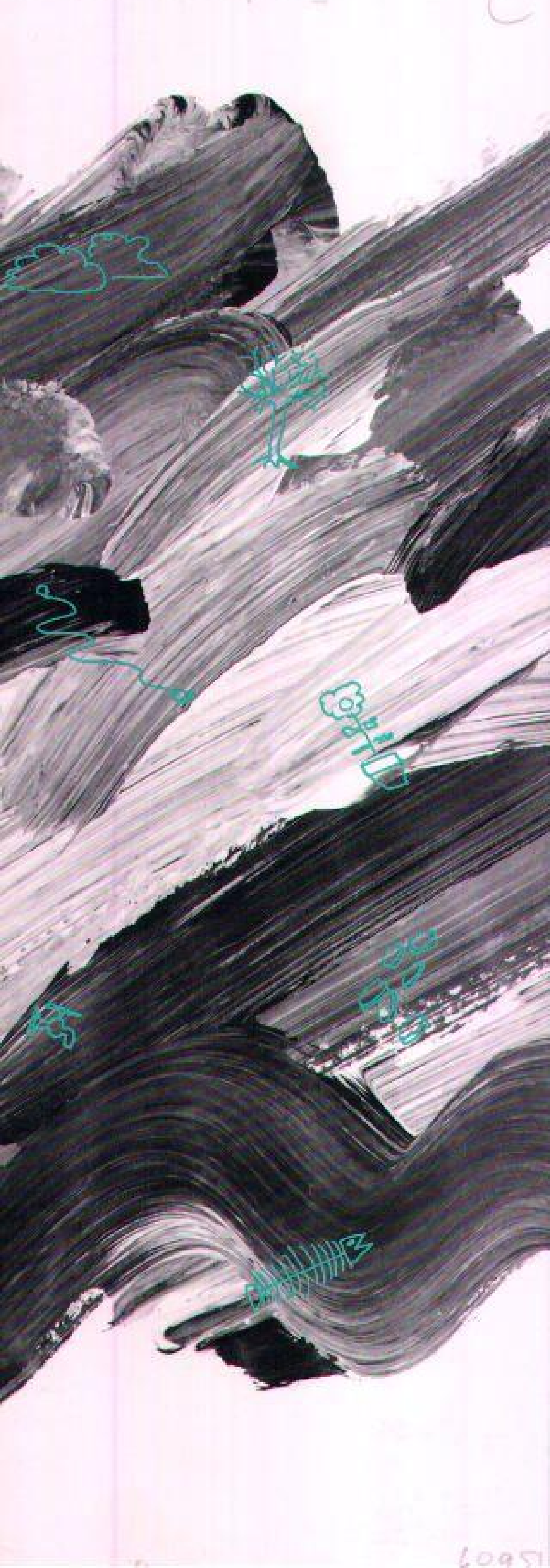

Depletable resources and the economy

W.J.M. Heijman

STELLINGEN

1. Het mensdom is verdeeld in diegenen die zo zuinig leven alsof ze eeuwig zullen leven, en diegenen die zo verkwistend leven alsof ze de volgende dag dood zullen gaan.

   Aristoteles geciteerd door Diogenes Laërtius in: *Leven en leer van beroemde filosofen* (p. 157), vertaald uit het Grieks door R. Ferwerda en J. Eykman. Ambo, Baarn 1989.

2. De negatieve relatie tussen de hoogte van de rentevoet en de levensduur van kapitaalgoederen en duurzame consumptiegoederen is in essentie terug te vinden in Böhm-Bawerks *Kapital und Kapitalzins*.

   E. von Böhm-Bawerk, *Kapital und Kapitalzins II, 1: Positive Theorie des Kapitales.* vierde druk, Fischer, Jena 1921 (1889).

3. De bijziendheid van een politicus kan niet worden verholpen met een bril.

4. Voor de instandhouding van een 'stationary state' is technische ontwikkeling niet onder alle omstandigheden noodzakelijk.

5. De term 'duurzame ontwikkeling' duidt op een proces van gestage groei gekoppeld aan ecologisch evenwicht.

6. Kleinschaligheid is geen garantie voor milieuvriendelijkheid.

7. Het milieuvraagstuk is in essentie identiek met het bevolkingsvraagstuk.

8. Het 'scheermes van Ockham' is in de economische wetenschap een verwaarloosd instrument.

9. Het gebruik van openbare wandelgebieden door zowel trimmers als bezitters van loslopende honden genereert een, vooral voor trimmers, kwalijke vorm van kwalitatieve concurrentie.

10. Een al dan niet optimistische visie op de toekomst van de mens wordt niet bepaald door de feiten, maar door het karakter van de voorspeller.

11. Bij het onderhoud van grote beboste natuurgebieden in Centraal-Europa dient de kettingzaag te worden vervangen door de wisent.

12. Van 'perestroika' en 'glasnost' resteren thans in ieder geval een tweetal aantrekkelijke opties voor de naam van een nieuw wodkamerk.

13. Bij de verpakking van nieuwe overhemden kan het aantal spelden met minstens 50% worden verminderd zonder afbreuk te doen aan de kwaliteit van de verpakking.

W. J. M. Heijman
Depletable resources and the economy
Wageningen, 27 september 1991.

DEPLETABLE RESOURCES AND THE ECONOMY

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W. J. M. Heijman

DEPLETABLE RESOURCES AND THE ECONOMY

Proefschrift

ter verkrijging van de graad van doctor
in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
dr. H. C. van der Plas,
in het openbaar te verdedigen
op vrijdag 27 september 1991
des namiddags te vier uur in de Aula
van de Landbouwuniversiteit te Wageningen.

Heijman W. J. M., *Depletable resources and the economy.* Ph.D. thesis, Department of General Economics, Wageningen Agricultural University, Wageningen, The Netherlands, 1991.

Without knowledge there are no resources.

PREFACE

For an economist, studying the effects of the economy on the depletion of resources and the environment is a challenge. When we look at the growth of the world population, it is clear that a growing world production is a necessity. That is why the central question to be answered in this thesis is not whether production can keep on growing or not, but rather how production can grow without depleting resources irresponsibly and without damaging the environment too much. Is this sustainable growth an illusion or is it a growing reality?

Writing a thesis is a lonely journey. To keep on going, one needs encouragement. Fortunately, in my case, this encouragement was amply present. I would like to thank Professor Dr H. W. G. M. Peer, Dr J. J. Krabbe and Professor Dr H. Folmer for their support. Without the stimulating discussions I have had with them and their suggestions to me I would not have been able to finish this study. I am indepted to Dr P. van Mouche for his valuable help in finding the best mathematical form for a substantial number of economic models. Further, he read and commented on several drafts of the manuscript. I would like to thank Ir R. Jongeneel for giving me useful suggestions and for checking some of the calculations. Further, I want to thank my colleagues at the Department of General Economics for their good-fellowship; writing a thesis is easier in a good atmosphere. I also want to thank the Foundation 'LEB fonds' for its financial support for the publication of this thesis. Correcting my English was the task of Mrs Rigg-Lyall. Her contribution as well as that of Mrs. Kooyman-Timmer for her translation of a Dutch text into English is gratefully acknowledged here. Finally I must thank my wife Antoinette and Jeroen for having the patience to endure my impatience to finish this thesis.

W. J. M. Heijman
Wageningen, june 1991

ABSTRACT

The subject of this thesis is the depletion of scarce resources. The main question to be answered is how to avoid future resource crises. After dealing with the complex relation between nature and economics, three important concepts in relation with resource depletion are discussed: steady state, time preference and efficiency.

For the steady state, three variants are distinguished; the stationary state, the physical steady state and the state of steady growth. It is concluded that the so-called sustainable growth is a combination of the physical steady state and the state of steady growth. Next time preference is discussed. This empirical phenomenon is important in determining the optimum depletion speed of non-renewable and renewable resources. The market interest rate is probably too high to serve as a rate of time preference. The efficient depletion speed of a non-renewable resource is determined by the Hotelling rule, while the optimum depletion speed of a renewable resource is determined by an adapted Hotelling rule which takes into account the renewal rate of the renewable resource. Indeed, both rules can be deduced from the Faustmann rule.

The analysis is continued with the integration of the optimum depletion rules in traditional growth theory. It appears that sustainable growth is just one of several growth paths, and not a necessary one. Short term cyclical developments are discussed with the help of the multiplier-accelerator model, the Cobweb model and a neoclassical cycle model with a so-called KLEM production function.

It appears that market forms influence the depletion speed of depletable resources. For instance, a monopoly depletes a resource less quickly than firms under perfect competition. Another matter which is dealt with extensively is the influence of the property rights on the depletion pattern. Ways in which government can influence the resource use of firms are discussed extensively. The main solutions of possible future resource crises are to be found in special types of technological development, recycling, substitution between resources, substitution between resources and capital or labour and economies of scale. Finally the question is answered whether scarce resources should be considered relatively or absolutely scarce.

Contents

1. Introduction

Types of resources

Human economy depends for a great deal on the use of resources. A resource can be defined as a stock of primary material or as a flow of primary energy suitable as an input in the production process (see also Randall, 1987). It has to be realized that in this definition, resources only have meaning in combination with human knowledge, culture and skills in relation to a specific resource. Fish, for example, is no resource for those who do not eat it. Or, to give another example, oil was not a resource in the seventeenth century, while, today, it is of vital importance to the world economy.

Some resources, for instance wind and sunlight, cannot be depleted by the economic process, while others, like coal and wood, can. Depletable resources[1)] can be further divided into exhaustible or non-renewable resources, like iron ore, and renewable resources, such as timber. The difference between the exhaustible and the renewable resources is clear. Renewable resources have a limited natural renewal capacity, which exhaustible resources have not[2)].

For an economist, these physical distinctions of resources are useful, but not sufficient. Indeed, the central question for an economist is whether a resource is scarce or not. If a resource is scarce, a rent must be paid for the use of it. If it is not scarce, in other words, if the resource is superabundant in an economic sense, the resource can be considered free, which implies that there is no rent to be paid[3)].

Figure 1.1 shows the categories of resources which can be distinguished on the basis of physical as well as economic qualities of a resource. Indeed, the division of resources into the categories scarce and superabundant is by no means fixed over time. This means that resources that are superabundant at present can become scarce in the future, and resources that are scarce at present, can become superabundant in the future, for example, because of innovations in the production process.

This thesis deals with the resources that are placed in the shaded area of Figure 1.1, which include the scarce depletable resources. It might perhaps be wondered whether there are scarce non-depletable resources. Of course, wind and sun are not scarce yet. Nevertheless, non-depletable energy sources like water power and geothermic energy can at present be scarce.

For scarce depletable resources, an important distinction can be made between exclusive and non-exclusive resources. The property rights of exclusive resources are well defined. On the other hand, non-exclusive resources are common property. As far

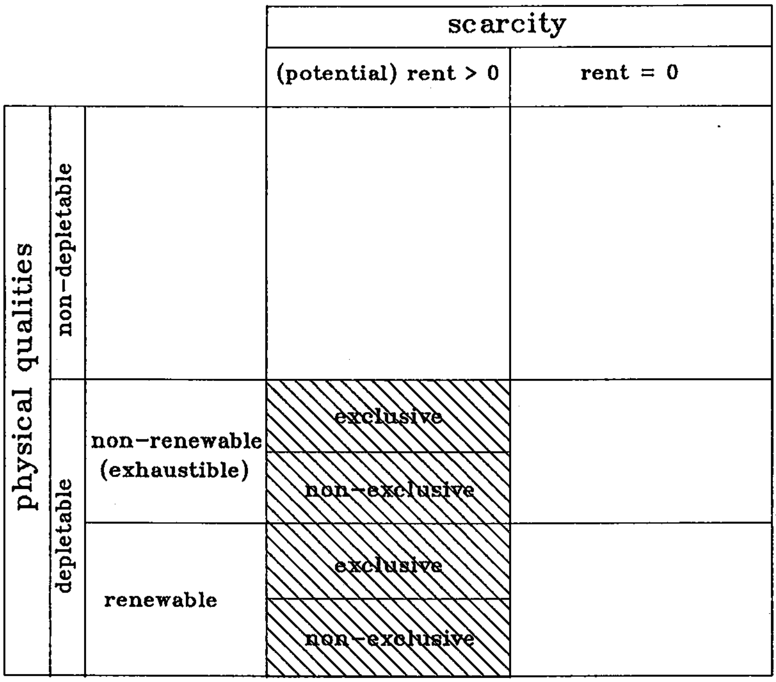

Figure 1.1: Categories of resources.

as these resources are concerned, it could be said that everybody's property is nobody's property. These resources generate problems which are quite specific (see Chapter 9). Though non-exclusive resources do not generate rent, they can still be scarce. In that case it is possible to speak of a potential rent, indicating that, if property rights are properly described, such a kind of resource will generate a rent based on the scarcity.

In the seventies and eighties, the world economy was shocked by two severe oil crises. On top of that, it is expected that, because of the growing world population, in the near future the world economy will have to grow rather robustly. This implies that there is a risk that humanity will run out of some depletable resources, which could profoundly influence the production level and the level of welfare in the future (Reijnders, 1989). This makes the relation between the human economy and the depletion of scarce depletable resources a subject of high priority.

From neoclassical times onward, economists have studied human economy more or less as a closed system without any relation to the surrounding environment. Because of environmental problems and resource crises during the seventies, economists were forced to include environmental variables in their models. In other words, they were forced to look upon human economy as an open system, which here means a system related to nature.

Faced with the threat of new resource crises and environmental pollution, the World Commission on Environment and Development (WCED) has developed a programme aimed at leading to a sustainable development, described as:

> development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (WCED, 1988, p. 8).

This definition is not an exact one. In the following section I develop some precise conditions for sustainable development.

Fundamental conditions for sustainable development

Suppose an economy disposes of one exhaustible resource. The question to be answered is how fast its economy may grow if the exhaustible resource is not to be depleted fully, taking into account the possibility of a diminishing use per unit product of the resource concerned. This diminishing use per unit product can be caused by technical innovations, by substitution between other production factors and the resource[4], and by economies of scale. The total amount of the resource used per period is the resource output ratio (μ_t) multiplied by total output (y_t), while, in period 0, total stock equals V units. This stock is to be used over an infinite time, after which it is assumed that the stock is depleted. This means that:

$$(1) \qquad \sum_{t=0}^{\infty} \mu_t \cdot y_t = V.$$

Further it is assumed that the resource output ratio decreases by $i \cdot 100$ percent per period, while production grows $\alpha \cdot 100$ percent per period. This means that:

$$(2) \qquad \mu_t = \mu_0 \cdot (1-i)^t$$

$$y_t = y_0 \cdot (1+\alpha)^t.$$

Equations (1) and (2) give:

$$(3) \qquad V=\frac{\mu_0\cdot y_0}{1-(1-i)\cdot(1+a)}=\frac{\mu_0\cdot y_0}{i-a+i\cdot a}.$$

Neglecting the second order effect $i\cdot a$ (3) gives:

$$(4) \qquad y_0=\frac{i-a}{\mu_0}\cdot V \qquad (i>a).$$

Equation (4) gives the maximum output in period 0 if production is to grow with $a\cdot 100$ percent each period. Equation (4) can be called the exhaustible resource condition for sustainable development. An assumption for this development is, of course, that the relative reduction in the resource output ratio in each period exceeds the growth rate of production[5] $(i>a)$. In fact, this condition implies that the stock-depletion ratio for the exhaustible resource must be kept constant in every period. This can be proved as follows. The stock-depletion ratio for period t equals:

$$(5) \qquad \frac{V-\sum_{j=0}^{t-1}\mu_j\cdot y_j}{\mu_t\cdot y_t}=\frac{V-\sum_{j=0}^{t-1}\mu_0\cdot(1-i)^j\cdot y_0\cdot(1+a)^j}{\mu_0\cdot(1-i)^t\cdot y_0\cdot(1+a)^t}$$

$$=\frac{\frac{V}{\mu_0\cdot y_0}-\sum_{j=0}^{t-1}((1-i)\cdot(1+a))^j}{((1-i)\cdot(1+a))^t}=\frac{\frac{1}{1-(1-i)\cdot(1+a)}-\frac{1-((1-i)\cdot(1+a))^t}{1-(1-i)\cdot(1+a)}}{((1-i)\cdot(1+a))^t}=\frac{1}{i-a+i\cdot a},$$

and is thus independent of t. As an illustration stock-depletion ratio's are computed for a number of scarce resources in the next section.

Next, an economy with only one renewable resource is assumed. Further it is assumed that the depletion of this renewable resource equals the natural renewal of it[6], so that the stock W will not change. The depletion in period t equals the resource output ratio (δ_t) multiplied by production. Natural renewal equals the renewal rate (b) multiplied by the stock (W). So that

(6) $\delta_t \cdot y_t = b \cdot W$

thus: $y_t = \dfrac{b \cdot W}{\delta_t}.$

The reduction in the resource output ratio is supposed to be $s \cdot 100$ percent per period, so that:

(7) $\delta_t = \delta_0 \cdot (1 - s)^t.$

Equations (6) and (7) give:

(8) $y_t = \dfrac{b}{\delta_0 \cdot (1 - s)^t} \cdot W.$

Because production is to grow each period by $\alpha \cdot 100$ percent each year, we can now conclude

(9) $y_t = y_0 \cdot (1 + \alpha)^t = \dfrac{b}{\delta_0 \cdot (1 - s)^t} \cdot W.$

Equation (9) can be called the renewable resource condition for sustainable development. Because $y_0 = (b/\delta_0) \cdot W$, it follows $1 + \alpha = 1/(1 - s)$, thus $\alpha = s/(1 - s) \approx s$ (if s is not too large). This implies that, in a situation of sustainable development, the maximum growth rate of production is about equal to the relative reduction in the resource output ratio of the renewable resource.

Now, suppose an economy is disposing of an exhaustible resource as well as a renewable resource. For a sustainable development, the condition for the exhaustible resource as well as the condition for the renewable resource must hold. Then, from equations (4) and (9) it follows:

$$(10) \qquad \frac{i-a}{\mu_0} \cdot V = \frac{b}{\delta_0} \cdot W,$$

$$\text{thus:} \quad s \approx a = i - \mu_0 \cdot \frac{b}{\delta_0} \cdot \frac{W}{V}.$$

Equation (10) might be called the equation of sustainable development because, if the growth rate of income a is not larger than indicated by this equation, the renewable as well as the exhaustible resource stock will never be depleted fully. To conclude, the fundamental conditions for sustainable development are that the stock-depletion ratio for exhaustible resources is to be kept constant in every period, and the human use of the renewable resource may not exceed natural production. In Chapter 3 these two conditions together are called the *physical steady state.*

Stock-depletion ratio for a number of scarce resources

As well as distinguishing between scarce and superabundant resources, it is also possible to distinguish between *reserves* and *subeconomic resources*. A reserve is a stock of recoverable scarce resource from identified deposits. The remaining resources consist of superabundant resources on the one hand and *hypothetical resources* on the other. A hypothetical resource is an, as yet, undiscovered resource. The reserves can be divided into *proved, probable* and *possible* reserves. The *world reserve - world demand ratio* can also be called the *stock - depletion ratio*. In this section this ratio is determined for a number of scarce resources (Brookins, 1990).

To do so I distinguish the following resources: 1. metals; 2. elements for the agricultural and chemical industry; 3. industrial minerals; 4. energy resources. For a number of metals the stock-depletion ratio is determined in Table 1.1 for the period 1984-2000.

In Table 1.2 the ratio for a number of elements used in agricultural and chemical industries is determined.

Table 1.1: Estimated world stock-depletion ratios for a number of metals, 1984-2000.[a]

Metal	World reserve (1984)	World demand (1984-2000)	stock-depletion ratio (in periods of 16 years)
Aluminum	21,000 Mt	825 Mt[b]	25.46
Chromium	360 Mt	74 Mt	4.87
Cobalt	4000 Kt	600 Kt	6.67
Copper	340 Mt	170 Mt	2.00
Iron	71,000 Mt	9900 Mt	7.17
Lead	95 Mt	61 Mt	1.56
Manganese	1000 Mt	110 Mt	9.09
Nickel	58 Mt	18 Mt	3.22
Tin	3.1 Mt	3.9 Mt	0.80
Tungsten	2800 Kt	970 Kt	2.89
Zinc	170 Mt	130 Mt	1.31

a) Reserves and demands reported in million short tons (Mt) or thousand short tons (Kt) contained metal, 1 short ton = 900 kilograms; a long ton equals 1008 kilograms; a metric ton equals 1000 kg.

b) The number of 15 Kt in Brookins (1990) for world use in the period 1984-1990 must be wrong, so I have used an alternative rating here.

Source: Brookins, 1990.

Table 1.2: Estimated world stock-depletion (reserve-demand) ratios for a number of agricultural and chemical elements 1983-2000.[a]

Element	World reserve (1983)	World demand (1983-2000)	Reserve/demand (in periods of 17 years)
Boron	360 Mt	22 Mt	16.36
Bromine	Adequate	7.5 Mt	-
Fluorspar	850 Mt	110 Mt	7.73
Phosphate	14 Gmt	3.2 Gmt	4.38
Potash (K_2O)	9.1 Gmt	590 Mmt	15.42
Salt	Adequate	4200 Mt	-
Soda ash	26 Gt	720 Mt	36.11
Sulfur	1.3 Gmt	1.3 Gmt	1.00

a) Reserves and demands reported in million short tons (Mt), billion short tons (Gt), million metric tons (Mmt) or billion metric tons (Gmt). 1 short ton = 900 kilograms; a long ton equals 1008 kilograms; a metric ton equals 1000 kg.

Source: Brookins, 1990.

In Table 1.3 the reserve-demand ratios are determined for major industrial minerals.

Table 1.3: Estimated world stock-depletion (reserve-demand) ratios for a number of important industrial minerals 1983-2000.[a]

Industrial mineral	World reserve (1983)	World demand (1983-2000)	stock-depletion ratio (in periods of 17 years)
Barite	160 million T	150 million T	1.07
Diamonds	600 million Ct	460 million Ct	1.30
Diatomite	800 million T	29 million T	27.59
Feldspar	Adequate	72 million T	-
Garnet	8.1 million T	860,000 T	9.42
Graphite	15 million T	7.8 million T	1.92
Gypsum	2.6 billion T	1.9 billion T	1.37
Perlite	700 million T	35 million T	20.00
Pumice	Adequate	260 million T	-
Sand and gravel	Adequate	14 billion T	-
Stone	Adequate	Adequate	-
Vermiculite	50 million T	11 million T	4.55

a) T: short tons, Ct: carats.
Source: Brookins, 1990 (adapted).

In Table 1.4 the reserve demand ratios are determined for the major energy resources.

Table 1.4: Estimated world stock-depletion (reserve-demand) ratios for the major energy resources 1976-1986.

Energy resource	World proved reserves (1986)	World demand (1976-1986)	stock-depletion ratio (in periods of 10 years)
Crude oil (billions of barrels)	1133.24	244.34	4.64
Natural Gas (trillion cubic feet)[a]	4,486.20	684.2	6.56
Coal (billion small tons)	986.53	43.07	22.91
Uranium (million small tons)	2	0.25	8

a) The Netherlands is the world's fourth largest producer of natural gas with 2.7 trillion cubic feet in 1984. The first three are the USSR (22.7 trillion cubic feet), the United States (16.4 trillion cubic feet) and Canada (3.0 trillion cubic feet).
Source: Brookins, 1990 (adapted).

From Table 1.4 it appears that coal has become by far the most favourable stock-depletion ratio of the energy resources. Unfortunately, coal is also the heaviest polluter of the world environment. A great deal of the greenhouse effect and the acidification problem are caused by the use of coal on a large scale. On the other hand, the use of uranium generates pollution in the form of radiation. Finally, it is important to realize that the stock-depletion ratio can not serve as a measure for economic scarcity. The only suitable measure for that is the rent. It might be suggested to consider the stock-depletion ratio as a measure for technical or absolute scarcity.

Further contents of this thesis

The main question to be asked in this thesis is how to escape the new scarcity of resources and to make clear what possible instruments exist for a government to attain this goal. In order to find possible answers to this question, a survey of the economic and related literature of the past and present has been made. Based on this aquired knowledge, the conditions for a sustainable growth are developed. Special emphasis is laid on the possibilities of substitution between resources and technical innovation as possible solutions to the question, as well as upon the role of time preference. The latter concept especially is crucial in the resource discussion and in the pursuit of sustainable growth.

In Chapters 2, 3 and 4, concepts that are important for the economic analysis of the problem are discussed. In Chapter 2 the treatment by economists of the production factor nature is dealt with. It appears that, especially in the early days of economics, then called political economy, economists developed a vision on the exploitation of nature, where later, in the days of neoclassical and Keynesian economics, this was no longer common. Chapter 3 deals with the so-called *steady state* situation. Several definitions of this concept and their possible consequences for economic growth are shown. In Chapter 4 the important issue of time preference is discussed. Its relation especially with the rate of interest makes this concept relevant for the speed of resource depletion and for efficiency in resource depletion. The concept of efficiency is discussed extensively in Chapter 5.

After the first five chapters, the analysis continues with an examination of the resource depletion on three different levels: the macro-level, the sector-level and the micro-level. The resource depletion on the macro-level is dealt with mainly in Chapters 6 and 7. In Chapter 6 resources are integrated into two growth models: the Harrod Domar growth model and the neoclassical growth model. In Chapter 7, cyclical aspects of resource use are dealt with. In this chapter the effects of a sudden rise in the oil price for a small non-oil-producing economy are examined. The sector level is discussed in Chapter 8, in which it appears that the specific market form may influence the depletion speed profoundly. Chapter 9 deals with the highly important common property problem. Since a great deal of existing depletable resources are non-exclusive, the market mechanism cannot function well for these resources. In this respect it is important to discuss the possibilities of government policies in managing the commons. The micro-level is discussed in Chapter 10. Since the influence of government measures finally reaches the firm, possible policy instruments of resource conservation are emphasized in this chapter. In the final chapter, Chapter 11, the scarcity of resources is discussed. There is a Dutch summary after Chapter 11.

Notes

1) Robinson (1989) uses the term *destructible resources* instead of *depletable resources*. These terms can be considered synonymous.

2) If only the proved reserves of exhaustible resources are taken into account then it is possible, within strict limits, to look upon exhaustible resources as a growing stock of capital assets, since new deposits are found continuously. It is clear that this will cease after all reserves have been discovered (Robinson, 1989, p. 31). Indeed, it is questionable whether there is such a thing as a fixed stock of an exhaustible resource (Adelman, 1990).

3) Following Gray (1914), no distinction is made between *rent* and *royalty* in this thesis. The rent is simply the whole of the surplus above the extraction cost. In other words, it is the market price per unit resource minus the sum of the return on capital and wage per unit resource (see also Robinson, 1989 and Repetto et al., 1989).

4) See Chapter 3 for an example of substitution between capital and an exhaustible resource.

5) This part of the model is very like Tinbergen's model (see Chapter 3).

6) In fact, it is assumed here that the natural renewal is at a maximum. This situation is called the *optimum steady state*. This subject is dealt with extensively in Chapter 3.

2. Nature and economics

The production factor nature plays an important part in the economic process and in economic science. In particular, the relation between economics and ecology is an important issue. This chapter concentrates on the border land between both disciplines; environmental economics or ecological economics, in which area the interdependency between economics and natural science is essential.

Economy as an open system

Till the time of the neoclassical and Keynesian economics in economic theory, there was always a clear perception of nature. The physiocrat Quesnay, who was one of the founders of economic theory, was well aware of the great value that nature has for man. Not without reason he considered agriculture as the one and only producer of wealth. According to him, it is only in agriculture that humanity benefits from 'the free gift of nature' (Weulersse, 1910). Also classical economists like Smith and Ricardo and economists in the German tradition of the Historical School were interested in nature (Dietz, 1987, Krabbe et al., 1986). It may be said that the classical production function takes the form $Y = f(N, K, L)$, in which N is nature including resources, K is capital and L is labour (Randall, 1987).

With the progression of the industrial revolution, economists lost their interest in agriculture and, as a result, in the relation between labour and nature (Chin, 1984). Instead, the emphasis was placed on the relation between labour and capital, which changed drastically during the 18th and 19th centuries.

As a result, in main stream general economic theory today, human economy is usually portrayed as being a closed system in which consumer goods are produced and consumed with the help of the production factors labour and capital. One might say that neo-classical theory reduced the classical production function to $Y = f(K, L)$.

However, since the mid sixties it has increasingly been realized that the economy of man has a strong relation with the surrounding ecology, which can be ignored only at his own peril. It has increasingly become clear that the economy is an open rather than a closed system. A simple picture of the openness of the system is given in Figure 2.1. (see also Folmer, 1989 and Nijkamp, 1979).

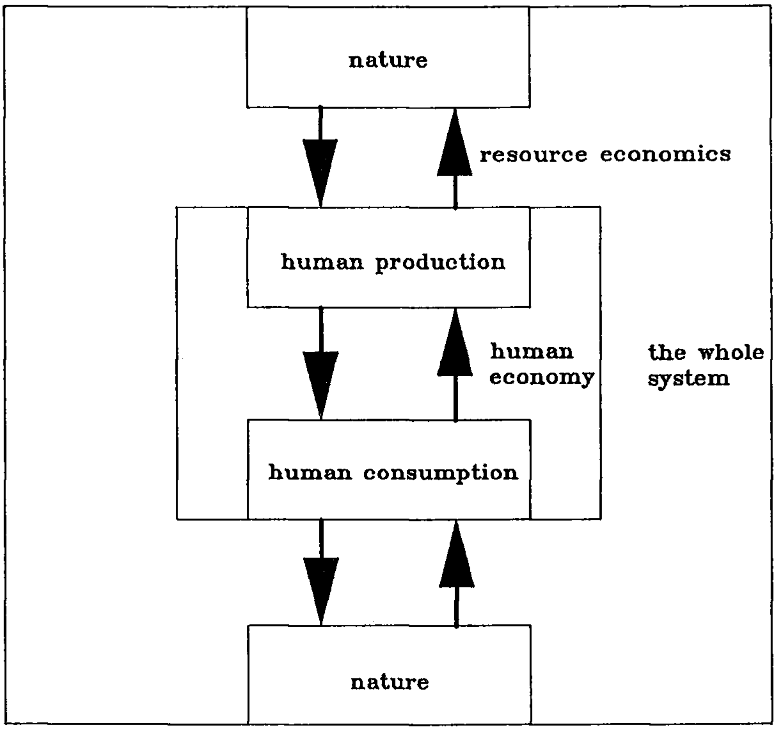

Figure 2.1: The economy as an open system.
Source: Krabbe J. J., 1986, p. 4.

In Figure 2.1 the inner rectangle represents the human economy with its demand and supply relations between the production sector and the consumption sector. Both these sectors have relations with nature. The production sector gains resources from nature on the one hand and dumps waste back into nature on the other hand. This subsystem, consisting of the production sector, natural resources and the relations between these two elements is specially studied in the field of the *resource economics*. The consumption sector is drawing consumer's goods from nature directly, like air, for instance, and dumps the waste of consumed commodities into nature. The whole system can be seen as the sphere of the *environmental economics*.

Externalities

In today's economic model-making the relation between the production factors labour and capital is studied thoroughly. Environmental problems are thereby seen as *negative externalities* or *diseconomies*, a concept introduced by Marshall (1890) and Pigou (1952). Nowadays the usual definition for externalities is:

> All the effects of economic activity which are external to the market (Victor, 1972).

From this definition it will be clear that externalities can be both positive and negative. Of course, when environmental pollution is at stake, negative externalities are discussed. At first, externalities were regarded as being unimportant theoretical refinements (Dietz et al., 1984), the price mechanism being regarded as the almost perfect working compass economists could sail by.

Thirty years ago nature was generally seen as a sheer inexhaustible reservoir containing all kinds of raw materials, fossil fuels and organisms. Although ecologists had often warned against the dissipating and disrupting character of the economic system as created by man, not until prices of raw materials increased and pollution and the spoiling of nature led to considerable costs for government, the public and industry did economists become interested. It was especially the sacred belief in the free functioning of the price mechanism that put up barriers against the ecological movement in economic thought. It was believed that, in the end, the scarcity of raw materials and the pollution of the environment would show in the price level. This explains why economists in those days were not concerned with environmental problems. After all, it was the consumer who was to pay for the sacrificed values via the market mechanism.

Although the macroeconomic conception that production equals income fits nicely into this way of thought, it is fundamentally wrong from an ecological point of view if income is not adequately defined. It was Schumacher (1973), among others who, in his book 'Small is beautiful', noticed this wrong conception of income. He stressed the capital character of nature, challenging the money-directed thinking by economists that leads to the exhaustion of the stock of capital goods that nature is, the using up of nature being regarded as 'income' rather than 'costs' (diseconomies or negative externalities). Schumacher's attack on the Western economic order concentrated on the market mechanism that does not differentiate between different types of goods. Figure 2.2 shows Schumacher's division of goods.

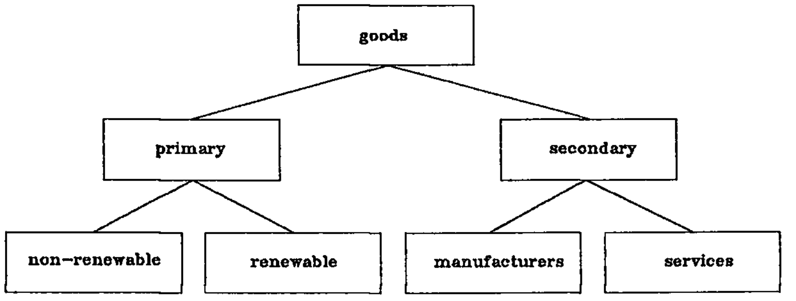

Figure 2.2: Schumacher's division of goods.
Source: Schumacher, 1973, p. 49.

By primary goods, Schumacher meant depletable resources. By secondary goods, he meant final products. Primary goods can be divided into renewable and non-renewable (or exhaustible) resources, while secondary products can be divided into manufactures, for which a relatively large quantity of primary goods are necessary, and services, for which a relatively small quantity of depletable resources are needed. His objection against the price mechanism is that:

> The market knows nothing of this distinctions. It provides a price tag for all goods and thereby enables us to pretend that they are all of equal significance (Schumacher, 1973, p. 50).

According to Schumacher, it is because of the money-directed thinking that it seems not to matter whether or not a product is produced at the expense of the use of large quantities of non-renewable resources. As a result the future scarcity of natural resources does not show in the market price. The unlimited functioning of the market mechanism, therefore, cannot but lead to the exhaustion of nature.

Daly (1986) shared Schumacher's opinion. He stated:

> The market does not distinguish an ecologically sustainable scale of matter-energy throughput from an unsustainable scale, just as it does not distinguish between ethically just and unjust distributions of income (Daly, 1986, p. 320).

Georgescu-Roegen (1976) expressed this in a similar way. He saw the identity production = income as the 'perpetual-motion idea' in economics. According to him, part of the value added should be regarded as being a compensation for the use of nature (see also: Daly, 1989). This idea is clarified in Figure 2.3.

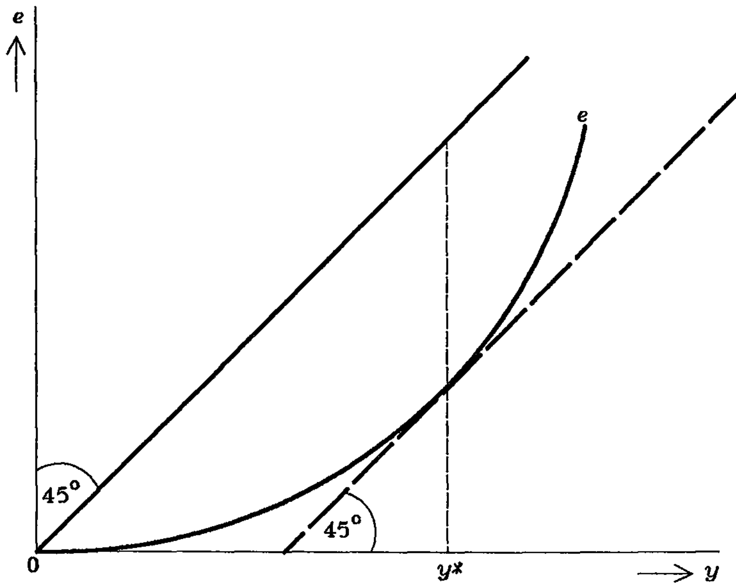

Figure 2.3: Production and diseconomies.

In Figure 2.3, production and diseconomies are shown in one diagram. In this figure e stands for diseconomies (negative externalities) and y stands for production[1]. As production grows, diseconomies increase per unit product since because pollution is accumulated in the environment (Krabbe, 1989). As a result of this, the money value of the diseconomies increases according to an convex rising function. To put it more exactly:

$$(1) \qquad e = e(y), \quad \frac{de}{dy} > 0, \quad \frac{d^2e}{dy^2} > 0.$$

Total social welfare (w) equals production (y) minus diseconomies (e). Together with equation (1) this gives:

$$(2) \qquad w(y) = y - e(y).$$

Maximizing welfare implies that the first derivative of w with respect to y equals zero. From this it follows:

$$(3) \qquad \frac{dw}{dy} = 0, \quad \text{so} \quad \frac{dy}{dy} - \frac{de}{dy} = 0 \quad \text{and} \quad \frac{de}{dy} = 1.$$

In Figure 2.3, this result has been shown by drawing a line making a 45-degree angle with the vertical axis tangent to the diseconomies curve. The point of tangency gives the production level for which welfare is at its maximum (y^*). If there is no change in the technical possibilities of decreasing the diseconomies per unit product, and if the objective of the economy is to gain maximum social welfare, y^* represents the limit of production growth. Indeed, in the case of technical innovation, this limit can be widened.

It is not always clear how large the diseconomies are in money terms. Both Kapp (1950) and Hueting (1974) pointed out that it is difficult to calculate a shadow price for environmental functions. Nevertheless, several methods for calculating the environmental damage have been developed (Folmer et. al., 1989, Ahmad et al., 1989 and Repetto et al., 1989). What can be done more easily in trying to sustain nature as a production factor is to set physical standards. In this vision, individual producers are pursuaded by the authorities, with market measures as well as direct regulations, to adapt their production processes in such a way that the environment is harmed as little as possible. The reason why this is not yet being done sufficiently has to do with the character of the 'commodity' nature. Nature is undoubtedly a collective good with all the characteristics of the prisoner's dilemma, which can be protected only by a firmly acting government. The prisoner's dilemma is when the 'homo economicus' behaves rationally on an individual level but irrationally on a collective level.

Up till now in this chapter it has been assumed that there was no abatement sector to abate pollution. If an abatement sector is assumed, the relations between resource use, the economic process and pollution can be clarified with the help of Figure 2.4.

Figure 2.4 contains the production sector and the abatement sector (quadrants IV and III respectively). In quadrant I the environmental pollution (p) is shown in physical terms. Further, the economy can periodically dispose of one resource (n) with quantity OE. In production[2] (y) as well as in abatement (a), a decreasing marginal productivity of this resource is assumed. If there is no abatement at all, the relation between production and pollution is represented by the p_1 – curve. This curve is assumed to be convex and rising. If EG units of the resource are put in the abatement

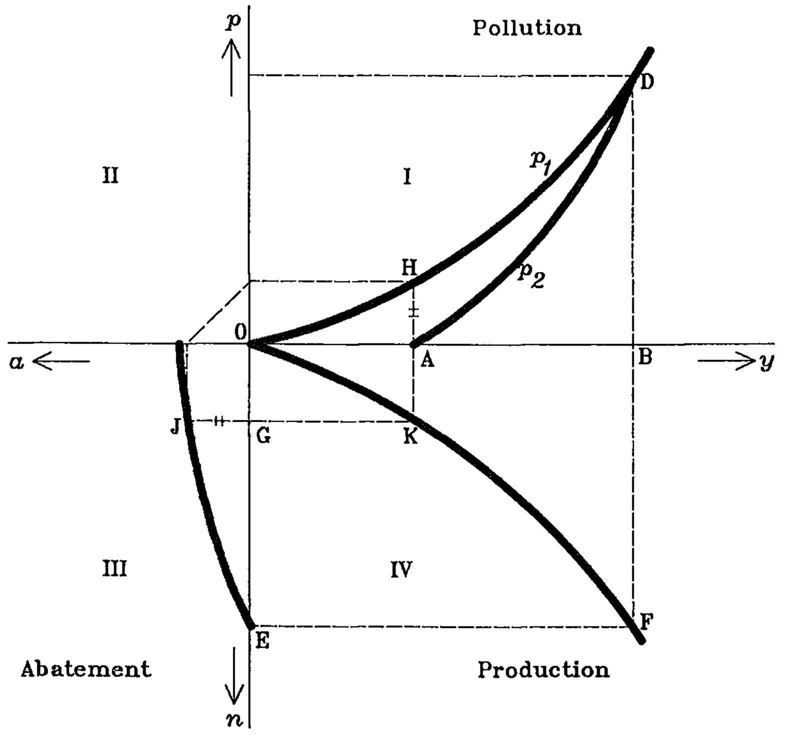

Figure 2.4: The relations between resource use, the economic process and pollution.
Source: Siebert, 1987.

sector, pollution can be totally prevented (JG = AH), which implies a relatively low production of OA units. Of course, if all of the resource is put into the production sector, then pollution as well as production will be at a maximum (BD and BF units respectively). So, if all the resource units are used up, the relation between pollution and production can be represented by the p_2-curve. Figure 2.4 shows the goal conflict between the need for a high production and the need for a high quality environment. If a social welfare function is known, the optimum combination can be determined (see Appendix 2.1).

Of course, the curves of Figure 2.4 only hold for a given technology. Technical change shifts the production function to the right, the abatement function to the left and the emission function downward. Technical change can relieve the goal conflict between production and environment. On the other hand, when the amount of resource available each year decreases, the goal conflict is intensified.

Resource economics

Adam Smith said of rent and natural resources:

> As soon as the land of any country has all become private property, the landlords, like all other men, love to reap where they never sowed, and demand a rent even for its natural produce. The wood of the forest, the grass of the field, and all the natural fruits of the earth, which, when land was in common, cost the labourer only the trouble of gathering them, come, even to him, to have an additional price fixed upon them. He must then pay for the licence to gather them; and must give up to the landlord a portion of what his labour either collects or produces (Smith, 1776, p. 44).

Smith had already realized that property rights are an essential feature in the paying of rent on a natural resource. Ricardo defined rent more adequately than Smith as follows:

> Rent is that portion of the produce of the earth which is paid to the landlord for the use of the original and indestructible powers of the soil (Ricardo, 1817, p. 33).

Ricardo and Smith both knew that not only land, but also mines and renewable resources like wood can generate a rent, and that this rent is higher in proportion to the scarcity of the resource (see also Robinson, 1989).

William Stanley Jevons wondered what was to be done when the coal stocks were exhausted (Jevons, 1866). He argued that it is impossible for an economy to keep on growing because of the limits of the resources. Jevons already saw that substitution of resources and technical innovations could provide relief to the limited coal stocks. However, his conclusion with respect to England in relation to this limited amount was:

> We have to make a momentous choice between brief greatness and longer continued mediocrity (Jevons, 1866, p. 376).

Another pioneer in the field of resource economics was L. C. Gray (1913, 1914). He dealt especially with the economic possibilities of conservation and the Ricardian concept of rent applied to natural resources. Gray made the following classification of resources (Gray, 1913, pp. 499-500):

I. Resources which exist in such abundance that there is no apparent necessity for economy, now or in the future. For instance, water in some localities.

II. Resources which will probably become scarce in the remote future, although they are so abundant as to have no market value in the present. For instance, building stone and sand in some localities.

III. Resources which have a present scarcity;
   1. not exhaustible through normal use: water power,
   2. necessarily exhausted through use, and non-restorable after exhaustion: mineral deposits,
   3. necessarily exhausted through use, but restorable: forests, fish,
   4. exhaustible in a given locality but restorable through the employment of other resources of a different kind or of similar resources in different locations: agricultural land.

Today, Gray's classification is no longer accepted. Firstly, exhaustible resources mean the non-renewable resources as opposed to renewable resources. Gray used the terms non-restorable exhaustible resources and restorable resources instead. Further, the first category of his classification can be ranked under non-depletable resources and the second and third under depletable resources.

The pioneer in the area of institutional resource economics must have been Ciriacy-Wantrup. In numerous publications between 1932 and 1975 he shows concern for the economic analysis of public policy towards natural resources. Wantrup was especially interested in the common property problem and was pessimistic about the forcasting qualities of economics. According to him, critical parameters like technology, tastes, institutions, population and income levels cannot be foreseen (Ciriacy-Wantrup, 1985).

The main roots of the present mainstream resource economics date from 1931. In that year Harold Hotelling wrote his article on the efficient depletion of exhaustible resources, in which he developed his famous efficiency rule. His contribution was more or less forgotten until the oil crisis in the seventies. Since then, numerous publications have appeared on the subject, of which one of the most remarkable is *Toward a new iron age?* (Gordon et al., 1987). This book examines the depletion of an exhaustible resource, copper. Indeed, the analogy between Jevon's *Coal question* and this book is very striking.

Materials balance and the concept of entropy

In 1789, the year of the French Revolution, Lavoisier's book 'Traité élémentaire de chimie' was published. In this book his famous law of the *conservation of energy* is developed. Today it is known as the *first law of thermodynamics*. It states that, although energy is transformed during the production and consumption process, no energy is either created or destroyed. An analogy of the first law of thermodynamics, the concept of the *materials balance*, was introduced into economics by D'Arge, Ayres and Kneese (Ayres et al., 1969, see also: van der Straaten, 1990, pp. 56-60). Figure 2.5 gives a schematic presentation of the materials balance.

In the production process, part of the mass used is converted into products, the remainder being brought into the environment as waste. The mass going into products during the production process will - with time - also be dumped in the form of waste. In Figure 2.5, the materials balance for the production sector is: Material inputs (A) equals Waste products (B) plus Final product (C). Put in an equation:

$$(4) \qquad A = B + C.$$

The materials balance for the household sector in words is: Final product (C) equals Waste products (D). In an equation:

$$(5) \qquad C = D.$$

Finally, the materials balance equation for the whole economy is gained by substituting equation (5) in (4):

$$(6) \qquad A = B + D.$$

In the materials balance approach, all flows are measured by mass. The concept of materials balance is further elaborated in Chapter 10.

The *second law of thermodynamics* deals with the tendency of entropy to increase. This law states that an isolated dynamic system tends to lead to disorder (randomness), which can only be rectified by the supply of energy from outside. The economic relevance of the two laws of thermodynamics is adequately described by Daly:

> The First Law tells us that matter and energy inputs are not created *ex nihilo*, but must be extracted from the environment, and that outputs must return to the environment in various forms which add up to equal the quantity of inputs. The Second Law says that although total input equals total output in quantitative terms, there is a big qualitative difference between the equal quantities of raw material inputs and ultimate waste outputs. Raw material is low-entropy matter-energy, waste is high-entropy matter-energy (Daly, 1986, p. 320).

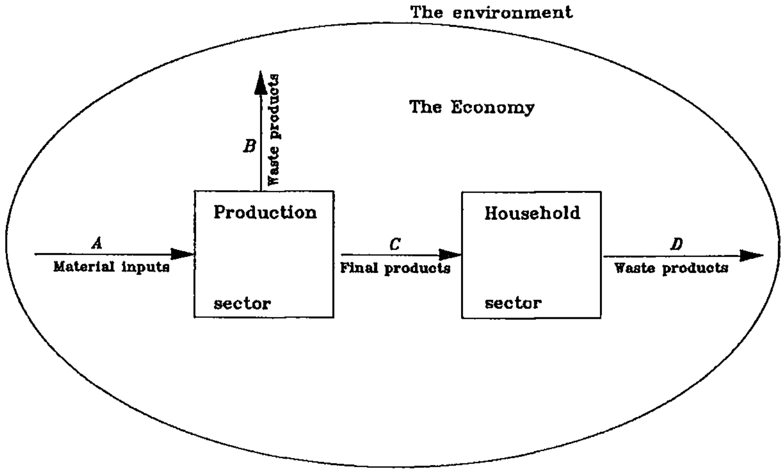

Figure 2.5: Materials balance.
Source: Freeman et al., 1973, p. 12.

Although the first law of thermodynamics may be important for economics, according to Georgescu-Roegen (1980), the second law is even more important. By entropy Georgescu-Roegen meant an index of 'dissipation' and 'disorder'. In his view, modern production can only lead to entropy because it destroys the natural order, since the quantity of energy used by the economic system exceeds the quantity of solar energy that the ecological system is able to transform into fossil fuels again[3]). Roegen concluded that the second law of thermodynamics implies that entropy must always increase on earth as a result of human economy. However, as long as the sun provides energy, entropy can become a constant so long as human economy does not use more than is provided (Ayres and Kneese, 1989).

Boulding (1981) described the concept of entropy as a loss of potential. In his view nature is a quantity of raw materials and energy sources that is ruthlessly exhausted by man. Boulding also considered nature to be a quantity of capital goods. Hueting (1974) spoke of loss of functions instead of entropy. In conclusion, it can be said that in economics the terms entropy, loss of function and negative externalities greatly overlap. It is also important to realize that, however much economic processes may look like physical processes, the application of the two fundamental laws of thermodynamics in economics can be no more than the application of useful analogies of these laws, since economics is fundamentally different from thermodynamics.

Spaceship earth

A renewable resource can be maintained at an optimum level if harvesting is restricted by the market or by regulations. However, fossil fuels are a different matter. The use of fossil fuels leads to a reduction of the total stock which cannot be replenished. Therefore, in this case, optimum exploitation means that the use of it should be spread over time as efficienctly as possible (Peer, 1987). Indeed this does not mean that the scarcity of these resources can only increase. As I have already pointed out, technical innovations and substitution may even lead to diminishing scarcity of exhaustible resources.

Some non-renewable raw materials such as the stock of iron ore can, in principle at least, partly be recovered from waste, and reused in a transformed form. In a sense this is also possible for energy resources, since if parts of worn out articles are reused, then the energy used to produce these parts for the first time can be reused as well. From the point of view of resource conservation it is desirable to have a development leading to a sustainable use of renewable resources and 'recycled' materials. Where this is pursued, Boulding (1966) spoke of a *spaceship*-economy in contrast to a 'cowboy'-economy in which the waste of nature is a legitimate means of keeping income at a certain level on the short term. However, as Boulding admitted, the metaphor spaceship has an important weakness:

> Perhaps the greatest weakness of the metaphor is that the spaceship presumably has a clear destination and a mission to acccomplish. It is essentially a planned economy (Boulding, 1980, p. 266).

Market economies are not centrally planned by definition, and *the clear destination* and the *mission to accomplish* for mother earth are also hard to distinguish.

Stocks of nature

It is not easy to describe natural stocks in more detail. The description of nature, given below fits in best with ecology (Odum, 1975). In this conception, 'nature' is the total of biotic (living) and abiotic (not-living) components on earth. In fact, the concept of nature encompasses the whole universe. In this economic thesis, however, I have limited myself to the bond between man and the planet Earth.

Abiotic components on earth form a closed system to which no substance can be added or extracted. Biotic components (organisms) are preserved by reproduction. During the course of time there is a gradual development of organisms by which new species are created and others disappear. New species are created by man through *domestication*. The relatively thin layer in which organisms live is called the *biosphere*[4]. Toynbee defines the biosphere rightly as follows:

> The biosphere is a film of dry land, water and air, enveloping the globe (or virtual globe) of our planet Earth. It is the sole present habitat - and, as far as we can foresee, also the sole habitat that will ever be accessible - for all the species of living beings, including mankind, that are known to us (Toynbee, 1976, p. 5).

It is possible to distinguish between animal life and plant life. All life on earth is based wholly on a process that can be best described as *photosynthesis* and *respiration*. Photosynthesis is the process by which carbon dioxide is converted into organic matter in the presence of chlorophyll under the influence of light. Only plants have this capacity.

Respiration can be described as a biochemical process by which carbon compounds are combusted through the intake of nutrients (carbon) and with the help of oxygen, resulting in the giving off of carbon dioxide (CO_2). In this process the energy which is necessary for the organisms is released. The respiration process can therefore be considered to be the opposite of the process of photosynthesis.

From the foregoing it can be concluded that the whole cycle of carbon and oxygen is maintained by solar energy and affects the whole biosphere. Since only plant life is capable of photosynthesis, humans and animals can be regarded as parasites of plants. The degradation of plant life as a result of human production and consumption is therefore perilous to human life itself. For, as Fast (1982) argues, when the host dies, parasites die as well.

The biosphere is organised into ecosystems. The biologist Tansley first used the term 'ecosystem' in relation to the coherent whole of plants and animals in their abiotic environment. However, he did not relate it to any particular scale (Weiss, 1977, Worster, 1985). The whole biosphere can therefore be regarded as being one ecosystem or organism called Gaia, after the Greek name for mother earth (Stortenbeker, 1987, p. 14). In this ecosystem we can distinguish producers of organic matter (plant life) and consumers of organic matter (humans, animals and plants). Each ecosystem is subject to changes that concern both the biotic and abiotic components. These changes occur when the supply of energy does not equal the use of energy by respiration (Odum, 1975). If energy supply exceeds energy consumption, then the ecosystem will grow. This growth will continue until a climax is reached. This can best be characterized as a phase in which there is a maximum of biomass as well as equality between energy supply and energy consumption. This situation is that of a steady state, in which plant and animal populations tend to remain constant as a result of density dependent mechanisms operating on birth rate, survival or death rate. This feed-back mechanism is called *homeostasis*.

If the consumption of energy exceeds the supply, then the ecosystem degenerates and the process of photosynthesis is no longer able to meet the demand created by the respiration process. Since human respiration (i.e. the process of human production and consumption) has grown too much, the biosphere (in the concept of being one ecosystem) has deteriorated. The choice is up to man. Either he opts for an exuberant existence, thus consuming nature in a relatively short time, or he chooses to safeguard nature as an ultimate source of prosperity. Georgescu-Roegen commented:

> Perhaps, the destiny of man is to have a short, but fiery, exciting and extravagant life rather than a long, uneventful and vegetative existence. Let other species - the amoebas, for example - which have no spiritual ambitions inherit an earth still bathed in plenty of sunlight (Georgescu-Roegen, 1976, p. 35).

and in another place

> ...the fact remains that the higher the degree of economic development, the greater must be the annual depletion ... and, hence, the shorter becomes the expected life of the human species (Georgescu-Roegen, 1976, p. 59).

Apparently, Roegen believed that is highly likely that mankind will become extinct long before the sun stops shining.

So long as the sun shines with sufficient power (estimated to be another 5 billion years) nature's limited capacity to renew itself through reproduction makes it a very special capital good. It is this capacity that enables the human species to continue, but only on the condition that man limits the use of renewable and recycleable materials. If, however, a relatively high production level on the short term is preferred to a relatively low production level in the long run, then nature's reproductive capacity will be affected, and mankind becomes threatened by extinction. As Toynbee remarked:

> The biosphere is rigidly limited in its volume, and therefore contains only a limited stock of those resources on which the various species of living beings draw in order to maintain themselves. Some of these resources are renewable; others are irreplaceable. Any species that overdraws on its renewable resources or exhausts its irreplaceable resources condemns itself to extinction. The number of extinct species that have left traces in the geological record is startingly great by comparison with the number of those that are still extant (Toynbee, 1976, p. 5).

What is at stake here is not a choice that can be made on economic grounds alone. Here a political issue is at stake that can only be solved by political measures. The outcome of this, therefore, is by no means predictable.

Technological development

If nature is left undisturbed, a climax stage will develop on earth. Subject to natural circumstances like temperature and rainfall, this climax stage will differ regionally. Sometimes it appears possible for man to fit into such a system. There are examples of tribes who are still able to support themselves by hunting and gathering food (Campbell, 1983; Bisschop, 1987). These communities know what their place in the ecosystem is, keeping their population limited through all kinds of natural customs so as not to endanger their habitat and disturb natural cycles.

The possibility of continuing a way of life as described above largely depends on the population density. When population density reaches a critical point, man is forced to use technological development to provide himself with a different habitat. Inevitably the point is reached where the climax stage is violated by man's need to cultivate land. In the beginning, shifting cultivation will suffice, but a gradual change to a more permanent agriculture is unavoidable. Nature's productivity, to be measured in biomass, deteriorates and must be replaced by human labour. Traditional economists tend to consider a society based on permanent agriculture to be more prosperous than societies that support themselves by hunting and collecting food. This viewpoint is fundamentally wrong. If food-collecting communities succeed in limiting their population growth, they need not work as hard for their daily bread as farmers do. If this avoided 'disutility' of labour is integrated into the standard of living, a totally different image of the differences in welfare between farmers and food-collectors may emerge.

It was therefore poverty, caused by the ever increasing population density, that forced man to farm and later to industrialize. The population surplus can also be blamed for the division of labour and the connected development of trade. Man prefers to remain self-supporting and independent. Only out of sheer necessity will he adapt to more complicated forms of economic life (Wilkinson, 1973).

Boeke (1946) described a similar development in his book 'Oosterse economie'; described the conflict between the pre-capitalist countryside and the capitalist town in South East Asia. The village is the social unity of pre-capitalism and this unity cannot grow continuously. If the village community grows too large, this will inevitably lead to people splitting off to form a new village. This system is based on the assumption that there is plenty of wasteland available. If this is no longer the case, the moment will inevitably come when a monetary economy is introduced and, with it, the necessity to produce for the world market in order to escape death by starvation.

Over the last few years, much attention has been paid to the ecological risks involved in permanent agriculture (Van Dobben, 1978, Opschoor, 1987). In regions around the Mediterranean, the results of an age-long improper use of the soil are obvious. There are also seemingly less spectacular symptoms, such as the overmanuring of the Dutch soil for years on end. In the long run this will no doubt negatively affect the agricultural production capacity. This is one aspect of the ecological picture. Another is the extraction of minerals from the soil in countries that provide Europe with feed stuffs used in intensive livestock breeding, leading to erosion and desert-forming in these countries. In the long run this will severely hamper the solving of the problems of developing countries (Heijman, 1985).

The climax-system is increasingly affected by the introduction of large-scale production. The technological development in the twentieth century has led to the processing of large quantities of non-renewable raw materials and resources and also to the large-scale polluting of the environment. The resulting scarcity of resources in the future, the so-called 'delayed scarcity' or new scarcity (Malthus, 1827, Hueting, 1974), will be even worse if we go on ruining the environment. This phenomenon is by no means new. As early as 1908, Gustav Schmoller was pointing out that, in the course of the process of technical development, man would never be able to free himself from nature, but

> ... will always be a parasite of the earth (Schmoller, 1908, p. 139).

In technological development Schumpeter (1939) distinguished between *inventions* (scientific discoveries) and *innovations* (the application of scientific discoveries in the production process). In this context technological development means the innovating process.

It is undoubtedly the development in the technological field that is to blame for the large-scale exhaustion of natural resources. However, it is also beyond question that technological development has proved a vital means of finding a way out of the ecological crisis that the earth is in. On the role technological development has played in the past Gordon et al. state:

> The economy is incessantly engaged in a struggle between two forces, advances in technology that enhance the productivity of labor and the exhaustion of resources that diminish it. Over the last two centuries technology has been the clear victor. But what of the future (Gordon et al., 1987, p. 155)?

Therefore a distinction has to be made between *resource conserving* and *resource affecting* technological innovations (Krabbe et al., 1986, p. 96, Heijman, 1987). To date, technology has been mainly based on the massive usage of raw materials and energy and must therefore be regarded as a main 'resource-exhauster'.

Resource-conserving technological development can lead to a greater use of sustainable sources of energy, such as solar and wind-energy, as well as to a more efficient use of fossil fuels. An example of such a resource-conserving technological development is that of fuel-cells, by which chemical energy can be converted directly into electric energy. Compare this with existing power plants, where chemical energy has to first be degraded to heat which in turn is converted by turbines into electric energy. The result is that more than two thirds of all chemical energy used is lost in power plants and in transport. These losses could be reduced considerably if the heat stadium could be avoided. Fuel cells are said to be the answer. However, the technical realization of this is still far off (Fast, 1982).

Implementation of resource-saving technological development will enable the global income to increase without endangering the stocks of resources while at the same time maintaining the production factor nature. This is called *sustainable growth* (WCED, 1987). Whether technology will develop in this desirable way is a political issue that should be given top priority. One thing is certain; it will take a lot more fundamental research, financed by society, before the results can be implemented. The speed with which this can be accomplished depends to a large extent on the number of voters in the Western world willing for tax-money to be spent on these purposes. It is therefore of the utmost importance to keep the public informed on the environmental situation so as to bring about a mental change towards the conservation of nature. The subject of resource-conserving technological change is elaborated further in Chapter 3.

Economic order and nature conservation

It still remains to be seen whether the present economic order can be thought able to adequately face the ever increasing problem of the scarcity of nature. As yet, this seems very unlikely. In the Western world the neglecting of externalities by governments has lead to the exhaustion of nature. The entrepreneur's primary task is not to economize greatly on the use of raw materials, but rather to keep his business sound. In this respect it will often not be beneficial to produce only a limited quantity of long-lasting quality, which will be too expensive to sell on a large scale. A massive sale of products that will not last long is more likely. However, there are also positive points. In the Western world, the provision of information through the mass media is extremely sophisticated, while society's democratic character makes it possible to influence political decision-making. For instance, in the Netherlands, environmental policy has undoubtedly led to a considerable improvement in the quality of surface water (Bressers, 1980).

In the present centrally-controlled economies, the pursuit of an effective environmental policy is blocked by a heavy bureaucratic system. Furthermore, because of the poor economic situation, as well as the lack of information given to the public, environmental matters are not given high priority.

What both market-oriented or centrally-controlled developed countries have in common is their dependency on developing countries for the supply of raw materals and for the markets for their final products. These developing countries, poverty-stricken by overpopulation, have no choice than to allow their labour force to be mobilized to serve the world economy, and this has great ecological consequences. For example, the growing of monocultures has lead to exhaustion of the soil, and the need for new farmland has brought a large-scale deforestation (Brown et al., 1987, Bisschop, 1987). Up till now, development aid has not solved the problem of poverty in these countries, and this enhances the exhaustion of nature (Kool, 1990).

Economic planning directed at the conservation of nature demands a collective effort. For many environmental problems it holds that they can only be tackled if they are dealt with on a global scale. It is especially at this point where the economic order fails. On a national level governments are hardly able to deal adequately with transboundary pollution. For the conservation of nature it is therefore essential that national governments cooperate worldwide to reach agreements similar to those in whale-fishery. If governments are to ban transboundary polluting manufacturing practices successfully, they need to think 'globally' or at least supranationally (Folmer, 1989, van Ierland et al., 1983, Koeman, 1989, Tinbergen, 1987).

Ecologism as a paradigm

The formal object of economic science is formed by scarcity, which can be defined as the pressure between consumers' needs and the resources necessary to satisfy these needs (Robbins, 1935, 1952: pp. 1-23). The *price* is a standard for *relative scarcity*. *Absolute scarcity* does not show up through the price mechanism. According to a number of writers, since nature is absolutely scarce it is not possible to allocate the production factor nature adequately via the price mechanism (Daly, 1977, Dietz et al., 1988). Instead of absolute scarcity versus relative scarcity, Achterhuis (1988, pp. 60-63) mentioned the contradistinction between *subjective* and *objective scarcity*. He believed that scarcity can only be subjective (see also Achterhuis (1989)). Unfortunately, Achterhuis did not make the relationship between the two pairs of scarcity concepts clear; relative versus absolute scarcity and subjective versus objective scarcity. It is possible that the concept of objective scarcity might be identical with absolute scarcity.

Daly maintained that since price mechanism does not function well, the answer to environmental problems lies in physical standards. These standards are to be delivered by ecology. According to him, biology and economics have many interfaces. However, he wondered:

> The outside-skin life process is the subject of ecology, but ecologists abstract from the human economy and study only natural interdependencies, while economists abstract from nature and consider only interdependences among commodities and man. But what discipline systematically studies the interdependences which clearly exist between the natural and the human parts of the outside-skin life process (Daly, 1980a, p. 244)?

He concluded that the economy and ecology of man are inseparable. Indeed, it seems to me that, although an environmental economist must have enough knowledge of biology to do a proper job, it is not possible for him to be a complete economist and a complete biologist at the same time.

Ehrlich held more or less the same opinion as Daly. He stated:

> Somehow a new ecological-economic paradigm must be constructed that unites (as the common origin of the words ecology and economics imply) nature's housekeeping and society's housekeeping, and make clear that the first priority must be given to keeping nature's house in order (Ehrlich, 1989).

Samuelson believed that population analysis is at the intersection of social science and biology. According to him, during the era of the great classical economists, demography belonged to political economy since it determined the supply of labour, which was one of the important endogenous variables in the models of Smith, Malthus, Mill and also Marx (Samuelson, 1985, p. 166). A feature of modern neoclassical economics is the removal of population as an endogenous variable, a sign that to most neoclassical economists the biological aspects of the economy were less relevant. However, for the near future, Samuelson predicted:

> ..., in the end, economists' demography will carve out an ecological niche for itself (Samuelson, 1985, p. 167).

Traditional neoclassical economic theory starts from voluntariness. This theory states that man is able to change nature at will (Leiss, 1974). Seen from this starting-point, the human economy is a closed system that bears no relation with the surrounding ecosystem. This opinion may originate from the economic methodological battle that took place at the end of last century between Schmoller, who was in favour of a holistic type of economic science, and Menger, who advocated an abstract type of economic science. At present, general economics unmistakably shows more traces of an abstract than of a holistic scientific approach.

Due to the environmental crisis, ecological awareness within economic science is gaining ground (Constanza, 1989, Tisdell, 1990a,b,c, Pearce et al. 1990). However, the mechanistic model-making practised in general economic theory is often inadequate for studying the economical and ecological gradient-zone (Swaney, 1985, 1987). For instance, Von Weizsäcker, a natural scientist himself, speaking about economics as a natural science and realizing that of all the social sciences, economics can make the most use of mathematics, stated:

> Yet, in the eyes of a natural scientist, its objective remains hopelessly complex (von Weizsäcker, 1982, p. 31).

Because of this complexity, the system's dynamics is insufficiently shown in a purely mechanical approach. Boulding (1984) blamed the mechanistic character of general economics on the foundations of the method used in economic science which, according to him, can be found in Newton's mechanics. Darwin's evolutionary theory did not exist at the time when economic science was conceived, and this, together with the 'battle of methods', explains the absence of a major evolutionary touch in economic theory.

However, a mechanistic approach to the environmental problem is also useful, since it allows the making of forecasts based on assumptions like, for instance, those found in the Club of Rome's first report, which roused everybody from their dreams about the welfare state (Meadows, 1972). On the one hand, the weak point of the evolutionary approach is that it cannot make predictions. On the other hand, the advantage of the evolutionary approach is that the past can be reconstructed, thus providing a genetic explanation for what exists.

It can be said that in environmental economics the evolutionary approach and the mechanistic approach should complement each other. An evolutionary type of approach will focus particularly on the individual as well as the political decision-making process concerning scarce environmental goods (Larking, 1986, Söderbaum, 1987), while the mechanistic method could be applied in scenario-studies and growth models (Krabbe et al., 1986).

Indeed, it should be remarked here that the synthesis between economics and ecology is not only a point of study within economic science. Ecological science also contributes to this fast-growing field of study, as can be seen in the development of energy models of economic activities (Odum, 1983; Heijman et al., 1986). Samuelson concluded:

> There is much territory between economics and biology that is still virgin ground. It will be tilled increasingly in the future. We should not be surprised if the first explorations are both crude and pretentious. Wisdom and maturity are the last settlers to arrive in pioneering communities (Samuelson, 1985, p. 172).

Towards a noosphere?

The relation between man and nature is a very complex one. On the one hand man's biological character makes him part and parcel of the biosphere. On the other hand, he is the only species on earth who is able to abstract from nature, which makes him able to purposely alter the ecosystem and to estimate the risks involved.

According to Teilhard de Chardin (1920, 1956) and Vernadski (1944) we can therefore justifiable speak of the development of the human intellect as being a state of its own that is evolving mentally and socially towards spiritual perfection. Teilhard called this state the noosphere[5)]. In this spiritually perfect state it is possible to properly administer the biosphere. In this concept the global administration is one step on the way towards the perfect state noosphere and, as such, it is an instrument to keep the world a place where man can live. Instead of a parasitic relationship, a symbiosis between man and nature could be brought about (Opschoor, 1989).

In 1974, at the end of his thesis, Hueting concluded that the hope of a sustainable environment in the future is best served by being optimistic towards human imagination and ingenuity, which are considerable, and by being pessimistic towards human institutions, which are slow (Hueting, 1974, p. 267). To this I would like to add that human institutions are the result of human imagination and ingenuity, and that faith in a liveable environment in the future should be directed towards developing *new* institutions in the broadest sense of the word (see also Meyer-Abich, 1988 and Morrisette, 1990).

Appendix 2.1: Optimum allocation of a resource over the production sector and the abatement sector[6)]

Total welfare (w) is assumed to depend on production (y) and pollution (p), while pollution is a function of production and abatement (a):

(1) $$w = w(y, p), \quad \frac{\partial w}{\partial y} > 0, \quad \frac{\partial w}{\partial p} < 0,$$

$$p = p(y, a), \quad \frac{\partial p}{\partial y} > 0, \quad \frac{\partial p}{\partial a} = -1.$$

It is assumed that an increase in production gives a net increase in welfare. From this it follows:

(2) $$\frac{\partial w}{\partial y} > -\frac{\partial w}{\partial p} \cdot \frac{\partial p}{\partial y}.$$

From (1) and (2) it follows:

(3) $$w = w(y, a), \quad \frac{\partial w}{\partial y} > 0, \quad \frac{\partial w}{\partial a} > 0.$$

The available amount of resource must be allocated over the abatement sector (n_a) and the production sector (n_y):

(4) $$\underline{n} = n_a + n_y.$$

In equation (4), to indicate that the amount of resource is fixed, n is underscored. Equations (5) and (6) are the production functions for the abatement sector and the production sector respectively:

$$(5) \qquad a = a(n_a), \quad \frac{da}{dn_a} > 0,$$

$$(6) \qquad y = y(n_y), \quad \frac{dy}{dn_y} > 0.$$

From equations (3), (5) and (6) it can be deduced that:

$$(7) \qquad w = w(n_a, n_y), \quad \frac{\partial w}{\partial n_a} > 0, \quad \frac{\partial w}{\partial n_y} > 0.$$

The optimum distribution of the resource for the achievement of the maximum welfare level can be determined with the help of equations (7) and (4). Equations (4) and (7) give that the function $f(n_a) = w(n_a, \underline{n} - n_a)$ of one variable has to be maximized, so $df/dn_a = 0$, $d^2f/dn_a^2 \leq 0$. This gives:

$$(8) \qquad \frac{df}{dn_a} = 0, \quad \text{so} \quad \frac{dw}{dn_a} - \frac{dw}{dn_y} = 0, \quad \text{which means that} \quad \frac{dw}{dn_a} = \frac{dw}{dn_y}.$$

and:

$$(9) \qquad \frac{d^2f}{dn_a^2} \leq 0, \quad \text{so} \quad \frac{d}{dn_a} \cdot \left(\frac{\partial w}{\partial n_a} - \frac{\partial w}{\partial n_y} \right) \leq 0,$$

$$\text{that is} \quad \frac{\partial^2 w}{\partial n_a^2} + \frac{\partial^2 w}{\partial n_y^2} - 2 \cdot \frac{\partial^2 w}{\partial n_a \cdot \partial n_y} \leq 0.$$

Notes

1) Production equals gross national product.

2) This production equals gross national product excluding the part which is generated in the abatement sector.

3) An indication for this is the rising concentration of carbon dioxide in the air. The pre-industrial concentration was about 275 ppmv, while in 1985 this concentration had increased to 346 ppmv. This means an increase of the carbon dioxide concentration of about 0.5% per year (Bertram et al., 1990).

4) According to Vernadski, the term biosphere was first used by Lamarck (1744-1829) (Vernadski, 1944, p. 3).

5) From the Greek words 'nous' (intellect) and sphera (envelope of the earth). Vernadski first heard of the concept noosphere in Paris during lectures given by the philosopher E. le Roy, who developed it in cooperation with Teilhard (Vernadski, 1944, pp. 8-9). So, it is clear that Vernadski did not develop the concept independently, as is suggested by Opschoor (1989).

6) For a practical elaboration of this allocation problem for the Dutch situation, see den Hartog and Maas (1990).

3. The steady state

Over the next 85 years world population is expected to grow from five to at least eight billion people. So a no-growth economy is not a realistic assumption for the near future. In the long run, however, a realistic option might be a steady state economy in which both population and production are constant. In this chapter, after taking a look at the development of the world population, I examine the economics of the steady state.

World population

Table 3.1 shows how world population has developed in the past and what the expectations for the future are. In this table the *developed countries* are: USA, Canada, western Europe, USSR, eastern Europe, Japan, Australia and New Zealand. All other countries are considered to be *developing countries.*

Table 3.1: The world population (millions)

Year	Total	Developed countries	Developing countries	Percent in developing countries
1850	1171	302	869	74
1875	1390	406	984	71
1900	1608	510	1098	68
1925	2062	631	1431	69
1950	2515	751	1764	70
1975	3936	1092	2844	72
2000	5893	1274	4619	78
2025	7364	1380	5984	81
2050	8197	1415	6782	83
2075	8446	1434	7012	83
2100	8500	1445	7055	83

Source: Clark W. C. and R. E. Munn, 1986, pp. 106-107 (adjusted), The Economist, 1990b, pp. 21-26 (adjusted).

A look at the world income situation shows that, on average, it improved in the period 1970-1990. In this period the growth rate of the real gross domestic product of the whole world was about 3.5% per year, while the world population rose by about 1.8% per year in the same period. From this it can be concluded that, during this time, real income per capita rose on average by about 1.7% each year (Srinivasan, 1988, World Bank, 1989, 1990). Of course, these statistics do not say anything about the poverty in the world, because this is also a matter of the distribution of world income. One of the major difficulties in overcoming world poverty is that poor countries tend to have higher rates of population growth than rich countries (van Marrewijk, 1990).

A study of Table 3.1 shows clearly that in the next hundred years total population can be expected to increase, mainly because the population in developing countries will increase. It should be stressed that only a moderate scenario is presented here (see for instance: RIVM, 1988, p. 15). The United Nations even reckons with the possibility that, by the year 2100, total population will have increased to 13 billion people, of which about 11 billion will live in developing countries (The Economist, 1990b, p. 21, see also: Arvill, 1983). The data of Table 3.1 are presented as graphs in Figures 3.1a and 3.1b. In Figure 3.1a both total population and the population living in developing countries are shown.

It is noticeable that the expected development of world population shows a logistic pattern, which here means that it is expected that by the end of the twenty-first century world population will be stabilized. Of course, this type of growth is not at all new. See for example Pearl (1925) and also Verhulst (1838).

The percentage of the total population living in developing countries is shown in Figure 3.1b. From Table 3.1 and Figure 3.1b it is clear that the share of people living in developing countries is increasing. In 1975 it was 72%, and by 2100 it is expected to be 83%.

Taking into account that only a moderate scenario is presented, it has to be concluded that world population will grow to a relatively high level in the next 85 years. This implies that to keep the average income per head at the present level total production must grow. It is clear that the prospected growth of the population could become a danger to the world environment and to the stocks of exhaustible and renewable resources (Ehrlich et al., 1968, 1971, Welles, 1971, Heilbroner, 1971). After this period of growth, hopefully it will be possible to maintain a stationary situation, which is what John Stuart Mill said would happen. However, what is certain is that the basic assumption made by John Maynard Keynes for the solution of the economic problem 'within a hundred years' (i.e. no important increase in population) does not hold (Keynes, 1931).

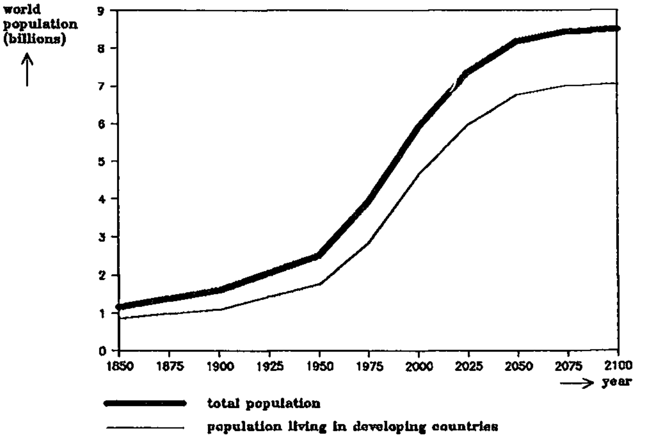

Figure 3.1a: World population.

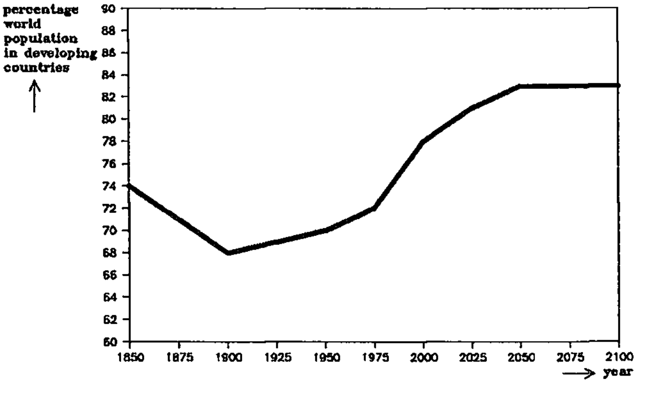

Figure 3.1b: Percentage population living in developing countries.

Steady state concept

There are at least three basic definitions of the steady state:

1. The steady state as a situation in which both production measured through the Gross National Product (GNP) and population are constant. Like Mill (1848), I call this situation the *stationary state*.
2. The steady state defined as a physical concept. In this definition, as far as the renewable resources are concerned, this steady state refers to a situation in which human use of nature expressed in physical terms equals natural production expressed in physical terms. As far as the non-renewable resources are concerned, this steady state refers to a situation in which the stock-depletion ratio is constant. I use the term *physical steady state* to refer to a situation in which both the stock of renewable resources and the stock-depletion ratio for non-renewable resources are constant.
3. The steady state as a situation in which production, consumption and investment grow with a constant percentage, maintaining a constant capital-output ratio. In this definition, which is the one economists are most familiar with, production is measured in terms of the GNP. I refer to this situation as *state of steady growth*, which in fact is a special case of a floquetian growth process (see Chapter 7 on this subject). This state of steady growth is extensively examined in Chapter 5. In this present chapter I want to look at the stationary state and the physical steady state respectively.

These three definitions are often combined. For example, the concept *sustainable growth* is a combination of the state of steady growth and the physical steady state (WCED, 1987, VROM, 1989). In other words, the physical steady state is a necessary condition to maintain sustainable growth (see also the appendix of Chapter 1). This is used to illustrate that a physical steady state is not the same as a no-growth economy in terms of the GNP.

Stationary state

In his *Principles of political economy* John Stuart Mill wondered:

> Towards what ultimate point is society tending by its industrial progress? When the progress ceases, in what condition are we to expect that it will leave mankind (Mill, 1848, p. 746)?

His answer to this question was *the stationary state,* which he assumed to be ultimately unavoidable. In his days most economists advocated the so-called *progressive state,* in which the economy of all nations could continue to grow. Mill, Jevons (1866) and also Malthus (1798), who was the first economist to write on the principle of population, were opposed to the assumption that:

> ... that in the natural and normal affairs population must constantly increase, from which it followed that a constant increase of the means of support was essential to the physical comfort of the mass of mankind (Mill, 1848, p. 747).

Mill considered a conscientious or prudential restraint on population to be indispensable. He saw the progressive state as a necessary condition for reaching the stationary state, which is also a mental and moral state of being:

> The best state for human nature is that in which, while no one is poor, no one desires to be richer, nor has any reason to fear being thrust back by the efforts of others to push themselves forward (Mill, 1848, pp. 748-749).

He was of the opinion that, because of the accumulation of capital, there is room in the world for a great increase in population, but that there is little reason to desire this. He pointed to the destruction of nature which would be the consequence of this.

> Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature; with every rood of land brought into cultivation, which is capable of growing food for human beings; every flowery waste or natural pasture being ploughed up, all quadrupeds or birds which are not domesticated for man's use exterminated as his rivals for food, every hedgerow or superfluous tree rooted out, and scarcely a place left where a wild shrub or flower could grow without being eradicated as a weed in the name of improved agriculture (Mill, 1848, p. 750).

The stationary state of capital and population does not imply a cessation of human improvement. Mill stated that in the stationary state much progress can be made morally and socially.

It will be clear that Mill believed that economic growth should not be continued infinitely. In the end, a steady state (or stationary state as he called it) will emerge and this is even a desirable situation, at least socially and morally.

In classical, neoclassical and also Marxist theory[1)], in the absence of population growth and technical innovations, the stationary state will generally be reached more or less automatically because of the decreasing marginal productivity of capital (Siebert, 1987, Mandel, 1980). This can be shown as follows. In the described situation, total production (y) is a function of the input of capital (k):

(1) $$y = y(k), \quad \frac{dy}{dk} > 0, \quad \frac{d^2y}{dk^2} < 0.$$

Savings (s), which equal gross investment, are supposed to be a fixed proportion (σ) of the total product:

(2) $$s = \sigma \cdot y(k).$$

Depreciation (b) is assumed to be a fixed proportion (π) of capital stock:

(3) $$b = \pi \cdot k.$$

Net investment in a certain period (dk/dt), which is the extension of the capital stock, equals gross investment minus depreciation:

(4) $$\frac{dk}{dt} = \sigma \cdot y(k_t) - \pi \cdot k_t.$$

In Figure 3.2, the development of an economy without population growth and without technical innovations is shown as a graph.

To the left of $k*$ in Figure 3.2, gross investment (s) exceeds depreciation (b). This implies that net investment (dk/dt) exceeds zero and, as a consequence, the stock of capital will grow. To the right of $k*$ net investment is less than zero, implying that capital stock will decrease. This means that $k*$ is a stable equilibrium of the capital stock. In this equilibrium capital, production, consumption, investment and population will be stationary. Indeed, it has to be admitted here that the above model reflects a rather specific situation since zero population growth and no technical development are both assumed. Besides, in the model there is no relation between depletable resources and capital stock.

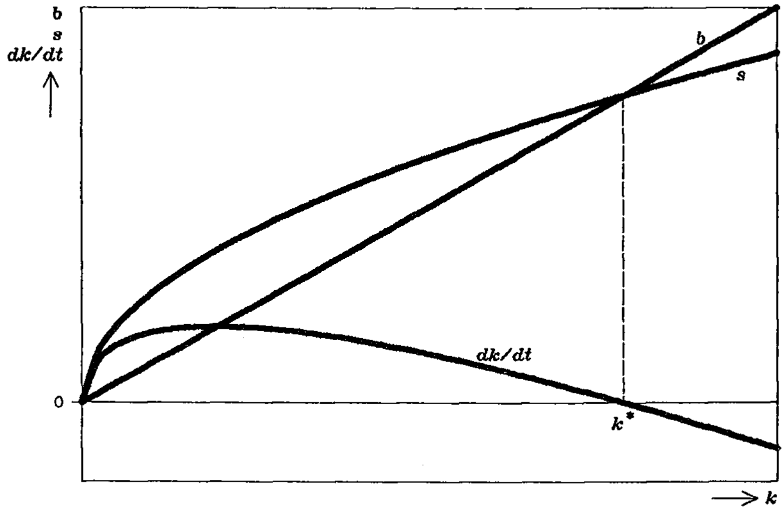

Figure 3.2: The development of a stationary economy.

Tinbergen's model

A modern contribution to the steady state concept of a stationary state has been made by Tinbergen (1987, 1989) for natural resources. For his steady state model, Tinbergen assumed:

- a stable world population,
- a constant consumption for all present and future generations,
- that the problem of the unequal world income distribution is solved.

Suppose in year 0 the total stock of a certain natural resource equals H_0, while the use of natural resources in this year equals h_0. The consumption then is c_0, implying a resource productivity of $c_0/h_0 = p_0$. Because of technical innovations, the amount of resource needed to produce c_0 units consumption goods decreases each year by factor f. This gives:

(5) $$h_t = f \cdot h_{t-1}.$$

Equation (5) implies that all future generations will use:

(6) $$\sum_{t=0}^{\infty} h_t = \frac{h_0}{(1-f)}.$$

Since the amount indicated in equation (6) must equal H_0, the use of the natural resource in period 0 must equal:

(7) $$h_0 = (1-f) \cdot H_0.$$

If, for example, factor f equals 0.976, which is true for the productivity of labour in the past 27 years, then h_0 can be 1/41 part of the total stock (Tinbergen, 1989, p. 677). Though this result is fairly optimistic, it still implies the following *rules of life:*

- keep population constant,
- continue technical development at factor f (see also Baumol, 1985),
- increase development aid, so that migration will not have to occur for economic reasons,
- continue the exploration for new natural resources.

Tinbergen's model is based on the use of exhaustible resources. Also, in his model, substitution between the resource (the non-reproductive factor) and capital (the reproductive factor) is not possible. These two circumstances imply that, in his model, for a constant population, technical innovation is necessary to maintain a constant level of consumption per head. Stiglitz (1974a) and Solow (1974a) showed that, for a production function with a substitution elasticity of one and constant production elasticities, a constant consumption per head can be maintained, even without innovations, so long as the marginal propensity to save is equal to the production elasticity of the exhaustible resource (see also Peer, 1990). Proof of this is given in Appendix 3.1 to this chapter. The economic significance of this is that, in this case, the pessimism of the Club of Rome is not justified (Van de Klundert et al., 1983, pp. 98-103). Indeed, the circumstances for which proof is given are rather specific. Another aspect which Tinbergen's model does not deal with is the productivity of nature. This aspect is looked at later in this chapter.

Physical steady state

A definition of a physical steady state has been given by H. E. Daly. According to him

> A steady state is defined by constant stocks of physical wealth (artifacts) and a constant population, each maintained at some chosen, desirable level by a low rate of throughput - i.e., by low birth rates equal to low death rates and by low physical depreciation rates, so that longevity of people and durability of physical stocks are high (Daly, 1974, p. 15).

Apparently Daly combined Mill's stationary state with the physical steady state. Three magnitudes are basic to his concept of the steady state: stock, service and throughput. Stock is the total inventory of producer's goods, consumer's goods and human bodies (Daly, 1980c, p. 325). In fact, this stock is equal to the concept of Irving Fisher's *capital goods* (Fisher, 1906, p. 66). Service is the satisfaction experienced by the use of the stock, which is something else than service in the normal sense of the word, while throughput is the entropic physical flow from natural sources through human economy (see also Boulding, 1966 and Georgescu-Roegen, 1971 and 1980). The relation between these three magnitudes can be specified as follows (Daly, 1980c, p. 326):

$$\frac{\text{service}}{\text{throughput}} = \frac{\text{service}}{\text{stock}} \cdot \frac{\text{stock}}{\text{throughput}} . \qquad (8)$$

A steady state economy exists when: 1. the stock is constant at a sufficient level; 2. service is maximised given the constant stock; 3. throughput is minimised given the constant stock (Daly, 1980c, p. 327).

In his definition of the steady state Daly deliberately excluded the services defined as non-material goods. However, economic growth is measured as an increase of the Gross National Product (GNP) *including* the services. According to this definition (GNP with services included) it is still possible for the GNP to keep on growing, provided the physical element in the production remains constant. In fact, Daly believed that the growth of production must be compensated by a decrease in the resource use per unit product of the same magnitude, which means that his anti-growth argument is not absolute, though in an earlier article he stated:

> A policy of maximizing GNP is practically equivalent to a policy of maximizing depletion and pollution (Daly, 1971, p. 83).

This statement is only true, when *'maximizing GNP'* is interpreted as *'maximizing the physical element in the GNP'*.

If it is possible for production to grow while maintaining the physical steady state, then it is also possible for the population to grow while maintaining this physical steady state while at the same time keeping the income per head constant. So it can be concluded that a physical steady state can be maintained while the GNP and the population grow, because Daly's concept of the steady state refers to a physical state of affairs; the GNP is an economic index referring to the economic value of goods and services. Indeed, it should be stressed here that the possibility of a growth of both the GNP and the population is constrainted by the physical conditions of the physical steady state. In fact, it might be said that Daly advocated a state of sustainable growth.

To attack the price mechanism, Daly distinguished between relative and absolute scarcity. According to him, price mechanism can only cope with relative scarcity, inducing substitution as the main solution to the scarcity of resources. Absolute scarcity can only be dealt with by the introduction of a steady state economy with direct regulations (Daly, 1974, p. 18). It is clear enough that absolute scarcity is something that cannot be handled by the price mechanism. However, it is not clear which resources are absolutely scarce and which are not. The part that is absolutely scarce may be smaller than Daly suggested, because the substitution possibilities between exhaustible resources are numerous (Nordhaus et al., 1977).

For institutions, Daly favoured the introduction of the following: 1. an institution for stabilizing population; 2. an institution for stabilizing physical wealth and keeping throughput below ecological limits; 3. an institution limiting the degree of inequality in the distribution of the constant stocks among the constant population (Daly, 1974, p. 20). Few scientists would disagree with the necessity of these three institutions. However, the question is how far a government can go in enforcing all kinds of measures for birth control, income distribution and production limitations. It is possible that in most developed countries these institutions more or less exist, while in developing countries, social structure has to change radically if such measures are to be succesfully implemented.

Paul Ehrlich's ideas are more or less compatible with Daly's and Georgescu Roegen's. He defined a steady state economy (SSE) as follows:

> An SSE is one in which material throughput is minimized by limiting resource depletion (and thus automatically limiting pollution), the quality of capital stocks is maximized, and the distribution of wealth is made relatively equitable. It is not necessarily a static economy - progress in efficiency and trade-offs among competing firms and activities can go within the constraint of minimal throughput (Ehrlich et al., 1980b, p. 40).

Ehrlich called a society based on an SSE a *sustainable society*. In such a society economic growth is limited by the constraints of the physical steady state. The most important constraint is the entropy law which says that:

> All physical processes proceed in such a way that the entropy of the universe increases (Ehrlich et al., 1980a, p. 47).

But under the assumption of reaching the sustainable society even this law does not absolutely forbid the growth of the GNP and the population.

Zoeteman's model

An interesting contribution to the thinking in terms of physical steady state was made by Zoeteman (1989). His model does not deal directly with the use of resources, but with the abatement of environmental damage. His central idea is that follows for the attainment of a steady state with respect for a certain polluting agency, for instance the emission of CO_2, the cleansing capacity for that agency has to equal the yearly emissions. The cleansing capacity in tons (Z) equals the density of the earthly biomass in tons per square mile (d) present on the natural area of the surface of earth multiplied by the cleansing productivity in tons per ton biomass weight (z), multiplied by the natural area of the surface of the earth. This natural area equals total area (O) minus the indurated part. The indurated part equals the necessary infrastructure per head (i) multiplied by the world population B. The total cleansing capacity for CO_2 can now be written as follows:

(9) $$Z = z \cdot d \cdot (O - i \cdot B).$$

The yearly emission in tons (V) equals total population (B), multiplied by the GNP per head (p), multiplied by the emission factor (v) in tons per monetary unit GNP. The yearly emission can now be written as:

(10) $$V = v \cdot p \cdot B.$$

In order to reach the steady state the yearly emission has, of course, to equal the cleansing capacity:

$$(11) \qquad V = Z, \text{ so } v \cdot p \cdot B = z \cdot d \cdot (O - i \cdot B).$$

It is clear that in this model, population is the most important variable. If the population grows too fast, it will be very difficult to reach a steady state. To achieve this huge emission reductions per unit product are necessary. This can be illustrated by the following example. If time is included, then equation (11) can be written as follows (with A for natural surface and t for time):

$$(12) \qquad v_0 \cdot p_0 \cdot B_0 \cdot e^{(\bar{v}+\bar{p}+\bar{b})\cdot t} = z_0 \cdot d_0 \cdot A_0 \cdot e^{(\bar{z}+\bar{d}+\bar{a})\cdot t}.$$

In equation (12) the bar indicates a growth rate. It can be deduced from equation (12):

$$(13) \qquad \bar{v} = \bar{z} + \bar{d} + \bar{a} - \bar{p} - \bar{b} - \frac{1}{t} \cdot \ln \frac{v_0 \cdot p_0 \cdot B_0}{z_0 \cdot d_0 \cdot A_0}.$$

From Table 3.1 it can be computed that, in a moderate scenario from 1975 till 2075, the world population will grow by 0.75% a year ($\bar{b} = 0.0075$). I have assumed further moderate values for $\bar{z}$, $\bar{d}$ and $\bar{a}$, -0.1%, -0.05%, -0.05% respectively, and a zero growth in the output per head ($\bar{p} = 0$). I have also assumed that the emission-cleansing capacity ratio of the world equals 6 in the year 1990 and that a world wide steady state must be reached in the year 2050 (Zoeteman, 1989, pp. 330-336). These assumptions give a necessary emission reduction per unit output of about 3.9% each year. This means that, relative to 1990, by the year 2050 the emission per unit product must be reduced by over 90%. Even if it is assumed that the emission-cleansing capacity ratio equals 1 in 1990, an emission reduction per unit output of almost 1% each year would be necessary. This implies that, by the year of 2050, total reduction of the emission per unit output must equal 45% of the 1990 emission. This example shows that if a physical steady state has to be reached within about sixty years even moderate assumptions may make a huge reduction in the emission per unit product necessary in the next sixty years.

Importance of renewable resources

Both exhaustible and renewable resources are depletable. Human production reduces the total stock of depletable resources. Renewable resources have a limited renewal capacity, so that the change in the total stock of depletable resources is the result of both human production and natural renewal. If natural renewal equals human expenditure of nature, then one condition for a physical steady state is fulfilled (the other is a constant stock-depletion ratio for exhaustible resources).

As the stock of non-renewable resources diminishes and the prices of these resources increase, the use of renewable resources becomes more important in an economic sense. However, the unlimited exploitation of these resources easily leads to overexploitation and exhaustion. Indeed, overexploitation of renewable resources is as great a danger today as the exhaustion of non-renewable resources. Therefore it is important to investigate the possibilities of ensuring an efficient and lasting use of renewable resources (Heijman, 1988).

Natural production, human production and the optimum steady state

In laboratory culture models of succession, the development of the amount of biomass of an eco-system (n_t) in time (t) from the first stage onwards can be expressed in a so-called 'logistic curve' (Odum, 1975, p. 153). Such a curve is presented in Figure 3.3. In the early stages there is a regressive development of the eco-system (in terms of biomass). After a certain point in time (t^*) the development of the volume of biomass becomes degressive. Finally the volume reaches its climax stage (n_c).

In such a model, net natural production[2)] in a certain period of time (dn_t/dt) can be approximately described as a parabolic function of the existing total stock of biomass at the beginning of this period. This function is given in equation (14)[3)].

$$(14) \qquad \frac{dn_t}{dt} = \alpha \cdot (n_c - n_t) \cdot n_t .$$

In this equation, α is a positive constant. The function is presented as a graph in Figure 3.4.

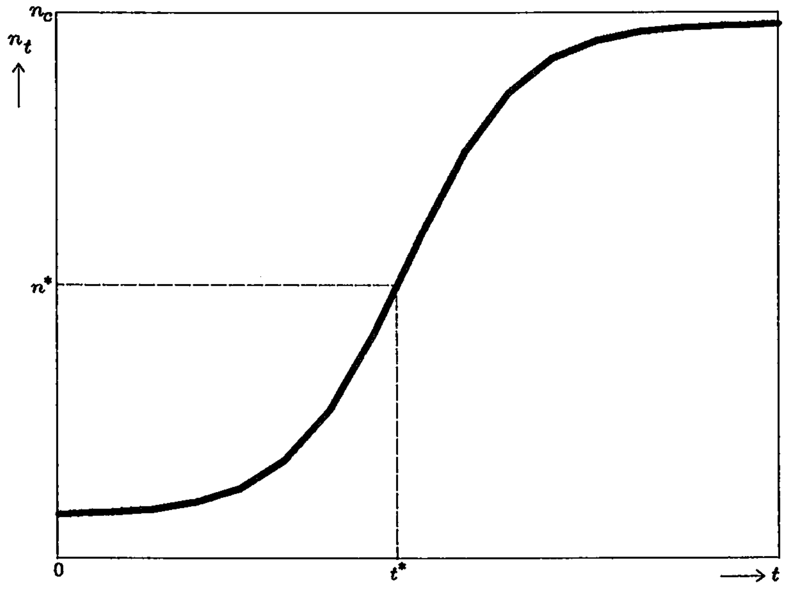

Figure 3.3: The development of nature in time in laboratory models.

The parabolic shape of the function can easily be explained. In the climax stage, net natural production equals zero. The same applies to a situation in which the total stock of nature equals zero. Net natural production is at a maximum when the stock of nature reaches the volume connected with the point of inflexion of the logistic curve. Net natural production is to be interpreted here as the increase of the volume of biomass. In laboratory models, no account is taken of the use of nature originating from the human respiration. Indeed, the 'growth of nature' in the real world is defined as net natural production minus the volume of the human use of nature.

If net natural production equals human use of nature (g_t), a physical steady state exists, since the volume of biomass is then constant. This is reflected in equation (15):

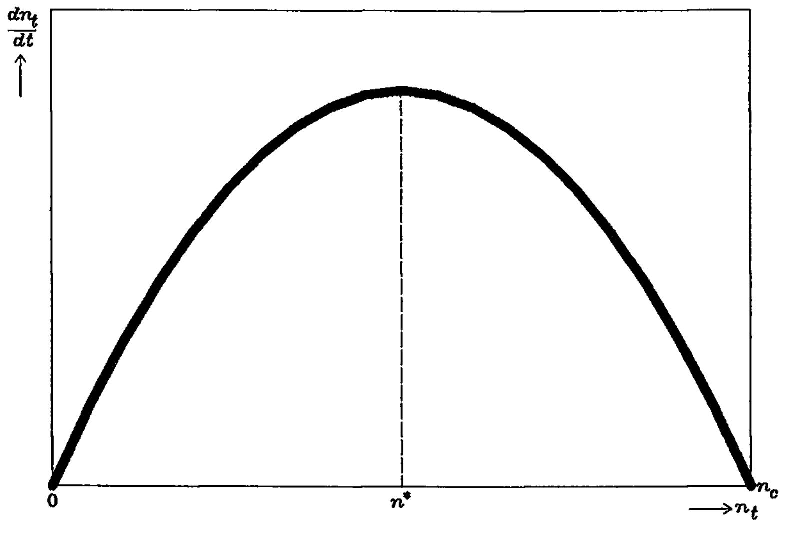

Figure 3.4: Net natural production as a function of the total volume of biomass.

$$(15) \qquad g_t = \alpha \cdot (n_c - n_t) \cdot n_t .$$

In this situation, the growth of nature equals zero, which implies a physical steady state. An optimum steady state can be defined as the physical steady state in which human use of nature is at a maximum. This is when net natural production reaches the top of the parabolic function, which is at point n^* in Figure 3.4. This maximum implies that the first derivative of the human use of dn_t/dt with respect to n_t must be zero, so:

$$(16) \qquad \frac{d(\alpha \cdot (n_c - n_t) \cdot n_t)}{dn_t} = -2 \cdot \alpha \cdot n_t + \alpha \cdot n_c = 0, \quad \text{so} \quad n^* = \frac{1}{2} \cdot n_c .$$

Equation (16) also explains the position of n^* in Figure 3.3. The outcome of equation (16) can be substituted in equation (15). This gives the optimum human use of nature:

$$(17) \qquad g^* = 0.25 \cdot \alpha \cdot n_c^2 .$$

For human production per unit of time, e.g. a year, a certain amount of energy is necessary. The total human need for energy (g_t) equals the need of energy per unit of product (β) multiplied by total human production (y_t):

$$(18) \qquad g_t = \beta \cdot y_t.$$

The optimum use of nature (g^*) of equation (17) substituted in equation (18) delivers the optimum human production (y^*)[4]:

$$(19) \qquad y^* = 0.25 \cdot \frac{\alpha}{\beta} \cdot n_c^2.$$

From equation (19) it follows that, without affecting total stock, human production can increase to a maximum level determined by the regeneration speed of nature, the need of energy per unit of product and the volume of biomass in the climax stage.

In this way human production does not affect future means of support in an irresponsible way, so that humanity may survive with enough power for as long as the sun shines (on estimate, another 5 billion years). Equation (19) gives a very strict prescription for human production. However, there are many kinds of (bio)technological innovations which may widen the ecological borders. These are studied in the next sections.

Development of technology and growth of human production

Without doubt it has been the technological developments which have caused the large-scale exhaustion of natural resources for a great deal. However, it is also clear that technology is an indispensable instrument in solving the ecological crisis which the world faces today (for a number of examples, see: Brown et al., 1990). So, a strict anti-technology attitude like that of Achterhuis makes no sense (Achterhuis, 1990). In fact, as has I have already said in Chapter 2, there is a distinction between 'nature-conserving' and 'nature-affecting' technological innovations.

Throughout human history most technological innovations have meant a further assault on the stock of depletable resources. When man first practised agriculture several thousands of years ago, he profoundly influenced the ecological system. Even more influential were the industrial revolutions in the eighteenth, nineteenth and twentieth centuries, when a great number of inventions and innovations made it possible to process large amounts of resources. Because of rapidly diminishing stocks of resources, a point has now been reached where it is realized that technological innovations ought to have a nature-conserving rather than a nature-affecting character. In economic terms, nature has become a scarce commodity.

As I have already said in the previous chapter, it is possible to distinguish between two types of technological change, inventions and innovations. An invention is a creative act of the human mind. An innovation is the application in the production process of an invention. So every innovation must be preceded by an invention, but not every invention is followed by an innovation. Whether innovation follows an invention is the outcome of a complicated economic and political process. It might even be that the character of the inventions is directed by this same process. If this is the case, then public opinion and politics decide which direction technological evolution will take, towards nature affecting inventions and innovations or towards nature conserving innovations.

Nature-sparing and nature-creating technological innovations

This section concentrates on nature-conserving technological change. This change can be subdivided into 'nature-sparing' and 'nature-creating' technological changes. Nature-sparing technological innovations are aimed at using less energy per unit of human production. This is represented mathematically by a reduction of parameter β in equation (6). This type of technological change can be demonstrated by several examples. The use of sun, wind and water as energy sources is one of them. Another is the invention of the fuel cell (see chapter 2).

The discovery of the super conductivity of certain materials at moderate temperatures is another promising development in this field. In future the loss of electric energy through the transport system might be eliminated by using materials which are even super conductive at normal temperatures. It has to be realized that these possible future innovations diminish the scarcity of the energy sources. It is even conceivable that a future invention might abolishe the scarcity of a specific resource, which would mean that a zero rent for this resource remained.

The total amount of organic matter generated by plants each year is enormous. It is the equivalent of one hundred billion (10^{11}) tons of carbon. This natural production needs only 1 per cent of all sunlight shed on the earth. *Nature-creating* technological development could try to retain a greater part of sunlight in plants and vegetables each year.

Think, for example, of fast-growing trees. Nature-creating technological innovations are expressed by an increase in parameter α in equation (19). It may also be possible to enlarge the possible volume of biomass in the climax stage by introducing new energy crops which can be grown in regions where climate and soil are less suitable for traditional crops. This type of biotechnological change is represented by an increase of n_c in equation (19).

The need for a nature-conserving technological innovations is obvious. How quickly technology will develop in the direction pointed to in this section is hard to predict since political decisions and public opinion play a major part in the process.

Economic growth and nature-conserving technological change

The aim of this section is to determine a sustainable growth rate of human production considering the possibilities of nature-conserving technological change. The starting point of this calculation is equation (19). Now, suppose that we start in period 0 and that the growth rate of production equals $\bar{y}$. Further let us assume that in period 0 mankind lives in the optimum steady state. If no technical changes occur, there can be no economic growth if the optimum steady state is to be maintained.

Next nature-sparing and nature-creating innovations are assumed. This means that equation (19) can be rewritten as follows:

$$(20) \qquad y_0 \cdot e^{\bar{y} \cdot t} = 0.25 \cdot \frac{\left(n_{c,0} \cdot e^{\bar{n}_c \cdot t}\right)^2 \cdot \left(\alpha_0 \cdot e^{\bar{\alpha} \cdot t}\right)}{\left(\beta_0 \cdot e^{\bar{\beta} \cdot t}\right)}.$$

In equation (20), $\bar{\alpha}$ and $\bar{n}_c$ represent the nature creating technological changes, while $\bar{\beta}$ represents the nature sparing technological change. Equation (20) gives:

$$(21) \qquad \bar{y} = 2 \cdot \bar{n}_c + \bar{\alpha} - \bar{\beta}.$$

It can be concluded from equation (21) that human production can grow, maintaining an optimum steady state, if growth equals the difference between the nature-creating technological changes and the nature-sparing technological changes. Indeed, in nature-sparing technological innovations, $\bar{\beta}$ will be negative, while in nature-creating technological innovations, $\bar{\alpha}$ and $\bar{n}_c$ will be positive.

Necessity of technological change

Normally economists define a steady state as being the same as the concept of *state of steady growth.* This means a state of the economy with a constant capital-output ratio, a constant rate of growth of output, consumption, wages etc. (Stiglitz, 1974a, p. 125, Daly, 1980b). Because of depletable resources some economists have reconsidered this definition. In this type of analysis, a steady state is characterized by a constant population, a constant output etc.; in other words, as Mill's stationary state. Tinbergen concluded that this state can be maintained if technical innovation sufficiently increases the productivity of the exhaustible resource. Stiglitz and Solow showed that this technical innovation is not a necessary condition if the exhaustible resource can be substituted by capital sufficiently. Another approach is that of making use of the productivity of nature. In this case, the focus is on the renewable resources in stead of the exhaustible resources.

Since the stock of non-renewable resources is decreasing, the stock of renewable resources is becoming more important. From my computations it is clear that a steady state with the use of renewable resources is possible without the assumption of technological change. Only if one assumes a growing population combined with a constant or growing production per head is technological change necessary. The same conclusion can be reached when a substitution between capital and an exhaustible resource is assumed. In this case, use is made of the productivity of capital, instead of the productivity of nature.

If a constant population with a constant income per head is to be maintained, two conditions must be fulfilled. First, the substitution possibilities of capital and the limited stock of exhaustible resources must be sufficient. Second, at least for renewable resources, a physical steady state must be maintained, which means that there will be a balance between natural production and human respiration. However, as has been shown in the first section, world population is not constant, but is expected to grow. This immediately implies that to assure a sufficient level of income per capita (bio)technical innovations are unavoidable. The overall conclusion must be that, even under the assumption of a growing population, the dismal forecasts by the Club of Rome need not materialize, provided technological change sufficiently increases productivity. No sustainable growth without (bio)technological innovations.

Role of time preference

As far as the depletion speed of depletable resources is concerned, the rate of time preference is crucial. This rate determines which distribution of a resource over time is most favourable, which means that it determines which distribution over time maximizes social welfare. To achieve this, for instance, for an exhaustible resource, the discounted marginal utility of this resource as represented by its rent should be equal for all vintages[5]). In other words:

$$(24) \qquad p_n(t) = \frac{p_n(t+1)}{(1+\upsilon)}, \quad \text{so} \quad p_n(t+1) = p_n(t) \cdot (1+\upsilon).$$

In this equation, p_n stands for the rent or the royalty of the resource, t expresses time and υ, the rate of time preference. This optimization rule is known as the Hotelling rule (Hotelling, 1931). The rate of time preference is dealt with extensively in the following chapter. The Hotelling rule itself is discussed in Chapter 5. The consequences of the Hotelling rule for economic growth are dealt with in Chapter 6.

Appendix 3.1: Constant consumption per head with a constant population by substitution of nature by capital

To prove Stiglitz' proposition I use the following linearly homogenous Cobb-Douglas production function, with y for production, k for capital, and n for the flow of the exhaustible resource:

$$y = k^{\beta} \cdot n^{(1-\beta)}.$$

The production elasticities of capital and nature, β and $(1-\beta)$ respectively, also indicate the income distribution, which means that:

$$\upsilon \cdot k = \beta \cdot y,$$

$$p_n \cdot n = (1-\beta) \cdot y.$$

In these two equations, υ stands for interest and p_n for the price of the resource (rent). The second equation can be written in growth rates as follows:

$$\overline{p}_n + \overline{n} = \overline{y}.$$

Because, according to the Hotelling rule (see the last section of this chapter), $\bar{p}_n$ equals υ and since a stationary economy is assumed, this equation can be rewritten as follows:

$$\upsilon = -\bar{n}.$$

The production function written in growth rates gives:

$$\bar{y} = \beta \cdot \bar{k} + (1-\beta) \cdot \bar{n}.$$

Knowing that $\bar{y}$ equals zero, the last two equations can be combined to form:

$$\bar{k} = \frac{(1-\beta) \cdot \upsilon}{\beta}.$$

The rate of interest (υ) multiplied by the capital-output ratio κ gives the production elasticity of capital as:

$$\upsilon \cdot \kappa = \beta.$$

A combination of the last two equations gives:

$$\bar{k} = \frac{(1-\beta)}{\kappa}.$$

Because the growth rate of capital $(\bar{k})$ equals the marginal propensity to save divided by the capital-output ratio (σ / κ), the last equation can be rewritten as:

$$\sigma = 1 - \beta.$$

This implies that, if the production process can be modelled with a Cobb-Douglas production function, a constant consumption per head with a constant population can be maintained so long as the marginal propensity to save equals the production elasticity of the exhaustible resource. Indeed, the marginal propensity to save must be lower than the production elasticity of capital, which implies that the production elasticity of capital must exceed the production elasticity of the resource (Stiglitz, 1974a, pp. 129-130). See also Solow (1974a, p. 43).

Notes

1) In fact the *tendency of the rate of profit to fall* is the Marxist counterpart of the *tendency of the marginal product of capital to decrease* in usual neoclassical theory. One might even consider the latter as the cause of the first.

2) The 'net natural production' of an ecosystem during a certain period is the difference between the gross natural production, i.e. the production by photosynthesis and the respiration of plants and animals, excluding respiration of man. The 'growth of nature' is the difference between net natural production and man's respiration, i.e. the human process of production and consumption.

3) The solution of this differential equation is:

$$n_t = \frac{n_c}{1 + \frac{n_c - n_0}{n_0} \cdot e^{-\alpha \cdot n_c \cdot t}}.$$

Further dn_t/dt is at the maximum for:

$$t^* = \frac{\ln\left(\frac{n_c - n_0}{n_0}\right)}{n_c \cdot \alpha}.$$

and:

$$n^* = \frac{1}{2} \cdot n_c.$$

4) As long as the optimum steady state has not yet been reached yet, the human use of nature should be less than natural production. In that case there will be a positive growth of nature if:

$$\frac{dn_t}{dt} > g_t \quad \text{for} \quad n_t < n_c.$$

Suppose, for instance:

$$g_t = \gamma \cdot \alpha \cdot (n_c - n_t) \cdot n_t \quad \text{with} \quad 0 < \gamma < 1 \quad \text{for} \quad n_t < n_c \quad \text{and} \quad \gamma = 1 \quad \text{for} \quad n_t = n_c.$$

From this it follows:

$$\frac{dn_t}{dt} = \alpha \cdot (n_c - n_t) \cdot n_t - \gamma \cdot \alpha \cdot (n_c - n_t) \cdot n_t = \alpha \cdot (1 - \gamma) \cdot (n_c - n_t) \cdot n_t .$$

Further it is assumed that the optimum steady state will have been reached within T years. So, by using note 3:

$$n_T = n^* = \frac{1}{2} \cdot n_c , \quad \text{so} \quad T = \frac{\ln\left(\frac{n_c - n_0}{n_0}\right)}{n_c \cdot \alpha \cdot (1 - \gamma)} , \quad \text{which means} \quad \gamma = 1 - \frac{\ln\left(\frac{n_c - n_0}{n_0}\right)}{\alpha \cdot T \cdot n_c} .$$

It will be clear that the above solution is not the only one possible.

5) This is true if the yearly depletion of the resource is a decreasing function of the royalty. If, in that case, discounted royalty should not be equal for all vintages, welfare could be increased by moving the marginal unit of a year with a relatively low marginal utility to a year with a relatively high marginal utility. From this it follows that maximum welfare is gained if discounted marginal utility is equalized over time.

4. Time preference and the rate of interest

The choice between the fullfilling of present or future needs plays an important part in economic action. These needs urge private householders as well as society as a whole to choose between the immediate consumption of income and the saving of it for future satisfaction. It is clear that there is an immediate link between this choice and the one between present and future resource use. This is why this chapter is devoted to the reviewing of theories on the phenomena of time preference and interest[1]). The main part is devoted to the treatment of the *locus classicus* of the theory on time preference and interest: Böhm-Bawerk's *Capital and Interest.*

Scholastic prohibition on interest

During the Middle Ages life was ruled by religious prescription. The mental outlook of medieval man can best be represented by the thoughts of Thomas Aquinas (1225-1274), a typical philosopher of those days and a representative of the Scholastic school.

> In Thomas Aquinas' philosophy and theology, the existence of God takes up a central position. From Him all finite beings proceed through creation. But God has not created the universe without any purpose. The several creatures are ordered to one another in a hierarchical way and the entire world is ordered towards God, who is the ultimate good of everything. In this way God is the first cause and the final end of all created beings (Hallebeek, 1986, p. 141).

At that time, the charging of interest was considered a sin. Almost every medieval Council had in its verdicts a passage on this sin of *usura.* Such Councils included: the second Lateran Council (1179), the third Lateran Council (1179), the fourth Lateran Council (1215) and the second Lyonnese Council (1274). At that time usury was a sin against justice. Thomas Aquinas, following Aristotle in this matter, voiced his opinion clearly in his Summa theologica. He wondered:

> Is it a sin to receive money as payment for providing a loan?

His answer to this question was:

> The receiving of usurious interest on a provided loan is unlawfull in itself, because one sells something that does not exist; through this an unequality is established which is incompatible with justice (Le Goff, 1987, p. 29).

This radical opininion was based on the difference between *res fungibiles*, goods which are destroyed by consumption (e.g. bread) for which no rent could be charged, and *res infungibiles*, goods which are not destroyed by consumption (e.g. a house) for which a rent could be charged. Money was considered to be 'res fungibiles'. Therefore a loan was seen as a sale of money for which the lender was paid by the paying back of the loan. To charge interest on top of that was considered unjust (Thurlings, 1978, p. 10).

The scholastics thought money to be infertile, and therefore they considered usury an act against nature and against God. The usurer was a special type of thief. In fact, he sold the time between the moment he gave the loan and the moment he received the money back for interest. However, as time was not his, but God's, he was stealing from no one less than God himself (Le Goff, 1987).

Although the church did not agree with the charging of interest on money loans, it nevertheless often occured, even in the Middle Ages. Sometimes the interest was paid in secret, sometimes openly, but still it was paid. For instance, in the Low Countries during the second half of the thirteenth century, interest varied from between 10 and 17 percent a year (van Houtte, 1979). The Scholastic tradition lasted until the seventeenth and eighteenth centuries. Naturally, long before that time, economic practice had outdated the prohibition on interest.

One of the opponents of the prohibition on interest was Anne R.J. Turgot (1727-1781). His ideas on interest can be found in his major work, *Reflections on the formation and the distribution of wealth*, published in 1766. He believed this prohibition to be harmful for the economy. In his view, interest is the price to be paid to the lender for his reduced liquidity. Turgot was convinced that interest is morally defensible. In essence, the loan at interest is nothing but a trading transaction in which the lender sells the use of his money to the borrower who buys it (Turgot, 1766, p. 160). The price or interest should be determined in the same way as the price of all other commodities, by the balance of supply and demand. Turgot criticized the Scholastic prohibition on interest rather sharply. Since lender and the borrower are equally interested in the loan, Turgot wondered:

> But in accordance with what principle can one conceive of any element of crime in a contract which is advantageous to the two parties, with which both are content, and which certainly does not injure anyone else? (Turgot, 1766, p. 161).

Turgot held that a proprietor of money may ask interest simply because the money is his own. On the other hand, the lender is able to pay the interest because of the profit he is going to make with the loan (Turgot, 1766, p. 163). So, in conclusion, it can be implied that, according to Turgot, the productivity of capital is a reason for the borrower to pay interest, and the reduced liquidity is a reason for the lender to demand interest. These two reasons are also the main elements of modern theories on interest.

Utilitarian tradition

The Utilitarian tradition of philosophy was founded in the eighteenth century. According to its founder, Jeremy Bentham (1748-1832):

> Nature has placed mankind under the governance of two sovereign masters, pain and pleasure. It is for them alone to point out what we ought to do, as well as to determine what we shall do (Bentham, 1789, p. 1).

He believed that the moral judgement of human action should be based on the principle of utility, which means:

> ...that principle which approves or disapproves of every action whatsoever, according to the tendency which it appears to have to augment or diminish the happiness of the party whose interest is in question: or: what is the same thing in other words, to promote or to oppose that happiness (Bentham, 1789, p. 2).

In Bentham's hedonistic philosophy, the value of pleasure or pain for an individual or a community is greater or less according to its intensity, its duration, its certainty or uncertainty, its propinquity or remoteness, its fecundity (the chance that it is followed by sensations of the same kind), its purity (the chance that it is followed by sensations of the opposite kind) and its extent (the number of people to whom it extends) (Bentham, 1789, p. 30). The circumstance of remoteness in time is especially important in the theory of value.

William Stanley Jevons (1835-1882) accepted most of Bentham's utilitarian philosophy:

> I have no hesitation in accepting the Utilitarian theory of morals which does uphold the effect upon the happiness of mankind as the criterion of what is right and wrong (Jevons, 1888, p. 23).

However, according to Jevons, the pleasures and pains an economist deals with are of the lowest rank (Jevons, 1888, p. 27). Consequently he only accepted Bentham's first four circumstances (intensity, duration, certainty or uncertainty and propinquity or remoteness) as circumstances to be taken into consideration in solving problems in economics. The last three circumstances (fecundity, purity and extent) were of high importance for the theory of morals but:

> ... they will not enter into the more simple and restricted problem which we attempt to solve in Economics (Jevons, 1888, pp. 28-29).

His ideas on time preference agree with Bentham's principle of remoteness (Krabbe 1974, p. 30). He stated that:

> The intensity of present anticipated feeling must, to use a mathematical expression, be *some function of the future actual feeling and of the intervening time*, and it must increase as we approach the moment of realization (Jevons, 1888, p. 34).

He was convinced that this "power of anticipation" must have a great influence in economics since all accumulation of stocks of commodity to be consumed at some future time is based upon this feeling. In his view, this ability to foresee was linked to civilization:

> The untutored savage, like the child, is wholly occupied with the pleasures and the troubles of the moment; the morrow is dimly felt; the limit of his horizon is but a few days off. The wants of a future year, or a lifetime, are wholly unforeseen. But in a state of civilisation, a vague though powerful feeling of the future is the main incentive to industry and saving (Jevons, 1888, p. 35).

The uncertainty of future events is of great importance to anticipated feelings:

> A great casualty, which is very unlikely to happen, may not be so important as a slight casualty which is nearly sure to happen (Jevons, 1888, p. 36).

Jevons believed that time should not have any influence upon human conduct, so that future feelings are of the same importance as present feelings:

> The factor expressing the effect of remoteness should, in short, always be unity, so that time should have no influence (Jevons, 1888, p. 72).

We could say that Jevons believed society to be more civilized when remoteness in time has less influence on the conduct of those in society. However, he admitted that:

> ...no human mind is constituted in this perfect way: a future feeling is always less influential than a present one (Jevons, 1888, p. 72).

With this idea Jevons posed the basis for the agio or premium theory of interest. In this theory, interest is seen as a compensation for the saver who is abstemious in the immediate use of part of his income.

Böhm-Bawerk's theory: first and second reasons

Böhm-Bawerk (1851-1914), the well-known Austrian economist of the second generation, analyzed the subject of time preference thoroughly and put forward an explanation for interest.

According to him, Bentham did not give a psychological theory for human conduct in this situation, but rather an empirical statement. Böhm tried to discover a mechanism for time preference. For him this mechanism was the "exchange of present against future commodities".

In fact Böhm was rather critical of Jevons' theory. Jevons did not discriminate between anticipated feelings connected with imagined future events and the estimated intensity of future feelings. According to Böhm, economic actions on behalf of future needs are based on the estimated intensity of future feelings and not on actual presentiments (Böhm, II, 2, pp. 227-229). Although Böhm may have been right, the result remains exactly the same. Present goods are valued higher than the same quantity and quality of future goods.

The core of Böhm-Bawerk's theory of time preference is formulated in the beginning of the fourth book of the second part of *Kapital und Kapitalzins*[2]:

> As a rule present goods are worth more than future goods of like kind and number (Böhm, II, 1, p. 318).

This shows that Böhm-Bawerk's theory is expressed in terms of goods; he believed that money only has the role of a technical device:

> More precisely, he held a crude quantity theory: the whole of money (taking account of velocity) buys the whole of the goods (Schumpeter, 1954, p. 928).

Böhm discriminated three reasons for the difference in the present value and the future value of a comparable good (Heijman, 1989).

The first reason lies in the difference between the ratio between need and satisfaction in the present and in the future. Böhm explained that if a person needs an amount of the good in the present very badly, although he may hope for better days in future, he will valuate this amount of a good higher in the present than in the future

(Böhm, II, 1, p. 328). He gave two cases which he believed to be especially typical for this situation. The first is the emergency case, for example, of a farmer who suffers from crop failure. Böhm saw proof for this motive in the very high interest rate these people are prepared to pay ('bis dat qui cito dat'). The second case is that of the poor beginner in some kind of art or business. He will value a soft loan almost as highly as a free gift of money.

In the opposite situation are those who earn a lot of money in the present, but expect to earn less in the future. For such people it seems that the marginal utility of money is clearly smaller in the present than in future (Böhm, II, 1, p. 329). However, this is not the case, since some present goods, especially money, can be preserved for future use. He concluded that, as far as people are able to store goods, they will prefer present goods to future goods, independent of the ratio of present to future needs (Böhm, II, 1, p. 331). Böhm made one exception to this rule; the relatively few cases in which goods are either not stocked or are difficult to stock:

> In autumn every greengrocer valuates a future hundredweight of grapes in April higher than a present hundredweight of grapes (Böhm, II, 1, pp. 330-331).

Böhm concluded that, according to the first reason, present goods have a moderate lead over future goods in objective exchange value, which in turn is based on subjective valuations (Böhm, II, 1, p.331). To this, Wicksell commented that the preservation of almost all goods requires special care, and further, that in a stationary economy, the higher valuation of present goods as compared to future goods based on the first reason will be very limited, apart from the possibility of a productive application (Wicksell, 1954, p. 109). In fact he believed it questionable whether the first reason for time preference could be isolated from the third reason.

Böhm considered a second reason for the individual time preference to be the systematic underestimation of future needs connected with the value of future means of satisfaction:

> How many tribes of Indians have, in senseless self-indulgence, sold to the palefaces their fathers' land, their only source of living, for a few barrels of firewater? (Böhm, II, 1, p.332).

He believed this same propensity to be an innate quality of all humans,

> ...including those with the greatest strength of character and the wisest (Böhm, II, 1, p. 332).

Here, he was in apparent agreement with Jevons who held the same opinion about human nature. According to Böhm, there are three motives responsible for this propensity. First, there is the imperfect image of future needs. This imperfectness might originate from a weak imagination or from a reluctance to take the trouble to use imagination. The second motive is the lack of will-power to withstand the temptation of immediate consumption, knowing that the choice for immediate consumption is, in fact, disadvantageous for total welfare:

> How often is one, out of 'sheer weakness', seduced into taking a step or into making a promise today knowing that it will be regretted tomorrow (Böhm, II, 1, p. 334).

In this case there is no lack of 'knowledge' but of 'will'. The third motive is the reflection that life is relatively short and uncertain:

> Even if we know for certain that a certain good will be obtainable in the future, we still do no know whether we will live to see it (Böhm, II, 1, p. 334).

Normally one estimates a future utility of 100 with a realization probability of 50 percent on 50:

> I am convinced that everybody will be glad to exchange a gift of fl. 100.000,- promised for his 100th birthday for a much lower amount in present goods (Böhm, II, 1, p.334).

Here again we can see a great similarity with Jevons' ideas. This low estimate of future utility is particularly important for people like the elderly and for soldiers before battle, who are forced to think a lot about the end of life. In many such cases it is possible to observe a high degree of extravagance. Böhm did not consider this to be a very powerful motive for people in normal life. Only when it concerns a relatively distant point in time does it become more powerful. However, because of this, it also influences exchange transactions in the immediate future:

> it is not possible that a certain payment of fl.1000 on 1 January 1920 represents a value of only fl.800 on 31 December 1919, and then suddenly reaches the value of fl.1000 (Böhm, II, 2, p. 335).

Böhm concluded that the first two motives have more influence than the third. Certainly all three motives have the same results. The estimation of the utility of future goods is lower than the utility of present goods of the same quantity and quality. Put in Böhm's words:

> We experience the marginal utility of future goods as it were in perspective diminution (Böhm, II, 1, p. 337).

Equation (1) shows the consequence of the first two reasons for time preference in terms of marginal income:

$$(1) \qquad \frac{u_t}{u_{t+1}} > 1.$$

In equation (1), u_{t+1} represents marginal utility attached to an income received in period $t+1$, while u_t represents marginal utility of the same income received in period t. To avoid ambiguity of speech, 'time preference' should be defined in terms of zero interest. Positive time preference then means that individuals prefer present income over the same amount of future income, despite the fact that this is available on the same terms. In Irvin Fisher's terminology, the indifference curves between present and future consumption have a slope greater than unity (when the consumption tomorrow is on the y-axis and the consumption today is on the x-axis) (Blaug, 1968, p. 505, p. 534).

To establish the equilibrium rate of interest (υ), it has to be assumed that consumers try to reach maximal utility over time. In that case the formula for consumer equilibrium is:

$$(2) \qquad \frac{u_t}{u_{t+1}} = 1 + \upsilon.$$

So an increase in the rate of interest will result in a rise in u_t relative to u_{t+1}, which means that the consumer postpones consumption. This explains why the neoclassical supply curve of savings as a function of interest has a positive slope.

Third reason for paying interest

According to Böhm, there is a third reason working in the same direction as the first two. Normally, present goods are better able to satisfying our needs than future goods because of technical circumstances. Say and Lauderdale point in the same direction. They call this third reason 'productivity of capital'. Böhm did not use this expression because he considered it confusing. According to him, nature and labour are the only two original factors of production. Capital is an intermediate factor and not productive in itself (Böhm, II, 2, pp. 120-121). On capital, Böhm, along with Marx and all (or nearly all) the British classical economists, should be considered a 'fundist' and not a 'materialist' (Hicks, 1977, p. 153). However we must acknowledge that the third reason is identical with the phenomenon called 'productivity of capital'. For Böhm, this productivity of capital was caused by the roundaboutness in production methods. According to this principle, the productivity of an amount of production means might very well be a positive function of the time the chosen production method takes. He illustrated this with tables in which he applied successive units of time to a given amount of resource (a month's labour). Compared with the classical wage fund theory, Böhm's theory maintains that the length of the production period is a variable, not a technically-given constant (Blaug, 1968, p. 503).

It is important to realize here that Böhm did not state that the longer the duration, the more productive a production method is. In this respect he referred to well-chosen methods of production. What he wanted to stress is that more productive methods take more time, which does not amount to the same thing as 'every method that takes more time is more productive' (Böhm, II, 1, p. 77, Zuidema, 1990).

Böhm tried to answer the question of whether a month's labour currently available has a higher value than a future month's labour. He believed that this "most certainly" must be the case. He argued that:

> if it places at our disposal more satisfycing means for every thinkable bundle of needs which we can use or want to use, then it must have a greater significance for our welfare (Böhm, II, 1, p. 341).

By the 'value' of a certain amount of physical product he meant marginal utility multiplied by the quantity of the physical amount. He realized that a larger amount of goods does not always have a higher value:

> Indeed, a bushel of corn in a hunger year is of more value than twice that amount after a more plentiful harvest. However, for the same person at the same time, a larger amount has a larger value: two guilders or two bushels which I possess today are of a higher value than one guilder or one bushel today (Böhm, II, 1, p. 342).

The same is true for present and future means of production. Böhm gave the following example. A month's labour, vintage 1910, could produce 470 units of product, with a roundabout method which takes till 1916 to deliver the final product while the same vintage could produce 350 units with the help of a production method which takes only three years, i.e. till 1913. Although the latter product might be of a higher value than the former, the input of a month's labour, vintage 1909, in a production process which lasts till 1913 could produce even more, e.g. 400 units. From this example Böhm concluded that the advantage of older (present) means of production over future means is maintained. He considered this to be one of the main pillars of his theory of interest.

Böhm tried to establish, in general terms, the value of a production input. According to him the marginal utility - and value - of a means of production depends on the marginal utility and value of its future products. However, since this marginal utility depends on the duration of the production method, it is ambiguous. Böhm's solution was to say that the value of a means of production is the maximum total value of its products. He explained this point with the help of tables (Böhm, II, 1, pp. 340-348), which are approximately reflected in equation (3), in which u is a decreasing function of n for given T:

$$(3) \qquad w_n(T) = y(T) \cdot u(T, n), \qquad dy/dT > 0, \quad \partial u/\partial T < 0.$$

w_n	value of the products of a month's labour, vintage n, at point of time 0.
y	total production out of one month of labour
T	duration of period of production
u	marginal utility of all products

In equation (3) the value of a month's labour (w), vintage year n at point of time 0 is equal to total production out of one month's labour (y) multiplied by the marginal utility of all products (u). The total production out of one month's labour depends on the duration of the production method (T). The marginal utility of products declines over time because of the first two reasons for time preference. So, $\partial u/\partial T$ is negative and u is a decreasing function of n, because both T and n positively affect the time till the future products will be available. Equation (3) has three variables: w_n, T and n.

The relevant value of a month's labour, vintage n, at point of time 0, $w_n(T^*)$, is found by differentiating equation (3) to T and setting the result to zero. Substitution of the value T^* found for T in equation (3) gives $w_n(T^*)$. From equation (3) and the above assumptions, we can conclude that current means of production have a higher value than the same amount of future means of production. In other words, the value of a vintage of labour is a negative function of n[3].

Taking the third reason as his base, Böhm argued that current means of satisfaction are also more highly valuated than future means. He illustrated this with the following example, taken partly from Roscher. Suppose there is a nation of fishermen with no capital, living on a diet of fish which are caught during ebb tide. Suppose in this way one fisherman can catch 3 fish a day. If he had a boat, he could catch 30 fish a day. Building a boat will take a month. He is not able to build a boat entirely on his own because he has to keep on catching fish to feed himself. Now suppose that another fisherman lends him 90 fish against the promise that after two months he will give 180 fish back. The fisherman agrees and builds his boat with which in the second month he is able to catch 900 fish. After giving back 180 fish he still has a 'profit' of 720 fish, which proves that the value of the fish borrowed must be higher than 90 and even higher than the 180 future fish he used to pay for them (Böhm, II, 1, p. 350).

There is an important parallel phenomenon connected with the third reason. This phenomenon is that the effort of creating a better lasting commodity containing more utility than a poorer lasting commodity takes a more roundabout method which yields a greater productivity. Böhm illustrated this relation between duration and roundaboutness with the following 'classic' example (Böhm, II, 1, p. 352-354). Suppose that a house which has a duration of 60 years contains the same amount of utility as 2 houses each with a duration of 30 years. Building a house with a duration of 30 years costs 30 years of labour, while building a house with a duration of 60 years costs 45 years of labour. Building two houses, one after the other, each with a duration of 30 years would take 60 years of labour. Böhm realised that this phenomenon fits entirely into the third reason for paying interest; a more roundabout method of production yields a greater productivity.

As a consequence, not mentioned by Böhm for this phenomenon, the duration of durable commodities is influenced by the rate of interest. This can be explained in the following way. Suppose that the two possibilities mentioned above are valued equally. In that case 15 present years of labour are valued as high as 30 years of future labour. Then the rate of interest (υ) can be computed as follows: $30/(1+\upsilon)^{30} = 15$, so $\upsilon = 0.023$. If the rate of interest is higher than 2.3 percent, a consumer would decide on two houses each with a duration of 30 years. If the rate of interest is lower than 2.3 percent, then the buyer would decide on one house with a duration of 60 years. From this example we may conclude that a high rate of interest is combined with a low duration of durable commodities, while a low rate of interest is combined with a long duration of durable commodities. In other words, high rates of interest imply relatively short production periods, while a low rate of interest implies long periods of production (Heijman, 1989).

It appears that Böhm-Bawerk was especially interested in the optimum duration of methods of production. However, this is difficult to measure in practice. Böhm's solution is the weighted average of the lengths of time between the separate inputs of labour in a production process and the moment the product is manufactured. Expressed algebraically [4] (Compayen, 1981, p. 167):

$$(4) \qquad T_a = \frac{l_1 \cdot t_1 + l_2 \cdot t_2 + \ldots + l_n \cdot t_n}{l_1 + l_2 + \ldots + l_3}, \quad \text{with}$$

T_a average waiting time,

l_j labour input on point of time j, $j = 1, 2, \ldots, n$,

t_j period of time between point of time j and point of time n when the final product is manufactured.

Böhm called this the average waiting time. If labour is divided equally over the production period, the average waiting time is equal to half the absolute production period, i.e. the time between the first input of a resource and the moment that the commodity is produced[5]. This particular average waiting time is referred to as the average period of production ('durchschnittliche Produktionsperiode') (Böhm, II, 1, p. 119).

This solution is not very satisfactory, since most products are the result of a complex production process. In such a situation, apart from exceptional cases, it is impossible to link a certain input of labour to a certain amount of output. Jevons had already recognized this difficulty. He remarked:

> ...it will seldom be possible to assign each portion of result to an exactly corresponding portion of labour. Cotton goods are due to the aggregate industry of those who tilled the ground, grew the cotton, plucked, transported, cleaned, spun, wove, and dyed it; we cannot distinguish the moment when each labourer's work is seperately repaid (Jevons, 1888, p. 231).

In his review of Böhm's work, Hutchison said of the principle of roundaboutness:

> Stripped of what is purely definitional, and somewhat arbitrarly so, and also of all doubtful technological generalizations, what remains in Böhm-Bawerk's analysis? That there are different methods of production, of different degrees of productivity: and that different methods would take different lengths of time, if one could agree on some method of measurement, but any such method of measurement would be arbitrary and without much economic significance. However, though Böhm-Bawerk did not answer the problem he posed, and though it is very doubtful whether he posed a meaningful problem, his discussion of the elusive relation between 'time' and 'productivity' ultimately perhaps completely elusive, may be said to have been a challenge that at one stage or another had to be met and disposed of (Hutchison, 1962, p. 172).

Interaction between the three reasons

In the preceding sections we saw that Böhm had three reasons for the existence of time preference: first, the difference between need and satisfaction of goods in the present and in the future; second, the systematic underestimation of future needs; third, the productivity of capital. An important problem to be solved is the question of the interaction between Böhm's three reasons. The difficulty here is that it is often not clear whether Böhm's analysis is microeconomic or macroeconomic. In an individual case it is perfectly possible for all three reasons to work separately. However, it is not possible to draw macroeconomic conclusions based on microeconomics without some comment.

At first sight, in a macroeconomic context, all three reasons appear to move in the direction of the time preference being strengthened by them. However, this is not actually the case. The influence of the three reasons depends on the state of the economy. This can be stationary (constant productivity and income per capita), growing (increasing productivity and rising income per capita) or declining (decreasing productivity and falling income per capita). Indeed, it is not so much the empirical state of the economy that is decisive, but what people think the state of the economy will be in future. Here we touch upon a difficult point in analysis. The definitions on the three states of the economy do not imply that the changes in income go in the same direction in every individual case. For example, in a stationary situation there could still be a rise in the income of one individual, compensated by a fall in income of another, which might change marginal utility of income even in a stationary situation defined in the above way. The way to solve this problem is to use the Paretian criterion for a change in welfare. This means that in a stationary economy, there is no change in income on the individual level, that in a growing economy, the income of some individuals rise but not at the expense of other individuals, and that in a declining economy one person's income must either decline or remain constant as a result of which the income per head will decline.

Let us look at how the three reasons interact in the three states of the economy. To analyze this I have used the ratio between today's and tomorrow's marginal utility of income. I suppose that marginal utility of income is a function of the level of income per head (productivity) (I) and time (t). Further I assume consumer equilibrium:

$$(5) \qquad \frac{u_t(I_t, t)}{u_{t+1}(I_{t+1}, t+1)} = 1 + \upsilon.$$

In a growing economy one expects to be better off in the future $(I_{t+1} > I_t)$. This means a lengthening of the period of production. In this case, apart from perspective diminution (the second reason), marginal utility of future income is less than marginal utility of present income, which is a sufficient reason for time preference and a positive real interest rate, according to the first reason. Following Fisher in his comment on this state of the economy Blaug stated:

> Assume that myopia is absent, so that we are interested only in maximizing the product, regardless of when it is maximized. The fact that capital is productive would not cause anyone to prefer income today over tomorrow since by definition we are indifferent about the date at which the final product emerges. The productivity of capital, however, will influence the relative abundance of goods today and tomorrow; with real income rising through time, people are willing to pay a premium for goods available today instead of tomorrow because of the law of diminishing utility of income, and a positive interest rate emerges (Blaug, 1968, p. 508).

In a declining economy, where the productivity of capital is declining because the period of production is becoming shorter, apart from perspective diminution, marginal utility of future goods is larger than marginal utility of present goods. In this situation real interest rate should be negative if it is based only on the first and third reasons. Positive real interest rates only emerge because of the second reason. We may conclude that, in a growing economy, the second reason for time preference is strengthened by the first and third, while in a declining economy, the second reason is weakened by the first and third.

In a stationary economy, future income is expected to be the same as that compared to present income based on constant productivity. So in this situation the first and the third reasons cannot provide a basis for a positive rate of interest. This means that in equation (5), marginal utility of income u_t is not influenced by the amount of income per head (I_t). So equation (5) can now be rewritten as:

$$(6) \qquad \frac{u_t(t)}{u_{t+1}(t+1)} = 1 + \upsilon .$$

On this situation Blaug commented:

> In the absence of something like the law of diminishing utility of income, only the undervaluation of the future can account for the fact that the productivity of capital leads to a positive rate of interest (Blaug, 1968, p. 508).

It appears that in this situation the productivity of capital is not a sufficient reason in itself for time preference and interest paying. We can conclude that in a stationary economy real interest rate will be zero if there is no time preference based on perspective diminution. In that case, assuming complete competition on the capital market, the supply curve of capital will be completely elastic if the rate of interest is zero. However, this is not a realistic situation since the period of production would lengthen, providing a poor present and a rich future that could only be reached after a long time. In this situation the first reason would, in the last resort, provide a positive time preference (Böhm, II, 1, p. 348):

> The true function of a positive rate of interest, then, is to act as a brake on the tendency to neglect present wants by overextending the period of production (Blaug, 1968, p. 509).

If we accept the above argument, it is possible to understand Böhm's explanation of the tendency of interest to fall as the capital-labour ratio rises (Böhm, II, 1, p. 464). Myopia will decrease in an economy with rising productivity and rising income per head since marginal utility of present as well as future income will both approach zero. This means that the ratio u_t/u_{t+1} approaches 1. At the same time the increment of product yielded by further extension of the period of production will be small. Both circumstances imply a rate of interest approaching zero.

Fisher on interest

An important clarification of Böhm's theory on interest was given by Irvin Fisher (1867-1947) in his book *The theory of interest* (1930). He too considered time preference (which he called *impatience*) and productivity of capital to be the main determining factors of the rate of interest. Further, he stressed, as Marshall and Thornton did, the difference between real and monetary rate of interest, real interest rate being the monetary interest rate minus the rate of inflation (Blaug, 1968, p. 538; Fisher, 1930, pp. 41-44). His theory may best be reflected with the help of Figure 4.1 (Pearce, 1983, p. 41).

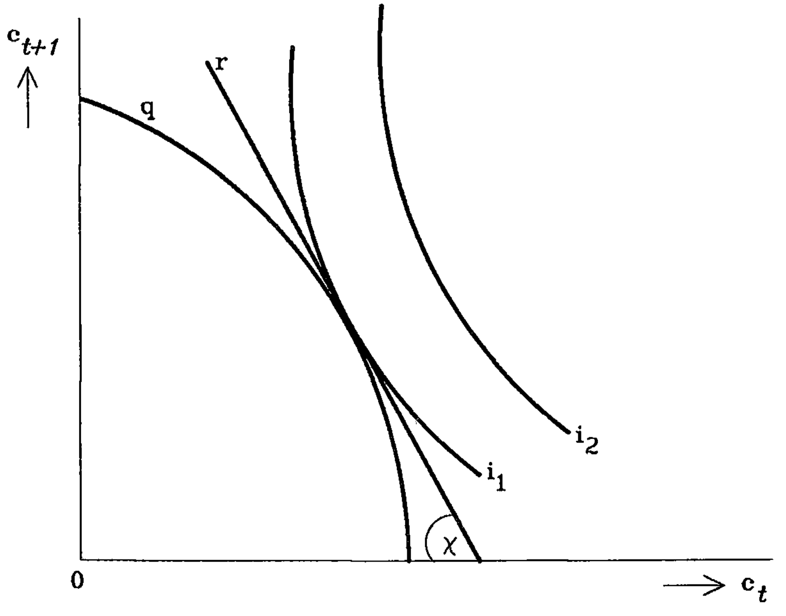

Figure 4.1: Fisher's theory on interest.

The consumption in period t (c_t), is placed on the x-axis, while the consumption in period $t+1$ (c_{t+1}) is placed on the y-axis. Further, the technical transformation curve q reveals the productivity of capital, while time preference is reflected by a map of social indifference curves represented by i_1 and i_2. The transformation curve is concave because of diminishing returns from sacrificing today's consumption to obtain future consumption, while the social indifference curves are convex because of the assumed diminishing marginal utility of income. The slope of the tangent to the transformation curve (χ) equals marginal efficiency of capital plus unity $(1+r)$:

(7) $$\frac{-dc_{t+1}}{dc_t} = 1 + r.$$

The slope of the tangent to the iso-utility curves reveals the ratio between the marginal utility of the consumption in period t to the marginal utility of consumption in period $t+1$. This ratio equals the social rate of time preference or the social rate of impatience plus unity:

$$(8) \qquad \frac{u_t}{u_{t+1}} = 1 + s.$$

Maximum utility is gained where the map of social indifference curves touches the transformation curve, or, in other words, when the marginal efficiency of capital equals the social rate of time preference, which means that $s = r$. In this optimum situation the rate of interest (υ) equals both the social rate of time preference (s) and the marginal efficiency of capital (r):

$$(9) \qquad \upsilon = r = s.$$

From Figure 4.1 it will be clear that, in such an optimum situation, a high rate of time preference causes a relatively high consumption level today and a relatively low level of consumption tomorrow, and vice versa. In this model a disequilibrium between the social rate of time preference and the rate of interest is restored by the market mechanism assuming that it is working perfectly on the capital market. Later, I show that this assumption is rather questionable.

So, as we have seen, productivity of capital and time preference or impatience play an important role in both Böhm-Bawerk's theory and Fisher's theory on interest. In neoclassical theory on interest, the only thing that matters is the productivity of capital. In this theory the marginal productivity of capital or the marginal efficiency of capital determines the rate of interest.

An interesting topic in Fisher's work is his treatment of George's theory on interest (Fisher, 1930, pp. 161-165). In his book *Progress and poverty* (1879) Henry George (1839-1897) developed a theory on interest which is worthwhile recapitulating, especially for renewable resources. According to George, interest arises from abstinence on the one hand and productivity of nature on the other. The aspect of abstinence is the same as the aspect of impatience or time preference. However, Böhm's productivity of capital is replaced by the productivity of nature:

> Now what gives the increase in these cases is something which, though it generally requires labour to utilize it, is yet disinct and separable from labour - the active power of nature; the principle of growth, of reproduction, which everywhere characterizes all the forms of that mysterious thing or condition which we call life (George, 1879, p. 181).

In his example of *cutting a forest* Fisher showed that it is not the average productivity of nature which determines the time the forest must be cut, but the marginal productivity. Besides:

> ... the point at which the forest is to be cut itself, depend, among other causes, upon the rate of interest (Fisher, 1930, p. 165).

George's theory of interest, as adapted by Fisher, says that a renewable resource must be harvested when, with constant prices, its growth rate equals the rate of interest. Assuming zero depletion costs, this can be proved as follows. Suppose p is the price of wood, q is the volume of wood in the forest, t is the time the forest grows and z is the cost of planting the trees. Now, the volume of wood in the forest is a function of the time the forest grows. For example, this may be the logistic growth function:

(10) $$q = q(t).$$

The net present value (s) of the harvest equals:

(11) $$s = p \cdot q(t) \cdot e^{-\upsilon \cdot t} - z.$$

Maximizing the net present value implies that the first derivative with respect to t equals zero. This means:

(12) $$p \cdot \frac{dq}{dt} \cdot e^{-\upsilon \cdot t} - \upsilon \cdot p \cdot q(t) \cdot e^{-\upsilon \cdot t} = 0, \quad \text{so:}$$

$$\frac{dq/q}{dt} = \upsilon.$$

From equation (12) it appears that, if the net present value is to be maximized, the growth rate of the renewable resource must equal the rate of interest. The interpretation is that, if this rule is maintained, the marginal increase in value from further growth just equals the opportunity costs of delaying the harvest. This is known in literature as the Faustmann rule (Bowes et al., 1985, pp. 534-535, Faustmann, 1849, Dasgupta, 1982).

Evaluation of Böhm-Bawerk's theory

Böhm's theory offers an extensive explanation of the phenomenon of interest. According to this theory, interest results from time preference and productivity of capital. Böhm did not present his theory in a very comprehensible way. Schumpeter even qualified his presentation as 'rather clumsy' (Schumpeter, 1954, p. 931), while Wicksell commented:

> His one fault, it seems to me, is that he sometimes wants to be too profound. He loves to pile up theoretical difficulties, in order, of course, to remove them later on, but in a way which is somewhat confusing to the ordinary reader (Wicksell, 1954, p. 106).

Because Böhm did not use mathematics, it is sometimes rather difficult to give a meaningful interpretation of parts of his work. This might be one of the reasons why his explanation of interest was not accepted by any economist of note at the time it was published. However, nowadays, a simplified version of Böhm-Bawerk's theory on interest has probably become the most widely accepted one.

This simplified version was formulated by Schumpeter as:

> Interest arises from the interaction of ('psychological') time preference with the physical productivity of investment (Schumpeter, 1954, p. 930).

In this view, the third reason is only one of the grounds for paying interest. For this simplified version it is not necessary to accept Böhm's explanation of the physical productivity of investment by the principle of roundaboutness. In this respect, his method of measurement of the duration of a production method is especially problematic. However, there is no doubt about the interest rate being linked to the growing of productivity of labour as a result of using capital (or 'intermediate goods'). On the supply side of the capital market, consumers demand compensation for their exchanging present goods for future goods. On the demand side, producers are able to pay interest because capital makes it possible to be more productive. If this were not the case it would not be possible to compensate the saver for his abstaining from immediate consumption without diminishing the future consumption possibilities of the investors below their present ones.

The first reason for time preference does not exist in a strictly stationary economy as defined above. If the ruling expectation in the economy is one of economic growth, the first reason can be assimilated with the third. Wicksell was right to question whether it is possible to separate the first and the third reasons. Indeed, in a growing economy the third reason combined with the first can provide sufficient explanation for the real interest rate. In a declining economy, these reasons should provide for negative time preference and negative real interest rates. In these circumstances only the influence of perspective diminution (the second reason) could be a reason for paying a positive real interest rate.

According to Böhm, the rate of time preference will decline if productivity grows as a result of longer production periods. So, from Böhm's theory in connection with Jevons' ethical criterion, the questionable conclusion can be drawn that society is becoming more civilized by getting more 'capitalistic'.

In a highly 'capitalistic' economy the difference between present and future marginal utility of income is low because they are both near zero. This means a relatively low rate of time preference. At the same time the degree of roundaboutness will be great, as a result of which a further lengthening of the period of production will only lead to a small increase of productivity and income per head. Under these circumstances the rate of interest will be low compared to the rate of interest in less developed economies.

Böhm-Bawerk's theory on interest influenced economic theory in a profound way. In fact, Böhm was one of the first authors to introduce the discounting process into economic theory. In its clarified form, put forward, for example, by Schumpeter and Fisher, his 'theory of capitalization' is, even today, still a major theory on interest.

Neoclassical theory on interest

The neoclassical theory on interest is based on Böhm's third reason for paying interest: the productivity of capital. In a state of equilibrium, interest will equal marginal productivity of capital (van den Goorbergh et al., 1979, Jones, 1975, Solow, 1970). This is demonstrated in Figure 4.2.

In Figure 4.2 the amount of labour is supposed to be constant. Because of the decreasing marginal productivity of capital, production (y) can now be represented by a concave function of capital (k). The tangents of the angles α and β represent the rate of interest in a situation of a relatively high capital-labour ratio and a relatively low capital-labour ratio respectively. Apparently marginal productivity of capital and the rate of interest in situation A is less than marginal productivity and the rate of interest

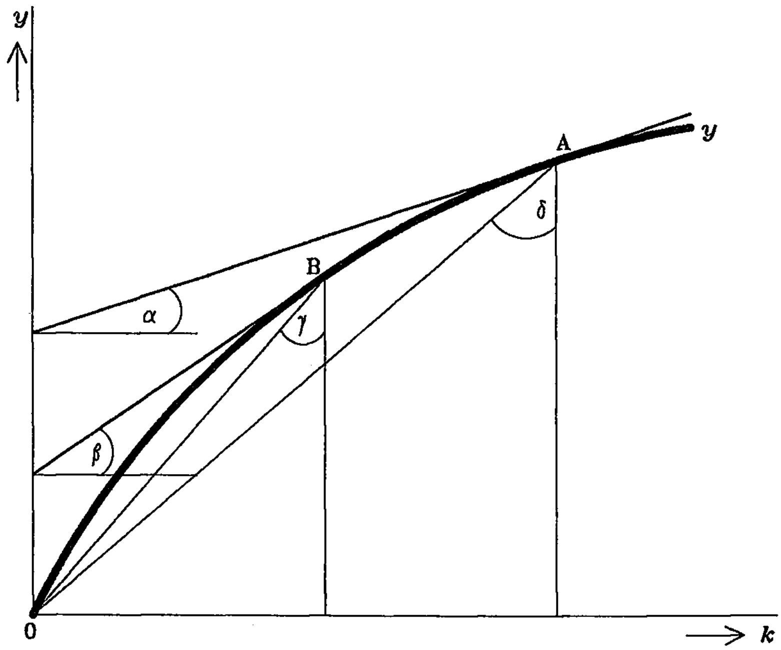

Figure 4.2: Rate of interest and marginal productivity of capital.

in situation B. The capital-output ratio in the two situations is represented by the tangents of the angles γ and δ. It is obvious that capital-output ratio in situation A exceeds the capital-output ratio in situation B. We can conclude from Figure 4.2 that a relatively high capital-output ratio corresponds with a relatively high capital-labour ratio (because labour is supposed to be constant) and a relatively low rate of interest. A relatively high rate of interest corresponds with a relatively low capital-output ratio and a relatively low capital-labour ratio.

The relation of the neoclassical theory on interest to Böhm's theory can be clarified by way of a simple dimension analysis of the capital-output ratio (de Jong, 1962). The dimension of capital is quantity: $[Q]$, while the dimension of production is quantity per unit of time: $[Q/T]$. From this it can be concluded that the dimension of the capital-output ratio is time. Formally this can be proved as follows:

$$(13)\qquad k \in [Q], \text{ so}$$
$$y \in [Q/T], \text{ so}$$
$$\frac{k}{y} \in \frac{[Q]}{[Q/T]} = [T].$$

From equation (13) it can be concluded that the capital-output ratio is the amount of production time represented by the total stock of capital. In other words, it is a measure for Böhm's roundaboutness in the production method. The conclusion is that the roundaboutness in the production method, which is represented by the capital-output ratio, is higher in proportion to the rate of interest being lower.

Social discount rate

Closely linked to the question of individual and social intertemporal distribution of consumption is the wider ethical question of how to distribute welfare over the present and future generations. Many have stated that a valuation of present consumption higher than future consumption is immoral or irrational (Ramsey, 1928; Pigou, 1952). Pigou, for instance, stated

> Generally speaking, everybody prefers present pleasures or satisfactions of given magnitude to future pleasures or satisfactions of equal magnitude, even when the latter are perfectly certain to occur. But this preference for present pleasures does not - the idea is self-contradictory - imply that a present pleasure of given magnitude is any *greater* than a future pleasure of the same magnitude. It implies only that our telescopic faculty is defective, and that we, therefore, see future pleasures, as it were, on a diminished scale.... This reveals a far reaching economic disharmony. For it implies that people distribute their resources between the present, the near future and the remote future on the basis of a wholly irrational preference (Pigou, 1952, p. 25).

Even important Austrians like Menger and Wieser criticized the second reason for time preference because it presupposes irrationality of behaviour. Opposed to this is the utilitarian tradition where a higher valuation of present day goods as compared to the same quantity and quality of future goods is defendable. In this tradition, full account is taken of future generations. However, because of the uncertainty of the future, a higher valuation of present day goods is considered justifiable. Bentham thought it ethically defendable to discount future pains and pleasures and Jevons introduced the criterion that the lower the social discount rate the more civilized a society was. In fact, the latter thought myopia to be simply a failure in the human character.

Hotelling justified the discounting of the future in relation to the depletion of exhaustible resources by stating:

> ... capital is productive ... and ... that future pleasures are uncertain in a degree increasing with their remoteness in time ... (Hotelling, 1931, p. 145).

With respect to the discount rate itself he remarked:

> It is likely, therefore, that in deciding questions of public policy relative to exhaustible resources, no large errors will be made by using the market rate of interest (Hotelling, 1931, p. 145).

To this remark Solow commented:

> Hotelling mentions, but rather pooh-poohs, the notion that market rates of interest might exceed the rate at which society would wish to discount future utility or consumer surpluses. I think a modern economist would take that possibility more seriously. It is certainly a potentially important question, because the discount rate determines the whole tilt of the equilibrium production schedule (Solow, 1974a, p. 8).

With respect to the relation between the discount rate and the time it takes to deplete an exhaustible resource, Koopmans has proved:

> ... discounting advances doomsday (Koopmans, 1974).

Doomsday means the day on which all earthly depletable resources are depleted.

According to Solow (1974b), there are several reasons for expecting the market interest rate to be too high to reflect the social discount rate. They can be divided into two classes. In the first class there are reasons from authors who take it for granted that society should discount future utility. However, these authors consider the market interest rate to be too high to be used as the social rate of discount. The first reason for that is that the sum of individual risks is not identical with total social risk. An important part of individual risks concerns the danger within society of transfers, which are not risks for society as a whole. Since the insurance market is not complete enough to cover these 'transfer risks', market interest rates will be too high to reflect the social discount rate (Arrow et al. 1970). A second example in this class of reasons is the existence of various taxes on income from capital:

> ...; since individuals care about the after-tax return on investments and society about the before-tax return, if investment is carried to the point where the after-tax yield is properly related to the rate of time preference, the before-tax profitability will be too high (Solow, 1974b, p. 8).

Baumol (1968) and Pearce (1983, p. 45) have provided a good example of this mechanism. If a company has to pay s percent to its lenders it must, in fact, earn r percent, where $r = s/(1 - \tau)$ and τ is the tax rate on companies. If the tax rate is 40 percent and the company has pay 10 percent on interest, then the latter has to earn 16.7 percent. A consequence of the above two reasons is that the discount rate may be too high, causing exhaustible resources being depleted too soon. To compensate this market failure, levies and direct regulation could be needed to express the social rate of time preference. Keynes also expressed this opinion:

> There remains an allied, but distinct, matter where for centuries, indeed for several milleniums, enlightened opinion held for certain and obvious a doctrine which the classical school has repudiated as childish, but which deserves rehabilitation and honour. I mean the doctrine that the rate of interest is not self-adjusting at a level best suited to the social advantage but constantly tends to rise too high, so that a wise Government is concerned to curb it by statute and custom and even invoking the sanctions of moral law (Keynes, 1936, p. 351).

Keynes even pleaded for a rehabilitation of the medieval usury laws as they could be essentially economically sound if imposed in a moderate way (Keynes, 1936, p. 352).

The second class of reasons for the expectation that the discount rate will be too high is the class of the ethical objections against discounting. Ramsey (1928) and Pigou (1952) and Rawls (1971) are among the main authors against discounting for ethical reasons. Solow (1974a) formulated Rawls' ethical principle with the so-called max-min criterion, by which he meant an equal distribution of consumption over all generations, which implies a zero discounting rate.

In general, authors who are against discounting argue that, while individuals might be myopic, in social-decision making every generation must be treated equally. In fact, they state that the social rate of time preference should be zero. However sympathetic this kind of reasoning is, it misses the point. When we talk in economic terms, the question is not whether it is ethically right to discount future wealth or whether it is rational for us to do so. The fact is that future wealth is discounted on the individual scale as well on the social one. An economist has to examine the consequences of this behaviour whether he agrees with it or not.

Blaug too was of the opinion that the importance of the ethical question on discounting is not very relevant for an economist:

> The argument that the assumption of inherent myopia must be rejected because it implies irrational behavior is methodologically unsound: and motives, rational or otherwise, that are shown to be significantly related to economic behavior ought to be considered by economists (Blaug, 1968, p. 506).

It is not the economist who has to decide what the ethically right individual or social rate of time preference is. In economics the question is not whether or not there should be time preference, but rather, what the impact of time preference on the intertemporal distribution of welfare will be (Rouwendal et al., 1985). Here the ethical question has to be separated from the economic one. Indeed, it is clear that market interest cannot be used for the expression of social time preference; for that purpose it is probably too high. However, this conclusion is not based upon ethical arguments, but upon the economic arguments of Solow's first class.

Van den Doel (1982) remarked that the market interest on perpetual state loans, provides a suitable starting point for computing the discount rate of collective projects. But even this generally rather moderate rate will have to be adjusted downward because of the arguments above. In this respect Glaser (1989) has argued that rational voters are inclined to less myopia in political decision-making than they would show if the decision was theirs alone to make, which would lead to a relatively low discount rate. According to Glaser, this lower rate of time preference in the political decision making has nothing to do with risk, altruism or, as Weingast (1981) argued, the influence of special interests. Rather, it is based upon two effects, the commitment effect and the efficiency effect. The commitment effect implies that the only way this year's voter can influence next year's policy is to vote for durable projects. The efficiency effect implies that this year's voter can discover that a durable project which starts this year and that lasts for several years has only a small additional cost compared to the same durable project starting next year. In conclusion, there is a bias towards durability and a low time preference based on these two effects (Glaser, 1989).

Notes

1) From the Latin *inter* (between) and *est* (is): what is in between.

2) The quotations from Böhm are my own translations.

3) if: $w_n(T) = y(T) \cdot u(T, n)$
and $u(T, n)$ is a decreasing function of n for all T,
and all w_n are at a maximum at T^*,
then $w_n(T^*)$ is a decreasing function of n.
Namely: $w_n(T^*) = y(T^*) \cdot u(T^*, n)$.

4) It is assumed that the time needed for the input is relatively very small compared to the absolute period of production.

5) If there is only one labour input at the beginning of the absolute period of production, then the average waiting time T_o is equal to the absolute period of production (symbol T in equation (3)).

5. Efficiency in resource depletion

In this Chapter the efficiency of resource depletion of exhaustible as well as renewable resources is examined. The Hotelling efficiency rule is applied to exhaustible resources. A similar rule is developed for renewable resources. Both rules describe resource depletion under the assumptions of well-defined property rights and perfect competition.

Hotelling efficiency rule for exhaustible resources

In a now famous article published in the Journal of Political Economy of April 1931, Harold Hotelling developed an efficiency rule for the depletion of an exhaustible resource. This rule is that the price of an exhaustible resource should rise by the rate of interest if the social value of the resource is to be maximized. The 'price of the resource' (p) means the net price received after paying the cost of extraction and placing the amount of resource on the market. Generally this 'price' is referred to as the royalty of the resource[1]. The social value $u(q)$ of a quantity of the resource put to market for a unit of time may be defined as follows:

$$(1) \qquad u(q) = \int_0^q p(\xi)d\xi.$$

This integrand is the area under the demand function for the exhaustible resource up to the quantity q actually placed upon the market. If future enjoyment is to be discounted with interest υ, the present value of the total flow of resource (V) can be computed with:

$$(2) \qquad V = \int_0^T u[q(t)] \cdot e^{-\upsilon \cdot t}dt,$$

with T for the time interval the resource is exploited. Because of (1) the derivative du/dq equals $p(q)$. So

$$(3) \qquad \frac{du}{dq}[q(t)] \cdot e^{-v \cdot t} = p(q(t)) \cdot e^{-v \cdot t}, \qquad (*)$$

which means that discounted marginal utility of q equals discounted royalty. Since $\int_0^T q(t)dt$ is fixed, the productive schedule which makes V a maximum must be such that a unit increment in q will increase the integrand as much at one time as at another. This means that the expression (*) has to be a constant. Calling this constant p_0, we have

$$(4) \qquad p(q(t)) = p_0 \cdot e^{v \cdot t}.$$

This necessary condition turns out to be sufficient because p is supposed to be a decreasing function of q. The above presentation essentially follows the original article of Hotelling. With his simple solution procedure Hotelling was, in fact, solving an isoperimetric problem in an intuitive way. In Appendix 5.1 the general solution procedure for such a kind of problem is formulated and the Hotelling problem is dealt with as an example.

With respect to the relation between royalty and the market price it should be remembered:

> The market price can fall or stay constant while the net price is rising if extraction costs are falling through time, and if the net price or scarcity rent is not too large a proportion of the market price. (Solow, 1974b, p. 3).

The Hotelling rule is gained by assuming perfect competition. However, according to Hotelling, this should not give rise to the idea that in the extracting industries the government should never interfere:

> ..., there are in extracting industries discrepancies from our assumed conditions leading to particularly wasteful forms of exploitation which might well be regulated in the public interest. We have tacitly assumed all the conditions fully known. Great wastes arise from the suddenness and unexpectedness of mineral discoveries, leading to wild rushes, immensely wasteful socially, to get hold of valuable property. (Hotelling, 1931, p. 144).

To illustrate this phenomenon, he used the drilling of 'offset wells' along each side of a property line over a newly discovered oil pool. Each owner must drill and get the precious oil quickly, for otherwise his neighbours will get it. As a consequence, incidental large amounts of natural gas and oil are lost since there is not enough storage capacity (Hotelling, 1931, p. 144). In fact, Hotelling was here stating that the property rights must be well-defined for his rule to work in practice. This problem of common resources is extensively dealt with in Chapter 9 of this thesis.

The reason for the socially irrational economic behaviour is clear. Since there is no proper agreement over the maximum amount of oil each firm can dispose of, the extracting firms are forced to spoil the crude oil. Of course, nowadays, normally such a socially irrational economic behaviour is seldom found in the oil and natural gas sector, but it shows how a resource can be wasted when the extraction is not properly organized.

An important question is whether, under ideal conditions, the time until exhaustion will be finite or infinite. The answer to this question depends upon the shape of the demand function. If the demand function is a linear decreasing function $(q = \alpha - \beta \cdot p)$ the stock will be exhausted in a finite time. If the demand function approaches the y-axis assymptotically (for example $q = p^{-b}$), the exploitation of the exhaustible resource may continue forever, though at a gradually diminishing rate. Solow did not consider these cases to be very numerous.

> There is a limiting case, of course, in which demand goes asymptotically to zero as the price rises to infinity, and the resource is exhausted only asymptotically. But it is neither believable nor important (Solow, 1974b, p. 3).

In conclusion, Hotelling's simple model describes the so-called 'cake eating' problem (Withagen, 1981, p. 504). The basic characteristic of his model is that a non-renewable resource of known magnitude exists, which should be exploited in such a way that the social value of the resource is maximized. The main assumptions are that consumers' preference schemes do not change over time and that the rate of time preference is equal to the market interest rate. Finally, Hotelling arrived at an efficiency rule which implies that the royalty of a non-renewable resource should rise with the rate of interest[2].

Efficiency rule for the use of a renewable resource

In contrast to an exhaustible resource, a renewable resource has a limited capacity to renew itself. Examples of renewables are woods, sea fish stocks and game. Another example is arable and grazing land, though this does not appear to be so at first sight. If land is managed properly, it is able to regenerate itself over a long period of time.

However, if used in excess, its quality will deteriorate. It is possible that, as a result of excessive use, soil will become valueless for agricultural use. In such a situation, water and wind can erode it erosion or it can be turned into a desert.

To a certain degree, the atmosphere and hydrosphere are able to clean themselves. These large reservoirs of air and water can be analysed as renewable resources. Of course, the time needed for this self-cleansing process depends on the degree of pollution (Dasgupta et al., 1979, p. 114). It might even be that pollution is so high that the cleansing process stagnates. In this section I try to determine an efficiency rule for the exploitation of a renewable resource.

Suppose there is a stock of a renewable resource available, for instance a forest. The question to be solved is how to harvest this stock in order to maximize its total utility, bearing in mind that the part of the stock which is not harvested is able to grow[3)]. In appendix 5.2 it is proved that in the case of a renewable resource under the conditions of perfect competition,

$$(5) \qquad p_t = p_0 \cdot e^{(v-a)\cdot t}.$$

This means that in order to maximize total utility of the stock of a renewable resource, the price must rise with the difference between the discount rate and the renewal rate of the renewable resource[4)].

If the growth rate of nature exceeds the discount rate, the price of the renewable resource will drop and the quantity which is supplied to the market each year will grow. If the discount rate exceeds the renewal rate of the renewable resource the price will rise, indicating that the quantity supplied each year to the market decreases. When the discount rate equals the renewal rate, there is a steady supply of the resource each year. This situation is called *equilibrium*. It is important to examine the circumstances under which, an equilibrium will occur.

Up till now it has been assumed that a renewable resource always renews itself by a constant percentage each year. This is not a realistic assumption, since most of the time a stock of renewable resource has a maximum point at which the renewal rate is zero. In fact, the growth in absolute figures of a lot of animal, bird and fish populations is often bell-shaped. A specific kind of this bell-shaped curve is where growth in absolute numbers is quadratic in the population size, n_r (Dasgupta et al., 1979, p. 117). The suffix r points to the fact that the resource is renewable:

(6) $$\frac{dn_{r,t}}{dt} = -\chi + \psi \cdot n_{r,t} - \phi \cdot n_{r,t}^2, \qquad \chi \geq 0; \;\; \psi, \phi > 0 \;\; \text{and} \;\; \psi^2 > 4 \cdot \chi \cdot \phi.$$

A special case of this function is found when $\chi = 0$. Equation (6) is then reduced to:

(7) $$\frac{dn_{r,t}}{dt} = \psi \cdot n_{r,t} - \phi \cdot n_{r,t}^2.$$

When this function is integrated, the result is:

(8) $$n_{r,t} = \frac{\psi \cdot n_{r,0}}{\phi \cdot n_{r,0} + (\psi - \phi \cdot n_{r,0})^{-\psi \cdot t}}.$$

Equation (8) is the equation of the logistic curve. For the sake of simplicity it has been initially assumed that the renewable resource at issue, in the absence of 'human predators', over time will develop according to the logistic curve. In that case, from equation (7) the renewal rate of the renewable resource can be deduced as a function of the total stock (population) of the renewable resource:

(9) $$a = \frac{dn_{r,t}/n_{r,t}}{dt} = \psi - \phi \cdot n_{r,t}.$$

As can be concluded from equation (9) the renewal rate of the renewable resource (a) is a decreasing linear function of total population (n_r). Returning to the result of equation (11), it can be deduced that the price of the renewable resource will rise if the discount rate exceeds the renewal rate of the renewable resource. In that case, the annual 'harvest' from the renewable resource must decrease. In the opposite case, the price of the renewable resource will decrease, which points to a annual increasing supply of the renewable resource. In Figure 5.1 both situations are presented graphically.

To the right of point S in Figure 5.1 the discount rate exceeds the renewal rate. In this situation, the yearly harvest together with total stock will decrease if the harvest is a constant fraction of total stock. To the left of point S the renewal rate exceeds the discount rate. In this situation, the annual harvest together with total stock will increase if the harvest is a constant fraction of total stock. The conclusion is that in a situation in

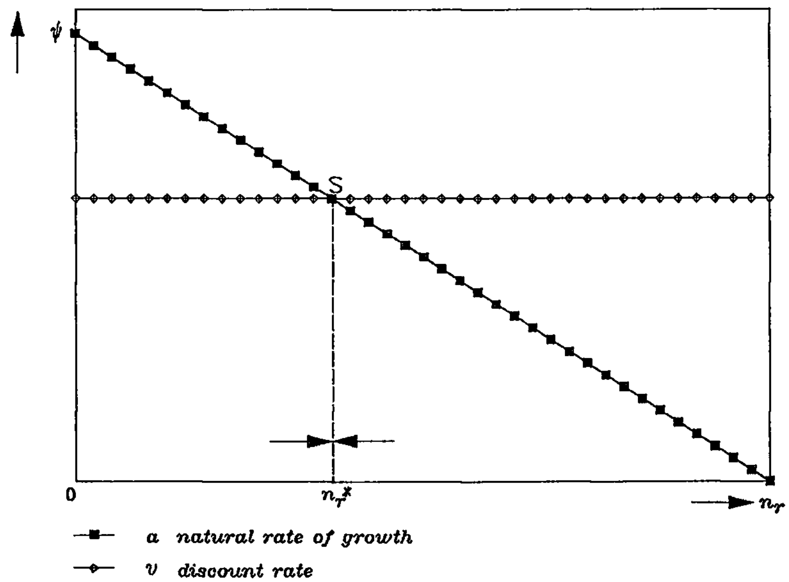

Figure 5.1: The discount rate and the renewal rate of a renewable resource as a function of total stock.

which total utility over time is maximized with respect to the depletion of a renewable resource, in equilibrium, the renewal rate of the resource will be equal to the discount rate total stock (population) being constant (n_r*). Indeed, it has to be realized that this equilibrium is not as such stable. It can be stabilized if provision is made that the harvest moves into the same direction as total stock. Of course, it has to be realized that it is still possible for species to become extinct because of excessive use, as it is possible that the discount rate exceeds ψ. Moreover, equation (6) is more appropriate than equation (7) for reflecting absolute growth as a result of which the chance of the discount rate permanently exceeding the renewal rate will increase. This is shown graphically in Figure 5.2.

Figure 5.2 shows the difference between the growth rate of a renewable resource as a decreasing linear function of total stock, and the growth rate of a renewable resource when a *threshold* is built into the function of the growth in absolute terms, as has been done in equation (6). The idea behind this is that, for very small population sizes, the chance that the species will become extinct is huge because mating encounters are low, given the thinness of the population. In deterministic models, this idea can be best

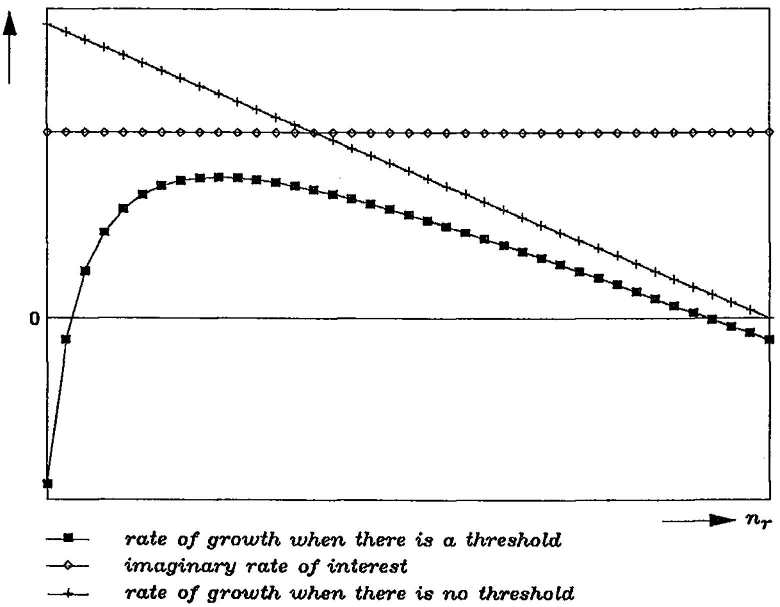

Figure 5.2: Different renewal rate curves and the discount rate.

reflected by building a threshold below which the population cannot restore itself (Dasgupta et al., 1979, p. 116). From Figure 5.2 it can be concluded that, if the notion of a threshold population is taken into account, the chance of the discount rate continuously exceeding the renewal rate is higher than if such a threshold is not considered. From the above section, three conclusions can be drawn:

1. The use of a renewable resource is efficient when its royalty rises by the interest rate minus the renewal rate of the renewable resource,
2. An equilibrium in a renewable resource sector occurs when the rate of renewal equals the rate of time preference,
3. An equilibrium, necessary for the sustainable use of a renewable resource, is a possibility and not a necessity. The equilibrium is threatened by too high a rate of time preference in relation to the renewal capacity of the renewable resource.

Appendix 5.1: Isoperimetric problem

Given numbers t_0, t_1, x_0, x_1, c and given functions I, G of three variables, define for a function x on $[t_0, t_1]$ the number $J(x)$ by:

$$J(x) = \int_{t_0}^{t_1} I(x(t), x'(t), t)dt.$$

The following problem is an example of a so-called isoperimetric problem:

Maximize $J(x)$ subject to the constraints

$$x(t_0) = x_0,$$

$$x(t_1) = x_1,$$

$$\int_{t_0}^{t_1} G(x(t), x'(t), t)dt = c.$$

This problem can be solved by the classical calculus of variations. One has the following result (Intrilligator, 1971, p. 318). If x^* solves the above isoperimetric problem, then there exists a number λ so that

$$\frac{\partial}{\partial x}(I + \lambda G) = \frac{d}{dt}\left(\frac{\partial}{\partial x'}(I + \lambda G)\right)$$

holds for x^*. This is a differential equation called the Euler equation. Notice that this is only a first order condition. Second order conditions can also be given, but this will not be done here.

Now I want to apply the above theory to the 'cake-eating' problem of an exhaustible resource. In that case:

$$I(q(t), q'(t), t) = u(q(t))e^{-vt},$$

$$G(q, q', t) = q.$$

Since there is no q' – dependency, then for the Euler-equation:

$$\frac{\partial}{\partial q}(u(q)e^{-\upsilon t} + \lambda q) = 0, \quad \text{thus:}$$

$$\frac{\partial}{\partial q}(u(q)e^{-\upsilon t}) = -\lambda.$$

So, it appears that

$$\frac{du}{dq}[q(t)] \cdot e^{-\upsilon \cdot t} \qquad (*)$$

has to be constant, which means that

$$p_t = p_0 \cdot e^{\upsilon \cdot t}.$$

Appendix 5.2: The optimum rule in case of a renewable resource under perfect competition

The problem in question is equivalent with

$$\text{Maximize} \quad K(n) = \int_0^T u(\alpha(n_t) - n'_t) \cdot e^{-\upsilon \cdot t} dt,$$

$$\text{where} \quad u(q) = \int_0^q p(\xi) d\xi$$

and with n_t such that $n_0 = M$, $n_T = N$, $N \leq M$.

This problem can be solved by the calculus of variations (see appendix 5.1) by taking

$$I(n, n', t) = u(\alpha(n) - n') \cdot e^{-\upsilon \cdot t},$$

$$n_0 = M, \quad n_T = N,$$

$$G = 0, \quad c = 0.$$

Using $u'(q) = p(q)$, the Euler equation

$$\frac{\partial I}{\partial n} = \frac{d}{dt}\left(\frac{\partial I}{\partial n'}\right)$$

gives

$$u'(\alpha(n)-n')\cdot\alpha'(n)\cdot e^{-v\cdot t} = \frac{d}{dt}(-u'(\alpha(n)-n')\cdot e^{-v\cdot t})$$

$$p(\alpha(n)-n')\cdot\alpha'(n)\cdot e^{-v\cdot t} = \frac{d}{dt}(-p(\alpha(n)-n')\cdot e^{-v\cdot t}).$$

In the case $\alpha(n_t) = a\cdot n_t$ this becomes with $p_t = p(\alpha(n_t)-n'_t)$

$$p_t\cdot a\cdot e^{-v\cdot t} = \frac{d}{dt}(-p_t\cdot e^{-v\cdot t}).$$

So, $p_t\cdot e^{-v\cdot t} = c\cdot e^{-a\cdot t}$

$$p_t = c\cdot e^{(v-a)\cdot t} = p_0\cdot e^{(v-a)\cdot t}.$$

Notes

1) Royalty equals selling price minus marginal extraction costs. In fact this definition of *royalty* equals the normal definition of *rent*. An example of the calculation of this royalty for a number of years for the Indonesian oil stocks can be found in Repetto et al. (1989). The rent in this situation was calculated as: FOB export price per barrel minus production costs per barrel gives rent per barrel. For instance the rent in dollars per barrel for the years 1980-1984 was $24.31, $30.33, $27.15, $25.60 and $24.30 respectively. It appears that, at least for Indonesian oil, from 1981 to 1989 the rent per barrel decreased rather sharply (Repetto et al., 1989, p. 41).

2) If one looks at the years 1970-1984, then the royalty at Indonesian oil rose at a rate of about 35%, while the average interest rate in the United States, Japan and Germany was about 8.5% in the same period. From this data one might conclude that the rent on crude oil has increased too quickly in that period (Repetto et al., 1989, IMF, 1986).

3) For instance, the annual biomass increment for the Indonesian forest is estimated to be 0.75% (Repetto et al., 1989, p. 30).

4) This rule can also be derived with the help of the Faustmann rule (see Chapter 4). It has to be assumed that price is not a constant over time. In that case (of a variable price), the formula for the net present value (s) of a renewable resource is:

$$s = p(t) \cdot q(t) \cdot e^{-v \cdot t} - z.$$

In this formula p stands for price, q is the volume of the renewable resource, t is time and z represents the initial cost of the renewable resource (for instance, in the case of timber, the cost of planting the trees). Maximizing the net present value of the renewable resource implies:

$$\frac{ds}{dt} = 0, \quad \text{so} \quad \frac{dp}{dt} \cdot q \cdot e^{-v \cdot t} + p \cdot \frac{dq}{dt} \cdot e^{-v \cdot t} - v \cdot p \cdot q \cdot e^{-v \cdot t} = 0 \quad \text{or}$$

$$\frac{dp/p}{dt} + \frac{dq/q}{dt} = v, \quad \text{which means that} \quad \bar{p} = v - a.$$

In the case of an exhaustible resource, a equals zero, and the Hotelling rule applies. If the rise of the royalty (p) is supposed to be zero, then the optimum rule that the renewal rate of a renewable resource (a) must equal the rate of interest (v) (Faustmann rule) applies. This rule has already been deduced in Chapter 4.

6. Growth models

This chapter deals with the integration of depletable resources into two growth theories: the Harrod-Domar growth theory and the neoclassical growth theory. It tries to answer the question whether a state of steady growth can be combined with a steady depletion of the exhaustible resources on the one hand and a sustainable use of renewable resources on the other. This combination of steady growth, steady depletion and sustainable use is called *sustainable growth*. Within this framework, special attention is paid to the critical role of interest rate and technical change.

Harrod-Domar growth model

In developing his efficiency rule, Hotelling was unable to use growth models since they did not exist at the time he wrote his article about exhaustible resources in 1931. It is therefore interesting to see whether by using growth models it is possible to obtain results different from those of Hotelling. The two main growth models at present are the post-Keynesian Harrod-Domar growth model and the neoclassical growth model mainly developed by Robert Solow. In this section I give a brief description of the Harrod-Domar model and in the following sections I show the relevance of this model for studying the depletion of depletable resources. The neoclassical growth model is dealt with later.

Harrod published his results in 1939, Domar in 1946. For Domar, the *rate of growth* was still:

> a concept which has been little used in economic theory (Domar, 1946, p. 77).

However, he saw that the problem of economic growth is both old and new, mentioning especially Marx and Keynes as theorists in this field (Domar, 1946, p. 77).

Krelle (1988, p. 62) also mentioned Schumpeter and Ramsey as contributors to the theory of growth after Marx. However, modern growth theory starts with the dynamization of Keynesian theory. Sen put it like this:

> The so-called Harrod-Domar model, in spite of generic similarities with earlier models of Marx, Cassel and others, broke fresh ground and started the snowball of modern growth theory (Sen, 1971, p. 41).

The model is called the Harrod-Domar model because the results gained independently by both men are very alike. In this brief discussion of the model I do not stress the minor differences between both theories but rather deal with what has become the Harrod-Domar growth model. The main assumptions for the model enumerated by Domar (1946, p. 65) are:

a. a constant price level;
b. no lags are present;
c. savings and investment refer to the income of the same period;
d. both savings and investment are net, i.e. over and above depreciation;
e. depreciation is measured not in terms of historical costs, but in terms of the cost of replacement of the depreciated asset by another one *of the same productivity;*
f. productive capacity of an asset or of the whole economy is a measurable concept.

The essential part of the model can be presented in 5 equations. Equation (1) states that there is income equilibrium in the economy, which means that ex ante net investment (i) equals savings (s):

$$(1) \qquad i = s.$$

Net investment is to be considered as the expansion of the capital stock (Δk)

$$(2) \qquad i = \Delta k.$$

Since it is possible that the depreciation of the stock of capital exceeds gross investment net investment can be negative.

Total savings equals the marginal propensity to save (σ) multiplied by the net national income (y):

$$(3) \qquad s = \sigma \cdot y.$$

Total capital (k) equals a given capital output ratio (κ) multiplied by production capacity $(\hat{y})$:

$$(4) \qquad k = \kappa \cdot \hat{y}.$$

As well as income equilibrium, it is also assumed that production capacity is fully utilized:

$$(5) \qquad \hat{y} = y.$$

From these 5 equations, the growth rate of the capital stock $(\bar{k})$[1] can be derived:

$$(6) \qquad \bar{k} = \frac{\sigma}{\kappa}.$$

From equations (4), (5) and (6) it can be concluded:

$$(7) \qquad \bar{k} = \bar{y} = \bar{\hat{y}} = \frac{\sigma}{\kappa}.$$

Total income consists of consumption c and net investment i:

$$(8) \qquad y = c + i.$$

If the absolute values of the variables in equation (8) are changed into relative ones, i.e. growth rates, then:

$$(9) \qquad \bar{y} = (1 - \sigma) \cdot \bar{c} + \sigma \cdot \bar{i}.$$

From equation (3) it follows that $\bar{c} = \bar{y}$. From this result, together with equation (9), it follows that $\bar{y} = \bar{i}$. From equation (7) and the results just arrived at, it can finally be concluded that, in the Harrod-Domar growth model, in a path of steady growth all variables increase by the same growth rate:

$$(10) \qquad \bar{k} = \bar{y} = \bar{\hat{y}} = \bar{c} = \bar{i} = \frac{\sigma}{\kappa}.$$

So it is possible to have a state of steady growth within the Harrod-Domar model. The growth rate σ/κ is called the warranted rate of growth. This result has been reached under the assumption of a constant marginal propensity to save and a constant capital output ratio.

The Harrod-Domar model does not guarantee full employment; it only gives the condition under which full employment can be maintained. If, with a given labour output ratio, there is full employment at point of time 0, then full employment will be maintained so long as the labour force does not grow faster than the warranted rate of growth σ/κ. Unemployment occurs when the labour force grows faster than the warranted rate of growth, while if the labour force grows less quickly than the warranted rate of growth, there will be a shortage of labour.

This rule holds as long as there is no labour-saving technical development. If there is Harrod neutral technical change, then productivity per unit labour will grow each year, say x %. In that case, if there is a situation of full employment, then to maintain it, the labour force has to grow each year by the warranted rate of growth minus x %. In other words, in equilibrium:

$$(11) \qquad \frac{\sigma}{\kappa} = \pi + \rho .$$

Equation (11) shows that, in equilibrium, the warranted rate of growth (σ/κ) must equal the growth of the population (π) plus the growth of the productivity of labour (ρ). The rate $\pi + \rho$ is called the natural rate of growth[2]. In the Harrod-Domar model, the gaining of growth equilibrium, which means a state of steady growth together with full employment, is just a matter of luck; there is no mechanism to restore the equilibrium if it is broken. This is the first cause of instability in the Harrod-Domar model. The second cause arises when the production capacity does not equal production. In that case, the expected rate of growth does not equal the warranted rate of growth and this will cause an unstable development of production.

Finally, in the question of the income distribution, the ratio total wages to total income (λ) is:

$$(12) \qquad \lambda = \frac{p_l \cdot l}{p \cdot y} .$$

In equation (12), p_l represents the nominal wage level, p the general price level, l the employment, which is assumed to be equal to the labour force, and y real national income. The real wage level is equal to p_l/p and l/y is equal to the labour output ratio, which is the reciprocal of the average productivity of labour. If the average productivity per unit of labour is represented by y/l and real wage by w, equation (12) can be rewritten as:

$$(13) \qquad \lambda = \frac{w}{(y/l)}.$$

Equation (13) rewritten in growth rates gives:

$$(14) \qquad \bar{\lambda} = \bar{w} - (\bar{y} - \bar{l}).$$

This result means that the income distribution remains unchanged $(\bar{\lambda} = 0)$ if real wage $(\bar{w})$ increases by the same percentage as the rise in average productivity of labour $(\bar{y} - \bar{l})$.

Of course, this brief description only deals with the essential part of the Harrod-Domar growth model. More information about this model can be found in the literature (for example Krelle (1987)). In the next section I look at the incorporation of the use of an exhaustible resource into the Harrod-Domar growth model.

Harrod-Domar growth model and an exhaustible resource

Suppose an economy has at its disposal one exhaustible resource. The question to be answered is whether steady growth is possible for an infinite time. At first glance, this question makes no sense since there is an exhaustible resource at stake. This means that the resource cannot renew itself, so that any use of it leads to a decrease of the total stock. However, there is a way out of this dilemma.

The depletion rate of total stock of the exhaustible resource $(\bar{n}_e)$ per period equals the use of the resource (g_e), which is a flow, divided by total stock at the beginning of the period (n_e):

$$(15) \qquad \bar{n}_e = \frac{-g_e}{n_e}.$$

From equation (15) it follows:

$$(16) \qquad \bar{\bar{n}}_e = \bar{g}_e - \bar{n}_e.$$

From equation (16) it can be concluded that the relative change of the depletion rate $\bar{\bar{n}}_e$ will equal 0 if the growth rate of the use of the resource $(\bar{g}_e)$ equals the depletion rate $(\bar{n}_e)$. This means, of course, a steady depletion of the resource stock. Indeed, this is not a stable relation, so that there is no mechanism to restore steady depletion if $\bar{g}_e \neq \bar{n}_e$ (see Appendix 6.1).

Since, according to equation (15), the rate of depletion is negative, it has to be concluded that to reach an infinite time period of using the resource, the growth rate of the use of the resource must also be negative. The reason for this is simply that if a stock of an exhaustible resource decreases during each period by the same percentage, total stock will approach zero when time approaches infinity. This result implies that, if a constant amount of the resource (μ) is needed per unit of product and if the resource is to be used over an infinite time, total production (y) must decrease during each period by the same percentage as the use of the resource. Put in another way:

$$(17) \qquad g_e = \mu \cdot y$$

$$\bar{g}_e = \bar{\mu} + \bar{y}.$$

If $\bar{\mu}$ equals 0, which is the case if a constant amount of the resource is needed per unit product, it follows from equation (17):

$$(18) \qquad \bar{y} = \bar{g}_e.$$

From equation (17) it can also be concluded that a steady depletion of the resource stock can be combined with a growing production if $\bar{\mu}$ is negative and $|\bar{\mu}| > |\bar{y}|$. This implies that it is possible to have a steady depletion of the resource combined with a growing production if the relative decrease in the resource use per unit of product exceeds the growth of production. If production, together with capital, investment and consumption grow each year according by the warranted rate of growth (σ/κ), and if there is a steady depletion of the resource stock $(\bar{g}_e = \bar{n}_e)$, then the necessary annual relative decrease in resource use per unit product can be derived from equation (17):

(19) $\bar{\mu} = \bar{n}_e - \frac{\sigma}{\kappa}.$

The income distribution must now be examined. According to Solow:

> The only way that a resource deposited in the ground and left in the ground can produce a current return for its owner is by appreciating in value (Solow, 1974b, p. 2).

In equilibrium, the price of the exhaustible resource must rise by the interest rate. The question still to be answered is whether this equilibrium is stable or not. Solow thinks it is not:

> If the net price were to rise too slowly, production would be pushed nearer in time and the resource would be exhausted quickly, precisely because no one would wish to hold resources in the ground and earn less than the going rate of return. If the net price were to rise too fast, resource deposits would be an excellent way to hold wealth, and owners would delay production while they enjoyed supernormal capital gains (Solow, 1974b, p. 3).

This attitude of the resource owner in a market of perfect competition seems rather doubtful to me. With prices rising faster than interest rate, owners must have some notion that rise in prices will slow down in the future. Besides, capital gain cannot be converted into money if the resource is not exploited. In the opposite case, prices rise too slowly. In this case, the owner must have some notion that in future the rise in prices will be more quick, and this should encourage him not to exhaust the resource too quickly. Moreover, if there is a futures market for the resource, the equilibrium can be stabilized. If prices rise faster than the rate of interest, then the supply for the future market will increase and the supply for the spot market will decrease. In the end, this will restore the equilibrium. If prices rise too slowly, supply for the future market will decrease and supply for the spot market will increase up to the equilibrium prices. The conclusion must be that the equilibrium is stable, not unstable.

Now, suppose that the proportion of the national income going to royalties is represented by ζ. Then, with p_n representing real royalty per unit:

(20) $\zeta = \frac{p_n \cdot g_e}{y}$

$\bar{\zeta} = \bar{p}_n + \bar{g}_e - \bar{y}.$

If the royalty share is to be constant, while $\bar{p}_n$ is equal to the interest rate υ and $\bar{g}_e = \bar{y} + \bar{\mu}$, equation (20) can be rewritten as:

$$(21) \qquad \upsilon = -\bar{\mu}.$$

This outcome means that, if the interest rate equals the yearly relative decrease in resource use per unit product, then there will be a steady growth together with a steady depletion of the non-renewable resource. What will happen to the resource stock if the rate of interest rises while a steady growth path is maintained? From equations (19) and (21) the following conclusion can be drawn:

$$(22) \qquad \bar{n}_e = \frac{\sigma}{\kappa} - \upsilon \qquad (\upsilon > \sigma/\kappa).$$

The resource stock decreases proportionately at a more rapid pace as the rate of interest rises. This conclusion agrees with the conclusion reached by Hotelling in 1931.

Harrod-Domar growth model and a renewable resource

If a renewable resource is growing at rate α, an appreciation in value is not the only source of a current return for its owner. Indeed, the renewal rate of the stock as a return to the owner of the stock should also be taken into consideration. The rate of depletion can then be written as:

$$(23) \qquad \bar{n}_r = \alpha - \frac{\mu \cdot y}{n_r}.$$

In this case, instead of a steady depletion, a sustainable depletion of the renewable resource must be aimed at. This means that the annual use of the renewable resource is exactly the same as the production of nature. This implies that, in equilibrium, $\bar{n}_r$ must be zero, while α is constant. This means that:

$$(24) \qquad \alpha = \frac{\mu \cdot y}{n_r}$$

$$\bar{y} = -\bar{\mu}.$$

Since the renewal rate of the renewable resource has to be considered as part of the return for the owner, the price of the renewable resource in equilibrium must increase each year by the difference between the rate of interest and the rate of renewal (see Chapter 5). This can be seen in the income distribution, which is considered to be constant on the steady growth path:

$$(25) \qquad \zeta = \frac{p_R \cdot \mu \cdot y}{y}$$

$$\bar{p}_R + \bar{\mu} + \bar{y} - \bar{y} = 0$$

$$\upsilon - a + \bar{\mu} = 0$$

$$\upsilon = a - \bar{\mu}.$$

Equation (25) describes a necessary condition for a steady growth path. This necessary condition is also a sufficient condition for the sustainable depletion of a renewable resource. This can be proved with the help of equation (15) from Chapter 5 $(a = \psi - \phi \cdot n_r)$ as it is then possible to determine the equilibrium renewable resource stock:

$$(26) \qquad n_r{*} = \frac{\psi - \bar{\mu} - \upsilon}{\phi}.$$

This solution can be illustrated with the help of Figure 6.1. which shows both $a - \bar{\mu}$ and a hypothetical rate of interest as functions of the total stock. Since $\bar{\mu}$ is supposed to be a constant, the former looks the same as the function of the renewal rate in Figure 5.1. Figure 6.1 makes it clear that there is only one n_r $(n_r{*})$ which agrees with equation (25). This means that, in a steady growth path, the stock of the renewable resource must be a constant, thus being used in a sustainable way $(\bar{y} = -\bar{\mu})$. Figure 6.1 also shows that the stock of the renewable resource will be larger in accordance with how much smaller the rate of interest is and the extensiveness of the nature-sparing technical change, which means the relative decrease in resource use per unit product $(\bar{\mu})$.

Neoclassical growth model

In the post-Keynesian Harrod-Domar growth model discussed in the previous section,

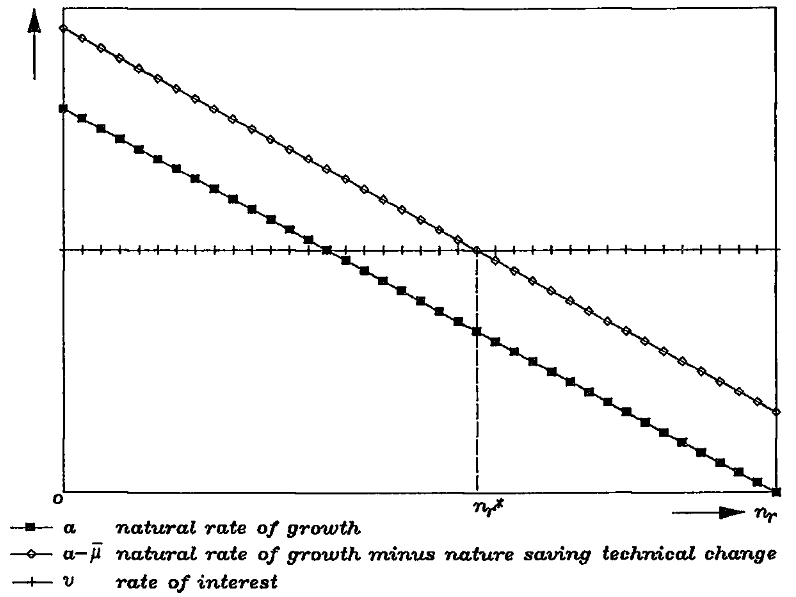

Figure 6.1: Equilibrium in the Harrod-Domar case of a renewable resource.

full employment is not attained automatically. Starting from a situation of full employment, if supply of labour grows faster than production minus labour-saving technical change, then unemployment begins. Since prices are fixed, the only way the government can attain full employment is by manipulating the effective demand. Thus steady growth in the Harrod-Domar growth model is not a sufficient condition for the growth equilibrium since full employment is not guaranteed.

In contrast to the Harrod-Domar model, the neoclassical growth model, developed mainly by Solow (1956), assumes that the price mechanism will clear all markets including the labour market. This means that in this model there is no room for unemployment and thus there is no role for government to play, since the price mechanism is supposed to function well. In the Harrod-Domar model, the question to be answered was under what conditions there would be a growth equilibrium. It appeared that there could be a steady growth maintaining full employment, although there seemed to be two causes for instability. The expected rate of growth might not equal the warranted rate of growth and the warranted rate of growth might not equal the natural rate of growth. This model has no mechanism to restore the growth equilibrium once it is disturbed. However, in the neoclassical growth model, there is full employment by definition, so the only questions left to be answered are whether there will be a steady growth path and by what circumstances this growth path will be determined.

Another difference between the Harrod-Domar growth model and the neoclassical growth model is the explicit presence in the latter of a production function with substitution possibilities. To show the consequences of this, I have used a Cobb-Douglas production function, which allows production factors to be substituted for each other with a substitution elasticity of 1. In general terms, a Cobb-Douglas production function presents a specified relation between the output or production (y) and the input or the production factors labour (l) and capital (k). Written in an equation $(\alpha$ and δ being parameters):

$$(27) \qquad y = \alpha \cdot l^{\delta} \cdot k^{1-\delta}.$$

The specific form of this production function implies that there are no economies of scale. It can be proved that, in this case, the marginal productivity theory gives a complete solution for the distribution of income (or production) assuming that the market form is characterized by perfect competition. Assuming only Harrod neutral technical change equation (27) written in growth rates gives:

$$(28) \qquad \bar{y} = \bar{\alpha} + \delta \cdot \bar{l} + (1 - \delta) \cdot \bar{k}.$$

The growth rate of capital equals net investment (i) divided by the stock of capital. Since investment is supposed to be a constant fraction (σ) of production, the growth rate of capital can be written as:

$$(29) \qquad \bar{k} = \frac{\sigma \cdot y}{k}.$$

The double growth rate of capital equals:

$$(30) \qquad \bar{\bar{k}} = \bar{y} - \bar{k}.$$

This result implies that, in the model, there is a mechanism working towards a constant capital output ratio. During this adaptation process, the capital output ratio is variable. If income grows faster than capital, the double growth rate of capital is positive, which means that the growth rate of capital is increasing. So, in equilibrium, the growth rate of income equals the growth rate of capital, the growth rate of investment and, since consumption also is a constant fraction of production $(1 - \sigma)$, the growth rate of consumption. Written in another way:

$$(31) \qquad \bar{y} = \bar{k} = \bar{i} = \bar{c} = \frac{\sigma}{\kappa}.$$

It can be concluded that, in the neoclassical model, a steady state growth is automatically maintained by the price mechanism and the variable capital-output ratio. Therefore, the two causes of instability in the Harrod-Domar model are absent in the neoclassical model. Assuming that an equilibrium $\bar{y}$ can be substituted for $\bar{k}$ in equation (28), then the following result can be reached:

$$(32) \qquad \bar{y} = \frac{\bar{\alpha}}{\delta} + \bar{l}.$$

$\bar{\alpha}$ as well as $\bar{l}$ are exogenous and $\bar{\alpha}$ is a measure for the technical development. This type of technical change is called Harrod neutral technical change. $\bar{\alpha}/\delta$ equals ρ, while $\bar{l}$ equals π. This means that, in equilibrium, production will grow by the natural rate of growth. In this case, the Harrod neutral technical change is a purely labour-saving type of technical change. It is remarkable that in this model the permanent rate of growth of output per unit of labour input depends entirely on the rate of technological progress and is totally independent of the savings (investment) rate (Solow, 1988, p. 309).

Turning to income distribution, it is possible to define the wage share and the profit share as follows (with w for real wage and υ for real interest) and, further, ϵ for the labour output ratio:

$$(33) \qquad \lambda = \frac{w \cdot l}{y}, \qquad 1 - \lambda = \frac{\upsilon \cdot k}{y} \quad \rightarrow$$

$$\lambda = \epsilon \cdot w, \qquad 1 - \lambda = \upsilon \cdot \kappa.$$

The level of wages and interest are determined by marginal productivity of labour and capital:

$$(34) \qquad \frac{\partial y}{\partial l} = w, \qquad \frac{\partial y}{\partial k} = \upsilon.$$

Equation (34) can be rewritten as:

$$(35) \qquad \frac{l}{y} \cdot \frac{\partial y}{\partial l} = \lambda, \qquad \frac{k}{y} \cdot \frac{\partial y}{\partial k} = 1 - \lambda.$$

Using equation (27) to determine the partial derivatives, equation (35) can be rewritten as

$$(36) \qquad \lambda = \delta, \qquad 1 - \lambda = 1 - \delta.$$

From equations (32) and (36) it can be concluded that the rise in average productivity of labour during the growth process $(\bar{y} - \bar{l})$ equals the percentage technical change divided by the wage share.

Since there is only Harrod neutral technical change in the neoclassical growth model, which means that δ is a constant, it can be concluded from equation (36) that during the process of steady growth there will be no change in the income distribution (λ is a constant).

Phelps (1961) introduced *the golden rule of accumulation* into this model. According to this rule, maximizing annual consumption per unit labour in a boundless golden age, capital accumulates optimally when the rate of interest multiplied by the capital output ratio $(\upsilon \cdot \kappa)$ equals the rate of investments (σ)[3]. Because $\upsilon \cdot \kappa$ equals $1 - \delta$ it can be stated that, according to the golden rule of accumulation, $1 - \delta = \sigma$.

After this brief description of the neoclassical growth model with two production factors, it can be concluded that the neoclassical growth model provides a stable and steady growth together with full employment, and this implies a growth equilibrium. In the next section a third production factor, a non-renewable resource, is introduced into the production function.

Exhaustible resource in a neoclassical growth model

An efficient depletion means that interest rate has to equal the proportional rise in royalty. Formerly, this rule was called the Hotelling efficiency rule. Since in the neoclassical growth model the price of the natural resource (p_n) equals its marginal product $\partial y/\partial g_e$, then:

$$(37) \qquad \frac{\partial y}{\partial k} = \overline{\frac{\partial y}{\partial g_e}} = \upsilon = \overline{p}_n.$$

Put like this, the rule is called the Solow-Stiglitz efficiency rule (van de Klundert et. al., 1983).

Introducing an exhaustible resource in the neoclassical growth model means that the number of production factors in the production function is expanded by one, that is, by the amount of exhaustible resource which is used in the production process. This flow is referred to as g_e. The production function can now be formulated as follows:

$$(38) \qquad y = y(l, k, g_e).$$

Specified as a linearly homogenous Cobb-Douglas production function, it can be formulated in the following way:

$$(39) \qquad y = \alpha \cdot l^{\delta} \cdot k^{\beta} \cdot g_e^{1-\delta-\beta}.$$

Equation (39) rewritten in growth rates gives:

$$(40) \qquad \overline{y} = \overline{\alpha} + \delta \cdot \overline{l} + \beta \cdot \overline{k} + (1 - \delta - \beta) \cdot \overline{g}_e.$$

Assuming that the capital output ratio and the labour output ratio are constant $(\overline{y} = \overline{l},\ \ \overline{y} = \overline{k})$, this implies that the production grows according to a steady growth path and that the Harrod neutral technical change is purely resource saving. In this case equation (40) can be rewritten as:

$$(41) \qquad \overline{g}_e = \overline{y} - \frac{\overline{\alpha}}{1 - \delta - \beta}.$$

The depletion rate of the non-renewable resource $(\bar{n}_e)$ equals $-g_e/n_e$. From this the double depletion rate $(\bar{\bar{n}}_e)$ can be calculated as:

$$(42) \qquad \bar{\bar{n}}_e = \bar{g}_e - \bar{n}_e.$$

It can be concluded from equation (42) that, in equilibrium, $\bar{g}_e = \bar{n}_e$ and that, in disequilibrium, there is no mechanism working to equilibrium. This means that the equilibrium is unstable (see Appendix 6.1). On a steady growth path, the royalty share in income must be stable. This implies that:

$$(43) \qquad \upsilon + \bar{g}_e - \bar{y} = 0$$

$$\bar{g}_e = \bar{y} - \upsilon.$$

From equations (41) and (43) it follows:

$$(44) \qquad \upsilon = \frac{\bar{\alpha}}{1 - \delta - \beta}.$$

The conclusion from equation (44) is that for both a steady depletion and a steady growth the rate of interest must equal the perunage technical change divided by the production elasticity of the exhaustible resource, which is equal to the royalty share.

If a steady depletion of the resource stock is assumed, then from equations (41), (42) and (44) the conclusion is:

$$(45) \qquad \bar{n}_e = \frac{\sigma}{\kappa} - \upsilon.$$

This implies that, on a steady growth path which is combined with a steady depletion of the resource stock, the depletion rate of the stock depends on the rate of interest, and also that the interest must depend on the resource-saving technological change. The overall conclusion is that a steady depletion together with a steady growth path is also possible within the neoclassical growth model.

The possibility of a steady growth path together with a steady depletion of the exhaustible resources does not guarantee that this path will be followed. In this respect, the social rate of time preference plays a critical role. Dasgupta and Heal (1974) and Solow (1974b) argued that, even when technology permits a plateau level of consumption per head or even a rising standard of living, positive social time preference can result in consumption per head going asymptotically to zero, leading society to prefer eventual extinction.

Renewable resource in the neoclassical growth model

If a renewable resource rather than an exhaustible resource is introduced, the production function can be represented as follows:

$$(46) \qquad y = y(k, l, g_r).$$

The production function is specified as a linearly homogenous Cobb-Douglas production function:

$$(47) \qquad y = \alpha \cdot l^{\delta} \cdot k^{\beta} \cdot g_r^{1-\delta-\beta}.$$

Equation (47) can be rewritten in growth rates as follows:

$$(48) \qquad \bar{y} = \bar{\alpha} + \delta \cdot \bar{l} + \beta \cdot \bar{k} + (1 - \delta - \beta) \cdot \bar{g}_r.$$

Assuming a steady growth process with constant capital output and labour output ratio's equation (48) can be rewritten as

$$(49) \qquad \bar{y} = \bar{g}_r + \frac{\bar{\alpha}}{1 - \delta - \beta}.$$

With a renewable resource, the question is whether a sustainable depletion is possible. There is a sustainable depletion when human use of the renewable resource (g_r/n) equals production of nature (α), and further, when the growth of human use equals zero $(\bar{g}_r = 0)$. This assumptions combined with equation (49) give:

(50) $$\bar{y} = \frac{\bar{\alpha}}{1 - \delta - \beta}.$$

From equation (50), the conclusion is that a steady growth depends completely on the resource saving technical change. On the other hand, an economy without resource-saving technical change completely depending on a renewable resource can be sustainable if the population growth equals zero.

In equilibrium, the rise of royalty has to equal interest minus the natural renewal rate, while the royalty share is constant. This gives equation (51):

(51) $$\upsilon - a - \bar{y} = 0.$$

From equations (50) and (51), the rate of interest follows:

(52) $$\upsilon = \frac{\bar{\alpha}}{1 - \delta - \beta} + a.$$

According to equation (15) from Chapter 5, the renewal rate of the renewable resource (a) is a linear decreasing function of total stock: $a = \psi - \phi \cdot n_r$. After having substituted this expression for a in equation (52), the equilibrium renewable resource stock is found:

(53) $$n_r{}^* = \frac{\bar{\alpha}}{(1 - \delta - \beta) \cdot \phi} + \frac{\psi}{\phi} - \frac{\upsilon}{\phi}.$$

In Figure 6.2, the rate of interest and $\bar{\alpha}/(1 - \delta - \beta) + a$ are presented as functions of total stock.

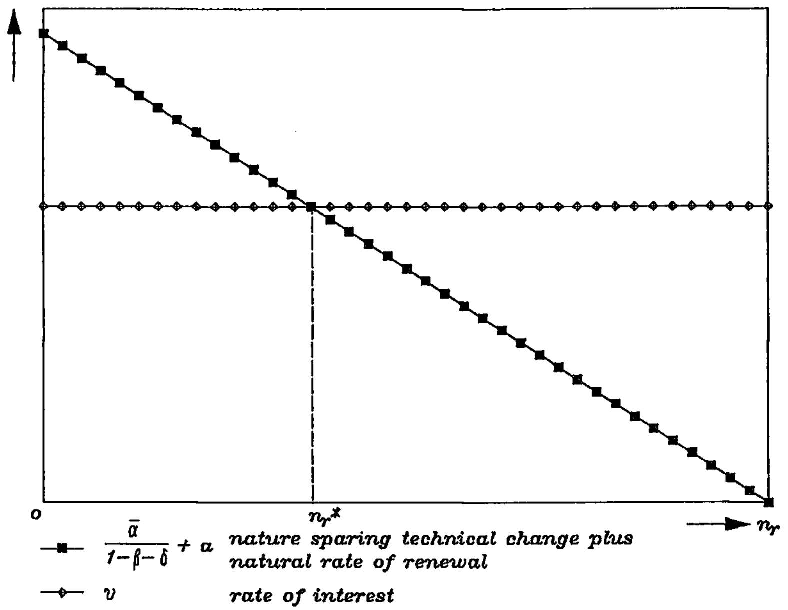

Figure 6.2: The rate of interest, the renewal rate and resource saving technical change in the neoclassical growth model.

It can be concluded from Figure 6.2 that, for steady growth, the total stock should be constant $(n_r{*})$, which means that $\bar{g}_r$ equals zero. From this it follows that a steady growth path implies a sustainable use of the renewable resource. Or, formulated a little differently, a sustainable use of the renewable resource is a necessary condition for steady growth. Another conclusion is that total stock (n_r) in a state of steady growth will decrease as the rate of interest increases. Again, in this case, it should be noticed that the possibility of sustainable use together with a state of steady growth does not guarantee that society will follow such a path. Also the social rate of time preference appears to be crucial.

Simultaneous use of exhaustible and renewable resources

For this there are four production factors: labour, capital, an exhaustible resource and a renewable resource. The production function can now be written as follows:

(54) $y = y(l, k, g_e, g_r)$.

This production function specified as a Cobb-Douglas production function gives

(55) $y = \alpha \cdot l^{\delta} \cdot k^{\beta} \cdot g_e^{\gamma} \cdot g_r^{(1-\delta-\beta-\gamma)}$.

If a steady growth is assumed, then both capital output ratio and labour output ratio are constant. In that case, equation (55) can be rewritten in growth rates as follows:

(56) $$\bar{y} = \frac{\bar{\alpha}}{1-\beta-\gamma} + \frac{\delta}{1-\beta-\gamma} \cdot \bar{g}_e + \frac{1-\beta-\gamma-\delta}{1-\beta-\gamma} \cdot \bar{g}_r.$$

Since during steady growth path, royalty shares are supposed to be constant, then:

(57) $$\bar{g}_e + \upsilon - \bar{y} = 0$$

$$\bar{g}_r + \upsilon - a - \bar{y} = 0,$$

So:

(58) $$\bar{g}_r = \bar{g}_e + a.$$

This can also be shown through the substitution elasticity (η_s), which is equal to 1:

(59) $$\eta_s = \frac{\bar{g}_e - \bar{g}_r}{\upsilon - a - \upsilon} = 1$$

$$\bar{g}_r = \bar{g}_e + a.$$

Equations (57) and (58) substituted in equation (56) give:

(60) $$\upsilon = \frac{\bar{\alpha}}{1-\beta-\gamma} + \frac{1-\beta-\gamma-\delta}{1-\beta-\gamma} \cdot a.$$

Equation (60) implies that in an economy with both renewable and exhaustible resources there can be a state of steady growth and a steady depletion of the exhaustible resource. Further, it proves that in this situation there can be a positive rate of interest even without resource-saving technical change.

A state of steady growth and a steady depletion of the exhaustible resource do not imply a sustainable use of the renewable resource. A necessary condition for sustainable growth is a constant use of the renewable resource ($\bar{g}_r = 0$). It can be concluded from equation (58) then that $\bar{g}_e = -a$. This implies an expression for the growth rate of net production which is different from equation (56):

$$(61) \qquad \bar{y} = \frac{\bar{\alpha}}{1-\beta-\delta} - \frac{\delta}{1-\beta-\delta} \cdot a.$$

From equation (61) it can be concluded that, in an economy depending on exhaustible and renewable resources and fixed capital output and labour output ratios, resource-saving technical change is indispensable even in a non-growth situation. In that case, $\bar{\alpha}$ must be equal to $\delta \cdot a$.

Since a is a decreasing function of n_r, there are now two consequences of a moderate rate of interest. In the first place, the renewable resource stock will remain relatively large and, in the second place, the depletion rate of the exhaustible resource will be relatively low. The first part of the conclusion can be verified with the help of equation (15) from Chapter 5 and equation (60) from this chapter:

$$(62) \qquad \upsilon = \frac{\bar{\alpha}}{1-\beta-\gamma} + \frac{1-\beta-\gamma-\delta}{1-\beta-\gamma} \cdot a,$$

$$a = \psi - \phi \cdot n_r, \quad \text{so:}$$

$$n_r = \frac{\bar{\alpha}}{\phi \cdot (1-\beta-\gamma-\delta)} + \frac{\psi}{\phi} - \frac{1-\beta-\gamma}{\phi \cdot (1-\beta-\gamma-\delta)} \cdot \upsilon.$$

As can be seen from equation (62), the renewable resource stock will decrease if there is an increase of the rate of interest.

Technical change, factor substitution and recycling

Technical change is an important phenomenon in economic growth. In fact, Malthusian pessimism about the fast decline of humanity was already being tempered by John Stuart Mill in his *Principles of Political Economy*. According to Mill, because of "the progress of civilization", by which he meant the progress of knowledge, skill and invention, the tendency of the cost of production to rise when labour increases because of a growing population can be stopped (Mill, 1973, p. 183). History has shown that, at least for the developed countries in the twentieth century, Mill was right. Gross output per hour of work in the United States doubled between 1909 and 1949. Some seven eighths of that increase can be attributed to technical change, only the remaining eighth being attributable to conventional increase in capital intensity (Solow, 1988, p. 313).

Another important aspect of growth theory concerns the embodiment of technical change. In growth theories, only the Harrod neutral type of technological change is dealt with, although a really convincing empirical justification of the assumption of Harrod neutrality does not seem to exist (Sen, 1971, p. 22). Indeed, when using a Cobb-Douglas production function, it does not matter what kind of neutrality is assumed (another type of neutral technical change would be Hicks neutral technical change) since the different types of neutral technical change coincide. Solow reported on an experiment carried out by Wolff (1987), who compiled data for seven large countries (Canada, France, Germany, Italy, Japan, United Kingdom, and United States). This experiment provides rather strong evidence for the embodiment of technical change. Comparing the data of these countries, Wolff found a strong positive correlation between the rate of technical progress and the rate of investment. On the other hand, Denison came to the conclusion that embodiment does not explain a great deal of the technical change, which contradicts to this result (Solow, 1988, p. 315). Consequently it is not certain whether the assumption of Harrod neutral technical change is a realistic one.

Resource-saving technical change is a major force working on the speed of extraction. An advantage of the two growth models dealt with is that resource-saving technical change can be modelled relatively easily as an exogenous development. The question is whether the assumption of resource-saving technical change is a realistic one. In terms of energy use, it certainly is. According to the World Commission on Environment and Development, by using the most energy-efficient technologies and processes now available, in the near future (say the next 30 or 40 years) a 50% fall per capita energy consumption in industrial countries and a 30% increase in developing countries can be reached while still maintaining an annual global growth rate of the Gross Domestic Product of around 3%. The problem here, of course, is the implementation of the highly energy-efficient technology, which would require no less than an energy efficiency revolution during which the inventions would be translated into innovations (WCED, 1987, pp. 171-173). The commission concluded rightly that the carrying out of such a revolution is a matter of fundamental political and institutional changes.

As regards renewable resources, there is a growing scientific consensus that species are disappearing at rates never before witnessed on this planet. For example, the Pantanal area of Brazil, which contains 110,000 square kilometres of wetlands supporting the largest and most diversified populations of water fowl in South America and which is classified by UNESCO as 'of international importance', is now being threatened by agricultural expansion (WCED, 1987, pp. 148-149). Another major global danger is deforestation. In 1975, 32% of the total global surface was covered by forest. If no proper measures are taken, this percentage will have dropped to 26.5 % by the year 2075. This will bring about serious problems for people directly dependant on the forest for their energy supply. Moreover, it will also bring about a degradation of land by water and wind erosion. Deforestation might even effect the global climate (RIVM, 1988). One way to conserve the forest is to increase the efficiency of the use of wood by introducing adapted technology in countries facing a shortage. In this respect, the newly introduced use of stoves for cooking in vulnerable regions of Africa to replace open fire can be regarded as a major technological improvement.

The growth models showed that positive interest rates need not be incompatible with a steady depletion of the exhaustible resource and a sustainable use of the renewable resources because of the rate of renewal of the renewable resource, the resource-saving technical change and the substitution between exhaustible and renewable resources. If we look at the case of zero technical change, it is clear that to reach a steady depletion of the exhaustible resources with fixed capital output and labour output ratios, total income will have to decrease. This means that, for the income per capita to be constant, a steady decrease of the population has to be maintained. If this were to be impossible, then for exhaustible resources, doomsday would be unavoidable. However, as has already been indicated, zero technical change is only an assumption and not a realistic one. At any rate, the conclusion must be that, for exhaustible resources, a steady depletion of the resources, combined with a constant or even rising income level, constant capital output and labour output ratios can only be achieved with resource-saving technical innovations. Also, to gain a rising consumption per capita, the percentage of technical change has to exceed the growth of population (Stiglitz, 1974b, p. 128).

Another way of dealing with the exhaustion of resources is to invest part of it in capital goods so as to provide a future substitute for these resources. In that case, the assumption of a fixed capital output ratio would be dropped. It can even be proved that, with a constant population, with no technical change and with zero production growth, it is possible to maintain a stationary economy if the marginal propensity to save (σ) equals the production elasticity of the exhaustible resource (see Chapter 3).

A perfect substitute for depleted resources is called a *backstop technology*. An example of such a backstop technology is fusion power. We could even consider the amounts of non-renewable resources as a means to gain time to develop an appropriate backstop technology. Once this has been done, all problems concerning the exhaustion of non-renewable resources can be solved. However, it must be admitted that the invention of such a technology is also an assumption, and perhaps an overoptimistic one.

I want to conclude this section with some remarks about recycling. Most economists rightly think of depletable resources as capital assets to society. However, more should be said about the nature of these capital assets. The difference between exhaustible and renewable resources has already been dealt with extensively. Depletable resources can also be divided into recycleable and non-recycleable resources (Solow, 1974b). An example of a recycleable resource is copper, an example of a non-recycleable resource is oil[4]).

There are three advantages of recycling and re-use techniques. Firstly, large energy savings in cases where the waste or scrap can be used as fuel or can provide raw material at a lower cost than the primary source; secondly, recycling decreases the need for all kinds of ore; thirdly, it has a favourable impact on the environmental quality since it helps to reduce the need for extraction from increasingly poor grade ore and since, in most cases, the recycling process itself scarcely pollutes the natural environment (Potier, 1977, p. 345). Of course, because of the second law of thermodynamics, account has to be taken of a leakage in every round of recycling (Pearce et al., 1990). This means:

> .... that we will never recover a whole pound of secondary copper from a pound of primary copper in use, or a pound of tertiary copper from a pound of secondary copper in use...(Solow, 1974b, p. 2).

By using a multiplier formula the total possible use of copper out of the initial endowment of copper can be computed (see Appendix 6.2). Suppose that the annual leakage is ι, that the initial endowment of copper is S, and that the copper grade of the ore is represented by π, then the total use of copper out of the initial endowment will be $(\pi/\iota)\cdot S$, where total use out of the endowment of a non-recycleable resource is represented by $\pi\cdot S$. The conclusion must be that, compared to a non-recycleable resource, total use out of an endowment of a recycleable resource will be higher ceteris paribus, but that recycleable resources remain exhaustible, despite the possibility of recycling.

Concluding remarks

Hotelling's rule is to be considered as

> the fundamental principle of the economics of exhaustible resources (Solow, 1974b).

However, in Chapter 5, I had to amplify his rule had to be amplified with a rule for renewable resources. The main difference between the two rules is that, in equilibrium, prices of exhaustible resources must rise, while prices of renewable resources in the same situation remain constant. In this chapter, a positive answer has been found for the question of whether a state of steady growth can be combined with a steady depletion of exhaustible resources and a sustainable use of renewable resources. Critical variables in both the Harrod-Domar and the neoclassical model are the rate of technical change, the rate of interest and the substitution of exhaustible with renewable resources. The positive answer on the existential question, which is contrary to the pessimistic one found by Malthus and Meadows, does not guarantee that sustainable growth will be maintained; such a type of growth is a possibility but not a necessity. Whether a sustainable growth path is followed or not depends for a great deal on the political will of society and, combined with that, public opinion.

The theory presented in this chapter is a theory for the long run and is macro-economic in nature. Also uncertainty has not been explicitly taken into account. However, this aspect has been dealt with via a risk premium integrated into the rate of interest. In this case, the theory does not change. Indeed, there are other more important aspects of resource depletion to be studied. In the following chapter I examine the macro-economic aspects for the short run of resource depletion.

Appendix 6.1: Instability of the depletion rate of an exhaustible resource

To investigate stability properties, the following model was used:

$$n_t = n_{t-1} \cdot (1 + \bar{n}_t),$$

$$\bar{n}_t = \frac{g_{t-1}}{n_{t-1}},$$

$$g_t = g_{t-1} \cdot (1 + \bar{g}).$$

From these three equations it can be deduced (remember that $-1 < \bar{n}_0 < 0$, and $-1 < \bar{g} < 0$) that:

$$\bar{n}_t = \frac{1 + \bar{g}}{1 + \bar{n}_{t-1}} \cdot \bar{n}_{t-1}.$$

Now, it is easy to see that:

(a) if $\bar{g} = \bar{n}_0$, then $\bar{g} = \bar{n}_0 = \bar{n}_1 = \bar{n}_2 = \ldots$

(b) if $\bar{g} > \bar{n}_0$, then $\ldots \bar{n}_3 < \bar{n}_2 < \bar{n}_1 < \bar{n}_0$

(c) if $\bar{g} < \bar{n}_0$, then $\ldots \bar{n}_3 > \bar{n}_2 > \bar{n}_1 > \bar{n}_0$.

This means that $\lim_{t \to \infty} \bar{n}_t = \epsilon$ exists.

I shall prove now that:

(a') if $\bar{g} = \bar{n}_0$, then $\lim_{t \to \infty} \bar{n}_t = \bar{g}$.

(b') if $\bar{g} > \bar{n}_0$, then there exists a T such that $\bar{n}_T \leq -1$.

(c') if $\bar{g} < \bar{n}_0$, then $\lim_{t \to \infty} \bar{n}_t = 0$.

Because $\lim_{t \to \infty} \bar{n}_t = \epsilon$, it follows that:

$$\lim_{t\to\infty} \bar{n}_t = \lim_{t\to\infty} \frac{1+\bar{g}}{1+\bar{n}_{t-1}} \cdot \bar{n}_{t-1}.$$

From this it follows:

$$\epsilon = (1+\bar{g}) \cdot \frac{\epsilon}{(1+\epsilon)},$$

which gives:

$$\epsilon = \bar{g} \quad \text{or} \quad \epsilon = 0.$$

This proves (a') and (c'). (b') is true, because I know that $\bar{n}_t$ is decreasing, while there is no finite limit. Indeed, the only limits are $\bar{g}$ and 0.

For example, in period 0 a total stock of 100 is assumed, while in the same period the extraction is supposed to be equal to 10. From this it can be derived that $\bar{n}_0$ equals -0.10. Now three cases are evaluated: the cases of $\bar{g} = -0.1$, $\bar{g} = -0.12$ and $\bar{g} = -0.08$. The results of the computations are shown in Figure 6a.1.

It appears that steady depletion only appears when the relative change in the use of an exhaustible resource equals the initial user's fraction (g_0/n_0). In this case, the relative change has to equal -0.10 each period. When the relative change of the use of the resource does not equal this fraction, a steady depletion pattern will not emerge. This means that there is no mechanism to bring about this steady depletion pattern when $\bar{n}_t \neq \bar{g}_t$.

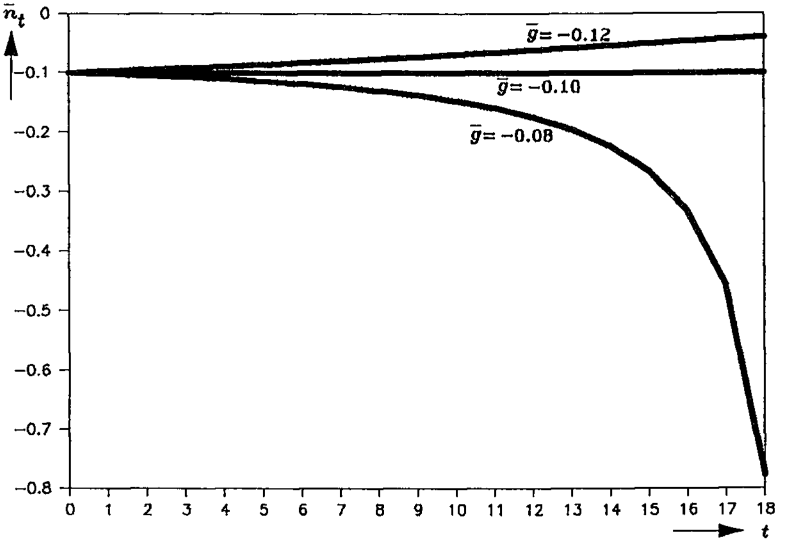

Figure 6a.1: The depletion rate of an exhaustible resource with different user's patterns.

Appendix 6.2: Recycling multiplier

Suppose there is a stock of ore (S). During each period (n), this stock is depleted by S_n. S_n is a fraction o_n of the inital stock of ore (S), so that:

(1) $$S_n = o_n \cdot S$$

and:

(2) $$\sum_{n=1}^{\omega} S_n = S,$$

in which ω denotes the number of periods during which the initial stock of ore is exhausted. From (1) and (2) it follows:

(3) $$\sum_{n=1}^{\omega} o_n = 1.$$

Now suppose that M represents the total generation of the raw material (for instance copper or iron) out of the initial stock of ore (S), and that M_n represents the generation of raw material out of one year's extraction of ore. Further, suppose that π represents the raw material-ore ratio (for instance the copper grade of the ore) and ι the fractional loss of iron when it is recycled. Then:

$$(4) \qquad M_n = \pi \cdot o_n \cdot S \cdot \{1 + (1-\iota) + (1-\iota)^2 + \ldots\}$$

$$M_n = \frac{1}{\iota} \cdot \pi \cdot o_n \cdot S.$$

Further it is known that:

$$(5) \qquad M = \sum_{n=1}^{\omega} M_n.$$

Equations (3), (4) and (5) give:

$$(6) \qquad M = \frac{\pi}{\iota} \cdot S.$$

So, the recycling multiplier equals π / ι.

Notes

1) If f is a function of time, than I define $\bar{f} = f'/f$, which is the relative growth speed.

2) This *natural rate of growth* is completely different from the physical concept *growth rate of nature*, which equals the growth rate of the total amount of biomass in the biosphere. In fact, the natural rate of growth postulates some kind of natural order in which the economy is to grow according to this growth rate. It seems to me that this natural order is some kind of relic from the era of the Enlightenment, during which time this type of thinking came into being.

3) This can be proved as follows. Assume the following linearly homogenous production function:

$$y = y(k, l) \qquad \frac{\partial y}{\partial k} > 0, \quad \frac{\partial y}{\partial l} > 0, \quad \frac{\partial^2 y}{\partial k^2} < 0, \quad \frac{\partial^2 y}{\partial l^2} < 0.$$

The relation between capital and investment, with l_p for labour potential, is:

$$\frac{\Delta k}{k} = \frac{i}{k} = \frac{\sigma \cdot y}{\kappa \cdot y}$$

$$i = \frac{\sigma}{\kappa} \cdot k$$

$$\frac{i}{l_p} = \frac{\sigma}{\kappa} \cdot \frac{k}{l_p} \quad \text{with} \quad l_p = l_0 \cdot e^{(\pi+\rho)\cdot t}.$$

If the consumption per unit labour potential is to be maximized for a given population, the function to be maximized can be formulated as follows:

$$\frac{c}{l_p}\left(\frac{k}{l_p}\right) = \frac{y}{l_p}\left(\frac{k}{l_p}\right) - \frac{i}{l_p}\left(\frac{k}{l_p}\right).$$

The first order condition for a maximum is:

$$\frac{d(c/l_p)}{d(k/l_p)} = \frac{d(y/l_p)}{d(k/l_p)} - \frac{d(i/l_p)}{d(k/l_p)} = 0$$

$$\frac{d(y/l_p)}{d(k/l_p)} = \frac{d(i/l_p)}{d(k/l_p)} = \frac{\sigma}{\kappa}.$$

Because $\frac{d(y/l_p)}{d(k/l_p)} = \upsilon$ it can be deduced that $\upsilon = \frac{\sigma}{\kappa}$.

This means that, for the specific case of the linearly homogenous Cobb Douglas production function of the main text, $\sigma = 1 - \delta$.

In equilibrium, σ / κ equals $\rho + \pi$. Because population increases by rate π, while production and consumption increase by $\rho + \pi$, consumption per capita will rise by rate ρ.

4) This distinction is based upon a technical concept of recycling. However, the possibility of recycling in the economic sense might be a feature of all resources, including energy resources. If, for instance, the recycling of a unit of output requires less energy than to produce a new unit, then, this is in fact caused by the recycling of the input of energy present in the old product (Robinson, 1989, p. 31).

7. Cycles in resource use

This chapter deals with three models. The first is the post-Keynesian multiplier accelerator model. Unlike the growth models discussed in the previous chapter, which deal only with the supply side of the economic process, this is a typical demand side dynamic macroeconomic model, which is used to explain the business cycle in resource depletion out of changes in the effective demand. The second model is the cobweb model, which can be used to explain the variation in the price level of resources. The third is a neoclassical model. This model is applied to the effects of a sudden increase in the price of oil on the economy of a small non-oil-producing country.

I. Multiplier accelerator model

The multiplier accelerator model was developed by Samuelson (1939) and Hicks (1951) to explain the trade cycle or business cycle (see also van Duijn, 1979). It is a typical demand side model in which production always follows the effective demand. This makes it an elaboration of the simple Keynesian multiplier model. It can be described as follows. Production (y_t), which, in a closed economy, is identical with income, equals consumption (c_t) plus investment (i_t):

(1) $$y_t = c_t + i_t.$$

Consumption is a linear function of income with a one period lag. With γ for the marginal propensity to consume and $\underline{c}$ for the autonomous part of consumption, this gives:

(2) $$c_t = \gamma \cdot y_{t-1} + \underline{c}.$$

In contrast to the simple Keynesian multiplier model, the investments in the multiplier accelerator model are induced. Samuelson assumed investments to be a lagged function of the change in consumption (see also Tinbergen, 1943, de Vries, 1989, p. 35 and Gabisch et al., 1989). However, investments itself are a part of production and in a simple one-good model there is no difference between investment goods and consumption goods. This makes it more plausible to assume investments to be a lagged function of income (Hicks, 1951, Kuipers, 1983)[1]. This leads to the following equation for investments:

(3) $$i_t = \alpha \cdot (y_{t-1} - y_{t-2}) + \underline{i}.$$

In equation (3) the induced net investment will be positive so long as income grows. This is plausible because a growing income needs a growing capital stock. The coefficient α is called the flexible accelerator[2]. If this flexible accelerator equals 0, what is left is the simple Keynesian multiplier model. The autonomous investment $(\underline{i})$ is explained by the *animal spirits* of the entrepreneurs.

Equations (1), (2) and (3) give the following difference equation of the second order:

(4) $$\alpha \cdot y_{t-2} - (\gamma + \alpha) \cdot y_{t-1} + y_t = \underline{c} + \underline{i}.$$

Equation (4) can be used to derive the equilibrium value for y (y^*):

(5) $$y^* = \frac{1}{(1-\gamma)} \cdot (\underline{c} + \underline{i}).$$

From equation (5) it can be concluded that the flexible accelerator does not influence the equilibrium value of production, which means that, even when the flexible accelerator does not equal 0, the equilibrium value of the production equals the multiplier $1/(1-\gamma)$ multiplied by the autonomous parts of consumption and investment $\underline{c} + \underline{i}$.

The questions left to be answered are whether the equilibrium is stable and whether there are oscillations. I call the equilibrium (y^*) stable if:

(6) $$\lim_{t \to \infty} |y_t - y^*| = 0 \qquad \text{for all solutions } y_t.$$

More generally, I call the difference equation stable if:

(7) $$\lim_{t \to \infty} |y_t - w_t| = 0 \qquad \text{for all solutions } y_t \text{ and } w_t.$$

In general, stability depends on the values of the coefficients γ and α. The equilibrium will be stable if the absolute value of the roots of the characteristic equation connected with the difference equation, $\lambda^2-(\gamma+\alpha)\cdot\lambda+\alpha=0$, λ_1 and λ_2, are both smaller than 1. This is the case if and only if $\alpha<1$ (Hicks, 1951).

Oscillations occur when the discriminant of the characteristic equation connected with the second order difference equation is less than 0, which means:

$$(8) \qquad (\gamma+\alpha)^2-4\cdot\alpha<0.$$

By putting the discriminant of the characteristic equation to 0, it is possible to show the border of the oscillations:

$$(9) \qquad (\gamma+\alpha)^2-4\cdot\alpha=0$$

$$\gamma=2\sqrt{\alpha}-\alpha.$$

This border is shown in Figure 7.1. Function $\alpha=1$ is also shown in the figure. As we also know that $0<\gamma<1$ and that $\alpha\geq 0$, it is possible to distinguish five areas. The results are summarized in Figure 7.1.

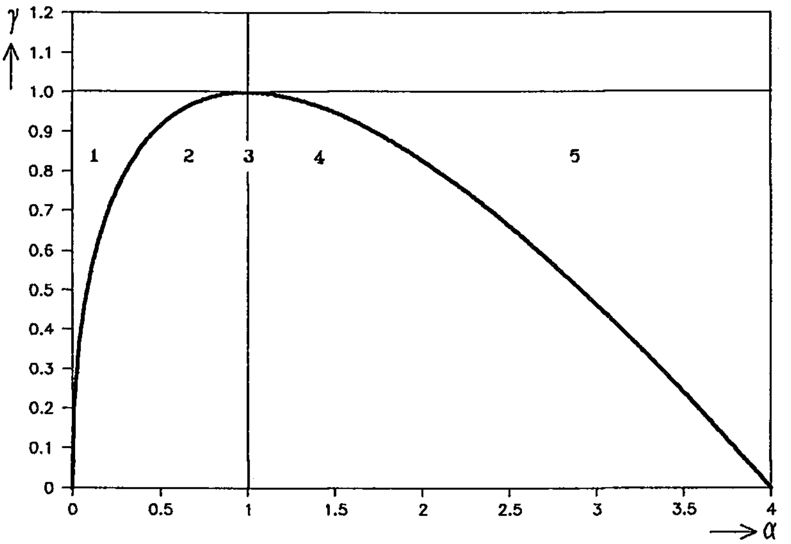

Figure 7.1: Possible values of γ and α.
Source: Kuipers et al., 1983, p. 29.

In Area 1 there is a stable equilibrium without oscillations and in area 2 a stable equilibrium with oscillations. In Area 3 (only a line) there are constant oscillations. In Area 4, the equilibrium is unstable with oscillations. Finally, in Area 5 there are no oscillations and the equilibrium is unstable. It can be concluded that the economy will develop more violently in proportion to the value of α, the flexible accelerator.

Resource in the multiplier accelerator model

To explain the cyclical pattern in the use of depletable resources, the multiplier accelerator model of the above section is extended by one equation in which the depletion of a resource (g_t) is expressed as a linear function of production:

(10) $g_t = \mu_t \cdot y_t$.

In equation (10), μ_t is the resource output ratio for a specific resource. For instance the resource output ratio for oil is determined in Table 7.1 for the years 1969-1986. Total world oil consumption is shown in Figure 7.2, while the estimated world resource output ratio for oil is shown as a graph in Figure 7.3. From this figure it can be concluded that the resource output ratio for oil is by no means fixed.

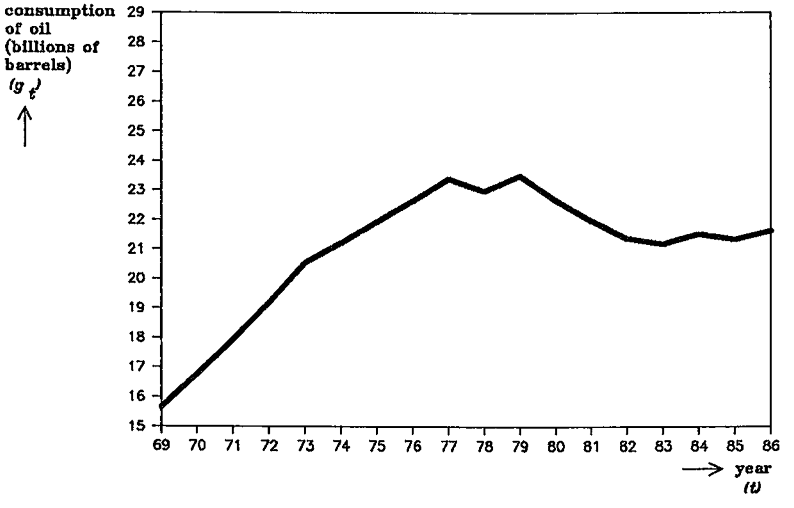

Figure 7.2: Total world oil consumption 1969-1986.

Table 7.1: World production, world oil consumption and the resource output ratio for oil.[a)]

Year	Estimated real world production (gnp) (billions of 1980 am. dollars) (a)	Estimated world oil consumption (billions of barrels[3)]) (b)	Estimated resource output ratio (barrels per am. dollar) (b)/(a)
1969	7864.125	15.67711	0.001993
1970	8202.282	16.77451	0.002045
1971	8554.980	17.94872	0.002098
1972	8922.845	19.20514	0.002152
1973	9306.527	20.54950	0.002208
1974	9706.708	21.22763	0.002186
1975	10124.090	21.92814	0.002165
1976	10559.430	22.65177	0.002145
1977	11013.480	23.39928	0.002124
1978	11487.060	22.99500	0.002001
1979	11877.620	23.50600	0.001979
1980	12127.050	22.66650	0.001869
1981	12345.340	21.97300	0.001779
1982	12419.410	21.38900	0.001722
1983	12742.320	21.20650	0.001664
1984	13302.980	21.53500	0.001618
1985	13715.370	21.35250	0.001556
1986	14113.120	21.64450	0.001553

Source: World Bank (1989, 1990), IMF (1982, 1986, 1987), adjusted.

a) Toman (1990) gives an amount of 22.8855 billions of barrels for 1987. This number is not included in the table because it is not certain whether it has been calculated in the same way as the other figures. Toman gives the following indication for the regional distribution of petroleum consumption in 1987: United States: 16.7%, Other North America: 3.0%, Central/South America: 3.6%, Western Europe/USSR: 10.8%, Middle East: 2.8%, Africa: 1.8%, Far East/Oceania: 11.4%.

From Table 7.1 and Figure 7.3 it can be concluded that between 1969 and 1986 the resource output ratio for oil varied between 0.0015 and 0.0022 and that it had been decreasing from 1973 on. Of course, it was the rise in oil prices in the seventies that must have played an important role in this development. Wahab (1990) investigated the relation between twelve important resources and manufacturing over the years 1974-1988. He concluded that production process is characterized by *dematerialisation*[4)]. This means that, because of resource-saving technological changes, the use of resources per unit product is decreasing and that only a relatively high economic growth can cause a rise in the total use of a specific resource.

Figure 7.3: The resource output ratio for oil.

The second order difference equation with a fixed resource output ratio can be rewritten in terms of resource use as:

$$(11) \qquad \alpha \cdot g_{t-2} - (\gamma + \alpha) \cdot g_{t-1} + g_t = \mu \cdot (\underline{c} + \underline{i}).$$

Of course, for this second order difference equation, stability and the oscillation pattern depend in the same way upon the coefficients as does production (see previous section). As we have seen, a fixed resource output ratio is not realistic. In the next section I attempt to overcome this difficulty.

Stability and the oscillation pattern for a resource difference equation of the second order, with variable coefficients

A more sophisticated way of analyzing the stability and oscillation pattern would be possible if one allows variable coefficients in the left side of the equation. Besides, a realistic approach also implies that the autonomous right side of the equation is also not constant. Although Samuelson referred to this refinement, but he did not elaborate any further. He said:

> Perfect periodic net government expenditure will result eventually in perfect periodic fluctuations in national income (Samuelson, 1939, p. 77).

The M-A model with variable coefficients can be written as follows:

$$(12)\qquad \begin{aligned} y_t &= c_t + i_t \\ c_t &= \gamma_{t-1} \cdot y_{t-1} + \underline{c}_t \\ i_t &= \alpha_{t-1} \cdot (y_{t-1} - y_{t-2}) + \underline{i}_t \\ g_t &= \mu_t \cdot y_t . \end{aligned}$$

Writing $\underline{c}_t + \underline{i}_t$ as $\underline{o}_t$, the first three equations of (12) gives:

$$(13)\qquad \alpha_{t-1} \cdot y_{t-2} - (\gamma_{t-1} + \alpha_{t-1}) \cdot y_{t-1} + y_t = \underline{o}_t .$$

Multiplying the left and the right sides of the equation by $\mu_t \cdot \mu_{t-1} \cdot \mu_{t-2}$ gives:

$$(14)\qquad \alpha_{t-1} \cdot \mu_{t-1} \cdot \mu_t \cdot g_{t-2} - (\gamma_{t-1} + \alpha_{t-1}) \cdot \mu_{t-2} \cdot \mu_t \cdot g_{t-1} + \mu_{t-2} \cdot \mu_{t-1} \cdot g_t = \mu_t \cdot \mu_{t-1} \cdot \mu_{t-2} \cdot \underline{o}_t .$$

What now needs to be answered is when the difference equation is stable and when it is not. Again, I call this type of difference equation stable if:

$$(15)\qquad \lim_{t \to \infty} |g_t - w_t| = 0 .$$

for all solutions g_t and w_t of the difference equation (14). Considering now q-periodic coefficients α_t and γ_t (i.e. $\alpha_{t+q} = \alpha_t$ and $\gamma_{t+q} = \gamma_t$) and resource output ratios of the form $\mu_{t+q} = x \cdot \mu_t$ (such coefficients are called floquetian coefficients), we can say that the the answer is positive, if and only if for the roots λ_1 and λ_2 of the characteristic equation:

$$(16)\qquad \lambda^2 - \left\{ \mathrm{Tr} \prod_{m=1}^{q} \begin{pmatrix} (\gamma_m + \alpha_m) \cdot \dfrac{\mu_{m+1}}{\mu_m} & -\alpha_m \cdot \dfrac{\mu_{m+1}}{\mu_{m-1}} \\ 1 & 0 \end{pmatrix} \right\} \cdot \lambda + x^2 \prod_{m=1}^{q} \alpha_m = 0$$

it is true that:

$$(17) \qquad |\lambda_1| < 1, \qquad |\lambda_2| < 1.$$

Moreover, if the roots of equation (16) are complex but not real, the homogenous equation of (16) will admit oscillatory solutions.

It can be proved that for a constant μ_t the difference equation is stable if all $\alpha_t < s$, for a certain s $(0 < s < 1)$.

Five cases

To illustrate the possible stable solutions I provide five cases concerning world oil consumption.

[1] All exogenous variables are constant.

[2] The marginal propensity to consume is periodic. In this case it is assumed that there are continuous preference shocks, these shocks showing a regular pattern.

[3] Both marginal propensity to consume as well and the flexible accelerator are periodic. This case, except for the preference shocks, also provides for a regular pattern in the speed of adjustment, keeping the capital output ratio constant.

[4] Marginal propensity to consume and flexible accelerator are both periodic, while autonomous expenditure is increasing.

[5] Marginal propensity to consume and a flexible accelerator are both periodic, while autonomous expenditure is increasing and the resource output ratio is decreasing.

The values of the parameters are more or less arbitrarily chosen on the basis of plausibility[5]. These values are shown for the first case in Table 7.2. Period 0 stands for the year 1986. The results of the simulation procedure are shown in Figure 7.4.

In the second case, I have assumed that the marginal propensity to consume is periodic with period 6 as is shown in Table 7.3. The results of the simulation procedure are shown in Figure 7.5.

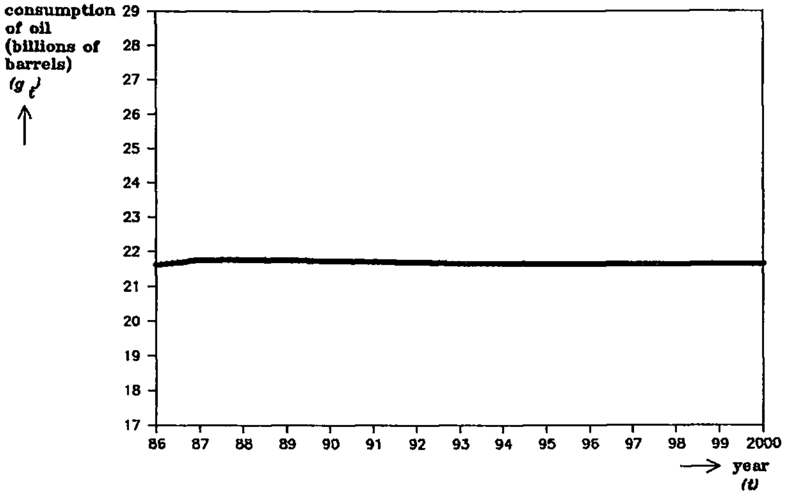

Figure 7.4: Simulation results of world consumption of oil with fixed parameters (Case [1]).

Table 7.2: The values of the exogenous variables with fixed parameters (Case [1]).

$o_t = o_0$	2160.3 (billions of Am. dollars)
$\gamma_t = \gamma_0$	0.845
$\alpha_t = \alpha_0$	0.4
$\mu_t = \mu_0$	0.001553

characteristic equation (16):

$\lambda^2 - 1.245 \cdot \lambda + 0.4 = 0$, $\lambda_{1,2} = 0.623 \pm 0.112 \cdot i$, $|\lambda_1| = |\lambda_2| < 1.$[a]

a) All these calculations disregard of rounding errors.

In the third case, the flexible accelerator has also been made periodic. It is assumed that the flexible accelerator is periodic with period 2. This is shown in Table 7.4. The results of the simulation procedure of this case are presented in Figure 7.6.

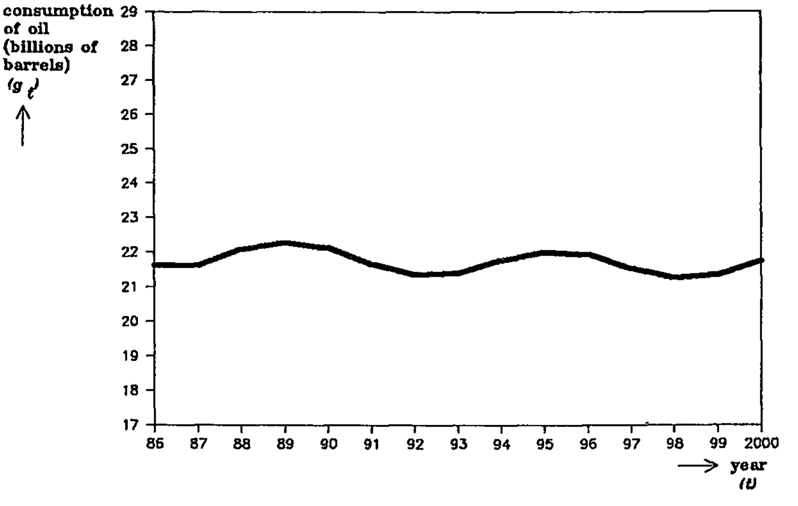

Figure 7.5: Simulation results of world oil consumption with periodic marginal consumption to consume (Case [2]).

Table 7.3: Values of exogenous variables with periodic marginal propensity to consume (Case [2]).

$o_t = o_0$	2160.3	
γ_t	0.83 0.84 0.85 0.86 0.85 0.84 0.83 ...	(period 6)
$\alpha_t = \alpha_0$	0.4	
$\mu_t = \mu_0$	0.001553	

characteristic equation (16):

$\lambda^2 - 0.061 \cdot \lambda + 0.0041 = 0, \quad \lambda_{1,2} = 0.031 \pm 0.056 \cdot i, \quad |\lambda_1| = |\lambda_2| < 1.$

It appears that the results of Case [3] are similar to the results of Case [2]. Of course, this depends on the values of the flexible accelerator.

In Case [4], I have assumed that the exogenous expenditure increases by the same rate as total output in the period 1977-1986, which means approximately by a rate of 0.025. The values of the exogenous variables for this case are shown in Table 7.5. The results of the simulation procedure of Case [4] are shown in Figure 7.7.

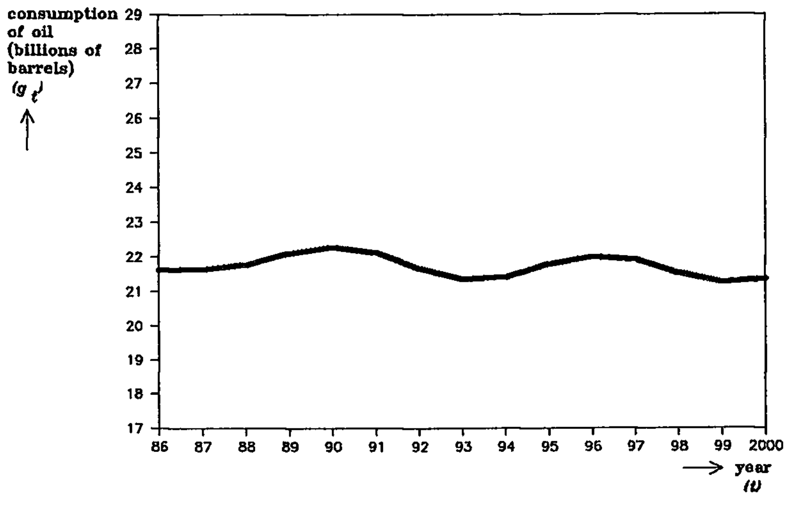

Figure 7.6: Simulation of world consumption of oil with periodic marginal propensity to consume and a periodic flexible accelerator (Case [3]).

Table 7.4: Values of exogenous variables with periodic marginal propensity to save and a periodic flexible accelerator (Case [3]).

$o_t = o_0$	2160.3	
γ_t	0.83 0.84 0.85 0.86 0.85 0.84 0.83 ...	(period 6)[a]
α_t	0.3 0.5 0.3 ...	(period 2)[a]
$\mu_t = \mu_0$	0.001553	

characteristic equation (16):

$\lambda^2 + 0.088 \cdot \lambda + 0.0056 = 0, \quad \lambda_{1,2} = -0.044 \pm 0.061 \cdot i, \quad |\lambda_1| = |\lambda_2| < 1.$

a) The first number always refers to $t = 0$.

In Appendix 7.1 two alternative solutions are given to show that even the development of the difference equation in Figure 7.7 is stable. It appears that the alternative solutions approach the original solution of Figure 7.7, thus illustrating the stability of the difference equation.

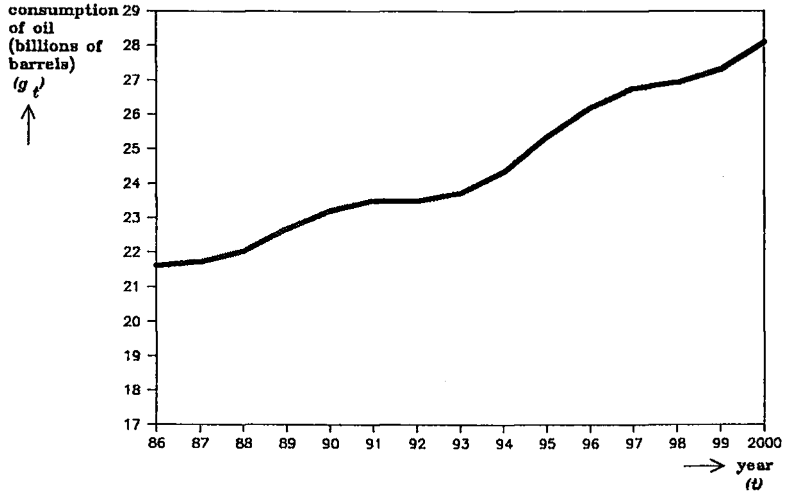

Figure 7.7: Simulation of world oil consumption with periodic propensity to consume, periodic flexible accelerator and increasing autonomous expenditure (Case [4]).

Table 7.5: The values of the exogenous variables in Case [4].

$o_t = o_0$	$2160.3 \cdot (1.025)^t$	
γ_t	0.83 0.84 0.85 0.86 0.85 0.84 0.83 ...	(period 6)
α_t	0.3 0.5 0.3 ...	(period 2)
μ_t	0.001553	

characteristic equation (16):

$\lambda^2 + 0.088 \cdot \lambda + 0.0056 = 0, \quad \lambda_{1,2} = -0.044 \pm 0.061 \cdot i, \quad |\lambda_1| = |\lambda_2| < 1.$

Finally, in the fifth case, I have assumed that, from 1986 on, the resource output ratio continues to decrease at the same speed as it did between 1977 and 1986, i.e. at the rate of 0.035 each year. The values of the exogenous variables in Case [5] are listed in Table 7.6. The simulation results of this case are shown in Figure 7.8. In Appendix 7.2 the stability of the difference equation is illustrated by a figure.

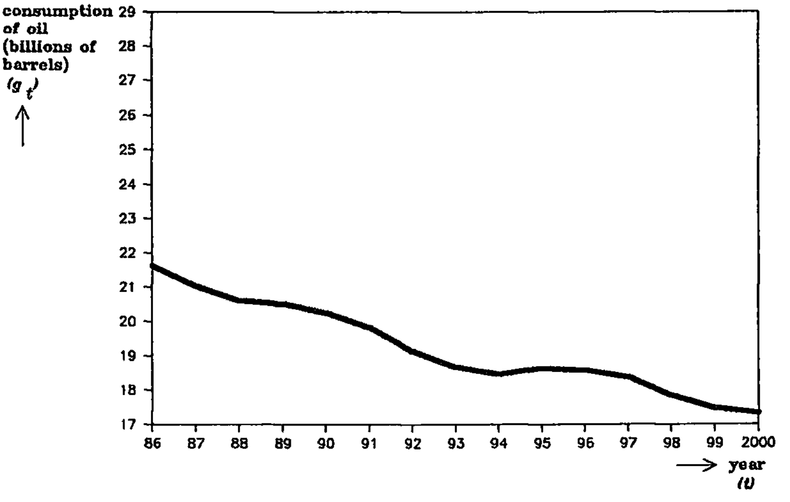

Figure 7.8: Simulation results of world oil consumption with periodic marginal propensity to consume, periodic flexible accelerator, decreasing resource output ratio and increasing autonomous expenditure (Case [5]).

Table 7.6: Values of exogenous variables for Case [5].

o_t	$2160.3 \cdot (1.025)^t$	
α_t	0.3 0.5 0.3 ...	(period 2)
μ_t	$0.001553/(1.035)^t$	
γ_t	0.83 0.84 0.85 0.86 0.85 0.84 0.83 ...	(period 6)

characteristic equation (16):

$\lambda^2 - 0.009906 \cdot \lambda + 0.000968, \quad \lambda_{1,2} = 0.004953 \pm 0.0307 \cdot i, \quad |\lambda_1| = |\lambda_2| < 1.$

All the cases dealt with in this section are concerned with stable difference equations. This is based, of course, on the chosen values of the coefficients. Indeed, unstable difference equations are generally considered as economically less relevant (Gabisch et al., 1989).

As long as the difference equation is stable and the decreasing resource output ratio more than compensates for the increase of the autonomous expenditure (which means that the right part of the difference equation is decreasing), we may conclude that, in the long run, the use of oil will be 0.

II. Resource price model

The previous section does not deal with prices. To explain price movements of resources I use the following model with q for quantity, p for price and α, β, γ, δ, and ρ for coefficients:

$$(18) \qquad q_t^d = \alpha \cdot p_t + \beta \qquad \text{demand} \quad \alpha < 0, \quad \beta > 0.$$

$$q_t^s = \gamma \cdot [p_{t-1} - \rho \cdot (p_{t-1} - p_{t-2})] + \delta \qquad \text{supply} \quad \gamma > 0, \quad \delta < \beta.$$

In a state of equilibrium ($q_t^s = q_t^d$), the following second order difference equation can be derived from equation (18):

$$(19) \qquad p_t = \frac{\gamma \cdot (1-\rho)}{\alpha} \cdot p_{t-1} + \frac{\gamma \cdot \rho}{\alpha} \cdot p_{t-2} + \frac{\delta - \beta}{\alpha}.$$

If ρ equals zero, the result is a simple cobweb model (see for instance Tinbergen, 1943, Allen, 1973, Chiang, 1987). In this simple model the expectation on the supply side is that the price of the previous period will continue. In fact it assumes that suppliers never learn. In the extended model above, the suppliers have a longer memory. Here it is assumed that the expectations of the supply side are influenced by experience. The *experience coefficient* is ρ. Normally ρ will have a value between zero and one, and then the price should move in the direction opposite to that of the previous period. Of course, ρ can also be negative, in which case the supply side expects a continuation of the price movement (Goodwin, 1947, Allen, 1973).

I now assume that all coefficients are periodic. This can be motivated by the consideration that all the coefficients are based on the conduct of producers and consumers. On the one hand, this means that it is plausible that changes in consumers' preference schemes cause changes in coefficients of the demand function. On the other hand, the reaction of producers might differ as well through time, for example because of variations in cost functions or variations in expectations for future prices. On these assumptions, equation (19) must be rewritten into:

$$(20) \qquad p_t = \frac{\gamma_t \cdot (1-\rho_t)}{\alpha_t} \cdot p_{t-1} + \frac{\gamma_t \cdot \rho_t}{\alpha_t} \cdot p_{t-2} + \frac{\delta_t - \beta_t}{\alpha_t}.$$

I shall now analyze the stability and oscillation behaviour in the case of periodic coefficients. For this model it can be proved that equation (20) is asymptoticly stable if the roots $\lambda_1, \ \lambda_2$ of

$$(21) \qquad \lambda^2 - \left\{ \mathrm{Tr} \prod_{m=1}^{q} \begin{pmatrix} \frac{\gamma_{m+1} \cdot (1-\rho_{m+1})}{\alpha_{m+1}} & \gamma_{m+1} \cdot \frac{\rho_{m+1}}{\alpha_{m+1}} \\ 1 & 0 \end{pmatrix} \right\} \cdot \lambda + \prod_{m=1}^{q} \frac{\gamma_m \cdot \rho_m}{\alpha_m} = 0$$

satisfy $|\lambda_1| < 1, \ |\lambda_2| < 1$. Assume the values of the coefficients of Table 7.7.

Table 7.7: Assumed values for the coefficients in the resource price model.

t	α	β	γ	δ	ρ
1	-0.6	22	0.3	2	0.4
2	-0.5	24	0.2	3	0.5
3	-0.6		0.3		
4	-0.7		0.4		
	period 4	period 2	period 4	period 2	period 2

Characteristic equation (21):

$\lambda^2 - 0.0388 \cdot \lambda + 0.00228, \qquad \lambda_{1,2} = 0.0194 \pm 0.0436 \cdot i, \qquad |\lambda_1| = |\lambda_2| < 1.$

Assuming a starting value for both p_0 and p_{-1} of 20, then we get the pattern of price line a in Figure 7.9. By contrast, if the model is simulated with a positive unique impulse of 10 for δ in period 3 (price line b), then a sudden exogenous change can be simulated. One might, for instance, think of a heavy storm causing an extra supply of home-grown timber which would result in a fall of the timber price. From Figure 7.9 it appears that, for the chosen values of coefficients, this exogenous impulse has a considerable effect on the development of the price level. This must be because both the demand curve and the supply curve are fairly inelastic, which, for resources, is probably the case in general. The pattern of the price lines a and b confirms that the difference equation (20) is stable with the coefficients of Table 7.7. Indeed, after a number of years, a and b converge, which means that the influence of the heavy storm gradually fades away.

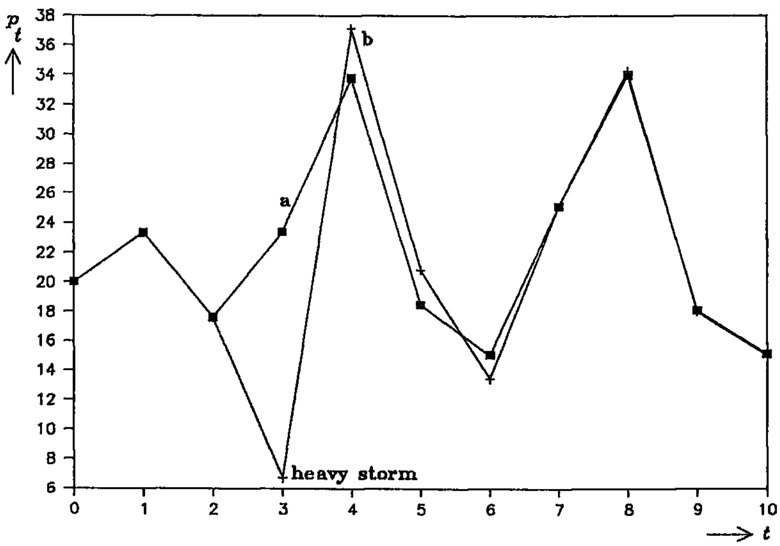

Figure 7.9: Simulation of the effects of a heavy storm on the real price of timber.

Now, it must be asked whether the analysis of the influence of exogenous impulses on a market system can be confirmed by empirical data. In Figure 7.10, real prices of three types of home-grown Dutch standing timber ("stumpage value")[6] are shown: larch, Douglas fir and spruce. In 1973, there was a heavy storm in the Netherlands and it appears that this storm severely influenced the price of timber.

Another question is what happens if there is a permanent exogenous impulse as, for instance, in the case of the two oil crises. Such an impulse can be simulated by a permanent decrease of δ. In the case of two shocks, this will generate a price (rent) line in different levels as is shown for Indonesian oil in Figure 7.11.

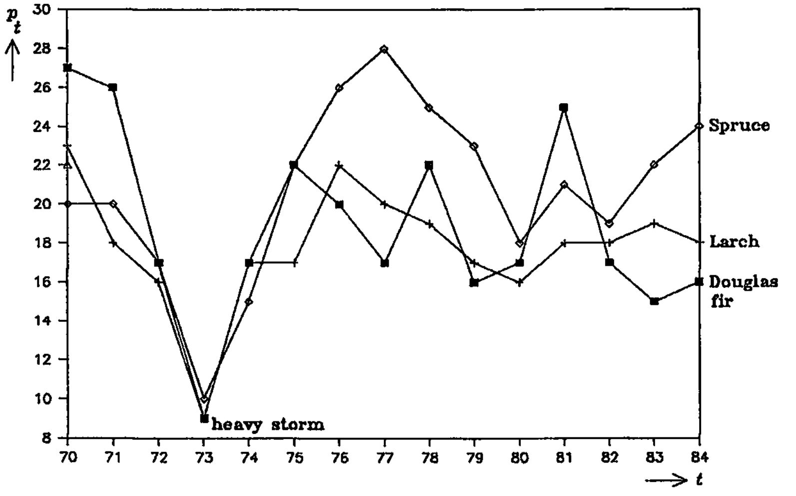

Figure 7.10: Prices of home-grown larch, Douglas fir and spruce standing timber in the Netherlands 1970-1984 (Dutch guilders per m^3).
Source: Slangen, 1987.

Apart from the two oil crises, the oil price line develops rather smoothly. According to Adelman (1990), another indicator of crude oil scarcity (development investment per unit of reserves added) did not increase in the United States before the 1970's. It could very well be that the rent on crude oil was negligible indicating that crude oil was only slightly scarce at that time. In the last section of this chapter I investigate the effects of an increase of the oil price on a non-oil-producing small open economy.

III. Effects of an increase in the oil price on a non-oil-producing small open economy
I want to begin by looking at the KLEM-production function. In this, production is a function of capital (k), labour (l), energy (e) and materials (m) (Magnus, 1979). Since the measurement of input of (m) is generally considered too difficult a task, I have assumed that k, l and e are homothetically seperable from m.

The following model is a simplified version of the model in van de Klundert (1983). The effects of an oil price rise are studied using a linearly homogenous Cobb-Douglas production function with the three inputs above mentioned[7]:

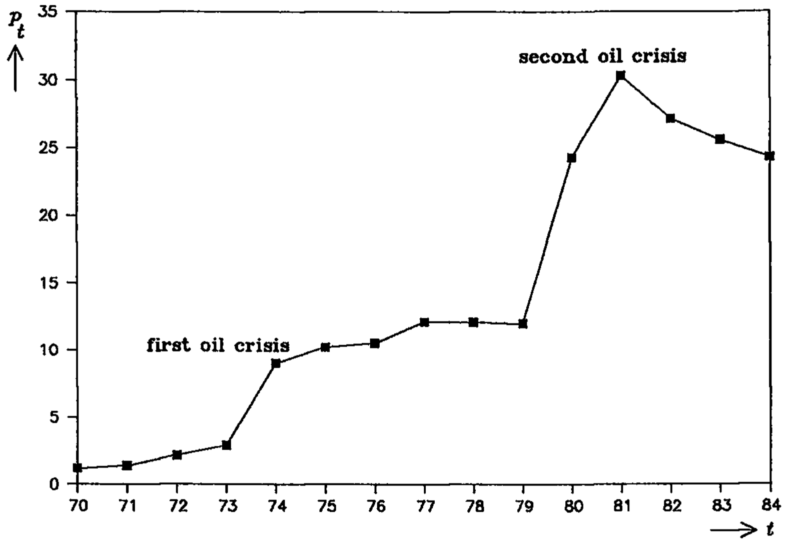

Figure 7.11: Nominal rent[a] per barrel Indonesian oil (in dollars).
a) Rent: FOB export price minus production costs.
Source: Repetto et al. 1989.

(22) $$q = \alpha \cdot k^{\beta} \cdot l^{\gamma} \cdot e^{1-\beta-\gamma}.$$

In equation (22), q, k, l and e stand for production, capital, labour and energy respectively, while α, β, and γ are coefficients. Equation (22) written in percentages gives:

(23) $$\bar{q} = \bar{\alpha} + \beta \cdot \bar{k} + \gamma \cdot \bar{l} + (1 - \beta - \gamma) \cdot \bar{e}.$$

Since in equilibrium the production elasticities β, γ and $(1 - \beta - \gamma)$ also determine the distribution of production over the three production factors, the return to labour, capital and energy can be written as:

(24) $k \cdot r = \beta \cdot q,$

$l \cdot p_l = \gamma \cdot q,$

$e \cdot p_e = (1 - \beta - \gamma) \cdot q.$

In equation (24), r is the rate of return, p_l represents real wage and p_e equals the real oil price. Further it is assumed that the balance of payment is continually in equilibrium. National income, which would then equal national spending, can be written as:

(25) $y = k \cdot r + l \cdot p_l.$

From equations (23) and (24) it can be derived

(26) $y = (\beta + \gamma) \cdot q.$

Equations (24) and (26) written in percentages give:

(27) $\bar{k} = \bar{q} - \bar{r},$

$\bar{l} = \bar{q} - \bar{p}_l,$

$\bar{e} = \bar{q} - \bar{p}_e,$

$\bar{y} = \bar{q}.$

In the next part of this section I want to look at four cases: (a) the short-term effects of a sudden rise in the oil price, assuming flexible real wages, (b) the short-term effects of a sudden rise in the price of oil, assuming non-flexible wages, (c) the long-term effects of a sudden rise in the price of oil, assuming no technical innovation and (d) the long-term effects of a sudden rise in the price of oil, assuming technical innovation.

In the first case it is assumed that real wage is so flexible that employment does not change $(\bar{l} = 0)$, that capital stock will not change in the short run $(\bar{k} = 0)$ and that there are no technical innovations $(\bar{\alpha} = 0)$. These assumptions, together with equations (23) and (27), lead to the effects on the economy as shown in Column (a) of Table 7.8.

Table 7.8: The short-term and long-term effects of an oil price shock (perunages).

Variable	Cases			
	short-term, flexible real wages ($\overline{k}=0$, $\overline{l}=0$, $\overline{\alpha}=0$) (a)	short-term, non-flexible wages ($\overline{k}=0$, $\overline{p}_l=0$, $\overline{\alpha}=0$) (b)	long-term, no technical innovations ($\overline{r}=0$, $\overline{l}=0$ $\overline{\alpha}=0$) (c)	long-term, technical innovations, ($\overline{l}=0$, $\overline{r}=0$, $\overline{q}=0$) (d)
$\overline{q}$	$\frac{-(1-\beta-\gamma)}{\beta+\gamma}\cdot\overline{p}_e$	$\frac{-(1-\beta-\gamma)}{\beta}\cdot\overline{p}_e$	$\frac{-(1-\beta-\gamma)}{\gamma}\cdot\overline{p}_e$	0
$\overline{y}$	$\frac{-(1-\beta-\gamma)}{\beta+\gamma}\cdot\overline{p}_e$	$\frac{-(1-\beta-\gamma)}{\beta}\cdot\overline{p}_e$	$\frac{-(1-\beta-\gamma)}{\gamma}\cdot\overline{p}_e$	0
$\overline{e}$	$\frac{-1}{\beta+\gamma}\cdot\overline{p}_e$	$\frac{-(1-\gamma)}{\beta}\cdot\overline{p}_e$	$\frac{-(1-\beta)}{\gamma}\cdot\overline{p}_e$	$-\overline{p}_e$
$\overline{p}_e$	$\overline{p}_e$	$\overline{p}_e$	$\overline{p}_e$	$\overline{p}_e$
$\overline{p}_l$	$\frac{-(1-\beta-\gamma)}{\beta+\gamma}\cdot\overline{p}_e$	0	$\frac{-(1-\beta-\gamma)}{\gamma}\cdot\overline{p}_e$	0
$\overline{r}$	$\frac{-(1-\beta-\gamma)}{\beta+\gamma}\cdot\overline{p}_e$	$\frac{-(1-\beta-\gamma)}{\beta}\cdot\overline{p}_e$	0	0
$\overline{l}$	0	$\frac{-(1-\beta-\gamma)}{\beta}\cdot\overline{p}_e$	0	0
$\overline{k}$	0	0	$\frac{-(1-\beta-\gamma)}{\gamma}\cdot\overline{p}_e$	0
$\overline{\alpha}$	0	0	0	$(1-\beta-\gamma)\cdot\overline{p}_e$

In the second case, real wage is non-flexible, which means that $\overline{p}_l=0$, the capital stock is still unchanged ($\overline{k}=0$) and there are no technical innovations ($\overline{\alpha}=0$). These assumptions give the results shown in Column (b) of Table 7.8.

In the long-term, wages are supposed to be flexible ($\overline{l}=0$), while capital owners are assumed to restore real rate of return before the oil crisis ($\overline{r}=0$). Also in Case (c) it is assumed that there are no technical innovations ($\overline{\alpha}=0$). These assumptions give the results shown in Column (c) of Table 7.8.

In the last case it is assumed that in the long-term, energy-saving technical innovations are sufficient to compensate for the negative effects of the oil price rise. This means that $\bar{l} = 0$, $\bar{r} = 0$, and $\bar{q} = 0$. From these assumptions the necessary saving of energy per unit output follows. It appears that the necessary saving of energy per unit output equals the production elasticity of oil multiplied by the relative rise of the price of oil (see Column (d) of Table 7.8).

To give a numerical example, I have taken the same production elasticities as van de Klundert et al. (1983). This means: $\beta = 0.3$, $\gamma = 0.6$ and $(1 - \beta - \gamma) = 0.1$, the increase in the oil price being 10%. The results have been collected in Table 7.9.

Table 7.9: The short-term and long-term effects of an oil price shock (percentages).[a]

variable	Cases			
	short-term, flexible real wage ($\bar{k} = 0$, $\bar{l} = 0$, $\bar{\alpha} = 0$) (a)	short-term, non-flexible real wage ($\bar{k} = 0$, $\bar{p}_l = 0$, $\bar{\alpha} = 0$) (b)	long-term, no technical innovations ($\bar{r} = 0$, $\bar{l} = 0$, $\bar{\alpha} = 0$) (c)	long-term, technical innovations ($\bar{l} = 0$, $\bar{r} = 0$, $\bar{q} = 0$) (d)
$\bar{q}$	-1.11	-3.33	-1.67	0.0
$\bar{y}$	-1.11	-3.33	-1.67	0.0
$\bar{e}$	-11.11	-13.33	-11.67	-10.0
$\bar{p}_e$	+10.0	+10.0	+10.0	+10.0
$\bar{p}_l$	-1.11	0.0	-1.67	0.0
$\bar{r}$	-1.11	-3.33	0.0	0.0
$\bar{l}$	0.0	-3.33	0.0	0.0
$\bar{k}$	0.0	0.0	-1.67	0.0
$\bar{\alpha}$	0.0	0.0	0.0	+1.0

a The results of the first three columns in this table are also to be found in van de Klundert et al. (1983).

In general one may conclude that the effects of an oil price rise in the short-term for income and employment can be mitigated by the possibilities of substitution between the production factors and flexibility of real wages. In the long-term, flexible wages, substitution between production factors, and the possibilities of energy-saving technical innovations might even cause a zero effect on the main parameters of the economy, i.e. income and employment.

A weakness in the model is the assumed substitution elasticity of one. According to Magnus (1979), at least for the Netherlands, labour and energy are close substitutes (the substitution elasticity lies roughly between 0.95 and 1.29). However, interaction between energy and capital is totally different. According to his empirical results, energy and capital are highly complementary (the substitution elasticity lies roughly between -2.19 and -2.45).

To generate results based on substitution elasticities higher or lower than 1, another production function has to be used. A CES-production function or a combination of a Cobb-Douglas production function with a CES production function seems to be the most suitable. Other possibilities are the use of production functions of a flexible form, such as a quadratic production function or a translog production function[8)] (Arrow et all., 1961, Christensen et al., 1973, Caves et al., 1980, Bruno et al., 1985, Pollak et al., 1987). Appendix 7.3 shows an attempt to deal with this aspect.

Appendix 7.1: Stability of the difference equation of the M-A model in Case [4]

The starting values of the original solution a, which are deduced from Table 7.1, are: $g_{-1} = 21.6$, $g_{-2} = 21.4$. The starting values for the two alternatives, b and c, are $g_{-1} = 28$, $g_{-2} = 26.0$ and $g_{-1} = 16$, $g_{-2} = 14$ respectively. The results of the simulation procedure are shown in Figure 7a.1. Results confirm the stability of the difference equation in Case [4].

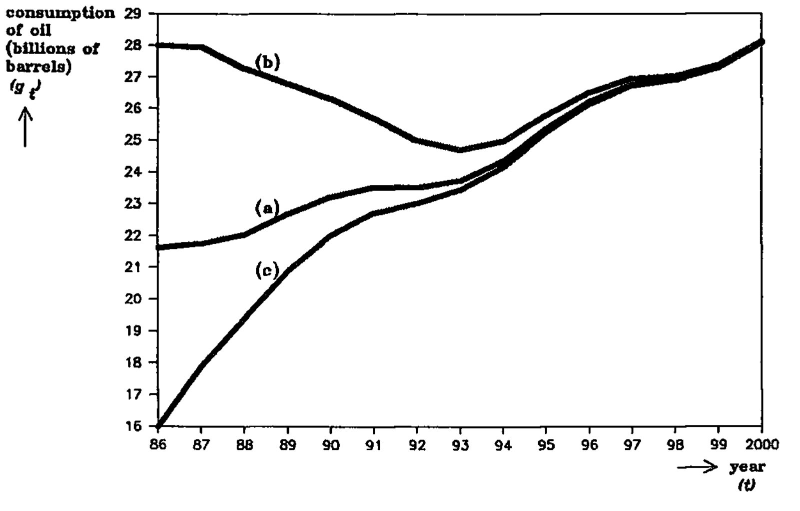

Figure 7a.1: The stability of the difference equation in Case [4].

Appendix 7.2: Stability of the difference equation of the M-A model in Case [5]

The starting values of the original solution a, which are deduced from Table 1, are: $g_{-1} = 21.6$, $g_{-2} = 21.4$. The starting values for the two alternatives, b and c, are: $g_{-1} = 15.0$, $g_{-2} = 16.0$ and $g_{-1} = 25.0$, $g_{-2} = 26.0$ respectively. The results of the simulation procedure are shown in Figure 7a.2. Results confirm the stability of the difference equation in Case [5].

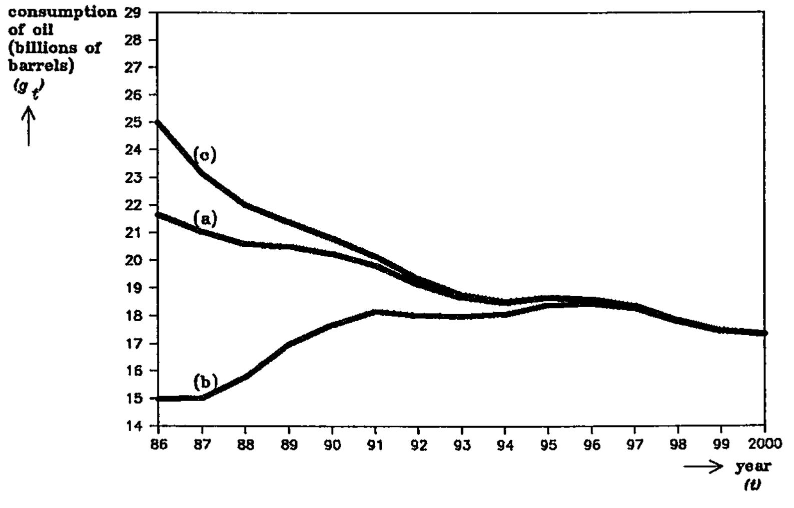

Figure 7a.2: The stability of the difference equation in Case [5].

Appendix 7.3: Effect of different substitution elasticities

In this appendix, I use a two-step production function that can be described as follows. Suppose a linearly homogenous Cobb-Douglas production function with two inputs, labour (l) and energy (e), producing a semi-manufactured article (v), that can be written in percentages as:

$$\bar{v} = \bar{\gamma} + \phi \cdot \bar{l} + (1 - \phi) \cdot \bar{e},$$

with $\bar{\gamma}$ for technical innovation, ϕ as the production elasticity of labour and $(1 - \phi)$ as the production elasticity for energy. This means that, in the optimum:

$$\bar{l} + \bar{p}_l = \bar{v} + \bar{p}_v,$$

$$\bar{e} + \bar{p}_e = \bar{v} + \bar{p}_v.$$

Further, the semi-manufactured article (v) together with capital (k) is used as input in a linearly homogenous CES production function to gain production (q):

$$q = \alpha \cdot \{\delta \cdot v^{-\rho} + (1-\delta) \cdot k^{-\rho}\}^{-1/\rho},$$

with α, δ and ρ as parameters. In percentages this production function can be written as[9]:

$$\bar{q} = \bar{\alpha} + \zeta \cdot \bar{v} + (1-\zeta) \cdot \bar{k}.$$

with ζ for the production elasticity of the semi-manufactured article (v) and $(1-\zeta)$ for the production elasticity of capital (k). The constant substitution elasticity (χ) between these two inputs equals:

$$\chi = \frac{\bar{v} - \bar{k}}{\bar{r} - \bar{p}_v}.$$

with $\bar{p}_v$ for the relative change in the real price of v and $\bar{r}$ for the relative change in the real rate of return. p_v equals marginal product of v, $\partial q/\partial v$, in the optimum. ζ equals production elasticity, $(\partial q/\partial v) \cdot (v/q)$. This together with the equations in note 9 give:

$$\bar{p}_v = (\rho + 1) \cdot (\bar{q} - \bar{v}).$$

Further it can be derived that (Chiang, 1987):

$$\chi = \frac{1}{(1+\rho)}.$$

The last two equations give:

$$\bar{p}_v = \frac{\bar{q} - \bar{v}}{\chi}.$$

Finally, the relative change in real income can be written as:

$$\bar{y} = \lambda \cdot (\bar{l} + \bar{p}_l) + (1 - \lambda) \cdot (\bar{k} + \bar{r}),$$

with λ for the wage share and $(1 - \lambda)$ for the non-wage share in national income. The model now consists of the seven equations of Table 7a.1.

Table 7a.1: A model with a Cobb-Douglas CES two-step production function.

$$\bar{v} = \bar{\gamma} + \phi \cdot \bar{l} + (1 - \phi) \cdot \bar{e}$$

$$\bar{q} = \bar{\alpha} + \xi \cdot \bar{v} + (1 - \xi) \cdot \bar{k}$$

$$\chi = \frac{\bar{v} - \bar{k}}{\bar{r} - \bar{p}_v}$$

$$\bar{l} + \bar{p}_l = \bar{v} + \bar{p}_v$$

$$\bar{e} + \bar{p}_e = \bar{v} + \bar{p}_v$$

$$\bar{p}_v = \frac{\bar{q} - \bar{v}}{\chi}$$

$$\bar{y} = \lambda \cdot (\bar{l} + \bar{p}_l) + (1 - \lambda) \cdot (\bar{k} + \bar{r})$$

I now want to look at the same four cases in the same way as I did in the pure Cobb-Douglas Case of the main text. The values of ϕ, ξ and λ are respectively 0.85, 0.70 and 0.60 respectively. The substitution elasticity between v and k is 0.4 and the rise of the oil price is assumed to be 10%.

The first case is the short-term one with flexible real wages ($\bar{l} = 0$, $\bar{k} = 0$, $\bar{\alpha} = 0$ and $\bar{\gamma} = 0$). The results of this case are shown in Column (a) of Table 7a.2. In the second case, the wages are supposed to be non-flexible, while the capital stock remains unchanged in the short-term ($\bar{k} = 0$, $\bar{p}_l = 0$, $\bar{\alpha} = 0$, and $\bar{\gamma} = 0$). The results of this case are presented in the second Column (b) of Table 7a.2. In the third case, of which the results are shown in the third Column (c) of Table 7a.2, the real rate of return is assumed to be unchanged, while real wage is flexible ($\bar{r} = 0$, $\bar{l} = 0$, $\bar{\alpha} = 0$ and $\bar{\gamma} = 0$). Finally in Column (d) the results are shown if, in the long-term, production remains unchanged because of technical innovations ($\bar{r} = 0$, $\bar{l} = 0$, $\bar{v} = 0$ and $\bar{q} = 0$).

Table 7a.2: The effects of a sudden oil price rise in a model with a Cobb-Douglas CES two-step production function (percentages).

Variable	Cases: short-term, flexible real wage ($\bar{k}=0$, $\bar{l}=0$, $\bar{\alpha}=0$, $\bar{\gamma}=0$) (a)	short-term, non-flexible real wage ($\bar{k}=0$, $\bar{p}_l=0$, $\bar{\alpha}=0$ $\bar{\gamma}=0$) (b)	long-term, no technical innovations ($\bar{r}=0$, $\bar{l}=0$, $\bar{\alpha}=0$ $\bar{\gamma}=0$) (c)	long-term, technical innovations ($\bar{l}=0$, $\bar{r}=0$, $\bar{q}=0$, $\bar{v}=0$) (d)
$\bar{q}$	-1.1	-1.4	-1.8	0.0
$\bar{y}$	-1.3	-1.7	-1.8	0.0
$\bar{v}$	-1.6	-2.0	-1.8	0.0
$\bar{e}$	-10.4	-10.5	-11.8	-10.0
$\bar{p}_e$	+10.0	+10.0	+10.0	+10.0
$\bar{p}_l$	-0.4	0.0	-1.8	0.0
$\bar{p}_v$	+1.2	+1.5	0.0	0.0
$\bar{r}$	-2.7	-3.5	0.0	0.0
$\bar{l}$	0.0	-0.5	0.0	0.0
$\bar{k}$	0.0	0.0	-1.8	0.0
$\bar{\alpha}$	0.0	0.0	0.0	0.0
$\bar{\gamma}$	0.0	0.0	0.0	1.5

The conclusion is that, in the short-term, some results are different from the pure Cobb-Douglas case. However, long-term results are nearly the same. Of course, this conclusion has been reached on the assumption that the substitution elasticity between labour and energy is 1. Indeed, for the Netherlands, this is a plausible value (Magnus, 1979).

Notes

1) Kuipers stated incorrectly that Hicks took investments as a function of consumption (Kuipers, 1983, p. 27). Apparently it was Samuelson who did so, referring to Hansen (Samuelson, 1939). Hicks took investments as a function of total production or income (Hicks, 1951).

2) In fact the flexible accelerator (α) equals the capital coefficient (κ) multiplied by the assumed speed of adjustment ξ. For instance if $\kappa = 2$ and it takes the economy three periods to adjust the capital stock to the new situation, which means that $\xi = 1/3$, then $\alpha = 2 \cdot (1/3) = 2/3$.

3) 1 barrel = 159 liter.

4) The resources investigated by Wahab were: oil, aluminium, iron, copper, lead, manganese, nickel, steel, tin, tungsten, zinc and sulphur.

5) It is only the possible effects of the variability of the coefficients of the difference equation which have been studied in this chapter. The question of the statistically right determination of the coefficients of the model is outside the scope of this thesis.

6) The stumpage value is the market value of standing trees per unit. For virgin forest the stumpage value equals the rent, for plantations the stumpage value includes the rent plus the expenses of planting and maintaining the trees. In the Netherlands there is no virgin forest left, so the stumpage value does not equal the rent in this case (See: Repetto et al., 1989).

7) The separability assumption strictly implies that if $w = f(k, l, e, m) = g(k, l, e) \cdot m$, then:

$$q = \frac{w}{m} = g(k, l, e),$$

with w for total production and q for the production per unit material.

8) CES means: Constant Elasticity of Substitution. The general form of this production function is:

$$q = \alpha \cdot [\delta \cdot l^{-\rho} + (1 - \delta) \cdot k^{-\rho}]^{-1/\rho}, \qquad (\alpha > 0; \quad 0 < \delta < 1; \quad -1 < \rho \neq 0),$$

where l and k represent two factors of production, and α, δ and ρ are three parameters (Chiang, 1987).

The general form of the translog production function with two inputs is:

$$\ln q = \alpha + \beta_l \cdot \ln l + \beta_k \cdot \ln k + \beta_{kl} \cdot \ln l \cdot \ln k + \frac{1}{2} \cdot \beta_{kk} \cdot (\ln k)^2 + \frac{1}{2} \cdot \beta_{ll} \cdot (\ln l)^2,$$

with $\beta_{lk} = \beta_{kl}$,

and with q, l and k for production, input of labour and input of capital respectively, α, β_l, β_k, β_{kk} and β_{kl} being parameters.

The general form of the quadratic production function with two inputs is:

$$q = \alpha + \beta_l \cdot l + \beta_k \cdot k + \frac{1}{2} \cdot \beta_{kk} \cdot k^2 + \frac{1}{2} \cdot \beta_{ll} \cdot l^2 + \beta_{kl} \cdot l \cdot k,$$

with $\beta_{kl} = \beta_{lk}$,

and with q, l and k for production, input of labour and input of capital respectively, α, β_l, β_k, β_{kk} and β_{kl} being parameters.

9) It appears that the CES production function can also be written as:

$$q^{-\rho} = \alpha^{-\rho} \cdot \delta \cdot \upsilon^{-\rho} + \alpha^{-\rho} \cdot (1 - \delta) \cdot k^{-\rho}.$$

This form written in percentages gives:

$$-\rho \cdot \bar{q} = -\rho \cdot \bar{\alpha} - \rho \cdot \zeta \cdot \bar{\upsilon} - \rho \cdot (1 - \zeta) \cdot \bar{k}, \quad \text{so} \quad \bar{q} = \bar{\alpha} + \zeta \cdot \bar{\upsilon} + (1 - \zeta) \cdot \bar{k},$$

in which:

$$\zeta = \alpha^{-\rho} \cdot \delta \cdot \left(\frac{q}{\upsilon}\right)^{\rho}, \quad (1 - \zeta) = \alpha^{-\rho} \cdot (1 - \delta) \cdot \left(\frac{q}{k}\right)^{\rho}.$$

8. Resource depletion and market forms

This chapter examines the influence of the market form upon the speed of depletion of exhaustible resources. After looking at the situation of perfect competition and that of the monopoly, I then turn to the cartel-versus-fringe model and the oligopoly dealing with it on the basis of a non-linear demand function. The influence of technological change is also taken into consideration. Some remarks on the depletion speed of renewable resources are also made.

Depletion time with perfect competition

In this section I determine the depletion time of an exhaustible resource within the given constraints of perfect competition, well defined property rights and a specified demand function. To determine the depletion time it is possible to use the Hotelling efficiency rule. As already described in Chapter 5, this rule is that the price of an exhaustible resource should rise by the rate of interest if the social value of the resource is to be maximized. The price of the resource (p) is the net price after paying the costs of extraction and placing the amount of resource on the market. This 'price' is referred to as the royalty of the resource.

According to the Hotelling rule, the royalty of the exhaustible resource (p_t) should rise each period by the rate of interest (υ), which means:

(1) $$p_t = p_0 \cdot e^{\upsilon \cdot t}.$$

The following specified demand function:

(2) $$p = K \cdot e^{-\alpha \cdot q},$$

implies that p approaches zero when q approaches infinity and that p equals K when q equals 0. This is shown in Figure 8.1. In this figure, two demand curves are shown with a value of 20 for K. For the first demand curve, it is assumed that α equals 0.25; for the second demand curve α equals 0.5. It appears that α determines the bend in the curve, so that if α increases, the curve lies closer to the y-axis. The figure also shows the absolute value of the demand elasticity $(|\eta|)$ of the first demand curve. This elasticity is, of course, negative and is equal to $1/(-\alpha \cdot q)$, which means that if q decreases, the absolute value of the demand elasticity will increase.

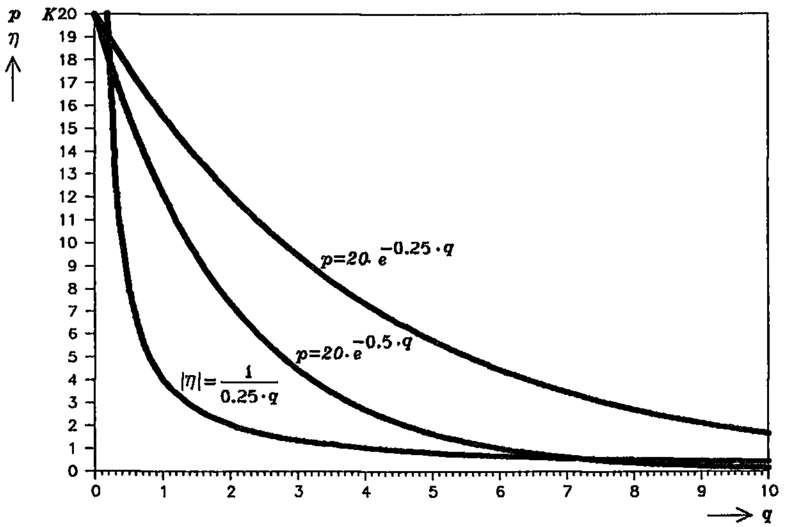

Figure 8.1: The specified demand function.

The total stock of the exhaustible resource is known to be equal to ω units. The question is to determinate the time (T) during which the stock of the exhaustible resource is completely depleted. Since we know that, in the end, p_t must equal K, this means that $K = p_0 \cdot e^{\upsilon \cdot T}$, or, written a little differently:

(3) $$p_0 = K \cdot e^{-\upsilon \cdot T}.$$

Equations (2) and (3) substituted in (1) give:

(4) $$K \cdot e^{-\alpha \cdot q} = K \cdot e^{\upsilon \cdot (t-T)}$$

$$\alpha \cdot q = \upsilon \cdot (T-t)$$

$$q_t = \frac{\upsilon}{\alpha} \cdot (T-t).$$

From equation (4) it follows:

$$(5) \qquad \int_0^T q_t dt = \int_0^T \frac{\upsilon}{\alpha} \cdot (T-t) dt.$$

Because $\int_0^T q_t dt$ equals ω, equation (5) can be rewritten as follows:

$$(6) \qquad \omega = \frac{\upsilon}{\alpha} \cdot [T \cdot t - \frac{1}{2} \cdot t^2]_0^T dt = \frac{1}{2} \cdot \frac{\upsilon}{\alpha} \cdot T^2.$$

From equation (6) the following expression for T follows:

$$(7) \qquad T^2 = \frac{2 \cdot \omega \cdot \alpha}{\upsilon}, \quad \text{so}$$

$$(8) \qquad T = \sqrt{\frac{2 \cdot \omega \cdot \alpha}{\upsilon}}.$$

With the help of equations (2), (3) and (8) it is possible to compute p_0 and q_0:

$$(9) \qquad p_0 = K \cdot e^{-\sqrt{2 \cdot \upsilon \cdot \omega \cdot \alpha}},$$

$$q_0 = \frac{\sqrt{2 \cdot \upsilon \cdot \omega \cdot \alpha}}{\alpha}.$$

In a perfect competition situation, the starting points of price and quantity at the beginning of the exploitation period (period 0) can be determined by using equation (9).

Monopoly situation
The usual goal of a monopolist is to maximize his profits or royalties over time. When r stands for the total amount of royalties, p for the royalty per unit product and q for the total production, a monopolist tries to maximize the following function:

$$(10) \qquad r = p(q) \cdot q,$$

subject to the condition:

$$(11) \qquad \int_0^T q_t dt = \omega.$$

Taking into account a discount rate υ, the function (J) to be maximized changes into:

$$(12) \qquad J = \int_0^T q \cdot p(q) \cdot e^{-\upsilon \cdot t} dt.$$

The problem formulated above can be solved in two ways. First, by using intuition and second, by using the calculus of variations. The first way of solving the problem is presented in the text, the second is presented in appendix 8.1.

When using intuition, the discounted marginal revenue must be equal for each period, because, if this were not the case, the monopolist could increase total discounted royalty by moving an extracted unit from a period with a relatively low discounted marginal revenue to a period with a relatively high discounted marginal revenue. To put it differently:

$$(13) \qquad MR_t \cdot e^{-\upsilon \cdot t} = c$$

$$MR_t = c \cdot e^{\upsilon \cdot t}$$

$$MR_t = MR_0 \cdot e^{\upsilon \cdot t}.$$

The marginal revenue (MR) function connected with the specified demand function (2) is:

(14) $$MR = -\alpha \cdot q \cdot K \cdot e^{-\alpha \cdot q} + K \cdot e^{-\alpha \cdot q}.$$

From equation (14) it can be concluded that marginal revenue equals K when q equals 0. This leads to the following expression for the marginal revenue:

(15) $$MR_t = MR_0 \cdot e^{v \cdot t}$$
$$K = MR_0 \cdot e^{v \cdot T}$$
$$MR_t = K \cdot e^{v \cdot (t-T)}.$$

The specified marginal revenue function of equation (14) does not enable an easy solution to the dynamic programming problem. That is why I use a function which is a fairly precise approximation of the marginal revenue function, through which the problem can be elegantly solved. This function is deduced in Appendix 8.2. The conclusion from this appendix is that, if the specified demand function is $p = K \cdot e^{-\alpha \cdot q}$, a workable approximation for the MR – function is:

(16) $$MR = K \cdot e^{-h \cdot \alpha \cdot q}, \qquad \text{with} \qquad h \approx 2.49.$$

Once this simplified expression for marginal revenue is known, it is possible to solve the dynamic programming problem in the same way as was done in the perfect competition case (Heijman, 1990). However, before doing this, I want to give a short recapitulation of the solution procedure. To maximize equation (12), subject to the condition formulated in equation (11), a rule formulated with equation (15) was deduced. Because the programming problem cannot be solved easily with the specified marginal revenue function (equation (14)), an approximation of that function (equation (16)) is used.

From equations (15) and (16) it follows:

(17) $$K \cdot e^{-h \cdot \alpha \cdot q} = K \cdot e^{v \cdot (t-T)}.$$

This means that:

$$(18) \qquad h \cdot \alpha \cdot q = \upsilon \cdot (T - t),$$

$$q = \frac{\upsilon}{h \cdot \alpha} \cdot (T - t).$$

Integrating equation (18) gives:

$$(19) \qquad \int_0^T q dt = \int_0^T \frac{\upsilon}{h \cdot \alpha} \cdot (T - t) dt.$$

Because total stock equals ω, equation (19) can be rewritten into:

$$(20) \qquad \omega = \int_0^T \frac{\upsilon}{h \cdot \alpha} \cdot (T - t) dt.$$

Computing the integrand of equation (20) from 0 to T gives:

$$(21) \qquad \omega = \frac{\upsilon}{h \cdot \alpha} \cdot \left[T \cdot t - \frac{1}{2} \cdot t^2 \right]_0^T dt$$

$$\omega = \frac{1}{2} \cdot \frac{\upsilon}{h \cdot \alpha} \cdot T^2$$

$$T = \sqrt{\frac{2 \cdot \omega \cdot h \cdot \alpha}{\upsilon}}.$$

With the help of equations (3), (17) and (21) it is possible to determine q_0 and p_0:

$$(22) \qquad q_0 = \frac{\sqrt{2 \cdot \upsilon \cdot \omega \cdot h \cdot \alpha}}{h \cdot \alpha}$$

$$p_0 = K \cdot e^{\frac{-\sqrt{2 \cdot \upsilon \cdot \omega \cdot h \cdot \alpha}}{h}}.$$

Equation (22) can be used to determine the starting values of price and quantity at the beginning of the exploitation period in a monopoly situation.

Table 8.1: Perfect competition and monopoly compared

perfect competition	**monopoly**
$T = \sqrt{\frac{2 \cdot \omega \cdot \alpha}{\upsilon}}$	$T = \sqrt{\frac{2 \cdot \omega \cdot h \cdot \alpha}{\upsilon}}$
$p_0 = K \cdot e^{-\sqrt{2 \cdot \upsilon \cdot \omega \cdot \alpha}}$	$p_0 = K \cdot e^{\frac{-\sqrt{2 \cdot \upsilon \cdot \omega \cdot h \cdot \alpha}}{h}}$
$q_0 = \frac{\sqrt{2 \cdot \upsilon \cdot \omega \cdot \alpha}}{\alpha}$	$q_0 = \frac{\sqrt{2 \cdot \upsilon \cdot \omega \cdot h \cdot \alpha}}{h \cdot \alpha}$

In Table 8.1, the results of the perfect competition situation are compared with the results gained from the situation of a monopoly (Heijman, 1990). From this table it is clear that a monopolist is more careful about the depletion of an exhaustible resource than the joint firms acting under perfect competition. Using the specified demand function (2), a monopolist multiplies $\sqrt{h}$ (≈ 1.6) by the time the firms under perfect competition take to deplete the resource stock completely. In a monopoly, prices will be higher and the quantities brought to the market each period will be smaller than they are with perfect competition. A monopoly has a much more careful attitude towards the natural resource than the firms acting under perfect competition. This is a remarkable aspect, because a monopoly is generally considered to be working against the common interest and the environment. It was this result that forced Solow to make the following much-quoted comment:

> The amusing thing is that if a conservationist is someone who would like to see resources conserved *beyond* the pace that competition would adopt, then the monopolist is the conservationist's friend. No doubt they would be surprised to know it (Solow, 1974b, p. 8).

Cartel-versus-fringe and oligopoly

In practice, the market forms of perfect competition and monopoly seldom occur. In the crude oil branch especially, some large producers dominate the market while there is still a fringe of small-scale producers providing a substantial amount of oil. Often the large producers form a cartel to compete the fringe. In that case, reality can be best described by a so-called cartel-versus-fringe model (Salant, 1976). The period of depletion of the total resource stock can then be divided in two sub-periods. In the first period, there is competition between the cartel and the firms in the fringe. In the second period, the stock owned by the fringe is exhausted, only the cartel still being able to provide the resource. This is a monopoly situation. The two periods are presented graphically in Figure 8.2. It should here be stressed that I have taken the Stackelberg equilibrium, which means that the cartel announces optimal price and extraction paths, explicitly taking into account the behaviour of the fringe as a price taker. I have also assumed that the fringe exactly meets the lack of supply for market equilibrium. Further I have assumed an absence of speculation, which means that the demand depends on the current price level.

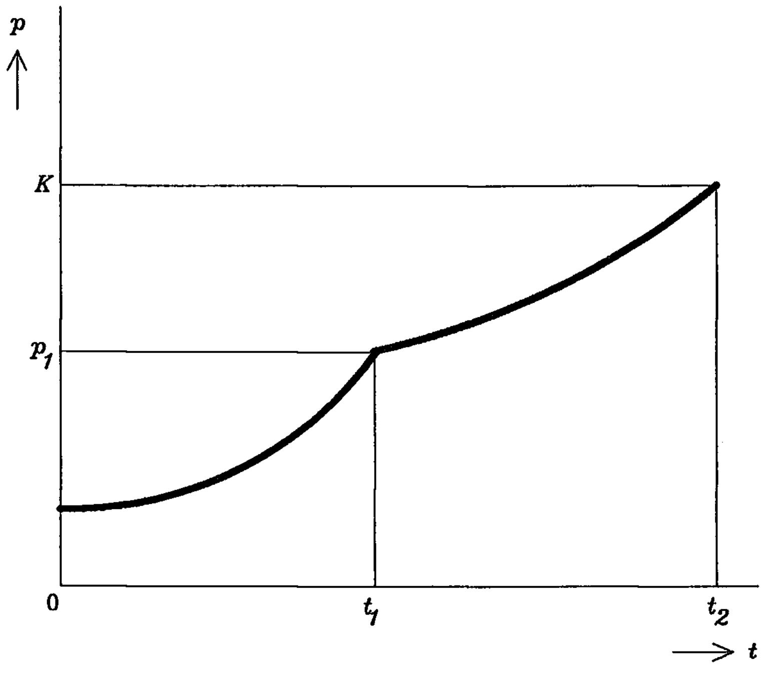

Figure 8.2: Two depletion periods in the cartel-versus-fringe model.

In the following analysis of period 1 (the period between $t = 0$ and $t = t_1$) the cartel can be seen as the price leader. To fulfil this role it has to provide a substantial part of the total supply. In the first period, the resource price (royalty) will rise according to Hotelling's rule, which means that it will rise by the rate of interest.

After the end of period 1, the cartel becomes a monopoly, implying that it is not the price but marginal revenue that will rise by the rate of interest. This means that, in period 2, the resource price will rise at a lower rate than the rate of interest. In the figure we see that at point of time t_1 period 1 has ended and the fringe is out of business. At t_2 the resource stock is depleted. At that point of time, the price has reached K.

I want to prove that, in the case in question, the cartel is able to choose the length of period 1 by determining the distribution of the total stock of resource which is owned by the cartel over period 1 and period 2. Of course, this way of acting has its limitations, because the cartel has to supply a sufficient part of total supply in period 1 from its role of price leader. In contrast to usual analysis of the cartel-versus-fringe, I have used a non-linear demand function (equation 2) (Salant, 1976, Newbery, 1981, Withagen, 1984, Groot et al., 1989). I suppose that p_1 is equal to $K \cdot e^{-\theta}$. When Θ has a high value, p_1 is low and when Θ is low, p_1 is relatively high. In other words, a high value of Θ implies a short first period (T_1) with competition, and a long second period (T_2) during which the cartel can operate as a monopoly.

For period 1, price (p) of the resource can be expressed as follows:

$$(23) \qquad p = K \cdot e^{-\theta} \cdot e^{-\upsilon \cdot (T_1 - t)}.$$

The demand function of the resource is:

$$(24) \qquad p = K \cdot e^{-\alpha \cdot q}.$$

Equations (23) and (24) combined give:

$$(25) \qquad \alpha \cdot q = \theta + \upsilon \cdot (T_1 - t)$$

$$q = \frac{\theta}{\alpha} + \frac{\upsilon}{\alpha} \cdot (T_1 - t).$$

From equation (25) it can be derived that:

$$(26) \qquad \int_0^{T_1} q\,dt = \left[\frac{\theta}{\alpha} \cdot t + \frac{\upsilon}{\alpha} \cdot T_1 \cdot t - \frac{1}{2} \cdot \frac{\upsilon}{\alpha} \cdot t^2 \right]_0^{T_1}.$$

which means that:

$$(27)\qquad \omega_1 = \frac{\theta}{\alpha} \cdot T_1 + \frac{1}{2} \cdot \frac{\upsilon}{\alpha} \cdot T_1^2.$$

I must now find a similar expression for ω_2, the amount of resource supplied by the cartel functioning as a monopoly in period 2.

We already know that the marginal revenue function derived from the demand function $p = K \cdot e^{-\alpha \cdot q}$ can be approached by $MR = K \cdot e^{-h \cdot \alpha \cdot q}$. Further it is known that, during period 2, the marginal revenue (MR) rises by the rate of interest since the cartel then acts as a monopoly. So:

$$(28)\qquad MR = K \cdot e^{-h \cdot \alpha \cdot q}$$

$$MR = K \cdot e^{-\upsilon \cdot (T_2 - t)}$$

$$\upsilon \cdot (T_2 - t) = h \cdot \alpha \cdot q.$$

From equation (28) it follows:

$$(29)\qquad q_t = \frac{\upsilon \cdot (T_2 - t)}{h \cdot \alpha}.$$

At the beginning of period 2, price equals p_1 (Figure 8.1), which equals $K \cdot e^{-\theta}$. This means that:

$$(30)\qquad K \cdot e^{-\theta} = K \cdot e^{-\upsilon \cdot T_2}$$

$$T_2 = \frac{\theta}{\upsilon}.$$

Combining equations (29) and (30) gives:

$$(31)\qquad q_t = \frac{\theta - \upsilon \cdot t}{h \cdot \alpha}.$$

From equation (31) the following expression for the amount of resource supplied in period 2 can be derived:

$$(32)\qquad \int_0^{T_2} q_t dt = \left[\frac{\theta}{h\cdot\alpha}\cdot t - \frac{1}{2}\cdot\frac{\upsilon}{h\cdot\alpha}\cdot t^2\right]_0^{T_2}$$

$$\omega_2 = \frac{\theta}{h\cdot\alpha}\cdot T_2 - \frac{1}{2}\cdot\frac{\upsilon}{h\cdot\alpha}\cdot T_2^2.$$

The expression for T_2 found in equation (30) substituted in equation (32) gives the final expression for the amount of resource supplied by the cartel in period 2:

$$(33)\qquad \omega_2 = \frac{1}{2}\cdot\frac{\theta^2}{h\cdot\alpha\cdot\upsilon}.$$

Equation (27) added to equation (33) gives an expression for the total amount of resource supplied by cartel as well as fringe $(\underline{\omega})$. This total amount is, of course, supposed to be known:

$$(34)\qquad \underline{\omega} = \omega_1 + \omega_2$$

$$\underline{\omega} = \frac{\theta}{\alpha}\cdot T_1 + \frac{1}{2}\cdot\frac{\upsilon}{\alpha}\cdot T_1^2 + \frac{1}{2}\cdot\frac{\theta^2}{h\cdot\alpha\cdot\upsilon}.$$

From equation (34) it appears that if T_1 is known, the value of θ is determined and that if θ is known, T_1 is determined. From this, together with equation (27), it appears that when T_1 is known, ω_1 can be determined.

Now, I want to compare the depletion time of the cartel-versus-fringe situation with the monopoly situation and with the perfect competition situation. In the perfect competition situation, θ equals zero. I already know from Table 8.1 (I can also derive the same conclusion from equation (34)) that in such a situation depletion time (T_{pc}) equals:

$$(35)\qquad T_{pc} = \sqrt{\frac{2\cdot\underline{\omega}\cdot\alpha}{\upsilon}}.$$

In the monopoly case, we know that T_1 equals zero. From equation (34) I can therefore derive that Θ equals $\sqrt{2 \cdot \omega \cdot h . \alpha \cdot \upsilon}$. This result substituted in equation (30) gives the depletion time of the resource in the monopoly situation (T_m):

$$(36) \qquad T_m = \sqrt{\frac{2 \cdot \omega \cdot h \cdot \alpha}{\upsilon}}.$$

I already derived this result in the previous section. Because the value of Θ can only be between zero and $\sqrt{2 \cdot \omega \cdot h \cdot \alpha \cdot \upsilon}$, depletion time of the resource in the cartel-versus-fringe situation (T_{cf}) must be between T_{pc} and T_m. Put in another way:

$$(37) \qquad 0 \leq \Theta \leq \sqrt{2 \cdot \omega \cdot h \cdot \alpha \cdot \upsilon}$$

$$T_{pc} \leq T_{cf} \leq T_m.$$

It should be realized here that, in the cartel-versus-fringe model, the Stackelberg equilibrium can be time inconsistent (Newbery, 1981), which conflicts with the assumption of rational behaviour. For the subject of time inconsistency, see, for instance, Groot et al. (1989). Instead of a Stackelberg approach a Nash-Cournot approach can be applied. A Nash-Cournot equilibrium is any situation where a player takes as given the optimum choice of the others, who are not able to increase their profits by altering their strategy. The Stackelberg procedure can be criticized because there it is assumed that one player can manipulate the reactions of the other. According to Salant, this is a non-explained asymetry. Moreover, it makes an extension from duopoly to oligopoly impossible (Salant, 1976, p. 1080). On the other hand, we may wonder whether the Nash-Cournot procedure is a sufficient reflection of the market power of the cartel (Groot et al., 1989).

For oligopolistic markets, Lewis and Schmalensee (1980) reached a simular result for the exhaustion time as the above cartel-versus-fringe model, which means that, if royalty rises by the rate of interest under perfect competition and marginal royalty, grows at the same rate under monopoly,

> ... noncooperative oligopoly equilibria are intermediate between these polar cases... (Lewis et al., 1980, p. 480).

Alternative resources and a backstop technology

In this section I look at the efficient depletion pattern which emerges if more exhaustible resources are involved and if perfect competition is assumed. A backstop technology is also assumed. This means that, in future, a superabundant resource is supposed to be available. Nordhaus described his view on the transition phase towards the phase of the backstop technology as follows:

> Ultimately, if and when the transition is completed to an economy based on resources present in superabundant quantities -whether this be nuclear fission or fusion, solar, geothermal, or some as yet undiscovered technology- the economic importance of the scarcity of exhaustible resources will disappear, and capital and labor costs alone will determine prices. This ultimate technology -resting on a super abundant resource base- is the *backstop technology*...Nordhaus (1979, p. 11).

How will prices develop during the transition phase when more exhaustible resources and, in the end, a backstop technology are available? In Figure 8.3 we can see, for example, the price curves (p_1, p_2) of two exhaustible resources and the price curve of the backstop technology (p_{bs}).

Starting at point of time 0, we can see that, until point of time t_1, exhaustible resource 1 is used with royalty r_1, rising by the rate of interest and depletion cost, i.e. the cost of labour and capital, z_1. This must be so, because until point of time 1 exhaustible resource 1, will be cheaper than exhaustible resource 2. Since $r_1 > r_2$, p_1 must rise faster than p_2, which consists of r_2 plus z_2. At t_1, resource 1 is completely depleted. Dashed extensions of the supply price curves indicate that these are purely accounting prices, since the resource is exhausted. Precisely at that time, exhaustible resource 2 must take over, p_2 rising further by the rate of interest. At t_2, resource 2 must be exhausted. At that time, p_2 must be exactly equal to the price of the backstop technology (p_{bs}). This price pays no royalty because, by definition, a backstop technology is a superabundant resource, which means that it is a free resource in the economic sense. At t_2, the supply price (OA) only consists of capital and labour costs (Nordhaus, 1979, p. 11). As Solow stated:

> The "backstop technology" provides a ceiling for the market price of the natural resource (Solow, 1974b, p. 5).

Now, I want to take a more precise look at the case of an exhaustible resource under perfect competition, assuming a backstop technology and assuming only one

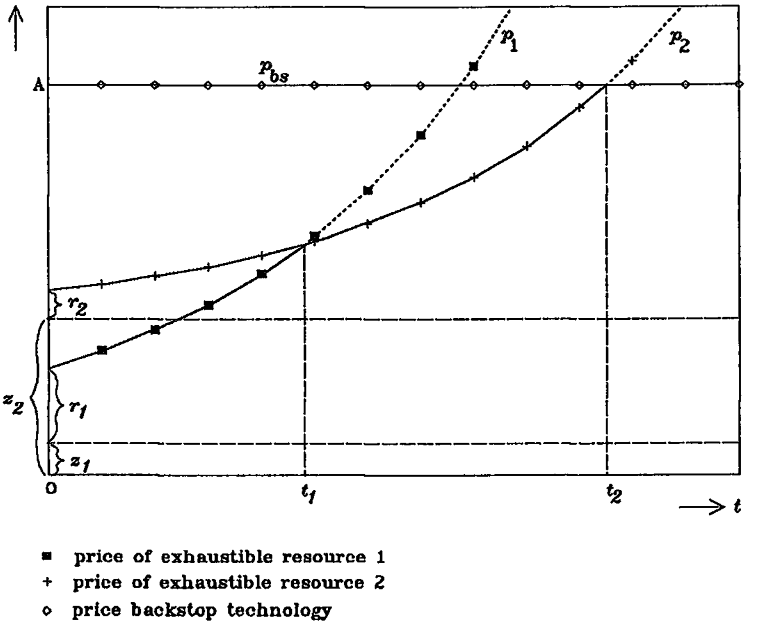

Figure 8.3: More exhaustible resources and a backstop technology.
Source: Nordhaus, 1979, p. 10.

exhaustible resource and a net backstop price p_{bsn}, equal to the supply price of the backstop technology minus the extraction costs of the exhaustible resource. Figure 8.4 shows these assumptions in graphic form.

Figure 8.4 shows the royalty curve of an exhaustible resource. Royalty (p) starts at p_0 and rises by the rate of interest until the net backstop price (p_{bsn}) is reached at t^*. After that point of time, the resource is exhausted.

The net backstop price technology can now be expressed as follows:

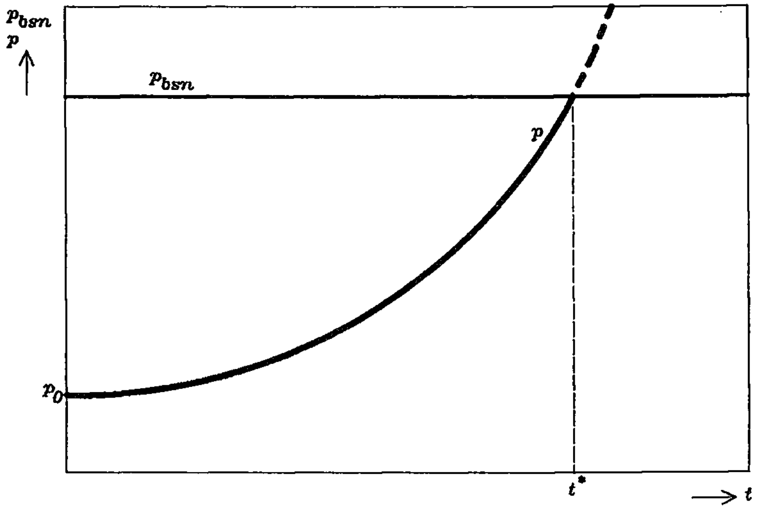

Figure 8.4: The net backstop price together with the royalty curve of one exhaustible resource.

(38) $\quad p_{bsn} = K \cdot e^{-\beta}, \qquad \beta \geq 0.$

Then, at time 0, royalty must be equal to:

(39) $\quad p_0 = K \cdot e^{-\upsilon \cdot T - \beta}.$

Royalty must also rise by the rate of interest:

(40) $\quad p_t = p_0 \cdot e^{\upsilon \cdot t}.$

From equations (39) and (40) it follows:

(41) $\quad p_t = K \cdot e^{\upsilon \cdot (t - T) - \beta}.$

Together with the specified demand function (equation 2), this results in:

$$(42)\qquad K \cdot e^{-\alpha \cdot q} = K \cdot e^{\upsilon \cdot (t-T) - \beta}$$

$$q_t = \frac{\beta}{\alpha} + \frac{\upsilon}{\alpha} \cdot (T - t).$$

From this it follows:

$$(43)\qquad \int_0^T q\,dt = \int_0^T \left\{ \frac{\beta}{\alpha} + \frac{\upsilon}{\alpha} \cdot (T - t) \right\} dt$$

$$\omega = [\frac{\beta}{\alpha} \cdot t + \frac{\upsilon}{\alpha} \cdot \left(T \cdot t - \frac{1}{2} \cdot t^2 \right)]_0^T$$

$$\frac{1}{2} \cdot \frac{\upsilon}{\alpha} \cdot T^2 + \frac{\beta}{\alpha} \cdot T - \omega = 0.$$

This quadratic equation has one negative and one positive solution for T, of which only the positive solution is relevant. This solution for the depletion time under perfect competition (T_{pc}) is:

$$(44)\qquad T_{pc} = \frac{-\beta + \sqrt{\beta^2 + 2 \cdot \alpha \cdot \upsilon \cdot \omega}}{\upsilon}.$$

A rise in β means that the backstop price is reduced, for example, because of the discovery of a new backstop technology at the beginning of the exploitation period. As β rises, the depletion time will be accordingly shortened as is shown in Table 8.2.

The backstop technology involved can be of a different nature. Generally, examples of non-depletable resources as solar power are given. However, in the category of depletable resources, a backstop technology might also be present. Of course, this cannot be a depletable resource of the exhaustible type, it has to be a renewable resource. In this respect, we might think of the use of agricultural products serving as raw materials in industry or as energy resources. This is generally known as the agrification of the resource base. Another example is wood. As a backstop technology it serves several purposes, such as building material or a source of energy. Of course, for those purposes, nothing less than a technical revolution in forestry and industry will have to take place. However, in the long run, it is not unthinkable. The economic aspect of these possible backstop technologies is situated in the price for

Table 8.2: The relation between the depletion time and the value of β.

β	$T_{pc} = \frac{-\beta + \sqrt{\beta^2 + 2 \cdot \alpha \cdot \upsilon \cdot \omega}}{\upsilon}$
0	31.62
1	23.17
2	17.42
3	13.59

$\omega = 100, \quad \alpha = 0.5, \quad \upsilon = 0.1$

these renewable resources. We saw that, if a non-depletable resource serves as a backstop technology, the price of it will only be determined by the input of labour and capital. If the backstop technology is a renewable resource, then the price of this resource (p_{bs}) can also be determined partly by a constant royalty. Indeed, it is not necessary for a renewable resource to be available in superabundant quantities, though serving as a backstop technology,

Technological change

To introduce technological change into the previous section's model, I follow the same line of thought as Nordhaus:

> An important extension is the introduction of technological change. Assume for simplicity that technological change is proceeding at rate λ throughout the energy sector relative to the rest of the economy. This affects the *costs* of extraction and of the backstop technology, but *not the growth rate of the royalty* (Nordhaus, 1979, p. 13).

This assumption implies that the price of the backstop technology, as well as the depletion costs of the exhaustible resource, will decrease by rate λ. This means that the net backstop price ($p_{bsn} = p_{bs} - z$) also decreases by rate λ.[1] Therefore, the royalty at time 0 can be written as:

(45) $$p_0 = K \cdot e^{-\beta} \cdot e^{-\lambda \cdot T} \cdot e^{-\upsilon \cdot T}$$

$$p_0 = K \cdot e^{-\beta - T \cdot (\lambda + \upsilon)}.$$

Royalty must rise by the rate of interest, which means that:

$$(46) \qquad p_t = p_0 \cdot e^{\upsilon \cdot t}.$$

From (45) and (46) it follows:

$$(47) \qquad p_t = K \cdot e^{-\beta - T\cdot(\lambda+\upsilon)+\upsilon\cdot t}.$$

Equation (47) together with equation (2) results in:

$$(48) \qquad K \cdot e^{-\alpha \cdot q} = K \cdot e^{-\beta - T\cdot(\lambda+\upsilon)+\upsilon\cdot t}$$

$$q_t = \frac{\beta}{\alpha} + \frac{T}{\alpha}\cdot(\lambda+\upsilon) - \frac{\upsilon}{\alpha}\cdot t$$

$$\int_0^T q_t dt = \int_0^T \left\{\frac{\beta}{\alpha} + \frac{T}{\alpha}\cdot(\lambda+\upsilon) - \frac{\upsilon}{\alpha}\cdot t\right\} dt.$$

Because total stock equals ω, I can rewrite equation (48) as follows:

$$(49) \qquad \omega = \int_0^T \left\{\frac{\beta}{\alpha} + \frac{T}{\alpha}\cdot(\lambda+\upsilon) - \frac{\upsilon}{\alpha}\cdot t\right\} dt$$

$$\omega = [\frac{\beta}{\alpha}\cdot t + \frac{\lambda}{\alpha}\cdot T \cdot t + \frac{\upsilon}{\alpha}\cdot\left(T\cdot t - \frac{1}{2}\cdot t^2\right)]_0^T$$

$$\left(\frac{\lambda}{\alpha} + \frac{1}{2}\cdot\frac{\upsilon}{\alpha}\right)\cdot T^2 + \frac{\beta}{\alpha}\cdot T - \omega = 0.$$

This is a quadratic equation with one negative and one positive solution for T, of which only the positive solution is relevant. This solution is:

$$(50) \qquad T_{pc} = \frac{-\beta + \sqrt{\beta^2 + 2\cdot(2\cdot\lambda+\upsilon)\cdot\alpha\cdot\omega}}{2\cdot\lambda+\upsilon}.$$

The suffix pc in equation (49) indicates that this solution is reached under the assumption of perfect competition. Technological change implies that total depletion time will be shortened. In fact, it has the same effect as an increase in the rate of interest. Table 8.3 illustrates this.

Table 8.3: The relation between the depletion time and technological change.

λ	$T_{pc} = \frac{-\beta + \sqrt{\beta^2 + 2 \cdot (2 \cdot \lambda + \upsilon) \cdot \alpha \cdot \omega}}{2 \cdot \lambda + \upsilon}$
0	23.17
0.02	20.52
0.04	18.66
0.06	17.25

$\omega = 100, \quad \alpha = 0.5, \quad \upsilon = 0.1, \quad \beta = 1$

Influence of market power in resource markets and a backstop technology

Until now I have looked at a backstop technology situation in a market of perfect competition. Now, suppose that an exhaustible resource stock is depleted by a cartel or a monopolist. Assume also that a backstop technology is finally available.

As I have already shown in this chapter, in the absence of a backstop technology, the time needed until complete depletion of an exhaustible resource by a monopolist will be longer than in a situation of perfect competition. In this case, if the shape of the demand curve is $p = K \cdot e^{-\alpha \cdot q}$, a monopolist will take about 1.6 times the period needed by firms under perfect competition to deplete the stock completely. The question is whether a backstop technology will influence this result.

According to the optimum rule of a monopoly, marginal royalty must rise at the interest rate. However, when royalty has arrived at the price of the backstop technology (minus the depletion costs of the exhaustible resource), marginal royalty will make a jump to this price, since at this point elasticity of demand will become infinite. This is shown as a graph in Figure 8.5. Indeed, the marginal royalty curve is AEFH. Until t_1, marginal royalty (AE) of the exhaustible resource increases by the rate of interest, while the royalty increases by a percentage which will be lower than the interest rate[2]. This implies that royalty always exceeds marginal royalty. At t_1, royalty reaches the price of the backstop technology (OD). At that time, both it and marginal royalty will become marginally lower than this backstop price (t_1F). The solution where a little less than the backstop price for the exhaustible resource is charged is called the *limit price solution*, indicating that the price is limited by the competitive backstop price. Nordhaus stated:

> The details of the solution are quite interesting because *in the inelastic range of the solution the monopolist behaves as if he were a competitor with a zero interest rate* (Nordhaus, 1979, p. 20).

Until the stock of the exhaustible resource is depleted (at t_3), this situation remains unchanged. After t_3 the backstop technology is used.

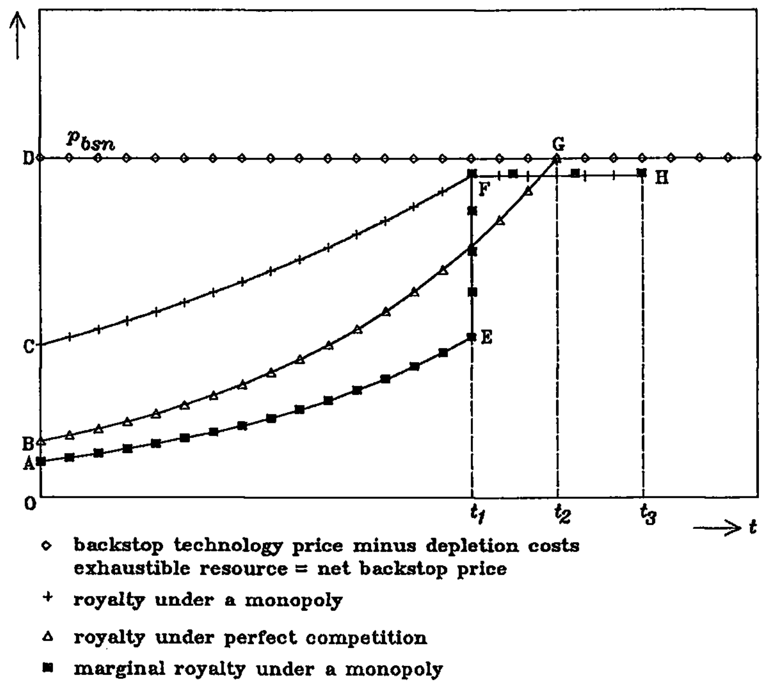

Figure 8.5: A monopolist competing against a backstop technology.

Figure 8.5 also shows the perfect competiton price path (BG). In a state of perfect competition the exhaustible resource will be depleted at t_2. Price under perfect competition rises at the interest rate. Since the monopoly price rises at a lower percentage than the rate of interest, the price path of the monopoly is mostly situated above the perfect competion price path. This implies that under a monopoly, the exhaustible resource is depleted later than is the case in a situation of perfect competition. A formal proof of this, using the specified demand function, follows.

Expressing the backstop price (p_{bs}) as $K \cdot e^{-\beta}$, and knowing that the specified demand function is $p = K \cdot e^{-\alpha \cdot q}$ and that the marginal revenue function equals $MR = K \cdot e^{-h \cdot \alpha \cdot q}$, I can determine q at the time of the *kink* in the demand function by stating that:

$$(51) \quad K \cdot e^{-\beta} = K \cdot e^{-\alpha \cdot q}$$

$$q = \frac{\beta}{\alpha}$$

$$MR = K \cdot e^{-h \cdot \beta}.$$

I know that the difference between the backstop price and the marginal revenue as determined with equation (51) must be bridged in T_2 periods, where T_2 is calculated as follows (see also Nordhaus, 1979, p. 19):

$$(52) \quad K \cdot e^{-\beta} = K \cdot e^{-h \cdot \beta + \upsilon \cdot T_2}$$

$$T_2 = \frac{\beta \cdot (h-1)}{\upsilon}.$$

Using equation (52), I have calculated the time between t_1 and t_3 as shown in Figure 8.5. The amount of resource delivered to the market in that time per year, as I have calculated with equation (51), equals β / α. This means that total amount delivered in period $t_1 t_3$ must be equal to:

$$(53) \quad \int_{t_1}^{t_3} q_t dt = \frac{\beta}{\alpha} \cdot \frac{\beta \cdot (h-1)}{\upsilon}.$$

This means that the total amount depleted in period t_1 must be equal to:

(54) $$\int_0^{t_1} q_t dt = \omega - \frac{\beta^2 \cdot (h-1)}{\alpha \cdot \upsilon}.$$

With the result of equation (54) it is possible to determine t_1. in the same way as I did before. Equation (55) gives the result of this calculation, and the total time a monopolist needs for total depletion of the exhaustible resource (T_{mon}):

(55) $$t_1 = \sqrt{\frac{2 \cdot \left\{\omega - \frac{\beta^2 \cdot (h-1)}{\alpha \cdot \upsilon}\right\} \cdot h \cdot \alpha}{\upsilon}}$$

$$t_3 - t_1 = \frac{\beta \cdot (h-1)}{\upsilon}$$

$$T_{mon} = t_3$$

$$T_{mon} = \frac{\beta \cdot (h-1)}{\upsilon} + \sqrt{\frac{2 \cdot \left\{\omega - \frac{\beta^2 \cdot (h-1)}{\alpha \cdot \upsilon}\right\} \cdot h \cdot \alpha}{\upsilon}}.$$

In Table 8.4, the depletion time of a monopolist is compared to the depletion time of firms under perfect competition for the situation in which a backstop technology is available.

Table 8.4: Comparing the depletion time of a monopolist with the depletion time of perfect competition in a backstop technology situation.

$T_{pc} = \frac{-\beta + \sqrt{\beta^2 + 2 \cdot \alpha \cdot \upsilon \cdot \omega}}{\upsilon}$	$T_{mon} = \frac{\beta \cdot (h-1)}{\upsilon} + \sqrt{\frac{2 \cdot \left\{\omega - \frac{\beta^2 \cdot (h-1)}{\alpha \cdot \upsilon}\right\} \cdot h \cdot \alpha}{\upsilon}}$
23.17	56.83
$\omega = 100, \quad h \approx 2.5, \quad \alpha = 0.5, \quad \beta = 1, \quad \upsilon = 0.1$	

It is clear that, for the specified demand function and marginal revenue function, a monopolist will also take more time in depleting the exhaustible resource in the case of a backstop technology than firms acting under perfect competition do.

Renewable resources and market forms

In Chapter 5 I showed that to reach an efficient depletion pattern in a perfect competition situation, the price of the renewable resource has to rise by the rate of interest, less the rate of renewal. In equilibrium, the rate of interest equals the rate of renewal, which implies that in this situation, the price of the renewable resource is stable as, of course, is the quantity supplied to the market.

In equilibrium the rate of renewal (α) equals the depleted quantity (q) divided by the stock of renewable resource $(\underline{n}_r)$, and is also stable. Stated algebraically:

$$(56) \qquad \upsilon = \alpha = \frac{q}{\underline{n}_r}.$$

Indicating an equilibrium stock, the symbol for the renewable resource is underscored. Equation (56) implies:

$$(57) \qquad q = \upsilon \cdot \underline{n}_r.$$

The (constant) price can be determined with the help of the specified demand function (equation (2)).

$$(58) \qquad p = K \cdot e^{-a \cdot \upsilon \cdot \underline{n}_r}.$$

In a monopoly situation the outcome is exactly the same as with perfect competition. The reason for this is because, with a monopoly, it is marginal revenue and not price which rises by the difference between the rate of interest and the rate of renewal:

$$(59) \qquad MR_t = MR_0 \cdot e^{(\upsilon - \alpha) \cdot t}.$$

This outcome follows from the optimal control procedure carried out in Appendix 8.3 of this chapter. In equilibrium, marginal revenue is a constant, which implies that the rate of renewal must equal the rate of interest. This leads us to the same conclusions as for perfect competition, which are formulated using the equations (57) and (58). These results are reached by using the following rather strong assumptions:

- Natural stock develops according to the logistic curve. Though this curve is a fairly good approach to the development of many living species and some non-living renewable resources (e.g. fresh water supplies), different growth processes are possible (Wilen, 1982, pp. 77-121).
- An equilibrium between the rate of interest on the one hand and the rate of renewal has to be possible. This means that the curve of the rate of renewal intersects the curve of the discount rate as has been shown in Figure 5.1 in Chapter 5. A relatively high discount rate and a relatively low renewal capacity of the renewable resource, as well as the presence of a rather high threshold in the development of the renewable resource, might eventually lead to the dying out of a species, since, in that case, an equilibrium cannot be reached. The speed by which the population will possibly die out also depends, of course, on the market form. Perfect competition will stimulate a fast dying-out process; monopoly will delay the dying-out process.
- For the market form of perfect competition, it is assumed that individual property rights are recognized, so that every private firm knows exacly which part of the stock it owns. Of course, there are a lot of renewable resources for which this is not true. Sea fish, game and parts of tropical rain forests are proper examples of the so-called common property phenomenon, as here there are no private property rights. Of course, with a monopoly this is no problem, since by definition, in that situation there is only one owner or exploiter. The consequences for the depletion of common resources will be shown in the next chapter.

Concluding remarks

In this chapter I have looked at resource depletion in relation to certain market forms. It appears that the depletion speed is slower in proportion to the market power of the individual firm. Thus, firms under perfect competition deplete a resource stock faster than firms in a cartel fringe situation, which in their turn, have a higher depletion speed than a monopoly. Indeed, it has to be stressed here that these results have been reached under the condition of partial equilibrium, which means that both the demand function of a resource as well and the discount rate are given (Withagen, 1990).

Appendix 8.1: Solving the dynamic optimization problem for the monopoly situation with the calculus of variations

As has been said in the main text, the optimization problem in case of a monopoly can also be solved by using the calculus of variations. According to this theory (see Appendix 5.1, also for the notations), the problem can be solved as follows:

$$\max \qquad J(q) = \int_0^T p(q(t)) \cdot q(t) \cdot e^{-\upsilon \cdot t} dt,$$

$$G(q, q', t) = q.$$

Since there is no q' – dependency, we find for the Euler equation:

$$\frac{\partial}{\partial q}(p(q) \cdot q \cdot e^{-\upsilon t} + \lambda q) = 0$$

$$\frac{dp}{dq} \cdot q \cdot e^{-\upsilon t} + p \cdot e^{-\upsilon \cdot t} + \lambda = 0$$

$$\frac{dp}{dq} \cdot q + p = -\lambda \cdot e^{\upsilon t}$$

$$MR_t = -\lambda \cdot e^{\upsilon t}, \quad t = 0 \text{ gives } MR_0 = -\lambda.$$

So, $MR_t = MR_0 \cdot e^{\upsilon t}$.

Appendix 8.2: Approximation of the marginal revenue function in the monopoly situation

The first thing to do in determining the approximation of the marginal revenue function is to set suitable standards to be met by the approximation. To do so, Figure 8a.1 is useful.

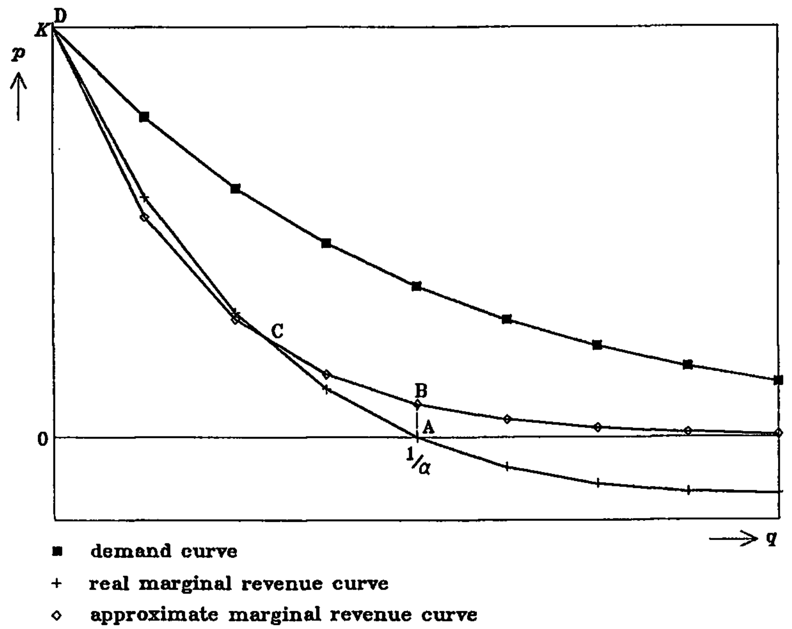

Figure 8a.1: **Real and approximate marginal revenue curve.**

The three curves in this figure are:

the demand curve:

$$p = K \cdot e^{-\alpha \cdot q}.$$

the real marginal revenue curve:

$$MR = -\alpha \cdot q \cdot K \cdot e^{-\alpha \cdot q} + K \cdot e^{-\alpha \cdot q}.$$

The approximate marginal revenue curve:

$$MR_a = K \cdot e^{-\beta \cdot q}.$$

The problem is to find a value for β so that the area under the real marginal revenue curve, up to the point of intersection with the x-axis (area OACD), equals the area under the approximate marginal revenue curve (area OABCD). The marginal revenue curve after the point of intersection is not relevant, since marginal revenue can never be negative if the monopolist operates efficiently.

As can be derived from the real marginal revenue curve, the point of intersection with the x-axis lies at $1/\alpha$.

The next thing to do is to find an expression for the area OACD:

$$\int_0^{1/\alpha} MR\,dq = K \cdot \int_0^{1/\alpha} e^{-\alpha \cdot q} - \alpha \cdot K \cdot \int_0^{1/\alpha} q \cdot e^{-\alpha \cdot q}\,dq$$

$$\int_0^{1/\alpha} MR\,dq = -\frac{K}{\alpha} \cdot [e^{-\alpha \cdot q}]_0^{1/\alpha} - \alpha \cdot K \cdot \left[-\frac{1}{\alpha} \cdot e^{-\alpha \cdot q} \cdot q - \frac{1}{\alpha^2} \cdot e^{-\alpha \cdot q}\right]_0^{1/\alpha}$$

$$= -\frac{K}{\alpha} \cdot \left(\frac{1}{e} - 1\right) + K \cdot \left(\frac{2}{\alpha \cdot e} - \frac{1}{\alpha}\right)$$

$$= \frac{K}{\alpha \cdot e}.$$

The area OACD must be equal to the area OABCD. This means that:

$$\int_0^{1/\alpha} K \cdot e^{-\beta \cdot q} = \frac{K}{\alpha \cdot e}$$

$$\int_0^{1/\alpha} e^{-\beta \cdot q} = \frac{1}{\alpha \cdot e}$$

$$\left[-\frac{1}{\beta} \cdot e^{-\beta \cdot q}\right]_0^{1/\alpha} = \frac{1}{\alpha \cdot e}$$

$$-e^{-\beta/\alpha} + 1 = \frac{\beta}{\alpha \cdot e}.$$

Now define $h = \beta/\alpha$. Then the above equation can be rewritten as follows (see Heijman, 1990):

$$\frac{h}{e} + e^{-h} = 1, \quad \text{so} \quad h = 2.494....$$

Because $\beta = h \cdot \alpha$, I can now conclude that the approximate marginal revenue function equals:

$$MR_a = K \cdot e^{-h \cdot \alpha \cdot q}.$$

From the above deductions it is clear that the approximate marginal revenue curve becomes more accurate as α becomes smaller. If α equals zero, the approximate marginal revenue curve is equal to the real marginal revenue curve.

Appendix 8.3: Solving the dynamic optimization problem for a monopoly in the case of a renewable resource

The problem in question is the same as:

$$\text{Maximize} \quad K(n) = \int_0^T p(\alpha(n_t) - n'_t) \cdot (\alpha(n_t) - n'_t).e^{-v \cdot t} dt$$

with n_t such that $n_0 = M, \quad n_T = N, \quad N \leq M.$

This problem can be solved by the calculus of variations (see appendix 5.1) by taking:

$$I(n, n', t) = p(\alpha(n) - n') \cdot (\alpha(n) - n') \cdot e^{-v \cdot t},$$

$$n_0 = M, \quad n_T = N,$$

$$G = 0, \quad c = 0.$$

Now the Euler equation $\dfrac{\partial I}{\partial n} = \dfrac{d}{dt}\left(\dfrac{\partial I}{\partial n'}\right)$ gives:

$$p'(\alpha(n)-n')\cdot\alpha'(n)\cdot(\alpha(n)-n')\cdot e^{-v\cdot t}+p(\alpha(n)-n')\cdot\alpha'(n)\cdot e^{-v\cdot t}=$$

$$\frac{d}{dt}(-p'(\alpha(n)-n')\cdot(\alpha(n)-n')\cdot e^{-v\cdot t}-p(\alpha(n)-n')\cdot e^{-v\cdot t}).$$

Because $MR_t=p'(\alpha(n)-n')\cdot(a\cdot n-n')+p(a\cdot n-n')$, we have

$$\alpha'(n)\cdot(e^{-v\cdot t}\cdot MR_t)=-\frac{d}{dt}(e^{-v\cdot t}\cdot MR_t).$$

So $e^{-v\cdot t}MR_t=c\cdot e^{-A(t)}$, where $A(t)$ is the primitive of $\alpha'(n_t)$.

So $MR_t=c\cdot e^{(v\cdot t-A(t))}$.

In the case $\alpha(n_t)=a\cdot n_t$ we can take $A(t)=a\cdot t$ and thus

$MR_t=c\cdot e^{(v-a)\cdot t}=MR_0\cdot e^{(v-a)\cdot t}$

Now let us determine an explicit formula for n_t. Because of the rule $MR_t=MR_0\cdot e^{(v-a)\cdot t}$, n_t is given by the first order differential equation

$$P'(a\cdot n_t-n'_t)\cdot(a\cdot n-n'_t)+p(a\cdot n_t-n'_t)=MR_0e^{(v-a)\cdot t}. \qquad (*)$$

Using a standard method, this equation can easily be solved for a linear demand function $p(q)=E\cdot q+B$, $(E<0,\ B>0)$. (*) becomes:

$$n'_t-a\cdot n_t=\frac{B}{2\cdot E}-\frac{MR_0}{2\cdot A}\cdot e^{(v-a)\cdot t},$$

with $n_0=M$, $n_T=N$.

The solution is then:

$$n_t = \left\{ \frac{B}{2 \cdot E \cdot a} + \frac{N - M - \frac{B}{2 \cdot E \cdot a} \cdot (e^{a \cdot t} - 1)}{e^{a \cdot T} - e^{(v-a) \cdot T}} \right\} \cdot e^{a \cdot t} -$$

$$\frac{N - M - \frac{B}{2 \cdot E \cdot a} \cdot (e^{a \cdot T} - 1)}{e^{a \cdot T} - e^{(v-a) \cdot T}} + M - \frac{B}{2 \cdot E \cdot a}.$$

Notes

1) This might be considered a rather specific case, since the costs of extraction may also increase because of the decreasing attainableness of the natural resource. For instance, for Indonesian oil, the real production costs per barrel (in 1970 dollars) increased in the period 1970-1984. This result was reached with the following regression equation, based on data gained from Repetto et al. (1989).

$$C = \underset{(t=5.90)}{0.2788} \cdot T + 0.0195 \qquad (R^2 = 0.73)$$

with C for production costs per barrel and T for time. In fact, this contradicts the conclusion reached by Adelman that there was no increase in development cost after 1955 (Adelman, 1990). Indeed, in other cases, the assumption of decreasing production costs per recovered unit might hold. For instance, for Dutch home-grown timber, Slangen has shown that production costs per m^3 decreased over the period 1970-1984 (Slangen, 1987).

2) This means that it is assumed that the price elasticity of demand rises when price increases (van de Klundert et al., 1983, pp. 156-159). This is true for the used specified demand function (equation 2). See Figure 8.1.

9. Common resources

Depletable resources can be divided into *exclusive* and *non-exclusive* resources. With exclusive resources, property rights are fully recognized; with non-exclusive resources, for instance fish at sea or game in the woods in some parts of the world, there are no property rights. That is why these resources are called *common resources*. In the last four chapters I examined exclusive resources; in this chapter I want to deal with these common resources, or commons.

Characteristics of the common resources

The essential element of common resources is that there is no right of ownership on these resources. The right of ownership implies: exclusivity (which provides incentives for those who own the resources to put them into the highest-valued use) and transferability (which makes it possible to transfer resources from less productive to more productive owners) (Pejovich, 1990). Common resources[1)] have several related characteristics:

- *Non-exclusivity.* There are no property rights on these kind of resources. Everybody who is able to use it may do so. No royalty is paid for the depletion of the resource, and there are no juridical barriers
- *Perfect competition.* On the supply side there are no barriers to entering the market - neither juridical, technical nor economic. There are also no restrictions on the demand side of the market, which means that there are many consumers.
- *The irrelevancy of efficiency rules.* Since no royalty is being paid, efficiency rules, for instance the Hotelling rule, are irrelevant to common resources. This means that the rate of interest in the case of a common resource is relatively unimportant. Indeed, every individual producer who limits his production for the sake of future needs will be at a disadvantage with his competitors, who will extend their production at his expense. This prisoner dilemma is often called the tragedy of the commons, and is of the most poignant extravagancies of a cowboy economy.

This exploitation of common resources was described by Garrett Hardin as *the tragedy of the commons.*

> The tragedy of the commons develops in this way. Picture a pasture open to all. It is to be expected that each herdsman will try to keep as many cattle as possible on the commons. Such an arrangement may work reasonably satisfactorily for centuries because tribal wars, poaching, and disease keep the

> numbers of both man and beasts well below the carrying capacity of the land. Finally, however, comes the day of the reckoning, that is the day when the long-desired goal of social stability becomes a reality. At this point, the inherent logic of the commons remorselessly generates tragedy (Hardin, 1980, p. 104).

Since each herdsman acts rationally, seeking to maximize his gain, he asks himself whether it is worthwhile adding one more animal to his herd:

> The positive aspect is a function of the increment of one animal. Since the herdsman receives all the proceeds from the sale of the additional animal, the positive utility is nearly 1.
>
> The negative component is a function of the additional overgrazing created by one more animal. Since, however, the effects of overgrazing are shared by all the herdsmen, the negative utility for any particular decision-making herdsman is only a fraction of -1 (Hardin, 1980, p. 104).

It is clear that, on this individual rational basis, each herdsman will extend his herd too much.

> Each man is locked into a system that compels him to increase his herd without limit - in a world that is limited (Hardin, 1980, p. 104; see also: Hartog, 1989).

As Dasgupta rightly said when commenting on these passages, it would be wrong to suppose that each herdsman in Hardin's example will add cattle without limit, because animals are not costless. Nevertheless, the core of Hardin's remarks, that depletable resources are likely to be over-used if free of charge, is completely correct (Dasgupta, 1982). This same conclusion was drawn by Gordon for fishery (Gordon, 1954).

Common resources can be exhaustible or renewable. Since analytical results are hard to gain because of the large amount of interacting variables, especially for the renewable resources (Dasgupta, 1982), I have chosen a special approach to the study of common resources. Instead of analytical models, a set of numerical models will be used. This involves a solution procedure based on simulation methods carried out on the computer. The advantage of this approach is that more complex models can be handled than can with an analytical procedure (see for instance van Wijngaarden, 1985). The methodological drawback is that the results gained by the simulation method are more specific than those gained by an analytical procedure. In the following section I apply the method to common exhaustible resources, and do the same for common renewable resources later in the chapter.

Common exhaustible resources

Suppose there is an amount of a common exhaustible resource, for instance an amount of coal or oil. Of course, nowadays the greater part of these two resources cannot be called a *common resource*, but when these fuels were first exploited, at least in most of the world, they bore all the characteristics of a common resource. A modern common exhaustible resource is the stock of manganese nodules on the ocean bottom. These nodules also contain iron, copper, nickel and cobalt (Brookins, 1990). It has been estimated that by the year 2000 about 35 % of the world supply of nickel will come from this stock of nodules (Mitchell Beazley, 1980). It is clear that without proper international regulation this stock will be depleted too quickly[2]. The questions to be solved are firstly, which factors determine the depletion speed of this common property and, secondly, how can governments influence the depletion speed of this common resource.

To be able to study the depletion process under these circumstances I developed the following model of an exhaustible resource sector. It consists of six equations. The flow of resource in period t (q_t) is found by the input of two production factors: the stock of resource at the end of the last period ($n_{e,t-1}$) and a factor which is called *human effort* (m_t), which is a composite of labour and capital. The production function used is the Cobb-Douglas production function of the linearly homogenous type:

$$(1) \qquad q_t = \beta \cdot n_{e,t-1}^{\alpha} \cdot m_t^{1-\alpha} \quad \text{where} \quad 0 < \alpha < 1.$$

In equation (1), α and β are parameters. The stock of the exhaustible resource at the end of year t depends on the stock at the end of the previous period minus the depletion in the present period[3]:

$$(2) \qquad n_{e,t} = n_{e,t-1} - q_t.$$

The price of the resource (p_t) on the market depends on the quantity brought to the market. I have assumed that the price is a linear decreasing function of the quantity[4]:

$$(3) \qquad p_t = \delta - \gamma \cdot q_t.$$

In equation (3), δ and γ are positive parameters. The annual turnover (o_t) equals the price multiplied by quantity:

(4) $o_t = p_t \cdot q_t.$

The annual costs (z_t) are assumed to be a linear increasing function of human effort:

(5) $z_t = \nu \cdot m_t.$

The yearly profit equals the annual turnover minus yearly costs. It is supposed that as well as the absence of property rights there is also perfect competition, meaning that no profit is being made. This implies that the annual turnover equals yearly costs:

(6) $o_t = z_t.$

Via substitution, equations (3), (4), (5) and (6) can be reduced to:

(7) $m_t = \frac{\delta}{\nu} \cdot q_t - \frac{\gamma}{\nu} \cdot q_t^2.$

I proceed now with equations (1), (2), (3) and (7), the last being shown in Table 9.1.

Table 9.1: A simulation model for a common exhaustible resource.

$q_t = \beta \cdot n_{e,t-1}^{\alpha} \cdot m_t^{1-\alpha} \quad (t \geq 1)$

$n_{e,t} = n_{e,t-1} - q_t$ however: see note 3 $\quad (t \geq 1)$

$p_t = \delta - \gamma \cdot q_t \quad (t \geq 1)$

$m_t = \frac{\delta}{\nu} \cdot q_t - \frac{\gamma}{\nu} \cdot q_t^2 \quad (t \geq 1)$

$n_{e,0} \geq 0$ given

One of the few things about the above model which can be analytically proved is the existence of unique positive solutions q_t, m_t, $n_{e,t}$ and p_t of the model in table 9.1. This fundamental proof is given in Appendix 9.1. To obtain more ideas on what can be proved analytically, I shall carry out a numerical experiment, for which the parameters of the model still have to be chosen. Suppose the following parameters: $\alpha = 0.5$, $\beta = 0.4$, $\gamma = 0.5$, $\delta = 50$ and $\nu = 10$. Further, assume the initial stock ($n_{e,0}$) to be 100 units. The results of the simulation procedure are shown in Table 9.2.

Table 9.2: Stock, yearly depletion, input of human effort and prices of the resource in case of a common exhaustible resource[5].

year (t)	stock ($n_{e,t}$)	yearly depletion (q_t)	input of human effort (m_t)	price (p_t)
0	100.0	-	-	-
1	55.6	44.4	123.5	27.8
2	24.8	30.8	106.5	34.6
3	8.2	16.6	69.1	41.7
4	2.1	6.1	29.0	46.9
5	depleted	2.1	8.0	50.0
6	depleted	0.0	0.0	50.0

$\alpha = 0.5,\ \beta = 0.4,\ \gamma = 0.5,\ \delta = 50,\ \nu = 10,\ n_{e,0} = 100$

As can be deduced from Table 9.1, the stock is depleted after 5 years. Yearly depletion and the input of human effort follow the same pattern as that of the resource stock. In the first period they are both relatively high and after five years they both decrease to zero. On the other hand, prices begin on a moderate level and rise to the maximum level after five years. It is worthwhile examining whether the depletion pattern always follows this pattern, which means that:

(a) $n_{e,0} \geq n_{e,1} \geq n_{e,2} \geq \ldots$

(b) $m_1 \geq m_2 \geq m_3 \geq \ldots$

(c) $q_1 \geq q_2 \geq q_3 \geq \ldots$

(d) $p_1 \leq p_2 \leq p_3 \leq \ldots$

(e) There exists a T so that $n_{e,T} \leq 1$[5].

Because of equation (2) (that is we are here dealing with an exhaustible resource), (a) is of course always true, (c) follows immediately from (a), (b) and equation (1), (d) follows from (c) and equation (3). This only leaves (b) and (e) to be proved. From

Appendix 9.2 it appears that (b) occurs if $n_{e,0} \leq \nu \cdot \beta^2/\gamma$, and that (e) always occurs. It can be surmised, that, if $n_{e,0} > (\nu \cdot \beta^2)/\gamma$, then (a), (c), (d) and (e) still occur, and that sometimes m_t will increase, reach a maximum and finally decrease again. It is still not clear under which circumstances this occurs.

In the next section I want to look at what can be done about the gold rush depletion pattern of Table 9.2.

Conservation policies

Even the greatest advocates of non-intervention will agree that the above depletion pattern does not benefit society as a whole. One way or another, governments will have to interfere in order to establish an efficient depletion pattern. Magrath (1989, pp. 30-35) mentioned the following policy options as fit for exhaustible resources:

- *Quantity controls*. In this option, transferable permits or depletion quotas are sold. The pricing of such permits on a free market would raise a rent on the resource, thus ensuring an optimum allocation. Nontransferable permits have the disadvantage that they do not promote an efficient use of the permits by the owners.
- *Privatization*. If the commons are privatized, they would become exclusive resources. According to the Hotelling rule, in this case the owner would demand a royalty which, for perfect competition, should rise by the rate of interest.
- *Nationalization*. Here there would be one owner of the common resource: the state. Theoretically, the state is able to run a common resource stock efficiently. However, to ensure this, adequate government investment in management, supervision and control are urgently needed.
- *Taxation*. In this option the state sees itself as the owner of the commons entitled to collect royalties from the producers. This might be efficient if the royalty is correctly determined. In the next section such an optimum tax has been computed for the situation shown in Table 9.1.

Towards an efficient taxation policy

In the case of taxation, the producer has to pay not only the costs of human effort, but also a royalty (r_t) per resource unit. If this is so, then equation (5) changes into:

$$z_t = \nu \cdot m_t + r_t \cdot q_t. \quad (8)$$

Equation (8) together with equations (3), (4) and (6) give:

$$(9) \qquad m_t = \frac{\delta \cdot q_t - \gamma \cdot q_t^2 - r_t \cdot q_t}{\nu}.$$

Further, we know from Chapter 5 that the Hotelling rule implies that royalty has to rise by the rate of time preference if there is to be social efficiency[6]. In other words:

$$(10) \qquad r_t = r_0 \cdot (1 + \upsilon)^t.$$

The same simulation procedure can be carried out with equations (1), (2), (9) and (10) as was done with the case of non-intervention. The model has been summarised in Table 9.3.

Table 9.3: A simulation model for optimum taxation of a common exhaustible resource.

$q_t = \beta \cdot n_{e,t-1}^{\alpha} \cdot m_t^{1-\alpha} \qquad (t \geq 1)$

$n_{e,t} = n_{e,t-1} - q_t$ however: see note 3 $\qquad (t \geq 1)$

$m_t = \dfrac{\delta \cdot q_t - \gamma \cdot q_t^2 - r_t \cdot q_t}{\nu} \qquad (t \geq 1)$

$p_t = \delta - \gamma \cdot q_t \qquad (t \geq 1)$

$r_t = r_0 \cdot (1 + \upsilon)^t \qquad (t \geq 1)$

$n_{e,0} \geq 0$ given

Assuming that the rate of time preference (υ) equals 0.08, the same parameters have been used. The problem now is to find the optimum r_0. According to the Hotelling rule, this parameter must meet the following requirement: its value must be maximized so that the resource stock is depleted at exactly the same time as the price of the resource reaches its maximum. If its value is too high the resource stock will never be completely depleted. If it is too low, the resource stock is depleted too soon. Beginning with values which are too high, r_0 has been computed by way of trial and error procedure. This parameter appears to be equal to 15.71. Further, the simulation procedure delivers the results shown in Table 9.4.

Table 9.4: Stock, yearly depletion, human effort and prices of a common exhaustible resource in case of optimum taxation[5]).

time (t)	stock ($n_{e,t}$)	yearly depletion (q_t)	human effort (m_t)	price (p_t)
0	100.0	-	-	-
1	70.6	29.4	53.9	35.3
2	47.8	22.8	46.3	38.6
3	31.1	16.7	36.5	41.6
4	19.7	11.4	26.1	44.3
5	12.4	7.3	17.0	46.3
6	7.8	4.6	10.3	47.8
7	5.1	2.7	5.9	48.6
8	3.5	1.6	3.3	49.2
9	2.5	1.0	1.8	49.5
10	1.8	0.7	1.0	49.7
11	1.5	0.3	0.5	49.8
12	1.2	0.3	0.3	49.9
13	1.1	0.1	0.1	49.9
14	depleted	0.1	0.1	50.0
15	depleted	0.0	0.0	50.0

$\alpha = 0.5$, $\beta = 0.4$, $\gamma = 0.5$, $\delta = 50$, $v = 10$, $\upsilon = 0.05$, $r_0 = 15.71$, $n_{e,0} = 100$

Now, I want to compare the results of the non-intervention situation with the optimum tax situation. The state of the stock ($n_{e,t}$) and yearly depletion (q_t) can be seen in Figure 9.1 and Figure 9.2.

It can be concluded from these two figures that depletion under taxation proceeds at a considerably lower speed than it does in the case of non-intervention. Figure 9.3 shows a comparison between the input of human effort in the case of non-intervention and the input of human effort under optimum taxation. Finally, in Figure 9.4, prices under both systems are compared. Obviously the depletion pattern (a) - (e) in the non-intervention situation are still valid for the intervention case.

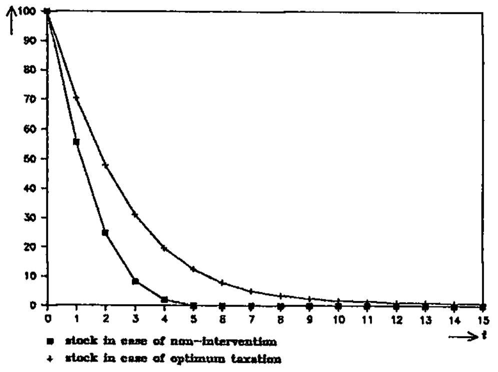

Figure 9.1: Stock in case of non-intervention compared with stock under optimum taxation.

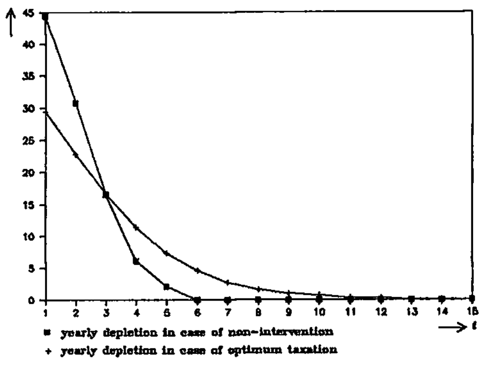

Figure 9.2: Yearly depletion in case of non-intervention compared with yearly depletion under optimum taxation.

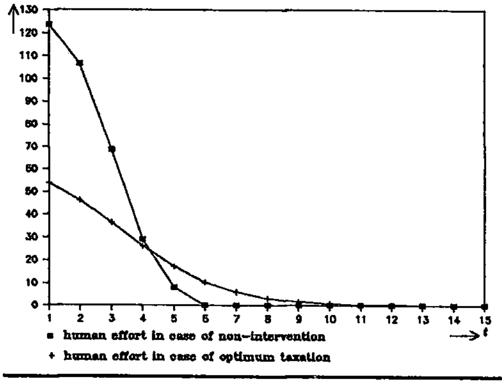

Figure 9.3: The input of human effort in case of non-intervention compared with the input of human efort under optimum taxation.

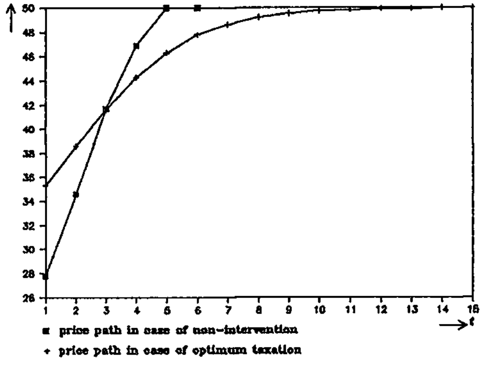

Figure 9.4: Prices in case of non-intervention compared with prices under optimum taxation.

Figure 9.3 shows that the input of human effort is more evenly spread under optimum taxation than under non-intervention. Figure 9.4 shows that with non-intervention, prices start at a lower level and rise quickly until the limit price of 50 is reached. In a situation of optimum taxation, this limit price is reached at a much later point of time.

As can be concluded from the outcomes of the simulation process, an optimum tax induces efficiency. However, in practice, the mere imposition of a fee for what had previously been free meets with resistance. In many cases, especially in developing countries, problems of enforcement, collection and responsible handling of revenues arise (Magrath, 1989). A way to solve these problems is to allow for depletion permits. These should be supplied for nothing to the initial exploiters of the common resource. Of course, the total depleted amount may not exceed the efficient yearly depletion, as is indicated in Table 9.4. If a user stops exploitation, he can sell the permit on the market. The price of such a permit in a situation of perfect competition is equal to the discounted value of the royalties gained in the future.

Common renewable resources

The aim of this section is to examine a sector in which a common renewable resource with a limited capacity to renew itself is exploited. This resource has a limited capacity to renew itself, such as a forest or a number of fish in a lake. An important concept, especially in relation to the fishery sector, is the *sustainable yield* (Clark, 1973; Munro et al., 1985). This concept is explained in Figure 9.5.

Figure 9.5 expresses the yearly sustainable yield as a function of the input of human effort. By *sustainable yield* is meant the yield which, since it equals natural renewal of the resource, does not affect total stock. If human effort increases, the total stock decreases and the sustainable yield increases up to a maximum. I have already pointed out this mechanism in Chapter 4. After reaching this maximum, natural renewal and sustainable yield decreases. Multiplying the physical sustainable yield by a constant price gives the sustainable yield expressed in money. Human effort multiplied by the cost per unit gives total costs. Sustainable yield minus the cost of human effort gives total profit.

With perfect competition and absence of property rights, human effort will increase up to the point where the sustainable yield expressed in money equals total costs (point C). At this point total stock will be relatively small. Maximum sustainable yield is gained at point B. A monopolist will put in an amount of human effort which equals OA, as, at that point profit is at a maximum. It is easy to see that in this situation perfect competition is not an efficient market form. The same turnover as is gained at point C would be gained with an input of human effort which equals OD. Moreover, with that input a profit would be gained, and the danger of overexploitation of the stock of renewable resource will have been avoided. Again, from this picture it appears that a

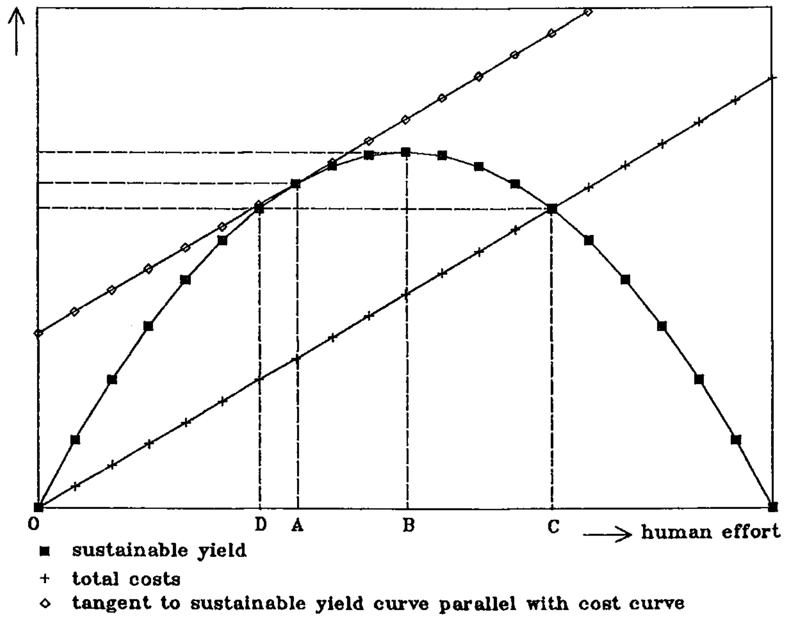

Figure 9.5: Sustainable yield.

monopolist is more careful about stocks of resources than are firms acting under perfect competition. Clearly the depletion of common resources under perfect competition can easily lead to overexploitation (Lette, 1985) and governments have an important task in trying to prevent this.

Proceeding with the dynamic version of the above static model, I want to first pay attention to the growth function of the renewable resource.

Growth function

The main difference between renewable resources and exhaustible reosurces is, of course, the fact that a renewable resource renews itself and an exhaustible resource does not. This renewal capacity is expressed in the following two equations:

$$(11) \qquad n_{r,t} = n_{r,t-1} + \Delta n_{r,t},$$

(12) $$\Delta n_{r,t} = \psi \cdot (n_{r,c} - n_{r,t-1}) \cdot n_{r,t-1}.$$

Equation (11) is a definition. The stock of the renewable resource at time t ($n_{r,t}$) equals the stock of the renewable resource at time $t-1$ plus the change of the stock in period t ($\Delta n_{r,t}$). Equation (12) is the equation for the change of the stock. In this equation ψ is a parameter. Parameter $n_{r,c}$ is the climax population of the stock. This climax population is the maximum extent of the stock of renewable resource if natural circumstances like space to live and food supply are taken into consideration (Krabbe et al., 1986). Now, suppose that $n_{r,c}$ equals 100, that total population in period 0 equals 1, and that ψ equals 0.005. In that case, population will develop as is shown in Figure 9.6.

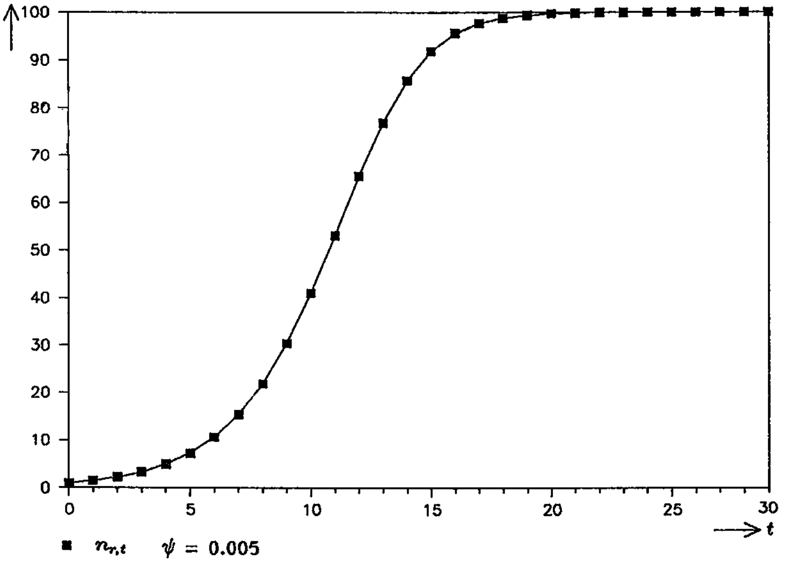

Figure 9.6: A logistic pattern in population development.

It can be concluded that these parameter values cause a logistic pattern in population development. The value of ψ appears to be especially crucial in gaining this result. If its value increases, then oscillations occur. Further increase of ψ can eventually even lead to a chaotic pattern in population development (May, 1976, De Vries, 1989). This has been elaborated further in Appendix 9.3. Here I confine myself to the usual logistic development pattern.

Extracting a common renewable resource

In this section I develop a dynamic model for the extraction of a common renewable resource. Because of this, equation (1) of this chapter has to be changed from:

(1) $$q_t = \beta \cdot n_{e,t-1}^{\alpha} \cdot m_t^{1-\alpha}$$

to:

(13) $$q_t = \beta \cdot n_{r,t-1}^{\alpha} \cdot m_t^{1-\alpha}.$$

Equation (11) is also needed. Equation (12) must be adjusted, because the annual extraction (q_t) has to be taken into account. That is why equation (12), $\Delta n_{r,t} = \psi \cdot (n_{r,c} - n_{r,t-1}) \cdot n_{r,t-1})$, becomes (14):

(11) $$n_{r,t} = n_{r,t-1} + \Delta n_{r,t}.$$

(14) $$\Delta n_{r,t} = \psi \cdot (n_{r,c} - n_{r,t-1}) \cdot n_{r,t-1} - q_t.$$

Equations (3), (4), (5) and (6) have been taken from the common exhaustible resource model:

(3) $$p_t = \delta - \gamma \cdot q_t,$$

(4) $$o_t = p_t \cdot q_t,$$

(5) $$z_t = \nu \cdot m_t,$$

(6) $$o_t = z_t.$$

Via substitution, the last four equations become:

(7) $$m_t = \frac{\delta}{\nu} \cdot q_t - \frac{\gamma}{\nu} \cdot q_t^2.$$

The final model consists of equations (13), (11), (14) and (7). This model is summarized in Table 9.5.

Table 9.5: A simulation model for the extraction of a common renewable resource.

$$q_t = \beta \cdot n_{r,t-1}^{\alpha} \cdot m_t^{1-\alpha} \qquad (t \geq 1)$$

$$n_{r,t} = n_{r,t-1} + \Delta n_{r,t} \qquad (t \geq 1)$$

$$\Delta n_{r,t} = \psi \cdot (n_{r,c} - n_{r,t-1}) \cdot n_{r,t-1} - q_t \qquad (t \geq 1)$$

$$p_t = \delta - \gamma \cdot q_t \qquad (t \geq 1)$$

$$m_t = \frac{\delta}{\nu} \cdot q_t - \frac{\gamma}{\nu} \cdot q_t^2 \qquad (t \geq 1)$$

$$n_{r,0} \geq 0 \quad \text{given}$$

This model belongs to those types which are called *predator prey* models, man here being a predator (Odum, 1975).

I now carry out a similar kind of simulation procedure to that which I did with the exhaustible resource. For parameters I have taken: $n_{r,c} = 100$, $\alpha = 0.5$, $\beta = 0.4$, $\gamma = 0.5$, $\delta = 50$, $\nu = 10$ $\phi = 0.005$ and $n_{r,0} = 100$. The results are recorded in Table 9.6.

What is remarkable is that where there is no human control of nature, for instance in national parks, some animals at the end of the food chain play the same role as man does in the case of common resources (Van Wijngaarden, 1985). It might be concluded that if there are no property rights, there is no real difference between the economic activities of man and the efforts of animals to survive.

Optimum tax for a common renewable resource

To prevent the renewable resource from dying out, one measure can be added to the list of policy options mentioned before: *seasonal restrictions*. This is a measure to allow a regeneration in the resources' growth cycles at specific critical times (Magrath, 1989, p. 33). Another measure, already mentioned, is the taxing of the exploiter of the renewable resource. In this section I determine an optimum tax for a renewable resource. To do this, the model in the previous section has to be slightly adapted. Since

Table 9.6: Stock, yearly extraction, human effort and prices for a common renewable resource in case of non-intervention[5].

Time (t)	Population ($n_{r,t}$)	Yearly extraction (q_t)	Human effort (m_t)	Price (p_t)
0	100.0	-	-	-
1	55.6	44.4	123.5	27.8
2	37.1	30.8	106.5	34.6
3	25.9	22.9	88.3	38.6
4	18.3	17.2	71.1	41.4
5	13.0	12.8	55.8	43.6
6	9.3	9.4	42.7	45.3
7	6.6	6.9	32.1	46.6
8	4.6	5.0	23.7	47.5
9	3.3	3.6	17.3	48.2
10	2.3	2.6	12.4	48.7
11	1.6	1.8	8.9	49.1
12	1.1	1.3	6.3	49.4
13	1.0	0.9	4.5	49.5

$n_{r,c} = 100,\ \alpha = 0.5,\ \beta = 0.4,\ \gamma = 0.5,\ \delta = 50,\ \nu = 10,\ \phi = 0.005$

the tax to be paid (r_t) is part of the total cost of the exploiter, equation (7), $m_t = (\delta/\nu) \cdot q_t - (\gamma/\nu) \cdot q_t^2$, has to be replaced by equation (9) (see also Nijkamp, 1977):

$$(9) \qquad m_t = \frac{\delta \cdot q_t - \gamma \cdot q_t^2 - r_t \cdot q_t}{\nu}.$$

In constrast to an exhaustible resource, the tax per unit product can be held constant *if the rate of renewal equals the rate of interest* (Chapter 5). The rate of renewal (α) equals:

$$(15) \qquad a_t = \frac{\Delta n_{r,t}}{n_{r,t-1}}$$

$$a_t = \frac{\phi \cdot (n_{r,c} - n_{r,t-1}) \cdot n_{r,t-1}}{n_{r,t-1}}$$

$$a_t = \phi \cdot n_{r,c} - \phi \cdot n_{r,t-1}.$$

In the case of a renewable resource the royalty rises by the rate of interest minus the rate of renewal. Because a discrete case with a variable renewal rate is dealt with, a proof different from the one given in chapter 5 is necessary here (see appendix 9.4):

$$(16) \qquad r_t = r_{t-1} \cdot (1 + \upsilon - a_{t-1}).$$

If the rate of interest is not too high for the regeneration capacity of the renewable resource, it is possible to find an initial tax value per extraction unit which causes infinite use of the renewable resource, thus maximizing total utility of the resource. This constant tax, or royalty, per unit (r_0) is to be found by trial and error. The whole model is summarised in Table 9.7.

Table 9.7: An optimum taxation model for a common renewable resource.

$$q_t = \beta \cdot n_{r,t-1}^{\alpha} \cdot m_t^{1-\alpha} \qquad (t \geq 1)$$

$$n_{r,t} = n_{r,t-1} + \Delta n_{r,t} \qquad (t \geq 1)$$

$$\Delta n_{r,t} = \psi \cdot (n_{r,c} - n_{r,t-1}) \cdot n_{r,t-1} - q_t \qquad (t \geq 1)$$

$$m_t = \frac{\delta \cdot q_t - \gamma \cdot q_t^2 - r_t \cdot q_t}{\nu} \qquad (t \geq 1)$$

$$p_t = \delta - \gamma \cdot q_t \qquad (t \geq 1)$$

$$a_t = \phi \cdot n_{r,c} - \phi \cdot n_{r,t-1} \qquad (t \geq 1)$$

$$r_t = r_{t-1} \cdot (1 + \upsilon - a_t) \qquad (t \geq 1)$$

$$n_{r,0} \geq 0 \quad \text{given}$$

After several trials, it appeared that, for the renewable resource in question, the initial royalty equals 36.378. During a steady state, royalty equals 41.640. Results of the simulation procedure are reported in Table 9.8.

Table 9.8: Population, extraction, human effort, price and regeneration of a renewable resource in case of optimum taxation.

Time (t)	Population ($n_{r,t}$)	Yearly extraction (q_t)	Human effort (m_t)	Price (p_t)	Regeneration (a_t)	Royalty (r_t)
0	100.0	-	-	-	-	36.378
1	90.5	9.5	5.7	45.2	0.048	39.288
2	86.9	7.9	4.3	46.0	0.066	40.560
3	85.3	7.3	3.8	46.4	0.074	41.140
4	84.6	7.0	3.6	46.5	0.077	41.408
5	84.3	6.8	3.5	46.6	0.079	41.532
6	84.1	6.8	3.4	46.6	0.079	41.590
7	84.1	6.7	3.4	46.6	0.080	41.617
8	84.0	6.7	3.4	46.6	0.080	41.629
9	84.0	6.7	3.4	46.6	0.080	41.635
10	84.0	6.7	3.4	46.6	0.080	41.638
11	84.0	6.7	3.4	46.6	0.080	41.639
12	84.0	6.7	3.4	46.6	0.080	41.640
13	84.0	6.7	3.4	46.6	0.080	41.640
14	84.0	6.7	3.4	46.6	0.080	41.640
15	84.0	6.7	3.4	46.6	0.080	41.640

$\alpha = 0.5$, $\beta = 0.4$, $\gamma = 0.5$, $\delta = 50$, $\upsilon = 0.08$, $\phi = 0.005$, $n_{r,c} = 100$, $r_0 = 36.378$.

The differences between population development and resource extraction in the non-intervention case and the optimum taxation case are shown in Figures 9.7 and 9.8. The differences in human effort and prices are shown in Figures 9.9 and 9.10.

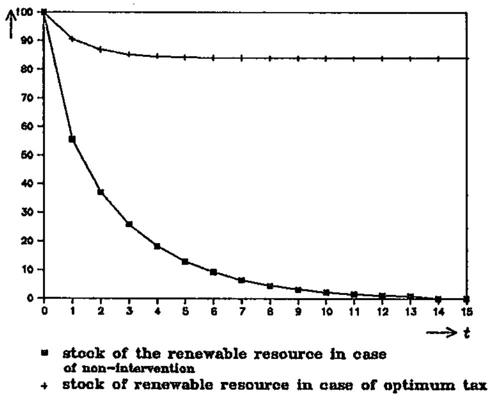

Figure 9.7: Development of stock in the non-intervention case and the optimum taxation case.

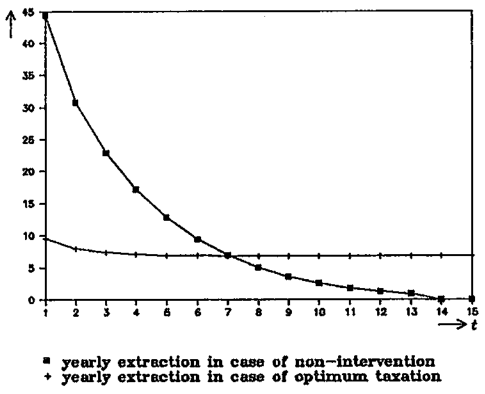

Figure 9.8: Extraction in the non-intervention case and the optimum taxation case.

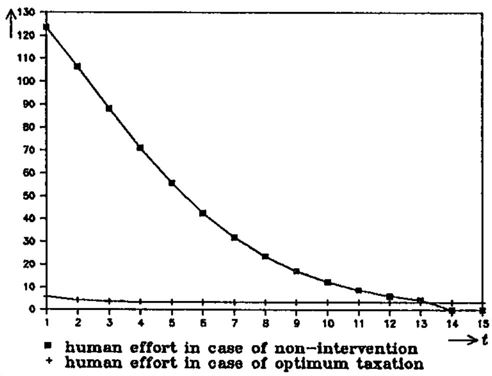

Figure 9.9: Human effort under non-intervention and optimum taxation.

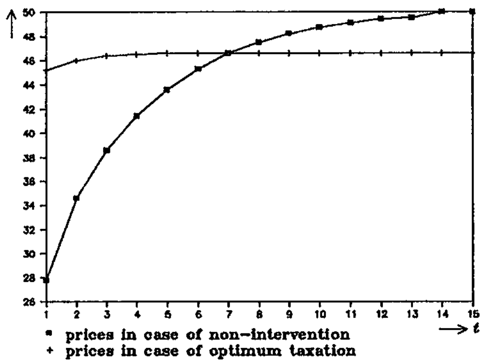

Figure 9.10: Prices under non-intervention and optimum taxation.

Figure 9.11 shows that after some time the rate of renewal will equal the rate of interest. Finally, the annual royalty is presented in Figure 9.12.

To conclude this section it should be said that to stimulate an efficient use of the resource, instead of using a depletion tax a government can also establish depletion permits based on the allowed yearly extraction shown in Table 9.8 (see also Førsund et al., 1988). Dupont and Phipps (1990) even suggest that for the British Columbian salmon fishery, a quota scheme per vessel generates a bigger rent than the potential

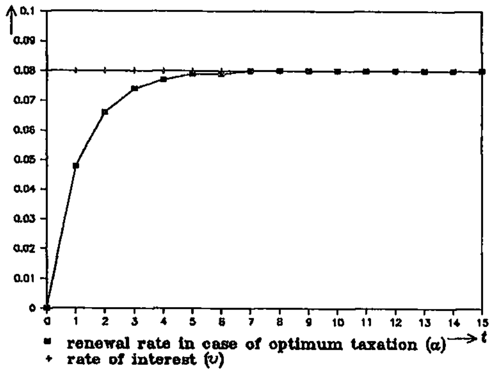

Figure 9.11: The rate of renewal and the rate of interest under optimum taxation.

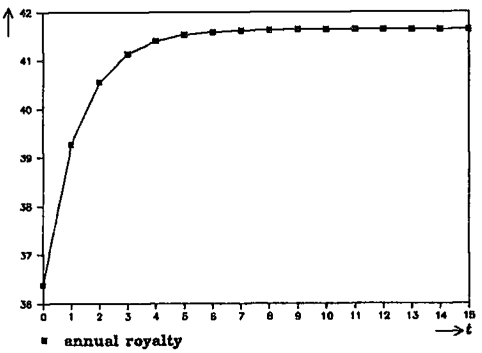

Figure 9.12: The royalty under optimum taxation.

rent gained from a royalty tax. Moreover, the advantage of a quota scheme is that the negative income effects can be avoided if the permits are given gratis to the initial users of the renewable resource. If an exploiter stops depletion, the permit can be sold on the market. In this way, it is the market rather than the government which generates royalty and this is more elegant, as part of the bureaucracy can be avoided in such a system. Of course, in this system also, government will have to guarantee that only the holders of permits have access to the resource, which in many cases will not be easy. A last remark is that all the models used in this chapter are single-species models. This is a disadvantage since there are many interrelations with other species that influence the real stock of a certain kind of renewable resource. This appears to be particularly important in the fishing sector (Fløystad, 1989). Therefore, a major improvement to the above models would be the introduction of multi-species models. Perhaps, this would not be too difficult in the numerical models I have used. However, I leave this question for research in the near future.

Appendix 9.1: Existence of unique positive solutions of the simulation model

If there is only one positive solution for m_t then there is only one positive value of $n_{e,t-1}$ in each period, and consequently there is also only one positive solution for q_t and p_t. Therefore a sufficient condition for the existence of a unique set of positive solutions is the existence in each period of only one positive solution for m_t. This can be proved as follows.

Via substitution:

$$m_t^{\alpha} = \frac{\delta \cdot \beta}{\nu} \cdot n_{e,t-1}^{\alpha} - \frac{\gamma \cdot \beta^2}{\nu} \cdot n_{e,t-1}^{2\cdot\alpha} \cdot m_t^{1-\alpha}.$$

This equation can be written as:

$$x^{\alpha} = A \cdot Y - B \cdot Y^2 \cdot x^{1-\alpha}, \quad \text{with}$$

$$x = m_t, \quad A = \frac{\delta \cdot \beta}{\nu}, \quad B = \frac{\gamma \cdot \beta^2}{\nu}, \quad Y = n_{e,t-1}^{\alpha}.$$

The question to be answered is how many positive zeros there are in the function:

$$f(x) = x^{\alpha} - A \cdot Y + B \cdot Y^2 \cdot x^{1-\alpha}.$$

Because:

$$f(0) = -A \cdot Y \leq 0 \quad \text{and} \quad \lim_{x \to \infty} f(x) = \infty,$$

the answer is at least one. Further, it can be proved that $f(x)$ has only one zero, because:

$$\frac{df(x)}{dx} = \alpha \cdot x^{\alpha-1} + B \cdot Y^2 \cdot (1-\alpha) \cdot x^{-\alpha} > 0,$$

which implies that $f(x)$ is a continuous, strictly-increasing function.

Appendix 9.2: Depletion pattern of the simulation model

This appendix shows under what conditions m_t will decrease and depletion occur:

(b) $m_1 \geq m_2 \geq m_3 \geq \ldots$

(e) There exists a T so that $n_{e,T} \leq 1$[2).

If A, B, and Y are written as in Appendix 9.1, then:

$$A = \frac{\delta \cdot \beta}{\nu}, \quad B = \frac{\gamma \cdot \beta^2}{\nu}, \quad Y_t = n_{e,t-1}^{\alpha}.$$

Now, m_t is the unique positive zero of the function $x \to g(x, Y_t)$ defined for $x \geq 0$ where:

$$g(x, Y) = x^{\alpha} - A \cdot Y + B \cdot Y^2 \cdot x^{1-\alpha}.$$

I want first to explain why it is useful to know that the unique positive zero x_Y of $x \to g(x, Y)$ is an increasing function of Y. Suppose that $Y \to x_Y$ is increasing for all Y in interval $[0, Y_1]$. Then, because $m_t = x_{Y_t}$, we see that:

$$n_{e,t-1} \geq n_{e,t} \quad \text{so} \quad n_{e,t-1}^{\alpha} \geq n_{e,t}^{\alpha}, \quad \text{so} \quad Y_1 \geq Y_t \geq Y_{t+1}$$

$$x_{Y_t} \geq x_{Y_{t+1}}, \quad \text{so} \quad m_t \geq m_{t+1}.$$

The meaning of the unique positive zero can be shown by differentiating:

$g(x_Y, Y) = 0$ with respect to Y:

$$-A + 2 \cdot B \cdot Y \cdot x_Y^{1-\alpha} + B \cdot Y^2 \cdot (1-\alpha) \cdot x_Y^{-\alpha} \cdot \frac{dx_Y}{dY} = 0.$$

So:

$$\frac{dx_Y}{dY} = \frac{A - 2 \cdot B \cdot Y \cdot x_Y^{1-\alpha}}{B \cdot Y^2 \cdot (1-\alpha) \cdot x_Y^{-\alpha}}.$$

And so:

$$\frac{dx_Y}{dY} \geq 0 \leftrightarrow A \geq 2 \cdot B \cdot Y \cdot x_Y^{1-\alpha} \leftrightarrow Y \cdot x_Y^{1-\alpha} \leq \frac{\delta}{2 \cdot \beta \cdot \gamma}. \quad (*)$$

Whether (*) is true depends on the specific parameters. If $\alpha = 0.5$ then x_Y can be calculated explicitly:

$$\sqrt{x_Y} - A \cdot Y + B \cdot Y^2 \cdot \sqrt{x \cdot Y} = 0$$

$$x_Y = \left(\frac{A \cdot Y}{1 + B \cdot Y^2} \right)^2.$$

Now (*) means:

$$\left(\frac{A \cdot Y^2}{1 + B \cdot Y^2} \right) \leq \frac{\delta}{2 \cdot \beta \cdot \gamma}$$

$$\frac{Y^2}{1 + B \cdot Y^2} \leq \frac{\delta}{2 \cdot \beta \cdot \gamma \cdot A} = \frac{\delta}{2 \cdot \beta \cdot \gamma \cdot \frac{\delta \cdot \beta}{\nu}} = \frac{\nu}{2 \cdot \beta^2 \cdot \gamma}.$$

Define:

$$f(Y) = \frac{Y^2}{1 + B \cdot Y^2}, \quad \text{then:}$$

$$f'(Y) = \frac{2 \cdot Y \cdot (1 + B \cdot Y^2) - Y^2 \cdot 2 \cdot B \cdot Y}{(1 + B \cdot Y^2)^2} = \frac{2 \cdot Y}{(1 + B \cdot Y^2)^2} \geq 0,$$

$$f(Y) = \frac{\nu}{2 \cdot \beta^2 \cdot \gamma} \quad \text{for} \quad Y = \frac{1}{\sqrt{\beta}}.$$

So, in the $\alpha = 0.5$-case, (b) is true if:

$$Y_1 \leq \frac{1}{\sqrt{B}} = \beta \cdot \sqrt{\frac{\nu}{\gamma}}, \quad \text{or} \quad \sqrt{n_{e,0}} \leq \beta \cdot \sqrt{\frac{\nu}{\gamma}}, \quad \text{or} \quad n_{e,0} \leq \beta^2 \cdot \frac{\nu}{\gamma}.$$

Now the only thing left to be proved is (e). We know that:

$$N = \lim_{t \to \infty} n_{e,t} \geq 0,$$

and further that:

$$\lim_{t \to \infty} q_t = \lim_{t \to \infty} (n_{e,t-1} - n_{e,t}) = N - N = 0.$$

From this and equation (7) it follows directly:

$$\lim_{t \to \infty} m_t = 0.$$

Because (see Appendix 9.1):

$$m_t^\alpha = \frac{\delta \cdot \beta}{\nu} \cdot n_{e,t-1}^\alpha - \frac{\gamma \cdot \beta^2}{\nu} \cdot n_{e,t-1}^\alpha \cdot m_t^{1-\alpha},$$

we know that if $t \to \infty$, then:

$$0 = \frac{\delta \cdot \beta}{\nu} \cdot N^\alpha - \frac{\gamma \cdot \beta^2}{\nu} \cdot N^\alpha \cdot 0, \quad \text{so:}$$

$$N = \lim_{t \to \infty} n_{e,t} = 0.$$

The conclusion is depletion will always occur in the model.

Appendix 9.3: Chaos in population development

It appears that the value of ψ determines whether in population development there is a steady maximum, constant oscillations or chaos. The steady maximum is dealt with in the main text. The other two possibilities are explored in this appendix. If it is supposed that ψ equals 0.023, then the development pattern of Figure 9a.1 is gained.

If ψ has the value 0.03, the stage of chaos is finally reached. In such a stage

> ... a sequence of population measurements can [visually] hardly be distinguished from a total random sequence - despite the underlying deterministic encoding (De Vries, 1989. p. 55).

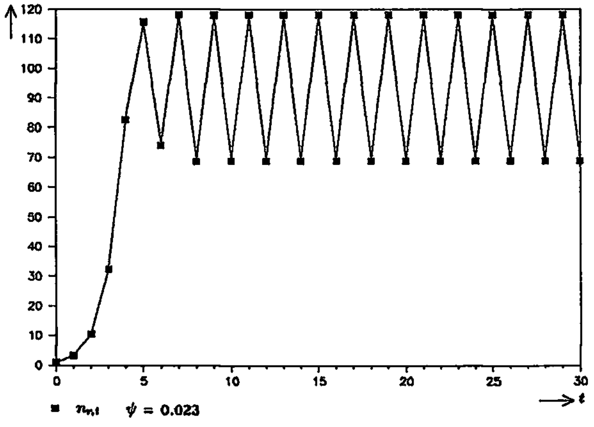

Figure 9a.1: Constant oscillations

Figures 9a.2 and 9a.3 show that the value of the growth parameter ψ (= 0.03) at first gives a relatively regular pattern which gradually passes into an irregular sequence. See also Gleick (1988) and Wilen (1985).

Figure 9a.2: Population development pattern when ψ = 0.03 (period 1-30).

Figure 9a.3: Population development pattern when ψ = 0.03 (period 100 - 130).

Though a chaotic pattern is mathematically possible, the majority of biologists believe that most biological systems are not chaotic in nature (De Vries, 1989). In economics, chaos theory is seldom applied. The main reason for this may be that it is very difficult to distinguish between a random process and a deterministic chaotic process. A chaotic time path is so complicated that it will pass most standard random tests (Baumol et al. 1989).

Appendix 9.4: Solving the optimisation problem in the discrete case

For the continuous case and a constant renewal rate α the optimisation problem has been solved in Chapter 5. Formal proof for the discrete case with a variable renewal rate was not given there. In this appendix it will be proved that in the discrete case for perfect competition the optimum rule is:

$$p_0 = \frac{p_1 \cdot (1+\alpha_0)}{(1+\upsilon)} = \frac{p_2 \cdot (1+\alpha_0) \cdot (1+\alpha_1)}{(1+\upsilon)^2} = \ldots$$

$$\text{so} \quad p_t = \frac{1+\upsilon}{1+\alpha_{t-1}} \cdot p_{t-1} \approx (1+\upsilon-\alpha_{t-1}) \cdot p_{t-1}, \qquad \text{if } |\alpha_{t-1}| \ll 1.$$

where p_t represents royalty per unit product. The proof is first given for the monopoly situation. After that the situation of perfect competition is dealt with.

Assume that there are N periods, that M_t is the amount of the renewable resource left in the beginning of period t, that $M_0 = M$ and further that q_t is the amount of the renewable resource placed on the market in period t and W_t is the total royalty in period t. Now:

$$W(q_0, \; q_1, \ldots, q_N) = \sum_{t=0}^{N} p(q_t) \cdot q_t \cdot \frac{1}{(1+\upsilon)^t}.$$

We have:

$$M_0 = M.$$

$$M_1 = (M_0 - q_0) \cdot (1+\alpha_0), \quad \text{where } q_0 \leq M_0.$$

$$M_2 = (M_1 - q_1) \cdot (1 + \alpha_1)$$

$$= (M_0 - q_0) \cdot (1 + \alpha_0) \cdot (1 + \alpha_1) - q_1 \cdot (1 + \alpha_1), \text{ where } q_1 \leq M_1.$$

$$M_3 = (M_2 - q_2) \cdot (1 + \alpha_2)$$

$$= (M_0 - q_0) \cdot (1 + \alpha_0) \cdot (1 + \alpha_1) \cdot (1 + \alpha_2) - q_1 \cdot (1 + \alpha_1) \cdot (1 + \alpha_2) - q_2 \cdot (1 + \alpha_2),$$

where $q_2 \leq M_2$.

$$M_3 = M_0 \cdot (1 + \alpha_0) \cdot (1 + \alpha_1) \cdot (1 + \alpha_2) - q_0 \cdot (1 + \alpha_0) \cdot (1 + \alpha_1) \cdot (1 + \alpha_2)$$
$$- q_1 \cdot (1 + \alpha_1) \cdot (1 + \alpha_2)$$
$$- q_2 \cdot (1 + \alpha_2).$$

In general: $M_t = M_0 \cdot (1 + \alpha_0) \cdot (1 + \alpha_1) \ \dots \ (1 + \alpha_{t-1}) -$

$$\sum_{j=0}^{t-1} q_j \cdot (1 + \alpha_j) \cdot (1 + \alpha_{j+1}) \ \dots \ (1 + \alpha_{t-1}), \qquad (0 \leq t \leq N + 1).$$

Now, with given $M_{N+1} \geq 0$, $W(q_0, q_1, \dots, q_N)$ is to be maximised. In order to do so, we form the Lagrange function

$$\tilde{W}(q_0, \dots, q_N, \lambda) = W(q_0, \dots, q_N) - \lambda \cdot \{M_{N+1} - M_0 \cdot (1 + \alpha_0) \dots (1 + \alpha_N)$$
$$- \sum_{j=0}^{N} q_j \cdot (1 + \alpha_j) \cdot (1 + \alpha_{j+1}) \dots (1 + \alpha_N)\}.$$

$$0 = \frac{\partial \tilde{W}}{\partial q_t} = \frac{\partial W}{\partial q_t} + \lambda \cdot \{(1 + \alpha_t) \cdot (1 + \alpha_{t+1}) \dots (1 + \alpha_N)\}$$

$$= p'(q_t) \cdot q_t \cdot \frac{1}{(1 + \upsilon)^t} + p(q_t) \cdot \frac{1}{(1 + \upsilon)^t} + \lambda \cdot \{(1 + \alpha_t) \dots (1 + \alpha_N)\}.$$

So: $$\frac{p'(q_t) \cdot q_t + p(q_t)}{(1 + \upsilon)^t \cdot (1 + \alpha_t) \cdot (1 + \alpha_{t+1}) \dots (1 + \alpha_N)} = -\lambda.$$

So, with $MR_t = p'(q_t) \cdot q_t + p(q_t)$,

$$MR_t = C\cdot(1+\upsilon)^t\cdot(1+\alpha_t)\dots(1+\alpha_N) \text{ for some constant } C, \text{ so}$$

$$MR_t = MR_{t-1}\cdot\frac{1+\upsilon}{1+\alpha_{t-1}}.$$

For the perfect competition case the marginal royalty can be seen as the royalty, so in that situation the optimum rule changes into

$$p_t = p_{t-1}\cdot\frac{1+\upsilon}{1+\alpha_{t-1}}.$$

Indeed, in this case we have to maximise

$$W(q_0,\dots,q_N) = \sum_{t=0}^{N} u(q_t)\cdot\frac{1}{(1+\upsilon)^t}, \text{ where } u(q) = \int_0^q p(\xi)d\xi,$$

under the constraint that M_{N+1} is given. As above we get, using

$$\frac{du}{dq}(q) = p(q):$$

$$0 = \frac{1}{(1+\upsilon)^t}\cdot p(q_t) + \lambda\cdot\{(1+\alpha_t)\cdot(1+\alpha_{t+1})\dots(1+\alpha_N)\},$$

so, with $p_t = p(q_t)$,

$$p_t = C\cdot(1+\upsilon)^t\cdot(1+\alpha_t)\dots(1+\alpha_N) \text{ for some constant } C, \text{ so}$$

$$p_t = p_{t-1}\cdot\frac{1+\upsilon}{1+\alpha_{t-1}} \qquad (t\geq 1).$$

This dynamic equation for the royalty determines the royalty completely if we know p_0, which can be found by choosing C such that

$$M_0\cdot(1+\alpha_0)\dots(1+\alpha_N) + \sum_{j=0}^{N} q_j\cdot(1+\alpha_j)\cdot(1+\alpha_{j+1})\dots(1+\alpha_N) = M_{N+1}.$$

To do this we have only to determine the q_j that depend on C.

Notes

1) Pearce et al. (1990, p. 76) called these resources 'open access resources', using the term 'common property resources' for resources that are owned by an identifiable group. Since I do not deal with the last kind of resources, I do not make this distinction.

2) Most countries with sea coasts have widened their jurisdiction to 200 nautical miles from the coast, so there is little dispute about who has the title to sell mining concessions in these areas. However, it is more difficult to decide who has the title for the bulk of the deposits which lie well away from the land. In 1970, a United Nations resolution stated that deep ocean resources are "the common heritage of mankind". The most recent LOS (Law of the Sea Treaty) was passed in 1982. In this treaty the principle of 'common heritage' was given an institutional form. However, most of the world's industrial countries did not sign it (Brookins, 1990).

   For almost all nations, including those that did not sign the 1982's LOS, it is clear that some institution supervized by the United Nations should be set up to control the depletion of deep ocean resources. The main tasks of this institution could be the selling of tradable mining concessions, the setting of quantitative limits to the depletion of deep sea resources, and the setting of environmental rules regulating mining activities. The United Nations will have to decide about the destination of the earned royalties.

3) $n_{e,t} = n_{e,t-1} - q_t$ if $n_{e,t-1} - q_t \geq 0$,
   $n_{e,t} = 0$ if $n_{e,t-1} - q_t < 0$.

4) The assumption of a decreasing demand function is plausible. Most estimates of long run residential energy demand-elasticities are within the range of -0.4 to -1.3 (Fisher, 1988, p. 118).

5) Total stock is considered depleted when $n_t \leq 1$.

6) Though in Chapter 5 proof for this rule was delivered for the continuous case, it will be intuitively clear that in the discrete model as described in this chapter social utility of the depletion of an exhaustible resource is maximised if

$$r_0 = \frac{r_1}{1+\upsilon} = \frac{r_2}{(1+\upsilon)^2} = \dots$$

   On top of that formal proof for a renewable resource is given in appendix 9.4. This proof also includes the case of an exhaustible resource. Indeed, for an exhaustible resource the renewal rate must be considered zero.

10. Use of depletable resources by the firm

In Chapters 5, 6, 7, 8 and 9, I analysed the depletion of resources on the macro and sector level. In this chapter I concentrate upon the main user of depletable resources, the individual firm. The analysis at this level is especially needed since in trying to decrease the depletion speed of some vital stocks of resources, governments often have to concentrate upon the individual firm. In the first sections the concept of *materials balance* is integrated into the micro economic theory on production. After that, two governmental policy instruments which aim at less pollution and less use of resources (direct regulation and levying) are introduced and discussed.

Efficiency as the firm's objective and the materials balance

The definition of efficiency is the gaining of maximum production from a given input of means of production or the gaining of a given production with the least possible input of means of production. Both definitions are of a non-ideological nature and useful in all kinds of economic systems. To make the analysis of the firm's behaviour as universal as possible, the firm's objective has to be as general as possible. That is why the striving for efficiency is considered the firm's objective throughout this chapter. Also, *means of production* are taken to be an amount of money with the help of which the management of the firm can buy production factors in order to reach the firm's objective. The effects on the environment can be determined with the help of a materials balance.

The materials balance developed by Ayres and Kneese (1969) (see also Freeman et al., 1973) is essentially a simple equation which states that the total amount of material used as an input in the production process will finally be found again in the products or in discharge. If q is the physical production per period, n the amount of material used as an input in the production process and r the amount of material discharged, then the equation of the materials balance is the following:

(1) $n = r + q$, so $r = n - q$.

Of course, this materials balance is very simple, since it assumes that there is only one kind of material. However simple it may be, in this form it is suitable for my analysis. In the next section, I integrate the materials balance into the microeconomic production theory.

Microeconomic production theory and materials balance

Suppose that, to reach a certain level of production (q), a firm needs two inputs: an amount of nature (n), by which a finite resource is meant, and another factor, e.g. labour (l). As a consequence of the production process, a residue is discharged into the environment. Figure 10.1 illustrates this process.

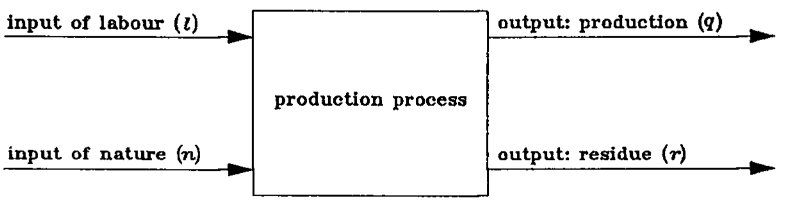

Figure 10.1: Production process with a discharge

It should be realized that the diagram shown in Figure 10.1 reflects a fundamental law, which can be formulated as: *no production without discharge*; or, as Mills put it:

> A zero-discharge economy would be a zero-withdrawal economy; a zero-withdrawal economy would be a zero-production economy and a zero-production economy would be a zero-people economy. A zero-discharge economy is a figment of dreamers' imaginations (Mills, 1978, p. 31).

The production process can be reflected by a production function:

$$(2) \qquad q = f(n, l).$$

Further, I suppose a fixed budget $(\underline{b})$ and fixed prices for labour $(\underline{p}_l)$ and nature $(\underline{p}_n)$. If the budget is completely spent then:

$$(3) \qquad \underline{b} = \underline{p}_l \cdot l + \underline{p}_n \cdot n.$$

Another important assumption is that the firm acts efficiently, which in this case means that within the given constraint of a given budget, it maximizes its production or, to put it another way:

$$(4) \qquad dq = 0.$$

Equations (1) – (4) form the microeconomic model with an integrated materials balance. If we want to look further at the effects of a firm's production on the environment and the stocks of finite resources we have to be more explicit about the production function and the optimum rule of equation (4). For the production function I take a Cobb-Douglas production function of the linearly homogenous type, which means that there are no economies of scale. This production function with $\alpha > 0$ and $0 < \beta < 1$ as coefficients is shown in equation (5):

$$(5) \qquad q = \alpha \cdot n^{\beta} \cdot l^{(1-\beta)}.$$

Via the Lagrange procedure, the optimum condition is given by

$$(6) \qquad \frac{\partial q / \partial n}{\partial q / \partial l} = \frac{\underline{p}_n}{\underline{p}_l}.$$

This means that in the optimum, the ratio between nature and labour for the given production function is as follows:

$$(7) \qquad \frac{n}{l} = \frac{\beta}{1-\beta} \cdot \frac{\underline{p}_l}{\underline{p}_n}.$$

Using a model consisting of equations (1), (3), (5) and (7) it is possible to determine the efficient level of production (q^*), the efficient levels of the inputs (l^*, n^*), and the pollution it causes (r^*). The outcomes are respectively:

$$(8) \qquad q^* = \alpha \cdot \left\{ \left(\frac{\beta}{\underline{p}_n} \right)^{\beta} \cdot \left(\frac{(1-\beta)}{\underline{p}_l} \right)^{1-\beta} \right\} \cdot \underline{b},$$

$$n^* = \frac{\beta \cdot \underline{b}}{\underline{p}_n},$$

$$l^* = \frac{(1-\beta) \cdot \underline{b}}{\underline{p}_l},$$

$$r^* = \left\{ \frac{\beta}{\underline{p}_n} - \alpha \cdot \left(\frac{\beta}{\underline{p}_n} \right)^{\beta} \cdot \left(\frac{(1-\beta)}{\underline{p}_l} \right)^{1-\beta} \right\} \cdot \underline{b}.$$

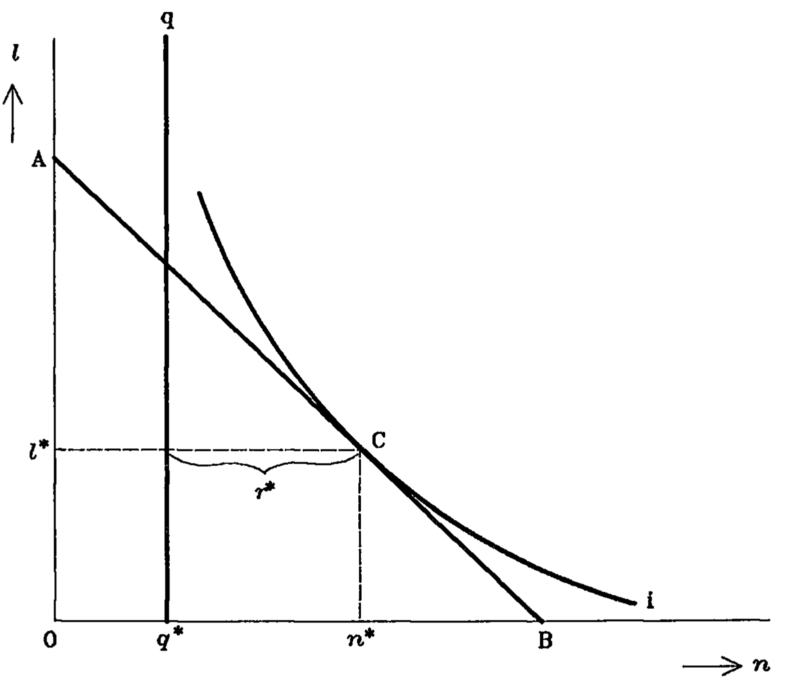

Figure 10.2: Producer's optimum with discharge.

This solution is shown as a graph in Figure 10.2. In this figure, the iso-production curve i touches the budget curve AB in C. The input of labour (l) is shown on the vertical axis. The optimum input of labour equals l^*. The input of nature (n) and the optimum production (q^*) are shown on the horizontal axis. Since by definition, the discharge (r) is always greater or equal to zero, the iso production curve cannot intersect the line indicating optimum production (q). In the optimum, discharge equals (r^*), which is the difference between the input of nature (n^*) and the optimum production.

Role of capital

Up till now I have not paid attention to the capital stock of the firm. However, as is shown in Figure 10.3, the accumulation of capital influences the use of nature on the input side of the production process. Capital accumulation equals gross investment (i) minus capital replacement (b). The replacement of capital takes place when the capital goods concerned are economically or technically used up.

Using capital in the production process has its consequences for the environment. First, capital is used in the production process as a production factor. However, it differs from the other two factors, since it has itself been produced by the input of nature and labour and capital in another production process. So, it can be said that the use of capital[1] implies the use of natural resources in an indirect way. Moreover, the input of capital almost always requires energy and maintenance.

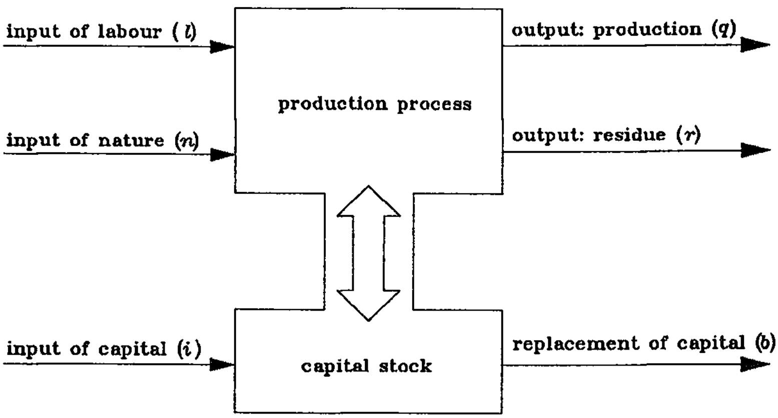

Figure 10.3: Materials balance including capital.

Second, by using capital, the number of large scale production units will increase, which will enhance the concentration of polluting agencies. On the one hand, this is a disadvantage for the environment of the immediate surroundings of the unit. On the other hand, pollution and the use of natural resources of some large scale units can be more easily controlled by policy measures than can pollution from a lot of small firms[2]. The use of nature can also be minimized because of economies of scale. Moreover, since the influence on the costs per unit product can be relatively small a large scale firm can more easily introduce nature-sparing innovations. It is to be concluded here that small is not necessarily beautiful.

The input of capital goods has two aspects: the quantitative and the qualitative. The quantitative aspect concerns the total input of capital goods, while the qualitative aspect concerns the duration of capital goods. The total input of capital is determined by the marginal product of capital, the price of capital and the price of the final product. If depreciation and interest are relatively low, the price of capital will also be relatively low, which enhances the input of capital and the indirect use of natural resources. However, in Chapter 5 we saw that a low rate of interest brought about a low depletion speed of resources. Indeed, a negative relation exists between the rate of interest and the absolute price level of natural resources which, in turn, influences the price of capital goods positively; a low rate of interest brings about a relatively high absolute price level of the natural resource and, consequently, a positive influence upon the price of capital goods. Therefore it can be concluded that a low rate of interest does not automatically lead to a high use of capital goods. This is the quantitative aspect of the input of capital goods. There also is a qualitative aspect: the duration of capital goods. This aspect, which is expressed in the capital replacement, is often neglected. More attention is given to it in Appendix 10.1.

Pollution abatement policies in the case of a single firm

A pollution abatement policy consists of an objective plus the instruments needed to reach that objective. Most of the time the objective is to lower the discharge from the average firm by a certain percentage. There are two ways of distinguishing the abatement instruments. In the first place, one can look at the way a firm's conduct is influenced. Here there are two kinds of instruments to reach fewer withdrawals and discharges. First, *direct regulation* or *non-market instruments* and second, *market instruments*. The essence of direct regulation is that the government decides how much each firm should be allowed to discharge and forbids discharges in excess of those amounts, subject to civil and criminal penalties. By 'market instruments' is meant effluent fees and subsidies on less polluting ways of production.

In the second place, one can take into consideration the stage of the production process at which an instrument influencing a firm's conduct is aimed. This can be either on the input side of the production process or on the output side. If it is on the input side, this instrument can be called an *instrument of prevention*. An instrument aiming at the output side of the production process is called an *end of pipe instrument* (Mensink et al., 1988; van Driel et al., 1988). On the basis of the two distinguishing criteria (market versus non-market and prevention versus end of pipe) it is now possible to divide all possible instruments into four categories. These categories are shown in Figure 10.4.

	non-market instruments	market instruments
end of pipe instruments	1	2
preventive instruments	3	4

Figure 10.4: Four categories of instruments.

To review the effects of the distinguished categories of instruments, I compare instruments from each category for the effects on production, use of nature and employment, assuming that these instruments are used in abating the discharge up to a chosen level. The categories, including the instruments to be studied, are summarized in Table 10.1. The numbers refer to the numbered categories in Figure 10.4:
In the evaluation procedure, the model with only two production factors, nature and labour, as formulated in equations (1) to (4) of this chapter are used. The factor capital is not represented as such:

> ..., because capital is a derived production factor, incorporating nature and labour. In the long run capital can be considered as being "liquid", and can be split into the original production factors (Krabbe, 1990, p. 54).

Table 10.1: instrument categories and instruments.

1. end of pipe regulations:	a maximum discharge level.
2. end of pipe market instruments:	a. a discharge fee;
	b. a discharge fee combined with a subsidy on labour.
3. preventive regulations:	a maximum level to the input of nature.
4. preventive market instruments:	a. a fee on the input of nature;
	b. a fee on the input of nature combined with a subsidy on labour.

In fact, the starting point of the production function is the KLEM-function of Chapter 7. The factors capital, labour, energy and material are separated into two main factors, labour and nature. In this production function, nature represents energy and material, while the composite capital is separated into the labour and nature needed to produce it.

Maximum discharge level

To study the effects of the instruments mentioned, it is useful to transform the main equations of the simple production model, which are formulated with equations (1), (3), (5) and (7), into percentages change. Then, the following model is formed (the bars above the variables indicate percentages change):

(5) → (9)

(9) $\bar{q} = \beta \cdot \bar{n} + (1 - \beta) \cdot \bar{l}$

(7) → (10)

(10) $\bar{n} - \bar{l} = \bar{p}_l - \bar{p}_n$

(3) → (11)

$$(11) \qquad \bar{b} = (1-\beta)\cdot(\bar{l}+\bar{p}_l)+\beta\cdot(\bar{p}_n+\bar{n})$$

(1) → (12)

$$(12) \qquad \bar{r} = \delta\cdot\bar{n}+(1-\delta)\cdot\bar{q}, \qquad \delta=\frac{n}{r}>1.$$

The first instrument I review is a maximum discharge level. In terms of the above model, this means that the discharge level is too high, implying $\bar{r}$ being negative at a fixed rate $(\underline{\bar{r}})$. Further, with this instrument, input prices remain constant $(\bar{p}_l = \bar{p}_n = 0)$. If we work this assumptions into the model, the following conclusions are reached:

$$(13) \qquad \bar{q} = \bar{l} = \bar{n} = \underline{\bar{r}}.$$

Equation (13) implies that production and the inputs labour and nature all decrease by the rate of prescribed pollution reduction.

Discharge fee

The same result as in the previous section is reached if a discharge fee is applied in order to reach a discharge decrease (see also Mills, 1978, p. 65-67). Again, input prices do not change, which means that $\bar{l}$ equals $\bar{n}$. After the relevant substitutions it appears that, to reduce discharge, the budget must be cut back by the rate of discharge reduction. The proper fee per unit discharge (f_r) can be computed as follows:

$$(14) \qquad f_r = \frac{-\underline{\bar{r}}\cdot \underline{b}}{\underline{r}\cdot(1+\underline{\bar{r}})}.$$

If, for example, the budget and the discharge equal 100 and 20 respectively, while the discharge is to be reduced by 20% $(\underline{\bar{r}} = -0.20)$, then the discharge fee equals $(0.20\cdot 100)/16 = 1.25$.

Discharge fee combined with a subsidy on labour

In this case it is assumed that total costs for the firm may not increase. This implies that the annual purchase of the discharge fee is spent entirely on the endowment of labour. This means that:

$$(15)\qquad \bar{b} \cdot b = l \cdot p_l \cdot \bar{p}_l$$

$$\bar{b} = (1-\beta) \cdot \bar{p}_l .$$

If we substitute this result into equation (11), knowing that $\bar{p}_n = 0$, we get:

$$(16)\qquad 0 = \beta \cdot \bar{n} + (1-\beta) \cdot \bar{l}$$

$$\bar{q} = 0.$$

Combining equation (16) with equation (12) gives:

$$(17)\qquad \bar{n} = \frac{1}{\delta} \cdot \bar{\underline{r}}.$$

To compute the effect on employment, equations (17) and (16) are substituted in equation (9):

$$(18)\qquad \bar{l} = \frac{-\beta}{(1-\beta)} \cdot \frac{1}{\delta} \cdot \bar{\underline{r}}.$$

The subsidy on labour can be computed as follows. Knowing that $\bar{p}_n$ equals 0, it follows from equation (10) that:

$$(19)\qquad \bar{p}_l = \bar{n} - \bar{l}.$$

Equations (17), (18) and (19) give:

$$(20)\qquad \bar{p}_l = \frac{1}{\delta} \cdot \left\{ 1 + \frac{\beta}{(1-\beta)} \right\} \cdot \bar{\underline{r}}.$$

Finally, the discharge fee is computed. From equations (17), (18) and (20) it follows:

$$(21) \qquad \bar{b} = \frac{(1-\beta)}{\delta} \cdot \left\{ 1 + \frac{\beta}{(1-\beta)} \right\} \cdot \bar{\underline{r}}$$

$$\bar{b} = \frac{1}{\delta} \cdot \bar{\underline{r}}.$$

The discharge fee (f_r) equals:

$$(22) \qquad f_r = \frac{-\bar{b} \cdot \underline{b}}{\underline{r} \cdot (1 + \bar{\underline{r}})}.$$

Combining equations (21) and (22) gives:

$$(23) \qquad f_r = -\frac{1}{\delta} \cdot \frac{\bar{\underline{r}} \cdot \underline{b}}{\underline{r} \cdot (1 + \bar{\underline{r}})}.$$

From equation (23) it follows that the required discharge fee will be higher if δ is smaller. This implies that the fee will be more effective in branches where a relatively large part of the input of nature is discharged.

Maximum level to the input of nature

In this case, prices of nature and labour remain unchanged. Then, from equation (10) it can be deduced:

$$(24) \qquad \bar{l} = \bar{n}.$$

Equation (24) together with equation (9) gives:

$$(25) \qquad \bar{q} = \bar{n}.$$

From equations (25) and (12) it can be deduced:

(26) $\bar{n} = \underline{\bar{r}}$.

From equations (24), (25), (26) and (13) it follows that a maximum level put to the input of nature generates exactly the same results as a discharge fee and a maximum discharge level.

Fee on the input of nature

Because, in this case, wages are assumed to be constant, it can be deduced from equation (10) that:

(27) $\bar{l} = \bar{p}_n + \bar{n}$.

Keeping in mind that the budget remains unchanged and, again, that wages are constant, equation (27) substituted in equation (11) gives:

(28) $0 = (1-\beta) \cdot \bar{l} + \beta \cdot \bar{l}$

$\bar{l} = 0, \quad \bar{n} = -\bar{p}_n$.

These results substituted into equation (9) give the following expression for production:

(29) $\bar{q} = -\beta \cdot \bar{p}_n$.

The expressions for nature and production, equations (28) and (29), can be substituted in equation (12). This gives:

(30) $\bar{p}_n = \dfrac{-1}{\delta \cdot (1-\beta) + \beta} \cdot \underline{\bar{r}}$.

Finally, equation (30) combined with equation (29) leads us to the expression for the relative change in production:

(31) $$\bar{q} = \frac{\beta}{\delta \cdot (1-\beta) + \beta} \cdot \underline{\bar{r}},$$

$$\delta > 1, \quad 0 < \beta < 1 \quad \text{so} \quad 0 < \frac{\beta}{\delta \cdot (1-\beta) + \beta} < 1.$$

Fee on the input of nature combined with a subsidy on labour

In connection with this policy, the substitution elasticity between nature and labour is important. In practice, labour and natural materials appear to be substitutes (Krabbe, 1990). In this case, I have studied the implications of a simple linearly homogenous Cobb-Douglas production function, which implies a fixed substitution elasticity of 1. From the assumption that total yield of the fee on nature is just enough to pay the subsidy on wages, and from equation (11), it follows:

(32) $$n \cdot (1 + \bar{n}) \cdot p_n \cdot \frac{dp_n}{p_n} = -l \cdot (1 + \bar{l}) \cdot p_l \cdot \frac{dp_l}{p_l}$$

$$\bar{p}_l = \frac{-\beta}{(1-\beta)} \cdot (\bar{p}_n + \bar{p}_n \cdot \bar{n} - \bar{p}_n \cdot \bar{l})$$

$$\bar{p}_l \approx \frac{-\beta}{(1-\beta)} \cdot \bar{p}_n.$$

In the outcome of equation (32) the second order effects ($\bar{p}_n \cdot \bar{n}$ and $\bar{p}_n \cdot \bar{l}$) are neglected. Since the budget does not change, equations (9), (11), (12) and (32) give:

(33) $$\bar{q} \approx 0, \quad \bar{n} \approx \frac{\underline{\bar{r}}}{\delta}.$$

The expressions for production and nature substituted into the production function (9) give the relative change of labour:

(34) $$\bar{l} \approx \frac{-\beta}{(1-\beta) \cdot \delta} \cdot \underline{\bar{r}}.$$

Substituting (32), (33) and (34) in (10) gives:

$$(35) \qquad \bar{p}_n \approx -\frac{1}{\delta} \cdot \underline{\bar{r}}.$$

Equation (35) together with (32) gives:

$$(36) \qquad p_l \approx \frac{\beta}{\delta \cdot (1-\beta)} \cdot \underline{\bar{r}}.$$

Evaluation of the single firm case

In choosing a policy it is useful to have an overview of all alternatives with their possible effects. Table 10.2 provides this overview. The numbers in this table refer to the possible policy options mentioned in Table 10.1.

Table 10.2: Abatement policy options and effects in the single firm case.

	1	2a	2b	3	4a	4b
$\bar{r}$	$\underline{\bar{r}}$	$\underline{\bar{r}}$	$\underline{\bar{r}}$	$\underline{\bar{r}}$	$\underline{\bar{r}}$	$\underline{\bar{r}}$
$\bar{q}$	$\underline{\bar{r}}$	$\underline{\bar{r}}$	0	$\underline{\bar{r}}$	$\frac{\beta}{\delta\cdot(1-\beta)+\beta} \cdot \underline{\bar{r}}$	0
$\bar{n}$	$\underline{\bar{r}}$	$\underline{\bar{r}}$	$\frac{1}{\delta} \cdot \underline{\bar{r}}$	$\underline{\bar{r}}$	$\frac{1}{\delta\cdot(1-\beta)+\beta} \cdot \underline{\bar{r}}$	$\frac{1}{\delta} \cdot \underline{\bar{r}}$
$\bar{l}$	$\underline{\bar{r}}$	$\underline{\bar{r}}$	$\frac{-\beta}{(1-\beta)\cdot\delta} \cdot \underline{\bar{r}}$	$\underline{\bar{r}}$	0	$\frac{-\beta}{(1-\beta)\cdot\delta} \cdot \underline{\bar{r}}$
g	0	$-\underline{\bar{r}} \cdot \underline{b}$	0	0	$\frac{-\beta\cdot\underline{b}}{\delta\cdot(1-\beta)+\beta} \cdot \underline{\bar{r}}$	0

By comparing the abatement policy options, it is possible to draw several conclusions:

a. Apart from the contribution to the Treasury, a maximum discharge level (1) generates the same results as a discharge fee (2a) or a maximum level to the input of nature (3).
b. If a fee is used to finance a subsidy on labour, then the end of pipe instrument (2b) as well as the preventive instrument (4b) give exactly the same results.

c. In the case of no revenues to the treasury (1, 2b, 3, 4b), it can be concluded from Table 10.2 that, in order to gain the end of a certain decrease in the discharge level, options 2b and 4b imply no decrease in production, while options 1 and 3 generate a decrease of production $(\bar{r})$. Further, if $\delta > \beta/(1-\beta)$, the decrease of employment with options 2b and 4b is less than with options 1 and 3. If $\delta < \beta/(1-\beta)$, then options 2b and 4b cause a bigger decrease in employment than options 1 and 3.
d. If a revenue to the treasury is needed, for instance because the money is needed for the construction of cleansing installations, policy options 2a and 4a must be compared. Because $0 < \beta/\{\delta \cdot (1-\beta)+\beta\} < 1$, the decrease in production is smaller with option 4a than with option 2a. Further, the decrease in the use of nature is smaller with option 4a than with option 2a. Finally, the contribution to the Treasury is less with option 4a than with option 2a.

Marginal abatement cost function

If more than one firm is concerned in the abatement policy, it is possible to evaluate the efficiency of abatement policies with the help of the marginal abatement cost function (Wiersma, 1989). This concept is based on the assumption that the marginal abatement costs are a rising function of the pollution abatement and that a given reduction in the pollution must be reached at the lowest possible costs. The concept is explained further with the help of Figure 10.5.

In Figure 10.5, the marginal abatement cost functions of two firms are shown $(mac_1$ and $mac_2)$. Total abatement in physical terms equals O_1O_2. The abatement of firm 1 is indicated from left to right on the x-axis, while the same is done for firm two from right to left on the x-axis. If both firms have to deal with an equal part of total abatement via direct regulations, firm 1 has to abate O_1T units and firm 2 O_2T units. In that case total abatement costs mount up to the area A+B+C+D. If a fee of f_e per emitted unit has to be paid, firm 1 will abate O_1S units and firm 2 O_2S units. Indeed a firm will abate pollution up till the level where marginal abatement costs (mac) equals the fee. In that case, total abatement costs equal the area A+B+C (see Appendix 10.2). It appears that under the assumptions mentioned, total abatement costs can be lower with an efficient fee than with direct regulations, which means that in this case the fee is a more efficient instrument. However, if the government develops regulations that differ from firm to firm, it is possible that direct regulations and fees are equally efficient. In my example, an efficient regulation could be that firm 1 should

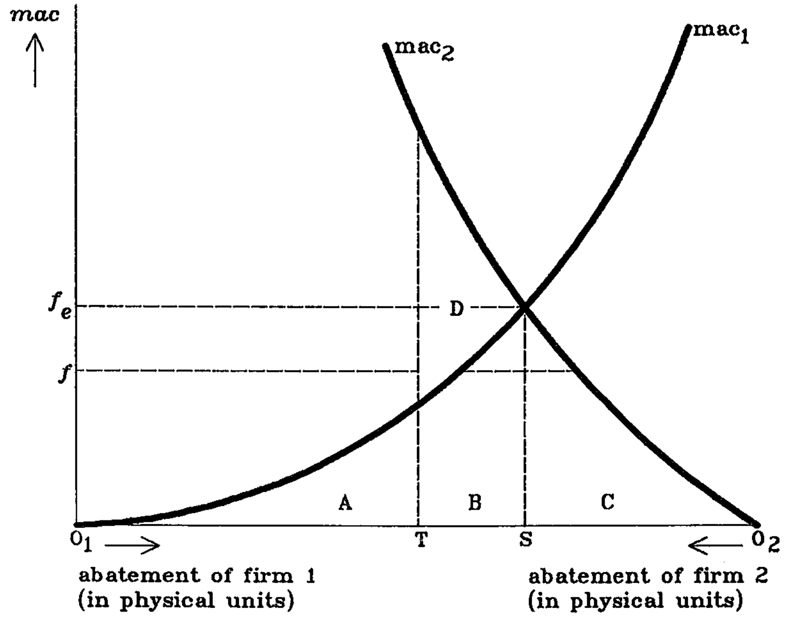

Figure 10.5: The marginal abatement cost functions in a two firms case.
Source: Wiersma, 1989, p. 138 (adjusted).

abate O_1S units and firm 2 O_2S units. Also, it is possible that government determines a fee which is too high or too low and this could cause inefficiency of the instrument. In the example given here, an inefficient fee could, for instance, be f.

It can be concluded that to meet the efficiency requirement with an efficient fee a policy per firm is not necessary. In the case of direct regulations, this can only be avoided if firms have the same marginal abatement cost functions.

Another difference between direct regulations and fees is the effect of inflation. Inflation does not affect the direct regulations. However, because the fee is expressed in an amount of money per unit pollution, it has to be periodically adapted to inflation (Wiersma, 1989).

Another way of inducing the market when dealing with environmental problems is to create a marketable permit system (Baumol et al., 1988). This means that a firm buys the right to pollute, the maximum tolerance of a certain kind of pollution being indicated by the government. The price of the pollution permit functions as an efficient fee to the firms. An advantage of this kind of measure is that it is not susceptible to inflation. Another advantage is that there will probably be less bureaucracy than with the usual fees per emitted unit and regulations. At least, for the greenhouse-effect, an internationally coordinated marketable permit system for the emission of greenhouse gasses like carbon dioxide seems to be the most promising alternative (Bertram et al. 1990).

Technological change

An important way of reducing withdrawals and discharges is to increase the technical efficiency with which materials are used, thereby increasing production of goods per unit input of nature (Mills, 1978). If there is Hicks-neutral technical innovation, then the production function in percentages change can be written as follows:

$$\bar{q} = \bar{\alpha} + \beta \cdot \bar{n} + (1 - \beta) \cdot \bar{l}. \tag{37}$$

Equation (37) substituted in (12), while knowing that $\bar{n}$ and $\bar{l}$ being zero, gives:

$$\bar{r} = (1 - \delta) \cdot \bar{\alpha}, \qquad \delta > 1. \tag{38}$$

From equation (38) it can be concluded that technological change may increase efficiency and, at the same time, decrease discharges. The only problem is how to induce the necessary technical innovations. As far as technical innovations are induced by high factor prices (in this case: nature), fees might have a stronger effect upon the firm's innovating conduct than regulations would (Binswanger, 1978). Besides, to avoid a too heavy financial burden for the average firm, the yield of these fees might be spent on research projects on abatement technics (Nentjes and Wiersma, 1989).

Choosing a policy

From a theoretical point of view it is not possible to prove that market instruments are always more efficient than direct regulations. There are a lot of cases in which direct regulations are the only way of dealing with an acute environmental problem (Baumol et al., 1988). However, where a market instrument can be applied, charges are probably more effective than direct regulations. The reason for this might be that a charge is a permanent pressure on the firm to reduce the emission of polluting materials, while a prescribed standard is not. This is because when the standard is met, the pressure stops. Indeed, most of the time a combination of both kinds of measures will be effective.

As far as market instruments are concerned, one can distinguish between emission charges and marketable permits (Hahn, 1989). Both instruments can be applied on the input side as well as on the output side of the production process. Which of both instruments is more efficient will depend on the specific case. Besides, as Hahn rightly remarked:

> The review of marketable permits and charge systems has demonstrated that regulatory systems involving multiple instruments are the rule rather than the exception. The fundamental problem is to determine the most appropriate mix, with an eye to both economic and political realities (Hahn, 1989, p. 111).

From the above discussions it must be clear that to decide on which policy option is best depends very much on the circumstances. In the case of Dutch water pollution, for example, Bressers (1988) proved that effluent charges can work. On the other hand, in the case of heavy acute polluting discharges, it is clear that regulation works better than market instruments. Indeed, to asses a proper fee, authorities nearly always have to use the trial and error method, which, for a heavy polluting discharge, may take up too much time. Indeed, a lack of knowledge of damage functions is a principal difficulty in applying charges (Pearce, 1990).

Further, it is clear that for a discharge maximum or fee the environment still becomes polluted, even if on a smaller scale than before those policies were applied (Nentjes and Wiersma, 1988). Therefore, authorities could be forced to install cleansing installations, which might be financed by a fee on the polluting discharge or the input of nature. Then, there is a risk of an over-large capacity of the cleansing installations, combined with too high a fee. Indeed the cleansing capacity is calculated on the discharge before the fee is there. Because of the introduction of the fee, firms will probably discharge less, which causes an over-large cleansing capacity. If the installation must be financed by the fee, this might even lead to a higher fee per unit discharge or input of nature. On the risk of *overshooting* the emission tax and the trial and error procedure to asses the fee Siebert said:

> This trial and error procedure may give rise to oscillations in the emission tax if the adjustments in pollution abatement take time. For instance, capital formation in the abatement activity may be a reason for a lagged response. It may take time to build pollution capital. Then a given emission tax may only yield the desired result with a time lag. If environmental policy reacts too quickly, the emission tax will "overshoot", and misallocation of resources will result (Siebert, 1987, p. 114).

Siebert mentioned the following requirements on information for applying an emission tax successfully:

1. The policy maker needs information on the quantity of emissions, which must be measurable with reasonable costs.
2. The policy maker needs information on the level of abatement costs for alternative states of the environment.
3. The policy maker must be able to determine (and to evaluate) prevented damage.
4. The diffusion function between emissions and pollutants ambient in the environment must be known (Siebert, 1987, p. 54).

An argument against direct regulations and in favour of taxation is the supposedly less bureaucratic procedure with fees. This argument does not seem correct. In order to control whether the maximum emission level is exceeded or to collect the fee and to check whether the fee is effective or not, it is necessary to have a bureaucratic apparatus for the application of the market instruments as well as for regulations. It is not clear in which of either category of policy options this apparatus is smallest. It seems the best arguments for taxation instead of direct regulations to control relatively light polluting economic activities are first, that it is sometimes more efficient than regulations, second, that it provides permanent pressure on a firm to change its way of production, third, that it does justice to the polluter-pays principle and fourth, that it provides the financial means for the authorities to maintain the bureaucratic apparatus and to construct cleansing installations. Especially for national budget deficits might the last argument appear to be decisive in the future.

Appendix 10.1: Duration of capital goods

If, for instance, the average duration of some kind of machine of a given capacity is ten years, while the total number of machines is 20, the average capital replacement is two machines a year. If the average duration of a machine in this situation is twenty years, the capital replacement would be one machine a year. In general, average capital replacement per period (r_c) equals total number of capital goods (v) divided by the average duration (T):

$$(1) \qquad r_c = \frac{v}{T}.$$

The question is what it is that determines the average duration of the capital goods (T). The situation of choice for the firm is characterized by the following three equations:

$$(2) \qquad q = s \cdot \left\{ \frac{1}{(1+\upsilon)} + \frac{1}{(1+\upsilon)^2} + \ldots + \frac{1}{(1+\upsilon)^T} \right\}.$$

In equation (2), q presents the discounted cash flow of a capital good. Annual cash flow is presented by s. It is assumed here that the cash flow per unit product equals 1, so that, in this case, s equals production per period. Further it is assumed that production per period is constant

$$(3) \qquad \underline{b} = \underline{p}_s \cdot s + \underline{p}_t \cdot T.$$

Equation (3) is the budget function. Total budget for one capital good can be spent on either a good with a high production per period (s) and a relatively short duration T, or a capital good with a low production per period and a long life time. It is assumed that the budget, as well as the shadow prices of duration (p_t) and capacity per period (p_s), are fixed parameters. Finally equation (4) represents the optimum condition:

$$(4) \qquad dq = 0.$$

This optimum condition can be transformed with the Lagrange procedure into:

$$(5) \qquad \frac{\partial q / \partial s}{p_s} = \frac{\partial q / \partial T}{p_t}.$$

From equation (5) it can be deduced that the capacity of a capital good (measured in units per period) and the durability of this capital good are two quality attributes of the capital good. In order to gain maximum production with a given budget the ratio between marginal productivity and price must be equal for each quality attribute (Steenkamp, 1989, p. 24). It is obvious that, in this case, quality is not considered to be a free commodity (Steenkamp, 1989, p. 13)[3]. A continuous form for equation (2) is

(6) $$q = s \cdot \int_0^T e^{-\upsilon \cdot t} dt$$

$$q = \frac{s}{\upsilon} - \frac{s \cdot e^{-\upsilon \cdot T}}{\upsilon}.$$

Equation (6) can be seen as a production function. This production function can be shown with the help of iso-production curves. In Figure 10a.1, a field of six iso-production curves are shown, the rate of interest being equal to 0.06. It is also clear from this figure that the iso-production curves are concave, which means that the optimization procedure delivers a maximum.

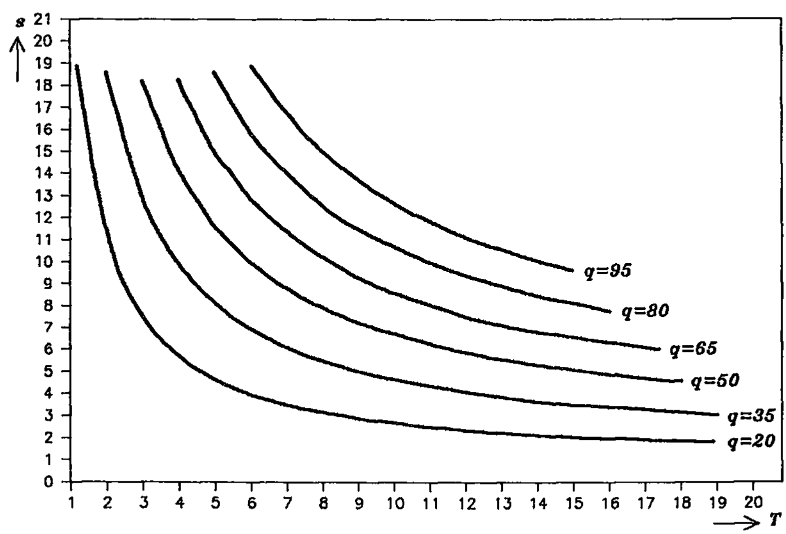

Figure 10a.1: iso-production curves combining s and T ($\upsilon = 0.06$).

Partial differentiation of equation (6) with respect to s and T, results in:

(7) $$\frac{\partial q}{\partial s} = \frac{1 - e^{-\upsilon \cdot T}}{\upsilon},$$

$$\frac{\partial q}{\partial T} = s \cdot e^{-\upsilon \cdot T}.$$

Substitution of equation (7) into the optimum condition (equation 5) yields the equation of producer's expansion path:

$$(8) \qquad s = \frac{p_t \cdot (e^{v \cdot T} - 1)}{v \cdot p_s}.$$

Differentiation of equation (8) with respect to T yields the tangent of the angle of inclination of the expansion path:

$$(9) \qquad \frac{ds}{dT} = \frac{p_t}{p_s} \cdot e^{v \cdot T}$$

It appears that the expansion path is steeper in proportion to the rate of interest, which means that a high rate of interest provides a short duration of the capital good, and therefore relatively much capital replacement, while a low rate of interest causes a long duration of capital goods and relatively little capital replacement[4)].

Appendix 10.2: Efficient fee

Assume that the abatement of firm 1 equals v_1 and that the abatement of firm 2 equals v_2. Total abatement equals v, which is a by the government given quantity, so that:

$$v = v_1 + v_2.$$

The total abatement costs of the given amount of pollution (c) equals the abatement costs of firm 1 (c_1) plus the abatement costs of firm 2 (c_2):

$$c = c_1 + c_2.$$

It is assumed that total abatement costs as well as marginal abatement costs are an increasing function of the abatement. This means:

$$\frac{dc_1}{dv_1} > 0, \quad \frac{d^2c_1}{dv_1^2} > 0, \quad \frac{dc_2}{dv_2} > 0, \quad \frac{d^2c_2}{dv_2^2} > 0.$$

We have to minimize the function:

$$f(v_1) = c_1(v_1) + c_2(v - v_1).$$

The first order condition is:

$$\frac{df}{dv_1}(v_1) = 0 \quad \text{so} \quad \frac{dc_1}{dv_1}(v_1) - \frac{dc_2}{dv_2}(v - v_1) = 0 \quad \text{so} \quad \frac{dc_1}{dv_1}(v_1) = \frac{dc_2}{dv_2}(v - v_1).$$

This will give v_1^* and v_2^* $(= v - v_1^*)$.

The total costs of the abatement are:

$$c_1(v_1^*) + c_2(v_2^*) =$$

$$(c_1(v_1^*) - c_1(0)) + (c_2(v_2^*) - c_2(0)) + c_1(0) + c_2(0) =$$

$$\int_0^{v_1^*} \frac{dc_1}{dv_1} dv_1 + \int_0^{v_2^*} \frac{dc_2}{dv_2} dv_2 + (c_1(0) + c_2(0)).$$

Indeed, if it is said that total abatement costs are equal to the area under the two marginal abatement costs functions, then it is assumed that the constant costs of abatement $c_1(0)$ and $c_2(0)$ are 0.

Notes

1) In this chapter, capital is defined as a physical concept.

2) A firm is considered identical with a production unit.

3) On the basis of empirical research, many authors believe that the rise in prevention costs (e.g employee training, quality reporting) to about 10-15% of total quality costs (the sum of prevention costs, appraisal costs and internal and external failure costs), both reduces total quality costs and increases the quality of the output of which duration is only one aspect. The notion *quality is free* is based on this empirical evidence. For product quality see: Steenkamp, 1989.

4) However, one might wonder whether a long duration of capital goods is always favourable to the conservation of natural resources. When the duration of capital goods is relatively high, then the introduction of nature-sparing technological innovations will take relatively much time. Indeed, a lot of (nature-sparing) innovations are bound to new capital goods. In other words, many technological innovations are *embodied*.

11. Scarcity of resources

This thesis has examined different ways of avoiding severe future resource crises. The main solutions to the question appear to be substitution between resources themselves, substitution between resources and capital, substitution between resources and labour, technical innovation and recycling on a sufficient scale, and economies of scale. To achieve these solutions the market mechanism has to function properly. On the other hand, direct regulations are also sometimes needed, depending on the type of scarcity of the depletable resources the economy has to deal with. We need to ask whether this scarcity is absolute or relative in nature. This is a relevant question. If scarcity is characterized as absolute for these resources, then price will not express it sufficiently, and the only hope for the conservation of sufficient amounts of these kind of resources for the future lies in direct regulation carried out by the government.

If we consider depletable resources of the exhaustible type, like coal, oil copper and iron, it seems as if the scarcity of these resources is absolute, since the use of these resources always diminishes the total stock. However, this does not mean that this type of resource is scarce in the absolute sense. Indeed, as we shall see, this is no reason for totally ignoring direct regulation as a proper instrument for the conservation of valuable stocks for the future.

There are several arguments against the idea of the absolute scarce diminishing stocks. In the first place, it may be that for every exhaustible resource there is a substitute which can be found. Fusion power, solar energy, wind energy and renewable resources are examples of substitutes for oil and coal. In this respect, the discovery of a cold fusion process as the almost ultimate backstop technology would have had tremendous advantages for the future energy supply in the world economy. Unfortunately, results of experiments all over the world show that the initial optimism was misplaced (Lopes Cardozo et al., 1990). Nevertheless, this does not mean that a similar discovery will not be made in the near future.

In the second place, the rise of the resource price may lead to a substitution of depletable resources by capital and labour[1]. Finally, resource-sparing technical innovations may lead to a decrease in resource use per unit product. It is even possible that substitution processes and technological change will decrease total use of an exhaustible resource while increasing total production. If the use of an exhaustible resource decreases at the same constant rate as total stock, then the stock will never be completely depleted. Though this case is rather theoretical, it does show that even exhaustible resources need not be absolutely scarce.

This conclusion does not imply that a government does not have the task of conserving stocks of exhaustible resources. I suggest the following reasons for this. Firstly, the total maximum amount of the total stock an extraction firm can dispose of must be stated as clearly as possible. In fact, this means that the exploitation rights must be properly described. If this is not the case, in a market form of perfect competition, a cowboy economy as described in the common property models of Chapter 9 will develop for the depletion of exhaustible resources. Proper government regulations can avoid the problem of the drilling of *offset wells* noticed by Hotelling (1931, p. 144). Secondly, it must be recognized that stocks of exhaustible resources are common property in principle, which means that governments, representing society, have a right to collect the royalty-taxes when the exploitation right is given to a private firm.

Thirdly, place damage to the environment caused by the exploitation of exhaustible resources must be prevented as much as possible. A proper planological concept resulting in depletion regulations and transport regulations is the way to avoid the sad sight of derelict mining areas and environmental disasters at sea caused by shipwrecked oil tankers in the future. Where environmental damage cannot be avoided by direct regulations, these externalities, should be internalized via proper direct levies. These levies imply a compensation in the welfare theoretical sense, and at the same time, mean an increase in depletion costs and selling price, which may stimulate the customer to use the resource in an efficient way. Besides, where technical innovations are induced by high factor prices, nature-sparing technological change is stimulated by such levies.

Another source of externalities is the use of exhaustible energy resources in the production process. The phenomena of *acid rain* and the heating of the atmosphere by the release of CO_2, known as the *greenhouse effect*, are directly related to the use of fossile fuels like coal, oil and natural gas[2)]. On the greenhouse effect Nordhaus commented:

> In analyzing the effect of man's impact on climate we are faced with a pure example of an externality. When an individual or firm burns gasoline in a car, or oil in a furnace, he pays for the capital equipment in the furnace and for the fuels. He pays nothing for his carbon dioxide emissions or the effect of his activities on the climate. Even if he is an altruist, he would have to recognize that his contribution to solving the long-run climate problem is negligible (Nordhaus, 1979, p. 135).

Government cannot keep aloof from these externalities either. Although the valuation of the environmental damage is not a simple matter, the atmospheric concentrations of chemical combinations that cause these effects have to be reduced via internationally coordinated levies and direct regulations like, for instance, placing a severe restriction on the use of CFC's (Folmer et al., 1989, The Economist, 1990a).

In many cases, a levy is suitable for internalizing the externality, as Bressers (1988) demonstrated for the Dutch water quality effluent charges can work. It seems justifiable to extend the application of the system of levying. This implies that not only the industrial sector should pay levies on a larger scale, but also the agricultural sector. Narrow crop rotation like that, for instance, in a number of regions in the United States and Western Europe has caused contamination by herbicides, insecticides, fungicides, nematocides and artificial fertilizers. This problem can partly be solved by the impositions of levies. Also the use of concentrates in intensive livestock breeding, with its disastrous effect on the soil of some developing countries and which causes a manure surplus in a number of European regions, can also be controlled by levies. Such levies would certainly help to diminish the use of the inputs mentioned and, at the same time, help to diminish agricultural surpluses (Laan et al., 1990, Harrington et al., 1990, Heijman, 1985).

Fourthly, governments have the task of correcting the market mechanism when it does not function well. According to Hotelling's rule for a situation of perfect competition, exhaustible resources royalties will rise by the rate of interest. However, the market interest rate probably does not equal the collective rate of time preference. In Chapter 4 I have given reasons why it will probably be too high, resulting in too fast a depletion of exhaustible resources. This means that governments have to correct market mechanism at this point. On way to do this is to control the distribution of exploitation permits. Another way of decreasing the extraction speed is represented by the use of the *severance tax*. This was recognized by Hotelling:

> Quite a different kind of levy is represented by the "severance tax". Such a tax, of so much per unit of material extracted from the mine, tends to conservation (Hotelling, 1931, p. 165).

Indeed, not every kind of levy will bring down the extraction speed. Hotelling showed that a *capital value tax* can even speed up the depletion:

> An unanticipated tax upon the value of a mine will have no other effect than to transfer to the government treasury a part of the mine-owner's income. An anticipated tax at rate α per year and payable continuously will have the same effects upon the value of the mine and the schedule of production as an increase of the force of interest by α (Hotelling, 1931, p. 164).

Another reason for government control of resource markets is their instability, which is not a favourable circumstance for economic development. If Hotelling's rule is to function well, an extended system of future's markets is necessary. Because such a system does not fully exist, heavy price fluctuations, like those in the seventies on the oil market, are unavoidable. Of course, in this respect, market imperfection also plays an important role. Superficially, it looks as if a cartel acts as a market stabiliser. In the short-term this may be so, but in the long-term, when cooperation between partners becomes strained (for example because of surpluses on the supply side of the market) the fall in resource price can be rather dramatic since the cartel has temporarily broken up. Indeed, cartels often function better in a seller's market than in a buyer's market (Van de Klundert et al., 1984, p. 232). The way to overcome heavy fluctuations, already promoted by Keynes as early as 1942, is to use mondial buffer stocks to control prices. Nowadays, the only resource with a functioning buffer stock system is natural rubber (Burger et al., 1990, Wahab, 1990). In order to secure the supply of energy it may be necessary to have the same kind of institution for the oil market, although not everyone agrees on this (Toman, 1990).

As far as renewable resources are concerned, the arguments against absolute scarcity can be extended by one. A renewable resource has a limited capacity to renew itself. In a steady state, total stocks of renewable resources remain constant, while the steady use of renewable resources may generate a steady growing economy when nature-saving technical innovations are introduced. Renewable resources might even serve as backstop technologies. However, the sustainable use of renewable resources require major adaptations of technical and organizational nature in this sector. If, for instance, this is not done for timber, then the uncontrolled deforestation for gaining sufficient land for agriculture will become a great danger for the environment. This practice contributes to global warming and may reduce the vital process of photosynthesis (Kneese, 1990). Moreover, the soil will partly vanish because of erosion[3)], which, in turn, will cause a loss of productivity. For instance, the average rate of soil erosion in crop land in the USA in 1990 was 5.9 tons per acre (Atwood et al. 1990). Deforestation also causes a loss of potentially useful genetic material of unique species (Pearce et al., 1990). It has to be concluded that it is mainly because of failing government policies that publicly-owned natural forests are wasted (Repetto and Gillis, 1988).

The first reason for government regulation of the exploitation of renewable resources is the imperfectness of the price mechanism. Here, also, the rate of interest is probably too high. Combined with the limitation of the *threshold population* of some species, the risk of over-exploitation of several renewable resources is severe. To prevent this and to ensure the future supply of renewable resources it is necessary for governments at least to protect these vulnerable threshold populations. One of the things that can be done is to stimulate *agroforestry*. For instance, the sustainable use of tropical wood on a large scale requires large plantations of several kinds of trees. Total destruction of tropical forests may be prevented by the controlled laying out of these plantations in and outside the area of tropical forests (Colinvaud, 1989, de Jaeger, 1990). Indeed, this is difficult if property rights on a specific renewable resource are not properly regulated. In this case, tropical forests are considered to be free which stimulates the actors to over-exploit it. This is, in fact, what is happening to tropical forests today. Generally speaking, royalties that have to be paid are far below the stumpage value of standing timber, which results not only in a loss of timber rents for the government, but also in a cowboy economy like the exploitation of forests by rent-seeking companies (Gillis et al., 1988).

Another example of this phenomenon is the fishery in the North Sea. Clark stated:

> Like any common-property situation, the fishing game has the basic structure of the prisoner's dilemma - all fishermen (hence society) can come out better if they cooperate, but each individual competitor has an incentive not to cooperate. The basic problem of fishery management, it would seem, is to devise a system of regulations (property rights) that will effectively resolve the common-property dilemma. Obviously no single approach is appropriate for all fisheries (Clark, 1982, p. 286).

Theoretically, one of the ways to protect the common property of fish would be to severely tax the catch. However, the difficulties that would arise in, for instance, computing the optimum tax makes it almost impossible to impose such a system. One of the main difficulties with a tax on the catch is the fall in income of the fishery. This means that the only way of protecting sea fish population is to have a system of tradeable fishery quotas per vessel.

In such a system, it is the market that generates the royalty and not the government, while the royalty stays in the hand of the fishery. The community profits from this system via normal income and profit taxation. Of course, the government still has to prevent fishermen from exceeding the quotum and has to impose proper penalties upon those who do so. All other kinds of measures, such as a quotum per fishing nation or shortening the harvest season, do not attack the root problem, which is the common property character of the resource. These measures nearly always result in an expansion of fishing inputs (for instance larger vessels) to catch as much as possible (Fisher, 1988).

An alternative for the catch of seafish would be the harvesting of fish from aquaculture systems like cage culture or ponds. The controlled laying out of these systems should ensure that no environmental damage in the form of pollution will be caused by unconsumed feeds and chemical pesticides. It has been estimated that aquaculture production, through the farming of fish and plants, will have increased to around 22 million tons by the year 2000, which is twice the 1985 level (Weld et al., 1990).

Finally, the consequences of public investment projects must be strictly evaluated. For instance, in the case of the depletion of forested wetlands in the Mississippi valley, Stavins and Jaffe (1990) showed that public infrastructure investments affected private land-use decisions, profoundly speeding up the depletion of a renewable resource. This case shows that public investment must be screened on unwanted, unintended, induced land-use changes. This and other cases show that there are major regional effects of resource depletion (see also Howe, 1987).

In general, it can be concluded that rent-yielding depletable resources are relatively scarce, which means that, in principle, the market mechanism can take care of an efficient allocation of these resources. However, this does not imply that the use of subeconomic resources is limitless. The resources, which are either hidden or whose usefulness is still unknown (hypothetical resources) must be protected by governments because of possible future needs. For example, the conservation of great parts of tropical forests is necessary since little is known about the resources of this and other ecosystems which might be useful for mankind in the future. In these cases, only direct regulation, not the market mechanism, can be used for conservation.

Notes

1) See Chapter 3 on the possibility of a stationary state by a continuing substitution between an exhaustible resource and capital.

2) The major greenhouse gases with their sources are: carbon dioxide (fossil fuel combustion, deforestation, biomass burning), CFC's (various industrial processes and applications), methane (biological decay in water-logged areas, such as rice paddies, enteric fermentation in cattle and termites), biomass burning, oil and gas exploitation), nitrous oxide (fertilizer use, fossil fuel combustion, biomass burning), ozone (reactions involving other pollutants, for instance carbon monoxide and methane, and sunshine).

Past and present levels of the greenhouse gases in the atmosphere are:

Type of gas	Pre-industrial concentration	1985 concentration	Growth rate per year (%) 1980-1987
Carbon dioxide	275 ppm	346 ppm	0.5
CFC-11	-	0.22 ppb	6.1
CFC-12	-	0.37 ppb	6.2
Methane	700 ppb	1650 ppb	1.0
Nitrous oxide	280 ppb	309 ppb	0.4

It is too dificult to assign meaningful global levels for ozone (Bertram et al., 1990).

3) For instance in Indonesia, according to the forestry accounts of Repetto et al. (1989), between 1970 and 1984 the forests suffered a net loss equal to over 1,863 million m^3 wood, which was about 7.2% of the standing timber in 1970. This was not only caused by the timber harvest, but also by erosion which often results from harvesting timber.

To give some impression of the quantity of the deforestation in Amazonia, in the Brazilian Amazon region where 0.6 percent of the area could be classified as 'cleared' in 1975. This percentage had risen to 12.0 by 1988. The total area is 5,005,425 km^2 (Pearce et al., 1990).

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Index

SAMENVATTING

Dit proefschrift bestaat uit elf hoofdstukken. In hoofdstuk 1 wordt het probleem van de uitputting van schaarse hulpbronnen aan de orde gesteld. In dit hoofdstuk worden tevens de belangrijkste begrippen gedefinieerd. Hoofdstuk 2 bespreekt de visie van economen op de produktiefactor natuur. De vraag in hoeverre de *steady state* een realistisch alternatief is voor economische groei, komt in hoofdstuk 3 aan de orde. De hoofdstukken 4 en 5 bespreken achtereenvolgens de concepten *tijdvoorkeur* en *doelmatigheid*. Deze zijn van belang bij de verdere behandeling van de probleemstelling in de hoofdstukken 6 tot en met 11. In hoofdstuk 6 wordt het gebruik van uitputbare hulpbronnen ingebouwd in de traditionele economische theorie van de economische groei. Hoofdstuk 7 behandelt conjuncturele aspecten van de aanwending van hulpbronnen. Hoofdstuk 8 bespreekt de invloed van marktvormen op het uitputtingstempo. Hoofdstuk 9 behandelt het belangrijke vraagstuk van de eigendomsrechten. De inzet van hulpbronnen door de individuele onderneming wordt in hoofdstuk 10 besproken. Tevens wordt in dit hoofdstuk nagegaan welke de mogelijke invloed van overheidsmaatregelen is op het terugdringen van het gebruik van schaarse hulpbronnen. Tenslotte behandelt hoofdstuk 11 het karakter van de schaarste aan hulpbronnen. Nu volgt een korte samenvatting van alle hoofdstukken.

1. Schaarse uitputbare hulpbronnen

Schaarse uitputbare hulpbronnen kunnen worden onderverdeeld in vernieuwbare en niet-vernieuwbare hulpbronnen. Bij een vernieuwbare hulpbron denken we bijvoorbeeld aan een populatie vis, bij een niet-vernieuwbare hulpbron aan een hoeveelheid olie. De uitputbare hulpbronnen kunnen ook worden onderverdeeld vanuit het oogpunt van de eigendomsrechten. Bij exclusieve hulpbronnen zijn de eigendomsrechten op individueel niveau vastgelegd, terwijl dit bij gemeenschappelijke hulpbronnen niet het geval is. Bij de laatste categorie van hulpbronnen kan dit tot overexploitatie leiden wanneer een gebruiker niet voldoende hoeft te betalen voor het gebruik van deze hulpbronnen. In dat geval komt de schaarste aan deze hulpbronnen onvoldoende in de marktprijs tot uiting.

Een maatstaf voor uitputtingssnelheid van hulpbronnen is de voorraad-verbruiksratio. Deze ratio geeft aan hoe lang de mensheid nog over een bepaalde hulpbron kan beschikken indien het absolute gebruik van een hulpbron per tijdseenheid constant is. Naarmate de voorraad-verbruiksratio kleiner is, komt het moment van totale uitputting dichterbij. Van de metalen hebben vooral kobalt, chroom, koper, lood, nikkel, tin, wolfram en zink een lage voorraad-verbruiksratio. Andere hulpbronnen met een relatief lage voorraad-verbruiksratio zijn zwavel, grafiet en gips. Van de energiebronnen hebben ruwe olie en aardgas de laagste voorraad-verbruiksratio's. De voorraad-verbruiksratio is als maatstaf voor de schaarste van een hulpbron ongeschikt. Een bruikbare maatstaf voor schaarste is de 'royalty' of 'rent'. Deze grootheid bestaat uit uit de prijs van een hulpbron minus de winningskosten. Naarmate de rent hoger is, kan men de hulpbron beschouwen als schaarser. Dit impliceert dat de schaarste van een hulpbron over het algemeen geen absoluut verschijnsel is.

2. *Natuur in de economische theorie*

Tot de tijd van de neoklassieke-Keynesiaanse synthese in de economische theorie hebben economen altijd een visie op de natuur gehad. Zeker de fysiocraten, maar ook de klassieken hebben plaats ingeruimd voor de natuur als produktiefactor. Voor een groot deel is dit veroorzaakt doordat de economie als wetenschap voortkomt uit een samenleving die nog voor een groot deel als agrarisch getypeerd kan worden.

Met het voortschrijden van de industriële revolutie verloor de economie haar belangstelling voor de relatie arbeid-natuur. De nadruk kwam nu te liggen op de relatie tussen arbeid en kapitaal, die zich in de achttiende en negentiende eeuw sterk wijzigde. Het gevolg is dat in de gangbare economische theorie het economisch proces wordt beschouwd als een gesloten systeem waarin met behulp van kapitaal en arbeid goederen worden voortgebracht, die vervolgens worden geconsumeerd.

Sinds het midden van de jaren zestig realiseert men zich echter ook meer en meer dat de economie niet als een gesloten systeem, maar als een open systeem dient te worden opgevat. Enerzijds onderhoudt de consumptiesector relaties met de natuur via het directe verbruik van door de natuur voortgebrachte goederen (bijvoorbeeld lucht), anderzijds worden de voor de menselijke produktie benodigde hulpbronnen rechtstreeks aan de natuur onttrokken door de produktiesector. Beide sectoren gebruiken de natuur tevens als stortplaats voor afval.

Dit besef heeft tot gevolg dat de negatieve externe effecten van de economie steeds meer in het centrum van de belangstelling komen te staan. Verder wordt het steeds duidelijker dat de natuur niet langer kan worden gezien als een onuitputbare hulpbron, maar beschouwd dient te worden als een voorraad kapitaalgoederen die op een verantwoorde wijze dient te worden gebruikt. Deze overtuiging zou uiteindelijk kunnen leiden tot het opheffen van de parasitaire relatie die momenteel bestaat tussen de menselijke economie en de natuur. Hiervoor in de plaats zou een symbiose tussen natuur en mens tot stand moeten worden gebracht.

3. De 'steady state'

Men verwacht dat in de komende eeuw de wereldbevolking zal toenemen van ruim vijf miljard tot minstens acht miljard mensen. Daarom dient een niet-groeiende wereldeconomie vooralsnog als niet realistisch van de hand te worden gewezen. Hiermee behoort een *steady state* economie echter nog niet tot de onmogelijkheden. Een steady state economie kan immers worden gedefinieerd als een toestand van de economie waarin het relatieve aandeel van het gebruik van een niet-vernieuwbare hulpbron in de totale voorraad steeds gelijk blijft en de voorraad van een vernieuwbare hulpbron constant is. Zo gedefinieerd is een steady state economie gelijk aan een economie die groeit overeenkomstig het principe van de duurzame groei.

Om een dergelijke toestand van de economie te bereiken zijn (bio)technologische ontwikkelingen, die een besparing van het hulpbron gebruik per eenheid produkt teweeg brengen, noodzakelijk. In principe zou een niet groeiende economie zich kunnen handhaven zonder deze vernieuwingen, namelijk via substitutie van niet-vernieuwbare hulpbronnen door kapitaal. Bij een groeiende economie die, zoals we zagen, in de volgende eeuw nodig is, is dit niet meer mogelijk. Overigens kan men zich bij een niet-groeiende economie afvragen of substitutie van niet-vernieuwbare hulpbronnen, zoals de belangrijkste energiedragers, en kapitaal voldoende tot stand zal komen, omdat energiedragers en kapitaal doorgaans geen substituten van elkaar zijn. Kapitaal en energie kunnen het best beschouwd worden als complementaire produktiefactoren. Dit impliceert dat zelfs in een niet-groeiende economie energiebesparende technische vernieuwingen noodzakelijk zijn.

4. De tijdvoorkeurvoet en de interest

Bij de bepaling van het optimale uitputtingstempo van een uitputbare hulpbron speelt de tijdvoorkeurvoet een cruciale rol. De tijdvoorkeurvoet komt in het economisch leven tot uiting in de hoogte van de marktinterest. Is deze interestvoet relatief hoog, dan zal, zo is de redenering, de maatschappelijke tijdvoorkeurvoet eveneens hoog zijn, hetgeen een relatief snelle uitputting van uitputbare hulpbronnen met zich mee zal brengen.

Er zijn twee categorieën bezwaren tegen bovenstaande redenering in te brengen. In de eerste categorie bevinden zich de bezwaren van morele en rationele aard. Velen vinden de hogere waardering van huidige goederen boven toekomstige goederen immoreel tegenover toekomstige generaties. Bovendien stellen zij dat de bijziendheid waarop de tijdvoorkeur is gebaseerd irrationeel van karakter is. Een uitputtingstempo van uitputbare hulpbronnen gebaseerd op het immorele en irrationele gegeven van de tijdvoorkeur beschouwen zij dan ook als onaanvaardbaar en zeker niet als optimaal.

De tweede categorie bezwaren richt zich op de interest als afspiegeling van de tijdvoorkeurvoet. In deze visie is de interestvoet te hoog vanwege twee redenen. De eerste reden is dat de risico-opslag in de interestvoet gebaseerd is op individuele overwegingen, die maatschappelijk gesproken niet van belang zijn. Het gaat hier om de zogenoemde 'transfer risks' die onvoldoende door het verzekeringswezen worden gedekt. De tweede reden is het bestaan van belastingen op inkomen uit het gebruik van kapitaal. Als gevolg hiervan wordt een bedrijf gedwongen vóór belastingen een hogere discontovoet te hanteren dan het rendement dat toevalt aan de kapitaaleigenaren na belastingen. Als het rendement na belastingen overeenkomt met de maatschappelijke tijdvoorkeurvoet, dan is de door het bedrijf gehanteerde discontovoet te hoog.

Het bestaan van de tijdvoorkeur dient door een econoom niet als een ethische kwestie te worden benaderd, maar als een empirisch verschijnsel. Vanuit dit standpunt gezien snijden de bezwaren uit de eerste categorie geen hout. Wel dient men zich af te vragen in hoeverre de marktinterestvoet een juiste afspiegeling is van de tijdvoorkeurvoet. Op basis van de bezwaren uit de tweede categorie komt men tot de conclusie dat de marktinterestvoet waarschijnlijk te hoog is om dienst te doen als maatschappelijke tijdvoorkeurvoet. Dit impliceert dat de uitputtingssnelheid van veel hulpbronnen, die overwegend gebaseerd is op de marktinterestvoet, waarschijnlijk te hoog is. Overigens is de vraag 'hoeveel te hoog?' hiermee nog niet beantwoord.

5. Efficiency in de exploitatie van hulpbronnen

Overeenkomstig de Hotelling efficiencyregel dient de exploitatie van een niet-vernieuwbare hulpbron op basis van de marktvorm volledige mededinging zó plaats te vinden dat het prijsniveau stijgt overeenkomstig de marktinterestvoet. Stellen we de marktinterestvoet gelijk aan de waarde van het marginale produkt van kapitaal, dan ontstaat de Solow-Stiglitz efficiencyregel, die stelt dat bij de exploitatie van een niet-vernieuwbare hulpbron de stijging van de waarde van het marginaal produkt van kapitaal gelijk moet zijn aan de prijsstijging van de niet-vernieuwbare hulpbron, welke stijging gelijk dient te zijn aan de interestvoet.

Een belangrijk vraagstuk betreft de stabiliteit van het optimale uitputtingspad. Indien de prijs sneller stijgt dan de interestvoet, zullen de hulpbroneigenaren het uitputtingstempo drukken, teneinde een grotere hoeveelheid van de hulpbron op termijn aan te bieden. Hierdoor onstaat een kleiner aanbod op de dagmarkt en een groter aanbod op de termijnmarkt, hetgeen zal zorgen voor stijgende dagprijzen en dalende termijnprijzen. Uiteindelijk zal hierdoor de evenwichtige prijsontwikkeling worden hersteld. In de omgekeerde situatie, waarbij de prijs van de hulpbron langzamer stijgt dan de interestvoet, doet zich uiteraard de omgekeerde ontwikkeling voor. Kortom, bij voldoende aanwezigheid van termijnmarkten is het evenwichtige prijspad van hulpbronnen stabiel. Uiteraard kunnen allerlei exogene ontwikkelingen heftige fluctuaties in het prijsniveau van hulpbronnen veroorzaken.

Een vernieuwbare hulpbron kan zich binnen zekere grenzen vermeerderen. Deze eigenschap leidt ertoe dat voor deze specifieke categorie van hulpbronnen een andere optimumregel moet worden ontwikkeld dan die voor niet-vernieuwbare hulpbronnen. De optimumregel voor vernieuwbare hulpbronnen is dat de prijs van de vernieuwbare hulpbron dient te stijgen met het verschil tussen de interestvoet en de natuurlijke vernieuwingsvoet. Indien de ontwikkeling van een vernieuwbare hulpbron verloopt overeenkomstig een logistische curve, zal in het evenwicht de interestvoet gelijk zijn aan de natuurlijke vernieuwingsvoet bij een constante voorraad van de vernieuwbare hulpbron. Over de stabiliteit van dit evenwicht kan worden gezegd dat het evenwicht stabiel is als de winning voortdurend een constant percentage uitmaakt van de voorraad.

Tenslotte valt nog op te merken dat beide efficiencyregels, die voor niet-vernieuwbare en die voor vernieuwbare hulpbronnen, zijn af te leiden uit de regel van Faustmann.

6. Groeimodellen

De bovenstaande optimaliteitsregels of efficiencyregels zijn ingebouwd in de traditionele theorieën van economische groei. Het betreft hier twee groeimodellen, namelijk het groeimodel van Harrod en Domar en het neoklassieke groeimodel. Het centrale vraagstuk hier is de verenigbaarheid van gestage economische groei met een constante voorraad vernieuwbare hulpbronnen en een vaste voorraad-verbruiksratio voor de niet-vernieuwbare hulpbronnen. Met andere woorden, de vraag luidt: kan gestage groei ook duurzaam zijn?

Het antwoord op deze vraag is bevestigend. Echter, het is al eerder opgemerkt, een noodzakelijke voorwaarde hiervoor is voldoende natuur-besparende technologische veranderingen en voldoende mogelijkheden voor substitutie tussen hulpbronnen. Uit de modelanalyses volgt dus niet dat een gestage groei automatisch duurzaam van aard zal zijn. Het duurzame groeipad is een mogelijk groeipad naast vele minder natuur vriendelijke varianten.

Een ander vraagstuk dat de aandacht trekt is dat van de mogelijkheden voor het hergebruik van hulpbronnen. Uiteraard zijn niet alle hulpbronnen geschikt voor hergebruik. Energiedragers zijn dat over het algemeen niet, terwijl metalen zich doorgaans wel voor hergebruik lenen. Men dient zich hierbij te realiseren dat men uit één kilogram oud ijzer nooit één kilogram nieuw ijzer kan verkrijgen. Op basis van dit gegeven is een hergebruiksmultiplier ontwikkeld, met behulp waarvan het mogelijk is te berekenen hoeveel nieuw metaal men in totaal kan winnen uit een bepaalde hoeveelheid erts. Ook al leent zich een hulpbron voor hergebruik, het neemt niet weg dat de betreffende hulpbron uitputbaar is.

7. Conjuncturele aspecten van het gebruik van hulpbronnen

Conjuncturele aspecten van het hulpbronnengebruik zijn bestudeerd met behulp van een drietal modellen: het multiplier-accelerator model, het spinneweb-model en een neo-klassiek conjunctuurmodel. Het multiplier-accelerator model verklaart het cyclisch verloop van het verbruik van hulpbronnen uit de vertraging in de consumptiefunctie en de aanpassing van de kapitaalgoederenvoorraad aan de gewenste situatie. Afhankelijk van de hoogte van de coefficiënten is de ontwikkeling van de produktie stabiel, al dan niet met golven.

Een meer geavanceerde benadering laat de waarde van de coëfficiënten variëren. Ook in deze situatie kan men het karakter van de golfbeweging bestuderen. Ook is het mogelijk het rechterlid van de differentievergelijking te manipuleren, met als doel een verandering in de hulpbroncoëfficiënt te simuleren. Dergelijke veranderingen treden op als gevolg van technische ontwikkelingen. Voor het gebruik van ruwe olie leidt het meest plausibele scenario tot een afname van het totale gebruik, bij een groei van de wereldproduktie.

In het microeconomische spinnewebmodel zijn het de veranderingen in de prijzen die veranderingen in gevraagde en aangeboden hoeveelheden genereren. In de meest eenvoudige vorm van dit model zijn aanbieders niet tot verandering van hun gedrag in staat omdat zij geacht worden geen lering te kunnen trekken uit hun ervaringen. In het meer geavanceerde model is dat wel het geval. Ook bij dit model is het weer mogelijk te experimenteren met niet constante coëfficiënten. Overigens zijn het vaak vooral de exogene ontwikkelingen die tot heftige fluctuaties op hulpbronnenmarkten leiden. Voor olie waren dat de beide oliecrises. Voor Nederlands hout was dat bijvoorbeeld de zware storm in 1973.

Met het neoklassieke conjunctuurmodel is het mogelijk voorspellingen te doen over de effecten van een olieprijsstijging op een klein niet-olieproducerend land. De effecten zijn over het algemeen tamelijk gematigd. Een gerechtvaardigde kritiek op dit model is het gebruik van een lineair homogene Cobb-Douglas produktiefunctie. Deze impliceert een substitutie-elasticiteit van 1, zowel tussen kapitaal en energie, als tussen arbeid en energie. Echter, het gebruik van een tweestaps CES-Cobb-Douglas produktiefunctie met een relatief lage elasticiteit tussen halffabrikaat en kapitaal (0,4) leidt niet tot wezenlijk andere resultaten. Dit wordt voor een groot deel verklaard door de Cobb-Douglas produktiefunctie van het halffabrikaat. Als gevolg hiervan is de elasticiteit tussen energie en arbeid gelijk aan 1, hetgeen voor Nederland overigens een plausible waarde is.

8. De invloed van marktvormen op de exploitatie van hulpbronnen

De optimumregel van Hotelling functioneert in een wereld met volledige mededinging. Bij de andere marktvormen, monopolie en oligopolie, zijn andere optimumregels van kracht. Bij het monopolie geldt voor niet-vernieuwbare hulpbronnen de optimumregel dat de marginale opbrengst met de rentevoet moet stijgen. In dat geval heeft het monopolie zijn gedisconteerde totale rentopbrengsten gemaximaliseerd. Het is daarbij opvallend dat het monopolie geneigd is de hulpbron aanmerkelijk minder snel uit te putten dan de gezamenlijke ondernemingen onder de marktvorm volledige mededinging.

Voor vernieuwbare hulpbronnen geldt bij volledige mededinging dat de prijs dient te stijgen met de rentevoet minus de natuurlijke vernieuwingsvoet. Bij een monopolie moet ook deze regel worden aangepast. Bij deze marktvorm zal de marginale opbrengst toenemen met het verschil tussen de rentevoet en de natuurlijke vernieuwingsvoet. Onder een monopolie zal het aanpassingsproces dat leidt tot een stabiel evenwicht overwegend trager verlopen dan bij volledige mededinging het geval is.

Bij het oligopolie kunnen in een *cartel-fringe*-situatie twee perioden worden onderscheiden. In de eerste periode handelen het kartel en de ondernemingen uit de fringe als actoren op een markt voor volledige mededinging. In de tweede periode, als het gedeelte van de hulpbron geëxploiteerd door de fringe uitgeput is, kan het kartel opereren als een monopolie. Het resultaat is dat de tijd die een oligopolie zal gebruiken voor de uitputting van een bepaalde hulpbron zal liggen tussen die van het monopolie en de ondernemingen onder de marktvorm volledige mededinging in.

Technische ontwikkeling in de zin van het steeds goedkoper beschikbaar komen van een *backstop technology* heeft voor niet-vernieuwbare hulpbronnen in het algemeen tot gevolg dat de uitputtingstijd van een bepaalde hulpbron wordt verkort. Uiteraard zijn ook hier weer verschillen tussen de marktvormen volledige mededinging en monopolie.

9. Gemeenschappelijke hulpbronnen

Het probleem met gemeenschappelijke hulpbronnen is dat de eigendomsrechten niet of onvoldoende zijn vastgelegd. Hierdoor lijkt het alsof een schaarse hulpbron niet schaars is als gevolg van het feit dat er geen 'rent' betaald hoeft te worden voor het gebruik van de schaarse hulpbron. Een goed voorbeeld van een dergelijke hulpbron is vis op zee. In principe kan iedereen die over voldoende hulpmiddelen beschikt deze hulpbron exploiteren zonder betaling van een rent. De zee wordt hierdoor overbevist, hetgeen het voortbestaan van deze hulpbron aantast.

De overheid kan op twee manieren op deze ongewenste situatie reageren. Op de eerste plaats is het mogelijk een royalty te heffen op de aan land gebrachte vis. Op de tweede plaats kunnen verhandelbare quota per schip worden opgelegd. Het eerste alternatief betekent een zware aanslag op het inkomen van de vissers. Het tweede alternatief leidt ertoe dat de royalty door de markt wordt gegenereerd. Deze royalty valt dan toe aan de eigenaar van het schip als hij zijn quotum verkoopt. Vanuit sociaal oogpunt gezien verdient het tweede alternatief de voorkeur, omdat hierbij de voor de vissers negatieve inkomenseffecten beperkt zijn.

Wat betreft de gebruikte modellen met behulp waarvan getracht zou kunnen worden de royalties of de quota's te bepalen, kan worden gesteld dat het sterk de voorkeur verdient *multi-species* simulatiemodellen te gebruiken.

10. Het gebruik van hulpbronnen door ondernemingen

Het *materials balance*-model leent zich uitstekend voor de bestudering van hulpbronnenverbruik door de onderneming. Het model legt een duidelijk verband tussen het hulpbronnenverbruik enerzijds en de uitstoot van afval anderzijds. De vervuiling van het milieu en het op grote schaal verbruiken van grondstoffen zijn immers twee kanten van dezelfde medaille.

Teneinde een zuiniger gebruik van hulpbronnen door een onderneming te stimuleren en een geringere uitstoot van afval te bewerkstelligen kunnen van overheidswege verschillende soorten maatregelen worden genomen. Op de eerste plaats kan men onderscheid maken tussen brongerichte maatregelen versus *end-of-pipe* maatregelen. Op de tweede plaats kan men voorschriften en financiële prikkels onderscheiden.

Wanneer het slechts om één bedrijf gaat, maakt het voor de verwachte effecten van het beleid weinig uit welk instrument men kiest. Gaat het om een relatief groot aantal bedrijven, dan werkt veelal een heffing efficiënter dan een voorschrift. Overigens zal vooral de aard van het milieuprobleem doorslaggevend moeten zijn bij de keuze van de instrumenten van het milieubeleid. Accute problemen zullen doorgaans uitsluitend met behulp van regelgeving kunnen worden opgelost. Anderzijds zijn er ook tal van milieumaatregelen die beter via een heffing kunnen worden bestreden. Dit geldt temeer in een situatie waarin de overheid met financiële tekorten kampt.

11. Het karakter van de schaarste van hulpbronnen

Zijn schaarse uitputbare hulpbronnen absoluut schaars of relatief? In het eerste geval zou het prijsmechanisme niet het goede allocatie-instrument zijn, in het tweede geval zou de allocatie juist wel via de markt geregeld moeten worden. Tegen het absoluut schaars zijn van niet-vernieuwbare hulpbronnen zijn een tweetal argumenten in te brengen. Op de eerste plaats kunnen deze hulpbronnen geheel of gedeeltelijk gesubstitueerd worden door alternatieve hulpbronnen, door de inzet van meer arbeid en door de inzet van meer kapitaal. Op de tweede plaats is het in principe mogelijk via hulpbron-besparende technische ontwikkeling een niet-vernieuwbare hulpbron voor een oneindig lange periode te gebruiken. Een belangrijk hulpmiddel daarbij voor sommige hulpbronnen zijn de mogelijkheden voor hergebruik.

Voor vernieuwbare hulpbronnen kan deze argumentatie nog met één argument worden uitgebreid. Vernieuwbare hulpbronnen hebben een beperkte capaciteit tot vernieuwing. Een, vanuit het oogpunt van het behoud van hulpbronnen, gunstige situatie zou ontstaan indien het grootste deel van de economie nog slechts gebruik zou maken van vernieuwbare of voor hergebruik geschikte hulpbronnen. Alhoewel deze situatie nog niet binnen handbereik is, biedt zij toch een perspectief voor toekomstige generaties.

De hulpbronnen die in ieder geval dienen te worden behouden, zijn de hulpbronnen die we nog niet kennen, maar die in de toekomst van groot belang kunnen worden, dat wil zeggen de *hypothetische hulpbronnen.* Omdat voor deze hulpbronnen geen markt bestaat, dienen de plaatsen waarop de aanwezigheid ervan wordt vermoed, te worden beschermd via directe regelgeving. Op deze wijze zou bijvoorbeeld aan de toekomstige schaarste van ons thans onbekende plantaardige hulpbronnen uit het tropisch oerwoud kunnen worden recht gedaan.

CURRICULUM VITAE

Wilhelmus Johannes Maria Heijman werd geboren op 2 februari 1953 te Schalkwijk in de provincie Utrecht. In 1971 behaalde hij het diploma HBS-A aan het St. Bonifatiuscollege te Utrecht. Het studiejaar 1971-1972 bracht hij door op de Koninklijke Militaire Academie te Breda. In 1972 begon hij met de studie Economie aan de Katholieke Hogeschool te Tilburg (thans Katholieke Universiteit Brabant). In 1979 behaalde hij daar het doctoraal diploma met als afstudeervakken Internationale Economische Betrekkingen en Agrarische Economie en Sociologie. Van 1979 tot 1982 was hij leraar economie op de Rijks Agrarische Scholengemeenschap en het Thorbecke college, beide te Utrecht. In 1979 begon hij tevens aan de studie Sociale Geografie aan de Rijksuniversiteit van Utrecht. Het doctoraal diploma van deze studie behaalde hij in 1986 met als hoofdvakken Sociale Geografie van de Stedelijke gebieden en Methoden en Technieken van sociaal-geografisch onderzoek. In 1982 trad hij in dienst van de Landbouwhogeschool (thans Landbouwuniversiteit) te Wageningen bij de vakgroep Staathuishoudkunde. Bovendien was hij van 1984 tot 1986 werkzaam als studiebegeleider economie aan het studiecentrum Nijmegen van de Open Universiteit. Bij de Landbouwuniversiteit is hij thans belast met het geven van onderwijs en het doen van onderzoek voornamelijk op het gebied van de milieu-economie.