Part I: Environmental Economics

2.2  Factor substitution and technology change
As will be demonstrated later, the supplies of most natural resources are finite and some argue that the continued depletion of key resources (i.e. complete utilization of petroleum reserve, erosional loss of arable land, salinization and depletion of aquifers) would impose a limit to further economic growth. To counter this argument, technological proponents have tested the potential increase in scarcity as a function of unit extractive output (what is called ‘the strong hypothesis of increasing economic scarcity’). The ‘strong hypothesis’ was set to find the physical measure of resource scarcity by using data from labor and capital (L_E and K_E, respectively), and the aggregate output (Q_E) of the extractive sectors (i.e. agriculture, fisheries, forestry, mining; Figure 19). The empirical data used in this analysis (Barnett and Morse, 1963) suggested that contrary to the stated hypothesis, real cost per unit of extractive good did not rise but fell instead (except for a few minor exceptions).

![Figure 19](image)

**Figure 19.** A graphical illustration of the strong hypothesis of increasing natural resource scarcity. The unit of labor and capital (L_E + K_E) used per unit of extractive output (Q_E) is increasing with time. The parameters α and β before L_E and K_E are weight factors of labor and capital, respectively (source: Hussen, 2004).

How can one explain that rapidly developing economies with strong population growth have not yet experienced increasing economic scarcity of natural resources? In fact, it seems that the mid-20^{th} century analysis may be outdated at present and the reported past trends of decreasing scarcity may not be sustainable over the foreseeable future. We will get back to this issue of sustainability, but in the meantime, let us explore two processes that may alleviate resource scarcity and thus facilitate economic growth despite increasing population growth. Both factor substitution and technological change are very important subjects in environmental economics. Factor substitution suggests that basic resources are used in combination and/or that resources and technology can freely replace one another in the production process (a quality called fungible).

**2.2.1  Factor substitution and its implications for resource scarcity**
The existing state of technology provides constraints as to how inputs (labor, capital, natural resources) are combined and used to produce goods and services. Economists can model these terms to obtain a mathematical function of output. However, they work with a fundamental assumption that inputs are freely substitutable, namely that any one element of the inputs can be replaced by another (or a series of) element(s) in the production process. Such substitutability may occur in three different ways: Constant, diminishing, and no factor substitution possibilities.

**Constant factor substitution possibilities** assume that any input element can be substitute at a constant rate (i.e. a set number of units of capital for another set number of natural resource). This implies that the cost of such elements of production (the opportunity cost) is constant over time. Under these circumstances, cost can be maintained constant by free substitution of any element(s). A corollary to this statement is that any element of production can be reduced to zero without any negative impact on total production (i.e. raising the overall opportunity cost of production).

Scarcity, under this vision, is resolved by the fungible nature of inputs. This is case appears difficult to conceive in natural systems where some qualities are difficult to replace or equate through substitution (i.e. the flood prevention capacity of natural wetlands in coastal zone vs. artificially constructed levees).

The notion of **diminishing factor substitution** accepts that an input could be substituted by other factors of production but not under a constant rate. The role of pristine sections in watersheds is a good example of such diminishing factor substitution. The integrity of certain regions of a watershed (the geographical area of land in which water flowing across the surface drains into a particular stream and ultimately flows a single point or outlet) is critical to maintain the quality of water in the streams thus acting as natural “filters”. The loss of such areas thus lead to a compromised water quality that can only be replaced, to some extent, by manufactured capital (i.e. water treatment plants). However, in such cases, the increased utilization and depletion of the natural capital (i.e. urbanization in pristine section of watersheds) often result in an increasing opportunity cost showing that factor substitution does not occur at a constant rate.

Under the **no factor substitution possibilities**, natural capital and other factors of production are used in predetermined fixed proportions to produce a given level of output. Under this assumption, a given level of output will require a certain minimum of natural capital without potential for substitution. This is the most extreme case of factor substitution and is the least likely.

Based on this short discussion, we can conclude that the concern over natural resource scarcity very much depends on where any particular natural resource rests along the continuum of substitution possibilities (from the extreme complete lack of substitutability to the perfectly substitutable). If the substitution possibility between a natural resource and other factors is zero, then the availability of the natural resource (and thus its scarcity) becomes a major concern since a decline in this resource below a critical minimum would entail an automatic lowering outputs, and thus living standards. These cases are rare, as most natural resources experience some level of substitutability. However, most often than not, such substitutability occurs at an increasing opportunity cost where a successive reduction in natural resources lead to incrementally larger increases in the requirements for other factors to support production at a constant level.

### 2.2.2 Technological change and its implications for resource scarcity

In the above discussion, the possibilities of factor substitution possibilities were presented assuming that technology of productions remained constant. However, this is a simplification since technological advances occur all the time and are a product themselves of market economies (investment in research and development assures new ways of production under more efficient
means). In production analysis, a technological advance is defined as the ability to produce a given amount of output by using less of all inputs. Viewed this way, technological advances in production technique lead to resource conservation. However, technological advances are often biased towards the increased efficiency of utilization of a particular input vs. other inputs. The technological advance may be capital biased or natural resource biased whether it enhances the productivity of manufactured or natural capital, respectively. Hence, it becomes clear that a discussion about scarcity of natural resources needs to include considerations of technological advances in addition to factor substitution in production. Consideration of technological advances is central to any attempt to assess the impact of natural resource scarcity on future standards of living. For example, changes in petroleum extraction technology have made possible the economic viability of exploration and extraction from oil deposits in deep ocean basins that were inaccessible in the past. For example, the rate of deepwater oil and gas production in the Gulf of Mexico has increased dramatically in the past decade (Figure 20) thanks to technological advances (and economic incentives) that have overcome the challenges to exploitation in such environments (water depth, reservoir pressure and temperature, reservoir fluids, etc).

**Figure 20.** Gulf of Mexico oil and natural gas production from shelf and deep water reserves. Panel a) Oil production. Panel b) natural gas production. Note: 2006 average annual gas production is estimated based on first 8 months of 2006. (source: Energy Tribune, 2007).

Technological proponents suggest that modern economies are still working far from their ceiling of system efficiency and that many solutions to resource scarcity lie in the potential for improvement of technological efficiency. Without a doubt, efficiency of energy consumption during production can be raised from its estimated dismal 1-5% to a value that at least reaches double digits. However, not all economists share the faith that technological advances may continually provide solutions to resource scarcity and thus sustain economic growth.

A few arguments are actually presented to counter the empirical evidence of Barnett and Morse. First, at the time these empirical studies were conducted, the statistical trends that help support the notion that economical growth occurred synchronously to an actual decrease in resource scarcity did not explicitly take environmental quality into consideration. The issue of external costs carried by degradation of environmental quality is one that we will explore in the next section so we will limit our discussion here to say that because of such an omission, the reported decrease in scarcity may actually need to be reevaluated. Indeed, the overall increase in extraction of natural resources has reduced the life-support and services of ecosystems (i.e. climate regulation, flood and acid buffering capacity, genetic diversity, etc). Some view this process as unsustainable, particularly when considering the loss of biodiversity.
Second, up to the mid-20th century, major transformations in the use of energy had occurred. In particular, higher quality fuels substituted lower quality ones in the production system (oil and natural gas replaced coal, which itself had replaced wood). According to some critics of the Barnett and Morse analysis, the measured reduction in labor-capital costs was biased by this shift in energy sources, which acted as a substitution of fuels for labor and capital in the extraction of resources. More recently, new empirical studies evaluated the actual extractive output ($Q_E$ from mining, agriculture, forest products, and fisheries) as a function of direct and indirect energy used to extract the resource ($E_d$ and $E_i$, respectively). One such analyses (Cleveland, 1991) eventually showed a decline in extractive output per energy input (Figure 21) pointing to an increase in physical scarcity or an increase in energy cost per unit of output.

![Figure 21](image.png)

**Figure 21.** Extractive output per unit energy input. The amount of extractive output obtained from the use of a unit of energy input (y axis) is declining over time, implying a decline in the efficiency of energy as a factor of production (source: Hussen, 2004)

Third, technological progress has evolved in a non-linear fashion over humanity’s history accelerating and being concentrated in the past few centuries. There is nothing that suggests that this historical trend ensures that technical progress will continue in the future at the same pace nor that technological improvements will lead to similar rates of return in terms of resource conservation. In fact, it seems that there are a number of ecological, energy, and technological factors that may prevent a continuing trend of decreasing resource scarcity.