t* is equivalent to $1/(1 + r)^{t-1}$ rupees in period 0. At a discount rate of 10 per cent, a firm will be equally well off if it earns Rs. 100 today (which can generate Rs. 10 of interest income) or if it earns Rs. 110 one year from now.

Transposing equation (1a) we have

$$(p1 - C) \ = \ (po - C)\ (1 + r) \qquad (2)$$

Equation (2) is the second condition of optimal depletion and is usually described as the fundamental equation (due, originally, to Hotelling, 1931) of exhaustible resource extraction. It says 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, that is, the user cost has to rise at a rate equal to the discount rate.* A numerical example may help to illustrate this fundamental condition. Suppose the interest rate is 10 per cent and the net price $(p - mc)$, that is, user cost per unit of the resource is Rs. 20. If the net price (user cost) is not expected to grow by 10 per cent to Rs. 22 next year, it pays to extract more of the resource in the current period, because the resulting income from sales will earn 10 per cent interest if invested in interest bearing assets. If the net price is expected to go above Rs. 22 that is, to grow faster than the rate of interest – the producer will have no incentive at all to extract in the current period. This is because any unit extracted today will (even after interest earning) be worth less in a year than a unit extracted and sold a year from now.

If *mc* of extraction is small relative to the price of the resource, equation (2) approximates to

$$p1/po = 1 + r \ \text{ or } \ p1 = po\ (1 + r).$$

Thus along the optimum path resource prices grow at the discount rate. The higher the discount rate the faster the rise of resource price along the optimum path. A higher discount rate reduces the user cost of the resource and causes mine owners to deplete their resource at a faster rate. In reality, of course, extraction costs are never zero. Whenever they are positive, a price increase equal to the interest rate would cause the net price to rise by more than the interest rate. For example, suppose the price per unit of a resource is Rs. 30 and the net price is Rs. 25. A 10 per cent price rise (in the rate of interest) would boost the net price from Rs. 25 to Rs. 28, or by more than 10 per cent. This difference would give every extractor an incentive to postpone extraction rather than satisfy current demand. If such imbalances are to be avoided, the price in successive years must rise by less than the interest rate.

We will see that this analysis may illuminate many questions of practical policy. Let us consider for illustration, the following questions (Salant, 1995):

- Suppose a state-owned or controlled enterprise say Coal India Limited (CIL) is entrusted with selling an exhaustible natural resource (in this example coal) on the world market. For a small country[3] can it be right to extract it to the point where the *mc* of extraction equals the world market price? Is it ever prudent to refrain from extracting a resource, even though it is profitable to begin with that is, current price exceeds the mc of extracting the first unit?
- Credit may be more tightly rationed (and interest rates higher) in one country than in another. How does this affect the former country's relative rate of resource extraction?
- Suppose a government decides to restrict the extraction of a resource that is privately owned and extracted because the resource is considered highly valuable (such as gold in India) or because the extraction process generates pollution (such as gold mining which uses mercury or arsenic). Is it right in such cases to give the extractor a grace period before the restrictions are effectively imposed to overcome the dislocations that such policies will cause?

Each of the questions raised above ceases to be puzzling once attention is properly refocused on the opportunity cost of current extraction and how that cost changes when a new policy is anticipated.

Expanding short-run coal production based on the equality of mc of extraction and market price is excessive because it fails to account for the future net return (profit) foregone, when an additional ton of coal is extracted. Moreover, if this opportunity cost is sufficiently high, no amount of the resource should

[3] A small country is one that sells on the world markets but that does not have a large enough market share to be able to influence world prices (a price-taker).

be extracted today even though the current price exceeds the current mc of extracting the first unit.

As regards the second problem, when the real interest rate rises, the *uc* of extracting another ton declines because the future profit (from the ton that must be foregone) is worth less today (that is discounted profit is low today). Hence, even if *mc* does not shift, the augmented *mc* (*amc*) in early periods will fall. As a result, the same sequence of prices would generate an initial expansion in extraction. This outcome can be used to explain differences in the behavior of two countries selling the same natural resource on the world market. Assume that both countries have approximately the same underground reserves and costs of extraction. If credit is rationed more tightly in one country, that country should extract more rapidly in the short-term in order to maximize national wealth.

In the third problem where (say) it is proposed to shut down a highly valued or/and polluting gold mine but the mine operator is permitted a grace period to mitigate the dislocations caused by the closure, during the grace period premature closing lowers the *uc* of an additional unit. Consequently, the *amc* in each period before the date of closing is lower than it was before the policy was announced. If the sequence of world price is unchanged, the mine operator will find it profitable to intensify mining throughout the grace period.

3.1 Towards a Substitute (Backstop)

Our discussion so far considered optimal depletion of an exhaustible resource when we implicitly ruled out availability of any substitutes or 'backstop' as it is sometimes called, of the resource concerned. However, it may so happen that a substitute resource, possibly a renewable resource, is available at a constant marginal cost. This scenario could pose the problem of optimal depletion of say oil or natural gas with a solar substitute. What would be the optimal depletion rules in these circumstances?

We note that the *amc* for the exhaustible resource cannot exceed the *mc* of the substitute. The society could always opt for the use of a renewable resource instead, whenever it appears cheaper to do so. Thus, although the maximum willingness to pay (the 'choke price') sets the upper limit on *amc* and for that matter on p when no substitute is available, the *mc* of extraction of the substitute sets the upper limit when a substitute resource is available at *amc* that is lower than the choke price.

3.2 Exploration and Technological Progress

In principle, extraction costs may rise over time as lower-cost reserves are depleted and higher-cost reserves remain to be exploited. The search for new resources involves costs. As more easily accessible resources are exhausted, we must move into less accessible areas, such as the bottom of the ocean or high slopes of the mountain. This suggests that the marginal cost of exploration, which is the marginal cost of finding an additional unit of the resource, should be expected to rise over time, just as marginal cost of extraction does.

Rising augmented marginal cost of a resource induces society to exploration activities. Some of this exploration would be successful. If the *mc* of extraction of the newly found resources is sufficiently low, this could lower, or at least moderate, the increase in *amc* and price.

Technological progress, in the present context would be manifested as reductions in the cost of extraction. However, with a finite amount of a particular exhaustible resource, the fall in *amc* would not last indefinitely, because ultimately it would have to rise. This period of transition could last quite a long time though.

3.3 Resource Extraction and Environmental Cost

Extraction of a natural resource may impose an environmental cost on society. In situations like this property-rights are not usually well-defined and hence this cost is not internalized by the extractors. The aesthetic costs of strip mining, the occupational health hazards associated with coal mining, and the acids leached into streams from mine operations are all examples of associated environmental costs. The cost of extraction and sale (including user cost) is borne by the resource owner and taken account of (internalized) in the calculation of how much of the resource to extract. The environmental damage, however, is an external cost and is not borne by the owner and as such it will not be part of the extraction decision. It is important to know how the market allocation, based on only the former cost would differ from the optimal allocation (depletion), which is based on both.

The inclusion of environmental costs results in higher resource prices, which tend to lower demand. All other things being equal, it would allow the resource to last longer. On the other hand when environmental side-effects are ignored by the resource extracting firm, the price of the exhaustible resource would be too low, demand too high, and the resource would be extracted too rapidly over time.

3.4 Resource Scarcity

Are resources getting scarce? We will consider two economic measures of resource scarcity, namely cost and price to confront the question raised.

Nineteenth century economist David Ricardo views 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 costs of production in modern economies. For all true extractive industries, costs over the long term declined relative to the costs in non-extractive industries.

These studies also examined the proposition, derived in the earlier sections, that because of the influence of user cost, prices of exhaustible resources should rise relative to those of reproducible resources. This proposition is also rejected by the evidence.

There are four basic reasons for the failure 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.

4. MANAGING RENEWABLE RESOURCES

The line dividing exhaustible resources and renewable resources is not always clearly drawn. Just as exhaustible resources, in a sense, can be renewed through exploration and technology, renewable resources can be exhausted. In fact, much of the current concern about resource exhaustion involves renewable resources (Fisher, 1981). However, renewable resources are different from exhaustible resources because of the fact that they are naturally regenerated on time frame that is relevant to human exploitation. Catching a fish or cutting a tree does reduce the population of fish or tree in any period. But unless the population has already been reduced to the point of the critical threshold, natural growth will replenish the loss of biomass due to the harvest within a relatively short period. So, although it is true that a renewable resource can exhausted, it need not be.

Mankind shares the planet earth with many other living species. When biological species become commercially valuable they are subjected to two opposing human objectives. On one hand, the value of the species to humans provides a reason for human concern about its future. On the other hand, commercially exploitable biological resources can also be pushed to the brink of extinction if not managed sensibly.

In case of biological resources the size of the resource stock (population) is determined jointly by biological factors and by actions taken by society. The size of the population, in turn, determines the availability of resources for 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? Using the fisheries as an example of a renewable resource we will address these issues here.

4.1 Biological Dimension: Growth Curves

Unlike exhaustible resources, renewable resources can be reproduced. Thus, even though available stocks are affected by human intervention via their levels of exploitation, the economics of renewable resources depends, crucially, on assumptions about their population dynamics.

Figures 2 and 3 show the population dynamics of a hypothetical renewable resource, which we assume to be a single fish species. The stock of fish (or biomass) is supposed to follow growth through time as shown in Figure 2. This shows cumulative growth, or the size of the stock, as a function of time. At low levels of stock the fish multiply, but as they begin to compete for food their rate of growth slows down and eventually the stock converges on some maximum level Xc, the ecosystem's *carrying capacity* for that species (in the absence of human intervention). The cumulative curve, thus, takes the general *logistic* shape with at first successively larger increments, then successively smaller ones. Note that the curve, as we have drawn, begins at $Xmin$ – the critical minimum level of population. If the size goes below this level the species is driven to extinction ($X0$).

It is useful for our purposes to look at the information contained in Figure 2 in a somewhat different way. Figure 3 shows the growth in the resource stock on the vertical axis and the level of stock (X) on the horizontal axis. The solid curve relates this growth of the species, measured as the net annual increment to the population or weights thereof (births minus death), to the stock level.

Left to nature and in the absence of human predation, *Xc* is the population level that willprevail. *Xc* is known as *natural equilibrium* because at *Xc* stock is just replacing itself. Reductions in the stock because of mortality or predator species or (in the case of fish) out-migration would be exactly offset by increase in the stock because of births, growth of the resource (weight) in the remaining stock, and in-migration (of fish).

This natural equilibrium would persist because it is stable. A stable equilibrium is one in which movements away from this equilibrium stock level set forces in motion to restore it. If, for example, the stock temporarily reduces below *Xc* then it will recover because for all stock levels below *Xc* growth is positive. Thus if the stock is reduced to *X1*, it will increase in the first year by *G(X1)*. In the next year the population level of *X1* + *G(X1)* will grow by less than *G(X1)*, but the growth will still be positive and the process will continue until the stock is back to *Xc*. If, on the other hand, the stock temporarily exceeds *Xc*, it would be exceeding the capacity of its habitat (carrying capacity). As a result, mortality or out-migration would increase until the stock settles down within the confines of the carrying capacity of its habitat at *Xc*.

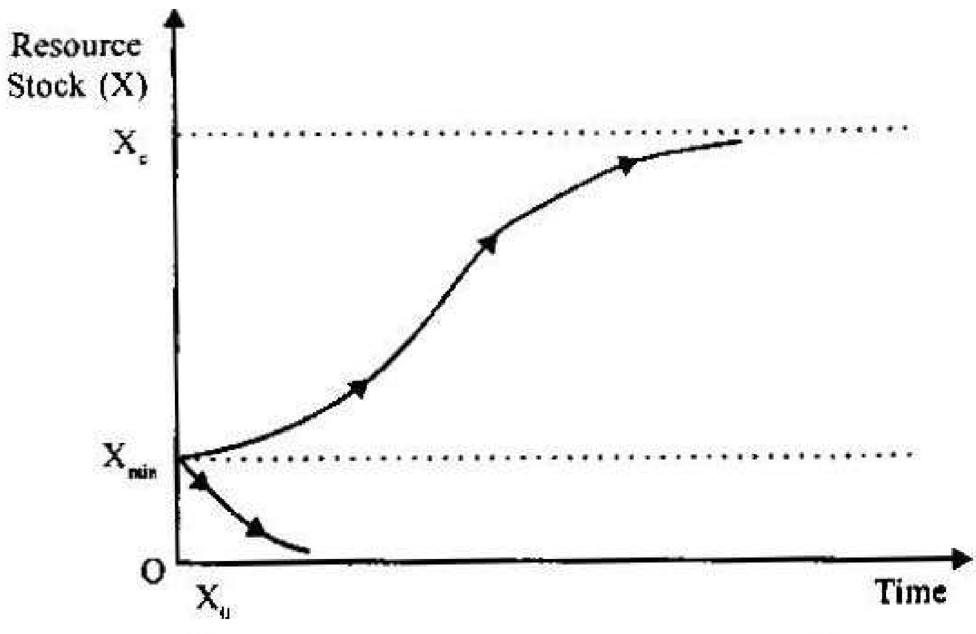

Figure 2: Logistic Growth Curve of a Renewable Resource where Stock Size is a Function of Time

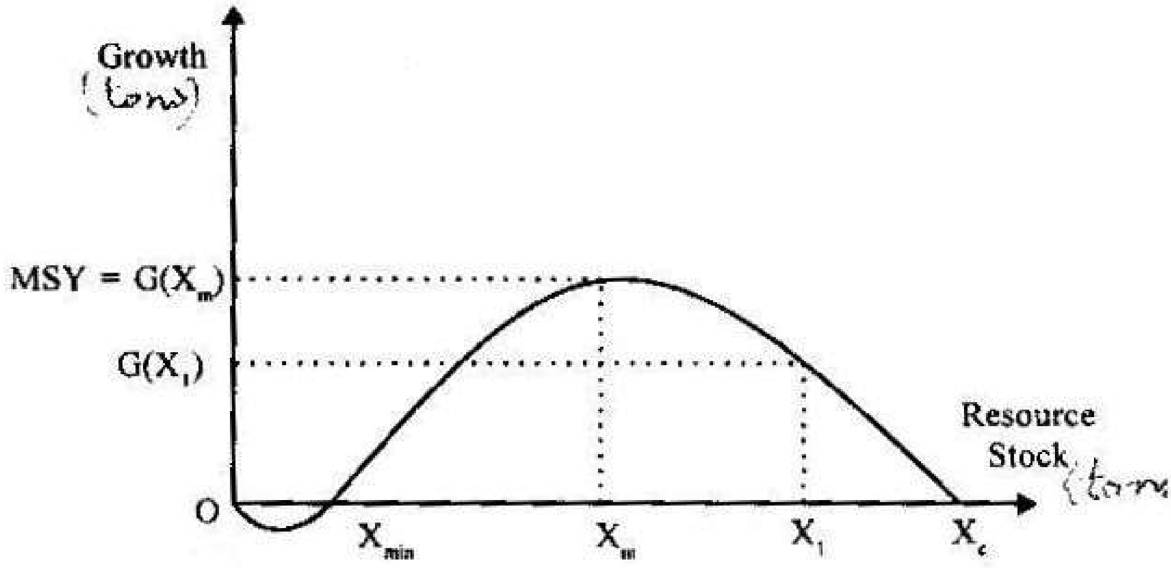

Figure 3: Relationship between Resource Stock and Growth

Xmin, in the diagram, is known as the *minimum viable population* and represents the level of population below which growth in population is negative (i.e., deaths and out-migration exceed births and in-migration). The reader can check that in contrast to *Xc*, this equilibrium is unstable. Here, once the stock moves away from *Xmin* no forces act to bring back the resource stock to a viable level.

With human intervention when catch (yield) level equals the growth of the stock, it is known as *sustainable yield*. Here the stock size, the growth rate and, hence, the catch all remain constant. Thus, in terms of Figure 3, *G(X1)* is the sustainable yield for resource stock *X1*.

Figure 3 helps to identify a concept widely used (particularly by biologists). This is the *maximum sustainable* take (*MSY*), which occurs when the growth of the resource is at a maximum. In Figure 3 it is *G(Xm)* corresponding to the *MSY* stock *Xm*. The apparent attraction of *MSY* should be obvious: if we harvest the renewable resource in such a way that we take *MSY* from the stock, it will regenerate itself and we can get *MSY* again in the next time period, and so on. If it takes one year to regenerate, *MSY* can be harvested each year. If it takes ten years, we must harvest *MSY* every tenth year only. *MSY* is the most we can harvest from the resource and maintain its sustainability without reducing its long term stock. We get the maximum from it each period. Herein lies attraction in the idea of setting our rate of harvest equal to *MSY*[4]. However, we shall see shortly that, *MSY* is unlikely to be an economically optimal policy.

4.2 Efficiency and Sustainable Yield

Allocation to be efficient has to equate marginal costs of harvest with marginal benefit (that is, maximize net benefits) and hence must include the costs as well as the benefits associated with harvests. For our present purpose we ignore discounting and define the static-efficient sustainable yield. It is the catch (harvest) level that, if maintained perpetually, would produce the largest annual net benefits. Dynamic-efficient sustainable yield will incorporate discounting. Initially we concentrate on static concepts and properties.

Our analysis, for simplicity will assume that: (1) The resource (fish) price is constant; (2) the marginal cost of fishing effort (to be explained subsequently) is constant; and (3) the amount of harvest (Y) per unit of effort E expended is proportional to the size of the resource stock (that is, the smaller the fish population, in our present example, the fewer fish caught per unit of effort).

We now introduce the level of exploitation or harvest or yield of the resource. Following assumption (3) above, we write

$$Y = EX \tag{3}$$

Then, the rate of harvest can be shown on Figure 3. To keep the diagram simple, we assume that $Xmin = Xo$. The choice of E will determine the equilibrium harvest Y and the stock level X, that is, where EX is equal to the growth of the resource and this is shown in Figure 4 where $E = E1$. This gives the harvest Y^* and the stock X^*. Any harvest level above Y^* along the line $E1X$ will mean that harvest is greater than the sustainable yield Y^* and the stock will decline to X^*. A harvest level below Y^* along $E1X$ will be less than the yield through natural regeneration (growth), and the stock will grow to X^* again.

It is easy to see that Y^*, though sustainable, is not *MSY*. However, by manipulating E we could set Y equal to EmX at Ym, the *MSY*. Introducing the

[4] It is to be noted that catches (harvests) larger than growth would be possible in the short-term, but these could not be sustained. They will lead to reduced stock size and, eventually, if the stock were drawn down to a level less than X_{min}, to the extinction of the species.

effort level, thus, helps us to determine the harvest and stock level. But it does not allow us to indicate the efficient sustainable yield. For that we need to introduce costs and benefits (revenue) into the picture.

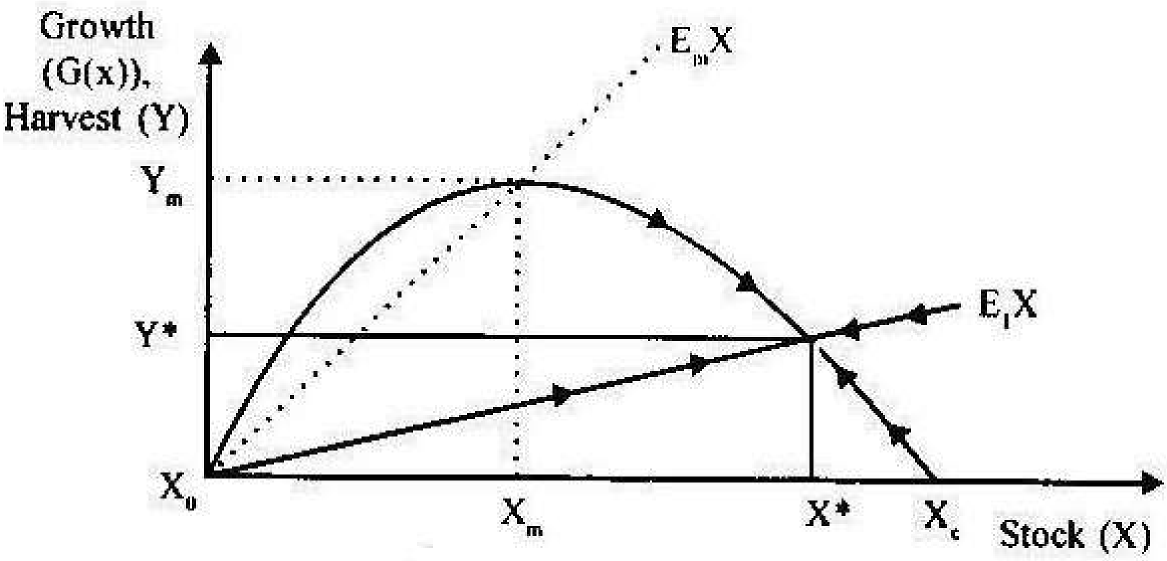

Figure 4: Effect-Growth Equilibriums

To introduce costs and revenues we transform figure 4 into Figure 5 showing the relationship between the harvest (yield) and the level of effort, that is, moving from (*X, Y*) plane to (*E, Y*) plane.

Figure 5 shows various equilibrium levels of yield (like *Y**, *Ym*, etc.) corresponding to various levels of effort (like *E1*, *Em* etc.), where *Em* > *E1* and so on. A little reflection will show that every effort level on this figure corresponds a stock level in Figure 4 and *Eo* corresponds to *Xc*, and *Emax* to *Xo*. Note that increasing fishing effort (a movement from left to right in Figure 5) would, in Figure 4, result in smaller resource stock and would be recorded as a movement from right to left.

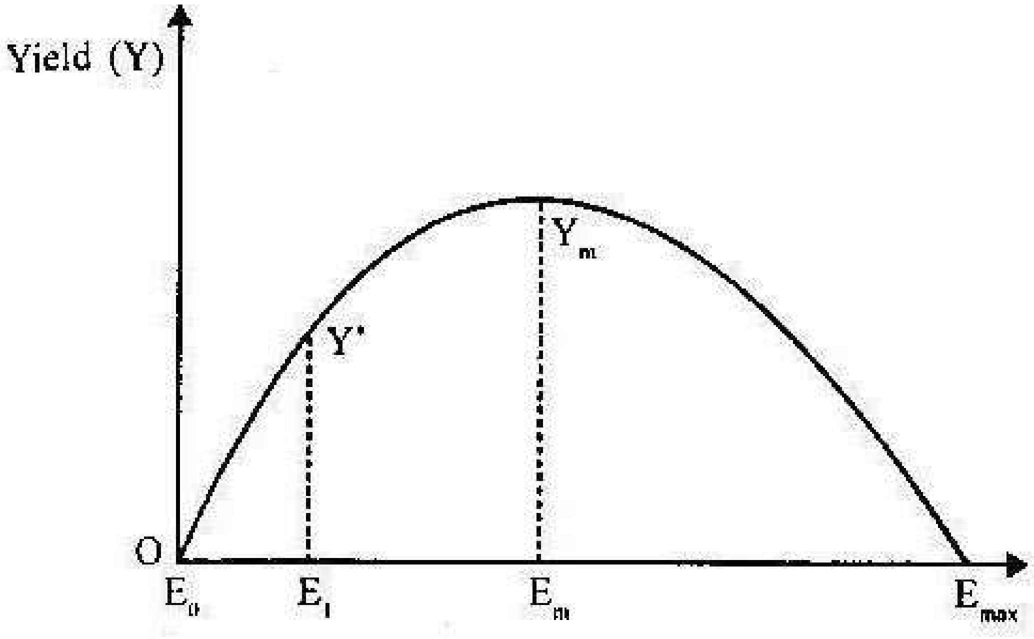

Figure 5: Effort-Yield Function

Now, the effort-yield curve depicted in Figure 5 can be translated into costs and revenue. In Figure 6, revenues (benefits) and costs are shown as functions of harvesting (fishing) effort. Because the price (p) of the harvested resource (fish) is assumed to be constant, total revenue (R) from harvest (Y) is

$$R = pY,$$

and the shape of the revenue function has the same shape as that of the effort-yield function of Figure 5.

As sustainable levels of effort are increased, eventually a point is reached (*Em* in Figure 6) where further effort reduces the sustainable catch (yield) and revenue for all years. That point corresponds to the *MSY* (*Ym* in Figure 5).

The net benefit is shown in Figure 6 as the vertical difference between the benefit $R = pY$ and costs, $C = cE$ (the constant marginal cost of effort times the units of effort expended). The efficient (optimum) level of effort is *Ee*, where the vertical distance between benefits and costs is maximized. In other words, *Ee* is an efficient level of effort, because it is where the marginal benefit (slope of the total benefit curve) is equal to the marginal cost (the constant slope c of the total cost curve). Once the efficient level of effort is determined we can determine the efficient level of yield from Figure 5.

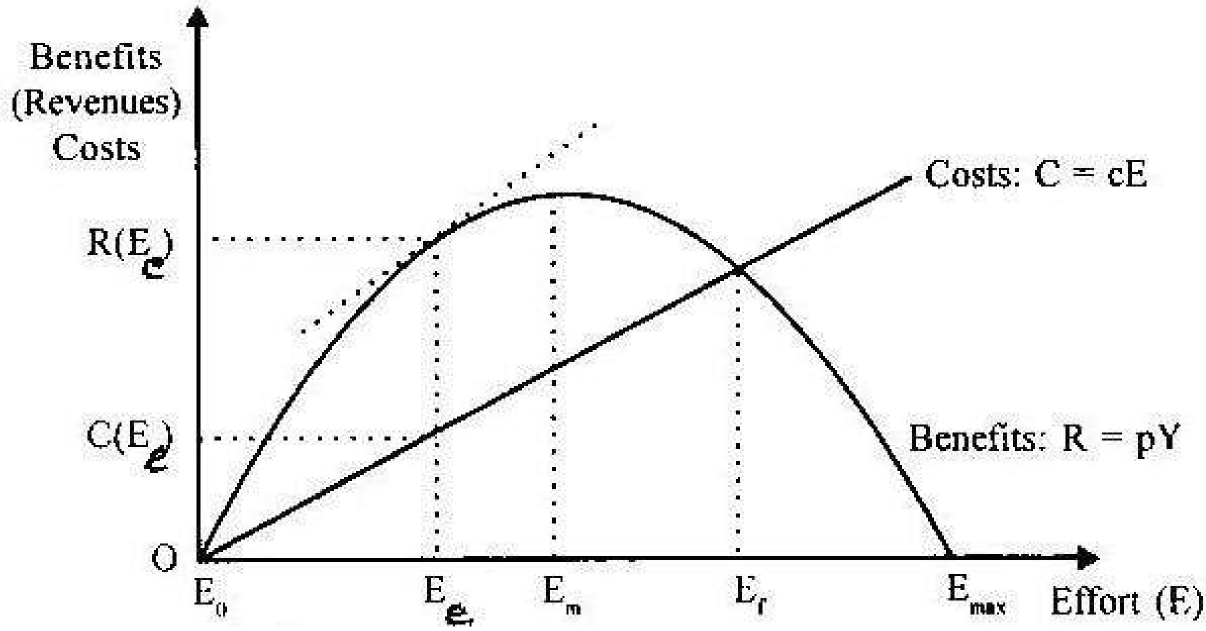

Figure 6: The Efficient (Optimum) Sustainable Yield for a Renewable Resource (Fishery)

Is, then, the MSY efficient? The MSY is efficient (in a timeless static world) only if the marginal cost of effort is zero. At the efficient level of effort this (zero) marginal cost has to be equal to (zero) marginal benefit and marginal benefit is zero at the MSY level only. Because this is not generally true, the efficient level of effort (*Ee*) is less than that necessary to harvest *MSY* (*Em*). Hence, the static efficient level of effort leads to a larger resource (fish) stock than does the *MSY* yield level of effort and MSY does not appear to be a socially desirable objective to strive for.

4.3 Market, Free (Open) Access and Common Property Resources

Having identified an efficient allocation of a renewable resource (fishery), we can now consider a competitive market allocation and compare these two allocations. A competitive sole owner is supposed to have well-defined property rights to the resource. A sole owner would want to maximize his profit. This will occur (ignoring discounting again) at an effort level where marginal revenue equals marginal costs. Clearly, this is effort level *Ee*, the static-efficient sustainable yield. This will provide positive profits equal to the difference between *R(Ee)* and *C(Ee)*. In the absence of any externality, maximizing net profits and maximizing net social benefits may be assumed to be the same thing, and hence lead to the same result.

While it is not difficult to think of privately owned fishing rights in lakes, private owners are not normal in ocean fisheries. Ocean fisheries may typically be international common-property; resources, no single fisherman exercises control over. Because no sole property rights to the fish belt are conferred to any owner, no single fisherman can restrict others from exploiting the resource. This characterizes free (open)-access resources.

What could be the consequences when access to the resource (fishery or forestry) is completely unrestricted? Free-access resources generate two kinds of externalities (Titenberg, 2001): (1) a contemporaneous externality, which is borne by the current generation. It involves congestion due to over-commitment of resources to fishing – too many boats, too many fishermen, too much effort. As a consequence, current fishermen earn a substantially lower rate of return on their effort[5]. (2) An inter-generational externality, which is borne by the future generations. It occurs because over-fishing reduces the stock of fish, which in turn lowers future profits from fishing (once, in the process, effort level exceeds that associated with the *MSY*).

When access to the fishery is free, an incentive to expend effort by each fisherman beyond *Ee* reduces profit to the fishery as a whole. Every one imposes a burden on everyone else. At the efficient level, each fisherman (boat) will receive a profit equal to its share of the scarcity rent. However, this rent serves as a stimulus for new fishermen to enter, driving up costs and eliminating the rent. Hence, open access results in overexploitation of resources.

In a free-access resource, as stated above, the individual fisherman has an incentive to expend further effort, until profits are drawn down to zero. This occurs at effort level *Ef* in Figure 6, where net benefits are zero ($R = C$). Contemporaneous externality manifests in too much effort being expended to catch too few fish, and cost (C) is substantially higher than it would be in an efficient allocation. In fact, many fisheries and forests in different parts of India and elsewhere are currently plagued by these kinds of problems.

[5] Some areas of deltaic West Bengal and coastal Kerala are experiencing this phenomenon.

A resource owner with exclusive property rights would balance the use value against the asset value of the resource (that is, would consider future flow of returns also). When access to the resource is unrestricted, exclusivity is lost. It is then rational for the individual fisherman to ignore the asset value, as he can never appropriate it. This process will dissipate all the scarcity rent.

However, free-access harvesting may or may not lead to the extinction of the species. It depends on the nature of the species and the benefits and costs of harvesting below the minimum viable stock (*Xmin* in Figure 2 or 3). The condition under which extinction will occur are: (a) that effort is costless – effort is at *Emax* in Figure 5 and the stock goes to zero; or (b) harvesting takes place at levels above the natural rate of regeneration, that is, the harvest is non-sustainable. The risk of resource extinction is high if there is a critical minimum size of the population (*Xmin*).

Are free-access resources and common-property resources synonymous concepts? Do they imply identical equilibra? The answer is generally no. We have seen that free-access means that no one owns the resource and access is open to all and unrestricted. A common-property resource, however, is one that is owned by a defined group of people – say a community. It is possible that within this group members may have free-access to the resource. But it is very likely that the group will develop rules and norms of use, restricting the use that any one individual is allowed to make of the resource. These rules are widespread where common property exists; tribal control of woodlands in Arunachal, community controlled irrigation systems in many parts of India and so on. The reason that such rules emerge is the cognizance of the fact that unrestricted use by each individual is more likely to lead to resource extinction, adversely affecting the welfare of everyone and perhaps imposing an irreversible damage (cost) on future generations. In terms of Figure 6 we might expect a common-property solution to be generally between the profit-maximizing solution and the free-access solution. However, common-property solutions can break down if, for instance, the defined group gets larger and larger because of population growth and in-migration. It may then pay any one individual to defect, breaking ranks and maximize individual benefit at the expense of the resource and the community's overall interests (Pearce and Turner, 1990).

4.4 Another Renewable Resource: Forests

Forests provide multiple benefits (goods and service) to humans. Forests are the source of timber which serves a variety of human needs (including fuel needs of people of the less developed world). Forests protect us from floods and soil erosion, cleanse the air, and act as the natural habitat of wildlife. They play a crucial role in the ecology of watersheds that supply much of our useful water.

Although forests share many attributes with other renewable resources, they also exhibit some unique features. Trees are commercially valuable when they are cut and sold. However if not cut, like a capital asset, standing forests also provide a stream of non-timber environmental services (as mentioned in the preceding paragraph). Each year, the forest manager has to decide about when to cut (harvest) a particular forest stand. Unlike many other renewable resources, the time period between initial investment (planting) and recovery of that investment (harvesting) may be quite long. Intervals of 25 years or more are common in forestry. Furthermore, most of the environmental benefits provided by the forest are positive externalities which normally cannot be captured by the resource managers. This leads to inefficient management.

Economics can be combined with forest ecology to arrive at an efficient management of this important natural resource. The standardThe starting point is to model the efficient decision to cut an even-aged homogeneous single stand (or cluster of trees). Here we assume that the forest provides only commercial value of timber. This model could then be used to indicate how the multiple values of the forest resource should influence the harvesting decision.

4.5 Tree Growth and Harvest

Data, based on measurement of volume, suggest that when even-aged trees are very young growth is rather slow in volume terms, though the tree may increase sufficiently in height. Then a period of sustained rapid growth follows. Ultimately, with the aging process growth slows down, stops or even reverses.

When should such a stand be cut (harvested)? Foresters adopt a biological approach to answer this question. They suggest a measure known as *mean annual increment* (*MAI*). The *MAI* is obtained by dividing the cumulative volume of the stand at the end of each decade by the cumulative number of years the stand has been growing up to that decade.

The biological decision rule then is: cut (harvest) the stand at the age when the *MAI* is maximized.

4.6 Economics of Forest Harvesting

To an economist, however, the above rule would appear somewhat arbitrary. This rule ignores the factors that seem to play a crucial role in an efficient harvesting decision. Some of these factors are, for example, the value of the timber, the time value of money, the costs of planting and harvesting. An economic model of the harvesting decision would, however, incorporate the basic biology of tree growth as shown in Figures 2 and 3 in Section 4. Economic efficiency would imply that the optimal time to harvest a stand would be that age that maximizes the present value of the net benefit from wood. .

In this framework, it can be shown that discounting (incorporated in time value of money) shortens the age when the stand is harvested. The use of zero discount rate implies that the opportunity cost of capital is zero; therefore, it pays to leave the money invested in trees as long as some growth is occurring and the value of timber is increasing in the process. With a positive discount rate, however, the trees will be harvested as soon as more will be earned from the money from the sale invested in a financial asset at rate r. Is economic efficiency compatible with sustainable forestry? According to one approach, sustainable forestry would imply harvesting limited to the growth of the forest, leaving the volume of wood unchanged over some specified period of time. Efficiency is not necessarily compatible with this definition of sustainable forestry. Efficiency requires maximizing the present value. Maximizing the present value, in turn involves, as shown above, an implicit comparison between the increase in value from delaying harvest (basically because of the growth in volume) and the increase in value from harvesting the timber and investing the sale-proceeds to earn r. If the growth rate in volume is small (as with slow-growing species), maximizing the present value may imply harvest volumes higher than the net growth of the forest.

It is interesting to note that the search for sustainable forestry that is also economically efficient has led to the emergence of rapidly growing tree species and plantation forestry (for example, eucalyptus). These species raise the attractiveness of replanting, because the invested money is tied up for a shorter period of time. These species are raised in plantations.

Plantation forestry, however, has raised many questions and has become controversial. It involves a single species of tree, endangering biodiversity so essential for many purposes including wildlife habitat. It also requires large chemical inputs and water, endangering growth of other species around. In Karnataka, a few years back, a popular movement developed against planting eucalyptus.

It is instructive to note that thus far we have abstracted from the amenity values of a forest while determining optimal rotation length. If standing trees provide amenity services in proportion to their volume, it can be shown that efficient rotation will be longer (Snyder and Bhattacharya, 1990). However, when amenity values are large and cannot be captured by the forest owner, the private rotation decision may fail to take account of these values, leading to inefficiently short rotation periods.

In India, soon after independence, in the first flush of industrial growth, vast stretches of bamboo forests were leased to paper and pulp mills. The agreements required the mills to pay a royalty to the government for the quantities of bamboo extracted. This royalty was fixed at a highly subsidized rate. Generous subsidies were also offered to forest-based industries for forest clearance and harvest. All these prompted destruction of the forest resource base. Lease of forest lands without creation of any stake in the future productivity of these lands has adversely affected the regeneration potential of these areas. Such policies have not only deprived the government of revenue, but also encouraged unsustainable, indiscriminate exploitation of the country's forest wealth.

Dense forests once covered India. As of 2010, the Food and Agriculture Organization of the United Nations estimates India's forest cover to be about 68 million hectares, or about 20 percent of the country's area. In qualitative terms, however, the dense forest in almost all the major Indian states has been reduced. Forest degradation is a matter of serious concern. India is the world's largest consumer of fuelwood. India's consumption of fuelwood is about five times higher than what can be sustainably removed from forests.

5. ECONOMICS OF WATER RESOURCE

Water is one of the essential elements of life. We humans depend not only on an intake of water to replace the continual loss of body fluids but also on food sources that themselves need water to survive. This resource deserves special attention.

The earth's renewable supply of water is governed by the hydrologic cycle, a system of continuous water circulation. Enormous quantities of water are cycled each year through this system, though only a fraction of circulated water is available each year for human use.

Available supplies are derived from two rather different sources – surface water and groundwater. As the name implies, *surface water* consists of the fresh water in rivers, lakes, and reservoirs that collects and flows on the earth's surface. By contrast, *groundwater* collects in porous layers of underground rock known as *aquifers*. Though some groundwater is renewed by percolation of rain or melted snow, most has been accumulated over geologic time and, because of its location, cannot be recharged once it is depleted.

In many parts of the world, water scarcity is already upon us, and that of other areas, including several parts of India, can be expected to experience water scarcity in the next few decades.

The problem with groundwater is even more severe. Groundwater levels have been declining in some areas of the country as a result of intensive pumping, and significant depletion of groundwater supplies has occurred in several regions. Around 29 per cent of ground water blocks in India are semi-critical, critical or overexploited and the situation is deteriorating rapidly. By 2025, an estimated 60 per cent of ground water blocks will be in a critical condition. Climate change will further strain ground water resources.

India is the largest user of ground water in the world, with an estimated use of 230 cubic km of ground water every year – more than a quarter of the global level. Now, ground water supports around 60 per cent of irrigated agriculture and more than 80 per cent of rural and urban water supplies.

Though the discussion thus far has focused on the quantity of water, that is not the only problem. Quality is also a problem. Much of the available water is polluted with chemicals, radioactive materials, salt, or bacteria. It is important to keep in mind that water scarcity has an important qualitative dimension that further limits the supply of potable water.

This brief survey of the evidence suggests that in certain parts of India groundwater supplies are being depleted to the potential detriment of future users. Supplies, which for all practical purposes will never be replenished, are being "minded" to satisfy current needs. Once used, they are gone. Is this allocation efficient, or are there demonstrable sources of inefficiency? In order to answer this question we must be quite clear about what is meant by an *efficient allocation* of surface water and groundwater.

5.1 The Efficient Allocation of Scarce Water

What efficiency means for the allocation of water depends crucially on whether surface water or groundwater is being tapped. In the absence of storage, the problem with surface water is to allocate a renewable supply among competing users. Intergenerational effects are less important, as future supplies depend on natural phenomena (e.g., precipitation) rather than on current withdrawal practices. For groundwater, on the other hand, withdrawing water now does affect the resources available to future generations. In this case, the allocation over time is a crucial aspect of the analysis. Because it represents a somewhat simpler analytical case, we shall start by considering the efficient allocation of surface water.

Surface Water

An efficient allocation of surface water (1) must strike a balance among a host of competing users, and (2) must supply an acceptable means of handling the year-to-year variability in surface water flow. The former issue is acute, because so many different potential users have legitimate competing claims:

Some (e.g., municipal drinking water suppliers or farmers) withdraw the water for consumption; others (e.g., swimmers or boaters) use but do not consume the water. The latter challenge arises because surface water supplies are not constant from year to year or month to month. Because precipitation, runoff, and evaporation all change from year to year, less water will be available to be allocated in some years than in others. Not only must a system for allocating the average amount of water be in place, above-average and below-average flows must also be anticipated and allocated.

With respect to the first problem, the dictates of efficiency are quite clear – the water should be allocated so that the marginal net benefit is equalized for all uses. If marginal net benefits have not been equalized, it is always possible to increase net benefits by transferring water from those uses with low net marginal benefits to those with higher net marginal benefits. By transferring water to the users who value the marginal water more, the net benefits of the water use are increased; those losing water are giving up less than those receiving the additional water are gaining. When the marginal net benefits are equalized, no such transfer is possible without lowering net benefits.

Groundwater

When withdrawals exceed recharge from a particular aquifer, the resource will be mined over time until supplies are exhausted or until the marginal cost of pumping additional water become prohibitive. The marginal extraction cost (the cost of pumping the last unit to the surface) would rise over time as the water table drops. Pumping would stop either (1) when the water table run dry or (2) when the marginal cost of pumping was either greater than the marginal benefit of the water or greater than the marginal cost of acquiring water from some other source.

Abundant surface water in proximity to the location of the groundwater could serve as a substitute for groundwater, effectively setting an upper bound on the marginal cost of extraction. The user would not pay more to extract a unit of groundwater than it would cost to acquire surface water. Unfortunately, in many parts of the country where groundwater overdrafts are particulars severe, the competition for surface water is already keen; a cheap source of surface water doesn't exist.

In efficient groundwater markets, the water price would rise over time. The rise would continue until the point of exhaustion, the point at which the marginal pumping cost become prohibitive or the marginal cost of pumping becomes equal to the next-least-expensive source of water. At that point the marginal pumping cost and the price would be equal.

5.2 Common Property Problems.

The allocation of groundwater must confront one additional problem. When many users tap the same aquifer, that aquifer becomes a common-property resource. Tapping a common-property resource will tend to deplete it too rapidly; users lose the incentive to conserve. The marginal scarcity rent will be ignored.

The incentive to conserve a groundwater resource in an efficient market is created by the desire to prevent pumping costs from rising too rapidly and the desire to capitalize on the higher prices that could reasonably be expected in the future. With common-property resources, neither of these desires translates into conservation, for the simple reason that water conserved by one party may simply be used by someone else because the conserve has no exclusive right to the water that is saved. Water saved by one party to take advantage of higher prices can easily be pumped out by another user before the higher prices ever materialize.

For common-property resources, pumping costs would rise too rapidly, initial prices would be too low, and too much water would be consumed by the earliest users. The burden of this waste would not be shared uniformly. Because the typical aquifer is bowl-shaped, users on the periphery of the aquifer tend to be particularly hard hit. When the water level declines, the edges go dry first, whereas the center can continue to supply water for substantially longer periods. Future users would also be hard hit relative to current users.

In conclusion we may say that we touched upon here some of the basics of the economics of natural resources using some representative resources. However, we need to remember that this is just a very brief introduction of a much larger issue.

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Centre of Excellence in Environmental Economics
Madras School of Economics
Gandhi Mandapam Road
Chennai - 600 025
Ph: 2235 2157/2230 0304/2230 0307
Fax: 2235 4847/2235 2155
Email: coe@mse.ac.in
Web: http://coe.mse.ac.in