Chapter 6: Economic theory

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6.1 Introduction

Economics is a well established discipline with an extensive use of theories, and a number of sub-disciplines. The basic building blocks come from microeconomics where it is studied how firms sell, or supply, goods and services and buy, or demand, production factors (raw materials, labour, etc.) while households (consumers) demand goods and services and supply labour. When seeing all firms and households together, theories of market interactions are analysed. Here we are concerned with the special sub-discipline, or branch, of economic theory called environmental and resource economics, which to a large extent builds on microeconomic theory. It includes also the choices of government agencies deciding how to control pollution and regulate the use of natural resources. The present exposition builds on mainstream economics, or *neoclassical economics*. For a deeper look, the reader should consult any standard text on microeconomics, or environmental and resource economics (e.g., Perman et al. 2003). *Ecological economics* is a competitive paradigm and addresses the interdependence and co-evolution between human economies and natural ecosystems. It takes the fact that economic system is part of the larger system planet Earth as its central organizing principle. The classical paper is Kenneth Boulding, *The economics of the coming spaceship earth* (Boulding 1966). The International Society for Ecological Economics was founded in 1989, and publishes the well-renowned journal Ecological Economics.

People and societies have for a long time been concerned with the economic principles of utilisation and management of natural resources like forests and mineral deposits, and the economic principles of how to cope with pollution of various types. Harold Hotelling formulated the theory of optimal extraction of non-renewable resources in his seminal contribution from 1931 (Hotelling 1931). One of the last century's great economists A.C. Pigou formulated the pioneering economic principles on how to deal with pollution problems in his famous book *The Economics of Welfare* (Pigou 1920). Today we find that many of the basic results from mainstream environmental and resource economics are embedded in practical policy. For example, the principle of buying and selling climate pollution permits, or quota trading, is an integrated part of the Kyoto Protocol. The so-called 'Polluter-Pay-

Principle' is another contribution (see below). The basic principles of cost-benefit analysis (chapter 11.3) and the theory of valuation of goods with no market value have also originated from environmental and resource economics.

Environmental and resource economics are closely related. Environmental economics is concerned with questions of excessive production of pollution and waste and the accompanying insufficient protection of people and nature due to ill functioning markets and institutions. A typical question might be: What are the driving forces determining air pollution in a given local area, and what type of regulation measures, if any, should be taken to deal with the problem? It is a distinction between direct regulation, or 'command-and-control', and indirect regulation where the regulating agency aims to change the behaviour of the polluting firm through various types of economic incentives. Within natural resource economics, on the other hand, utilization and management of renewable and non-renewable natural resources are studied. Renewable resources include fish, wildlife and forests while non-renewable resources include minerals and oil. However, renewable resources may be exterminated while non-renewable resources may multiply as new deposits are discovered. Over time, the border line between renewable and non-renewable resources is therefore more of the conceptual type than absolute and while renewable resources grow according to natural growth, non-renewable does not. Indeed, time is what makes natural resource economics interesting. Time may also be of interest in environmental economics when the accumulated amount of waste or pollutants causes damage. We then have a so-called stock pollution problem which analytically is close to, say, a fishery management problem. The most pressing environmental problem today, global warming, is a stock pollution problem. However, when the flow of emission, and not the accumulated stock, is the problem the time element is of no particular interest. The environmental problem is then static. Both a dynamic and static problem will be considered below.

Positive and *normative* analyses are two fundamental perspectives of environmental and resource economics. The positive perspective tries to explain what we see in the economy around us. The normative perspective, on the other hand, tries to explain how the allocation and distribution of environmental resources ought to be. The first perspective may be value free, while the second perspective certainly is not. Most environmental and resource economics analysis are of the normative type, and economists frequently try to assess what is the 'optimal degree of pollution' (see below). To ask 'what is optimal' is of course a normative question, and normative analysis is closely related to modern welfare economics. When evaluating the desirability of some proposed action one has to identify both the gain and losses from that action. Typically both the gains (benefit, or profit) and losses (costs) are lumped in a common monetary value, say, Euro. In most instances, some groups of people will loose, while others will win. In the economic jargon, this means that the proposed action represents no Pareto improvement. Pareto improvement means that at least one agent comes better out while no one loses. Within modern welfare theory, however, lack of Pareto improvement is not considered as a serious problem as the monetary gain of the winners *potentially* can compensate the monetary loss of the losers. This is known as the Kaldor-Hicks compensating theorem. The notion of ‘efficiency’ is therefore often seen as synonymous with the maximization of total wealth, or total surplus. This obviously means that problems of distribution are swept under the carpet. However, in many instances, it is crucial to take distribution issues into account, and ‘efficiency’ should therefore be seen in light of the *political question* of what is the socially desirable distribution of costs, benefits and environmental goods (Bromley 1990).

Mainstream environmental economics is, as noted, concerned with questions of pollution and waste due to ill functioning markets and institutions. Mainstream environmental economics is therefore not concerned with ‘too much’ production and pollution *per se*. Typically, it is the trade off between production (and consumption) and the accompanying rights to pollute that counts. Property rights are often the corollary to institutions, and a pivotal question is who has the right to pollute and who has the right to be protected from pollution. This question was raised in a famous article by Roland Coase (1960). Coase’s answer was that under certain (strong!) assumptions, where the absence of so-called transaction costs (the costs of collecting information, the costs of negotiating, and so forth) is of particular importance, the property rights issue did not matter for the total surplus maximisation level of pollution. This is the famous Coase-theorem. Crucial in the Coase analysis, as well as in the above mentioned book by Pigou, is the notion of an *external economic effect* where the production of, say, a firm directly influences the production in other firms (or households) beyond those bundled in market operations and the market price (more is explained on this below). External effects are also frequently prevalent in natural resource economic problems, and the well-known notion of the ‘tragedy of the common’ (Hardin 1968) is just dealing with an economic externality problem. This issue was also raised earlier in connection to the fishery in a famous article by Gordon (1954). Economic externalities are framing the global climate problem as well.

The values of most goods are established through their market prices. Many, if not most, environmental goods, however, are not traded in markets. There are also often no market prices to signal how people value their environment. Clean air, say, is not something that people can buy and sell in markets. An unspoiled landscape enjoyed by people living in a near by crowded city is not traded in markets. For such goods, no obvious markets prices exist and hence the value, as expressed through prices, of utilising the environment, is difficult to assess. For this reason, economists have constructed various methods to estimate the values of environmental goods. Such values may, however, also be expressed through so-called shadow prices which is beyond the scope of this overview to explain further (see e.g., Dasgupta 1982 and the references therein).

As a starting point for estimating environmental values, we note that there are several attributes of the natural environment from which people obtain benefits. The value of, say, a wilderness area covers not only its recreational value to current users, which is called its *use value*. In addition there are various types of *non-use values* since people value the wilderness for future uses. *Option value* is such a value and refers to a type of insurance premium individuals would be willing to pay to retain the option of future use. Uncertainty and irreversibility are crucial elements in determining option value. Irreversibility refers to the fact that once converted to other land-uses, wilderness land is not possible to bring back to its pristine state. *Bequest value* is related to the satisfaction that people gain from the knowledge that a natural resource like a piece of wilderness land is being preserved for future generations, while *existence value* refers to the satisfaction that people derive simply by knowing that the wilderness area or other natural resource exists, even if they do not ever expect to use it. All these types of values are so-called anthropocentric; that is, they are defined by human needs and nothing else.

Several techniques exist within mainstream environmental economics to measure environmental use values and the different types of non-use values. Basically, all these methods employ various methods designed to reveal people’s willingness to pay. The general methodology is called contingent valuation. In the contingent valuation approach, willingness to pay is elicited by conducting surveys where a carefully selected sample of people from the relevant population is asked to respond to a series of questions about their willingness to pay, contingent on changes in the availability and/or quality of an environmental amenity, such as a piece of wilderness land. The travel cost method is another method where the value is inferred from the distance and cost people use to visit various environmental amenities such as national parks. For an overview of these and other methods, see Freeman (2003). These methods may be questioned of various reasons, and especially the value of environmental goods with irreversible changes, such as biodiversity losses and wilderness land converted into agricultural land or other type of uses, may be, very demanding, if not impossible, to assess. Likewise, various existence values are hard, if not meaningless, to assess (‘what is the money value of a songbird?’).

In what follows, we first look at the classical static environmental problem where the current production of a firm causes a flow of pollution and harms other firms and households. The key term an external effect, or an externality, will here come clear. Next, in section 6.3, we present and study a more aggregate, and possibly more abstract, type of model where it is the accumulated amount of pollution, or waste, that has the damaging effect. This is a stock pollution problem and a natural resource economic problem, as the environmental medium where the pollution accumulates may be seen as a natural resources as the pollution stock generally decays.

6.2 The static pollution problem and the theory of externalities

6.2.1 Defining externalities

In many cases the activities of a firm directly influences other firms and/or the well-being of households. By direct influence, we mean that their activities in production and distribution may impose costs (or benefits) on other economic actors beyond those bundled in market operations and into the market price. A polluting firm may influence the production processes in other firms negatively; the living conditions of people living close to the firm may suffer; and household and production activities located far away may experience the pollution as well. These kinds of economic effects arise when, for example, the firm’s action reduces air and water quality, or blocks access to a beautiful vista. In the economic jargon, these types of adverse effects are known as negative externalities. The essence of a negative externality is hence that an action of one agent, say, a polluting firm, influences the well-being or profitability of other agents in the absence of any mechanism for compensating those that are harmed. See Baumol and Oates (1975) for a more formal definition. This type of action may be intentional or non-intentional. When intentional, it means that the polluting firm, through choice of production technology or in other ways, actively tries to impose (externalise) its production costs on other firms and households. When non-intentional, pollution may follow simply as a inevitable by-product of production.

Daily economic life is full of different kinds of externalities, and externalities may also be positive. A positive externality is created when the profitability of a firm is increased by the production of a neighbouring firm due to, say, getting easier access to certain types of information. Whenever the utility, or well-being, of a person is influenced by the actions of another person there are externalities, positive or negative, as well. The notion of pollution externalities can be traced back to the above mentioned book Pigou (1920) who was studying pollution problems in London, but Alfred Marshall was probably the first economist to use this term (for an overview, see Papandreou 1994).

In the case of a polluting firm, its *private* cost of production will not include the externalities associated with production. Private costs include labour cost, the purchase of raw materials, the costs of new equipment, and so forth; that is, the sum of all costs that shows up in the accounts (profit and loss statements) of the firm. The private cost of production should have the external costs added, altogether the social cost of the firm, in order to make decisions about production levels that are socially desirable, as the following analysis will show. This obviously means that the rights of the polluting firm are restricted while the rights of the victims, firms and people, are extended.

In Figure 6.1 we have drawn the marginal private cost curve of a firm, labelled, *MPC*. Marginal cost is the cost to produce an additional unit of the actual product. *MPC* is assumed to be increasing, meaning that it is more expensive, at the margin, to produce the next unit of output. Often, this situation may be different. The *MPC* may also decrease, at least up to the capacity constraint of the firm, giving lower cost for additional units produced, implying the presence of what economists call economy of scale (for firms within the manufacturing industry this may more be the rule than the exemption). The *MPC* curve will also be the supply curve of the firm. To simplify the analysis we have assumed that the firm is a price-taker, that is, the market price is not influenced by the level of the firm’s production. In the more general case, supply and demand are inter-related and the price depends on the size of the market. Price-taking behaviour implies a lack of market power, or strategic interaction among other firms and producers, an assumption more or less synonymous with so-called ‘free competition’. For a manufacturing firm, this assumption may seldom hold in reality, but for the sake of simplicity it is assumed here.

Given the market price *p*, in Euro per unit produced, a profit-maximising firm will produce X^* units of the output. Producing more than X^* means a loss because the cost on the margin, given by the value on the *MPC* line then will exceed the income the firm will get, *p*, if it sells the additional item. Likewise, producing less means that the firm is forgoing the potential profit it would get from the sales of producing more units until it reached the value, X^*. Some maths will help to illuminate the argument. Suppose that the cost function of the firm is given by $C(X) = c_0 + c_1 X + (c_2/2)X^2$ so that c_0 is the fixed cost (costs that occur either the firm produces, or not) and $c_1 X + (c_2/2)X^2$ the variable cost where c_1 and c_2 are positive constants. The income minus the cost, the profit, reads then:

$$\pi(X) = pX - [c_0 + c_1 X + (c_2/2)X^2] \qquad (6\text{-}1)$$

To see how the profit changes with production, we differentiate equation (6-1) with respect X; $d\pi(X)/dX = p - (c_1 + c_2 X) = p - MPC$. $MPC = c_1 + c_2 X$ is therefore linearly increasing, while the profit maximising output is given by $p = MPC$. This yields $X^* = (p - c_1)/c_2$ which is the (private) optimal production of the firm when the goal is as high profit as possible.

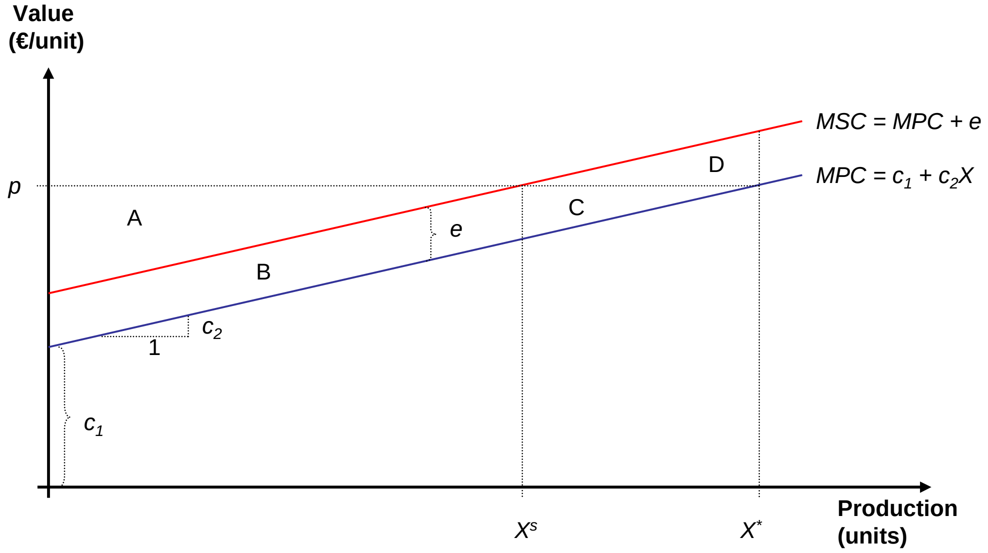

Figure 6.1: The marginal private cost curve of a firm, MPC; the social marginal cost curve MSC =MPC + e

The analysis so far assumes that there are no externalities involved, and the firm produces according to the rule; price is equal marginal private cost. Suppose now that the production of the firm pollutes a river and that a downstream fishery industry therefore experiences a loss. Their loss, in monetary terms, will depend on the size of their catch, the price of the catch, the biological productivity of the fish stock, and so forth. The external cost will typically also vary with the production level of the polluting firm. However, in Figure 6.1, again for simplicity and to make the argument clear, we assume the external cost to be fixed as *e* Euro per unit produced. From a societal point of view, the marginal production cost is the sum of the private and externality cost, *MSC* = *MPC* + *e*. If included as a cost, the level of production for a firm acting rationally (maximizing its profit) would be X^s instead of X^*. From a social perspective, the firm will produce too much, X^*, instead of the lower quantity, X^s, if allowed to externalize the social costs.

This argument may also be shown by simple maths. From a societal point of view the total surplus now reads:

$$S(X) = \pi(X) - eX = pX - [c_0 + c_1 X + (c_2/2)X^2] - eX \qquad (6\text{-}2)$$

where eX is the external cost when production is X. To find the maximum social surplus, we again differentiate; $dS(X)/dX = p - (c_1 + c_2 X) - e$. It may easily be confirmed that the maximum value occurs when $dS(X)/dX = 0$ which gives $p = MPC + e = MSC$; that is, the social marginal income is equal the social marginal cost. The social desirably supplied quantum of the firm is then $X^s = (p - c_1 - e)/c_2$ which also yields the optimum degree of pollution.

Thus, if permitted to pollute the stream, the profit maximising firm will produce and pollute too much, and the reason is that a part of the production cost is imposed on the fishery industry and not taken into account by the polluting firm. In the case depicted in Figure 6.1, the welfare gain of the market outcome in money terms will be the profit of the firm as given by the area (A+B+C), minus the social cost of pollution, given by the area between MPC and MSC, or (B+C+D), altogether (A-D). The quantity, X^s, on the other hand, representing the socially desirable (optimum) level of production, yields (A+B) as the profit of the firm while the cost of pollution is reduced to B, altogether A. The social gain of moving from the market outcome where the external cost is not taken into account to a situation where it is taken into account; that is reducing the production and polluting from X^* to X^s , is accordingly given by the area D. This assessment is based on the assumption that the one Euro for the polluting firms counts as much as one Euro for the victim, the fishery. This may, however, not always be the case (see above, and also chapter 11.3 about cost-benefit analysis). Notice also that if the external cost becomes sufficiently high (higher than $p - c_1$), the socially desirable production level will be zero as the social cost then exceeds the net social marginal benefit for all production levels. This is also easily recognized from the above mathematical expression.

Even with the simplifications in the above example, it is a valid representation of externalities and illustrates various types of reasoning about the economics of pollution. It can help identify institutional issues about pollution, for example, who has the right to pollute. Above it was assumed that the firm had the right to produce and pollute inflicting damages on the natural environment and the fishery. In other words, the firm was given the rights to pollute the river (implicitly or explicitly by the state) while the downstream fishery had no rights to be protected from pollution. However, an opposite property rights scheme where the fishery has the right to clean water is also a possibility. This brief discussion shows that the roots of the very existence of an externality lie in the *institutional* structure and the assignment of rights and duties. The issues of rights and duties and the institutional structure are important, but will not be pursued further here, see the seminal paper by Coase (1960) and Bromley (1991).

In the above model, the amount of pollution depends on the technology of the polluting firm, but no abatement was explicitly considered to take place by the polluting firm. However, it may readily be included when we distinguish between the production and the emission damaging the downstream fishing industry. On general form, the cost function of the polluting firm may then be written as $C(X, E)$ where the amount of physical emission is E and where more emission means lower production costs. In addition we need an abatement cost function indicating the connection between the cost of abatement and the amount of emission. Finally, the external costs function must be related to the amount of emission E, and not production X as above. Within such a model both the social desirable production and emission of the polluting firm should be determined. The abatement effort follows as a corollary. However, we will not pursue such a model further here.

6.2.2 Coping with negative externalities

The basic insight from the above analysis is that the market, if left alone, will lead to a socially undesirable level of environmental quality, representing a social cost. From a policy point of view this leads to the question: how to deal with pollution problems and negative externalities, and how to correct the misallocations of resources related to environmental externalities. In what follows, it is assumed that the government, or a governmental agency, has the authority to regulate the polluting firm. An obvious solution would then be to dictate, or ‘command and control’, the polluter to produce output consistent with what is considered to be socially desirably; that is the output level, X^s.

Another way to attain that goal would be to impose a tax per unit produced, in essence increasing the costs of production. In Figure 6.2, which is basically the same as Figure 6.1, this is accomplished by imposing the tax t which is a so-called Pigouvian tax (see also above). As shown in the figure, imposing the tax $t = e$ per unit produced will shift the polluting firms supply curve from *MPC* to *MSC*, where $MSC = MPC + t$ Now, the new curve intersects with the market price at X^s, the socially desirable level of production.

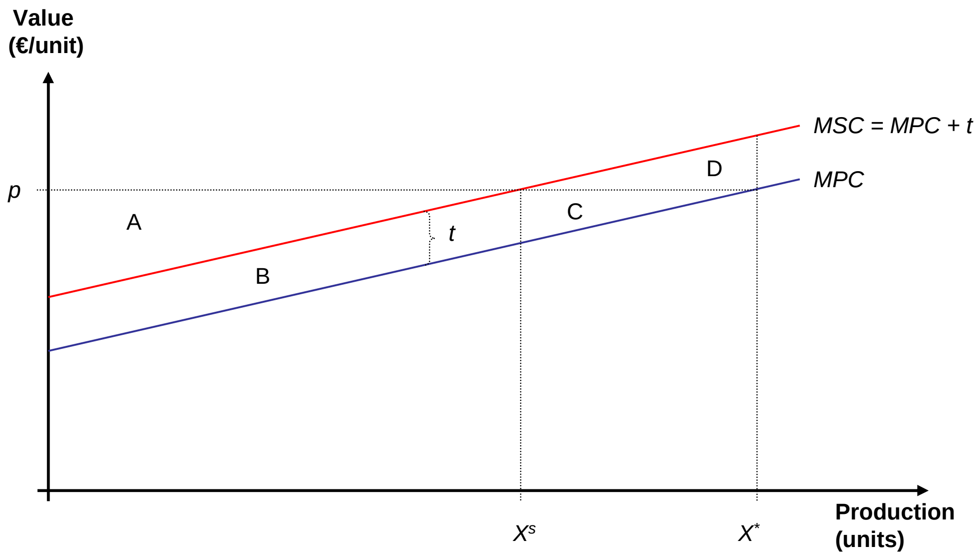

Figure 6.2: The marginal private cost curve of a firm when a Pigouvian tax is imposed

Pigou's theory is simple and elegant; the firm's supply curve will shift upwards. The polluting firm will view the tax as a payment for using the river to pollute; that is, the use of the river is no longer considered as a free good. The cost of using it now appears in the accounts just as the other costs. In such a way, the cost of pollution is internalised, and the marginal cost of the firm shifts up with the amount of *t*.

We may also show this argument by maths. If the firm is imposed the tax *t* per unit produced, the profit reads:

$$\pi(X,t) = pX - [c_0 + c_1 x + (c_2/2)X^2] - tX \qquad (6\text{-}3)$$

The condition for profit maximising is now $d\pi(X,t)/dX = p - c_1 - c_2 X - t = 0$, or $p - MPC - t = 0$. If *t* is set equal to *e* we find that this condition will result in an output just like the social desirably output. Accordingly, when the firm faces the tax $t = e$ it is in the self interest of the polluting firm to produce the socially desirable output.

In this scheme, the tax burden falls on the firm responsible for the pollution and is consistent with what is usually called the *polluter-pays-principle*. Although the result is socially desirable, the firm will have reduced profits from two causes. There will be a decrease in profit due to lower sales from X^* to X^s as given by the area C. In addition, the firm will pay a tax equal to X^s times the marginal tax rate t as given by the area B. The profit of the firm is therefore now A.

Unless some scheme is also instituted to compensate those who suffer the cost of the externalities which is given by the area B, they will still have losses under this scheme since the taxes will simply go towards general revenues. This will be the same either the polluting firm or the downstream fishery industry was established first. Therefore, from the viewpoint of the mainstream economic notion of efficiency, it does not matter “who comes first” and the polluter pays principle does not automatically redress the social ills created in the first place. The question of compensation, or not, has fuelled a continuing debate (again, see also Coase 1960 and Bromley 1990).

6.2.3 The real world

In this analysis, we have shown how a Pigouvian tax works to internalise the external cost in the above simple case. However, in the real world the task is much harder. One obvious problem is to decide on the right level of the tax. Setting the correct tax, demands that the regulating agency has accurate information about all the relevant cost and benefit components. The agency needs to know the monetary value of the damages related to the other production activities affected by the polluter. When the welfare of households is negatively influenced as well, such costs need also to be known. These costs might be even harder to assess. The regulating agency also ought to know the production cost of the polluting firm. In practice, this may also be a difficult task as the information between the regulator and the polluting firm is asymmetric, and according to the above example, the firm has incentives to report too low costs. There may also be various types of uncertainties and there are also certain costs of monitoring the polluting firms. Some of these questions were analysed in a famous paper by Weitzman (1974).

The effectiveness of the Pigouvian tax theory is based on the notion of a profit maximizing, or rational, firm. However, we know that firms, at least in the short term, may have other goals. One such goal is to maximise its market share while sacrificing an immediate level of profit (see, e.g., Baumol 1967). The production level of the polluting firm under this type of behaviour, if left alone, will then be above that of X^*, see Figure 6.1. A Pigouvian tax, under these circumstances will not produce the desired social level of production.

6.2.4 Indirect vs. direct regulation

When imposing a Pigouvian tax as a regulating instrument, market forces are used as it is in the firm's *own interest* to reduce pollution. The best the profit maximising firm can do is to produce the desired social amount of output. For this reason, Pigouvian taxation is also said to be an *indirect* way to regulate. Once the tax has been set and imposed, it is market forces that cause a firm to respond. Governments often employ another form of policy instruments, *direct* regulation where the regulating agency imposes a quantitative restriction on how much the firm is allowed to pollute. If the agency can relate the quantity of reduction precisely to the social costs of polluting, direct and indirect regulation can produce equivalent results.

Direct regulation, or 'command and control', has been the traditional and dominant way to deal with environmental regulations, rather than impose taxes of production. In the regulatory process, the regulating agency collects the information necessary to determine the physical actions to control pollution. The regulator then imposes restrictions on the polluter to take the physical steps to control the pollution. Direct regulation is often based on legislation, for example, some type of 'Clean Air Act', containing minimum standards of air quality, water quality, and so forth. Direct regulation has a major advantage compared to indirect regulation as it yields greater certainty in how much pollution will result from regulation in complex environmental processes (Weitzman 1974). Moreover, in situations with great uncertainty and where it may be unclear how a polluting firm might respond to economic incentives (see also above), direct regulation gives greater certainty on the actual level of pollution that will result. One disadvantage of direct regulation, however, is that the amount of information needed may be more demanding than that needed for indirect regulation. Another disadvantage is that it may reduce the incentives to find new, cleaner production processes or new technologies to control pollution. When coping with many firms and polluters, it is also difficult to obey the principle of cost-effective regulation, which can be shown to be that the marginal cost of polluting (or marginal abatement cost) should be equal among different firms for the same type of pollution. Most of these disadvantages may, however, be rescued when polluters have the possibility to trade polluting permits (quota trading).

6.3 A stock pollution problem

Pollution can be classified in terms of its damage mechanism. In the previous analysis damage aroused from current production and the accompanying pollution flow (emission). In many instances, however, it is the accumulated amount of emission, or *stock* of pollutant, that is the source of damage. For a stock of the pollutant to accumulate, it is necessary that the residuals have a positive lifespan and that emissions are being produced at a rate which exceeds the assimilative capacity of the environment. The best-known example of a stock pollutant is the climate problem caused by the atmospheric accumulated amount of carbon dioxide. But numerous local environmental problems, like polluted lakes, may be of this type as well. For an overview, see Perman et al. (2003).

A stock pollutant problem is basically a dynamic problem and is the mirror image of a renewable natural resource problem, like fishery. While the population dynamics of a fish stock, i.e. the growth in number of fish, or biomass, is governed by natural growth minus harvesting, the stock pollutant dynamics, i.e. the growth in the amount of pollutant accumulated, is governed by the emission minus the regenerative activity of the relevant environmental medium. If the emission flow exceeds the regenerative capacity, the accumulated amount of the pollutant increases and the damage typically increases. On the contrary, if the emission flow is below the regenerative capacity, the accumulated amount of the pollutant decreases and the damage reduces. The economics of a stock pollution problem was first analysed by Plourde (1972).

In what follows, we formulate an abstract and simple model that sheds some light on the basic nature of a stock pollution problem, and again we are not explicitly considering any abatement investment, or clean-up activity. In this model we imagine a small village where only one good is produced. The production of this good cause a flow of pollution that degrades a surrounding lake that the inhabitants of the village enjoy for various reasons. The fishery in the lake may suffer, and the recreational use of the lake may be reduced through pollution. It is the accumulated flow that causes damage, but the lake is naturally cleansing through biodegradation (mainly oxidation) of the organic pollutant. Accordingly, as above, on the one hand production and thus the flow of emission are beneficial, but on the other the production represents a trouble through the accumulated amount, or stock, of the pollutant. Following the economic jargon, the problem is now formulated as a *social planner* model where a benevolent social planner seeks to find an emission level evolving over time that is socially desirable. In essence, the social planner internalizes the external damage cost. This happened as well in the above flow pollution problem when a tax was imposed on the polluting firm. The difference is that the social planner directly makes a trade-off between costs and benefits.

As indicated, the benefit in this economy is related to the current production of the good. The monetary value of the production benefit at time t may be written as:

$$B_t = B(E_t) \tag{6-4}$$

where E_t is the emission. A higher production and emission means more benefit, $dB / dE_t = B' > 0$. In addition, no emission and hence no production, means no benefit, $B(0) = 0$. The benefit function is assumed to be constant over time; that is, the same amount of emission creates the same amount of benefit every year.

It is the stock of the pollutant at time t that causes damage in the surrounding lake at the same time. When A_t is the pollutant stock at time *t*, the monetary value of the pollution damage cost function may hence be written as:

$$D_t = D(A_t) \tag{6-5}$$

The damage cost function is assumed to be constant over time as well. No pollutant stock means no damage $D(0) = 0$, while a higher stock means more damage; $D' > 0$. As above, it may be difficult to find the exact form of the damage cost function and find the monetary value of the damage. In reality the damage function may also change over time and it may not be continuous as indicated above. However, all these problems are swept under the carpet, and no more cost and benefit components are included in this simple model. When the benefit and damage cost of production are lumped together, and where one Euro of the gain counts as much as one Euro related to the pollution (see above), the surplus in this economy is hence given as:

$$U_t = B(E_t) - D(A_t) \tag{6-6}$$

We then consider the stock-flow relationship of the pollutant. Current emission uses the lake as a deposit so that the pollution concentration level increases. However, offsetting factors are at work as some of the existing pollutant will be transformed into harmless substances by chemical processes and a fraction of the pollution stock decays. Generally, this relationship may be written as:

$$dA_t / dt = E_t - R(A_t) \tag{6-7}$$

where the stock growth dA_t / dt comprises the emission flow E_t minus the natural cleansing, or decay $R(A_t)$, depending on the stock of the pollutant. If emission exceeds decay we have $dA_t / dt > 0$ and the accumulated amount of the pollutant increases. In the opposite case, it decreases.

In Figure 6.3, the decay function $R(A)$ is illustrated by two different, stylized, functions (the time subscript is omitted). Panel a) yields a linear function, while panel b) depicts the widely applied logistic function. In the linear case $R(A) = \beta A$, where the parameter $\beta > 0$ yields the constant self cleansing fraction, the amount of decay increases proportionally with the stock. In the logistic case, the decay is positive, but decreasing, meaning that the fraction of self cleansing reduces with A. The logistic function may be specified as $R(A) = rA(1 - A / A^{\max})$ when $0 < A < A^{\max}$ and $R(A) = 0$ when $A \geq A^{\max}$. As we have $R(A) / A = r(1 - A / A^{\max})$ the parameter r hence represents the maximum self cleansing fraction within the range $0 < A < A^{\max}$, while $A^{\max}$ represents the concentration where the self cleansing capacity collapses. Accordingly, if $A \geq A^{\max}$ we have 'doomsday' in the sense that the pollution, even with no production and emission, can never come below $A^{\max}$.

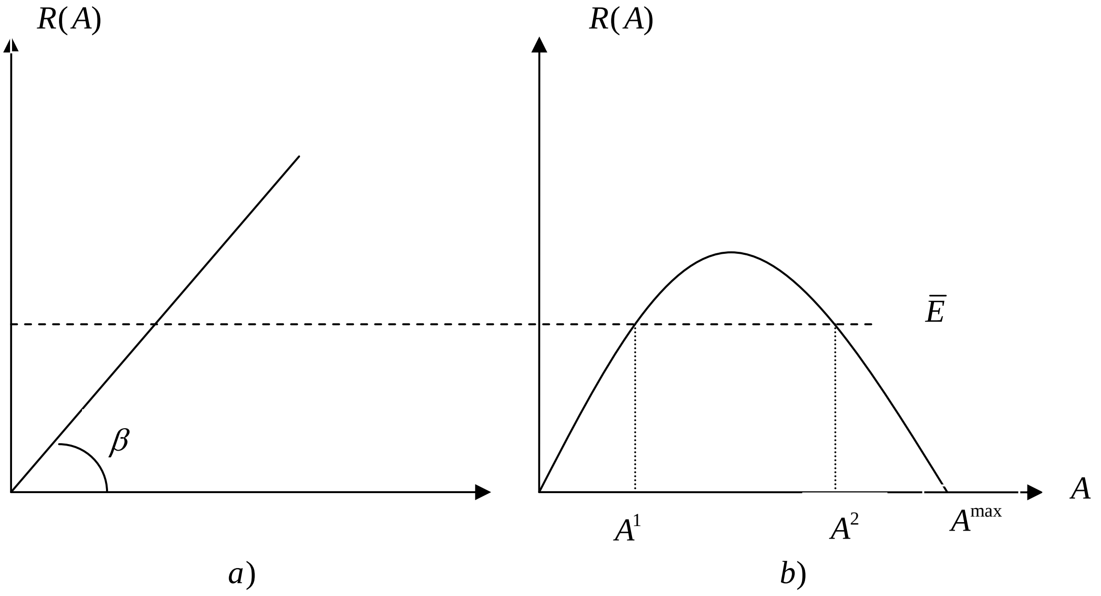

Figure 6.3: Naturally cleansing (decay) functions. The linear case a), the logistic case b)

It is obvious that the outcome of the economic problem may be quite different depending on how the actual decay function looks like. However, before we consider the economic problem, we assume for the moment being that production and emission is constant over time, illustrated by the locus $\bar{E}$ in Figure 6.3. Given $\bar{E}$ and a zero growth economy, there is one level of A for which emission equalizes decay in the linear case. It is hence just one *equilibrium* stock level according to this model. On the other hand, in the logistic case, there are two levels of A for which emission just equalizes decay, A^1 and A^2. Out of these two equilibrium points, however, only A^1 is (locally) stable. To see this, we find that being just to the right of point A^1 the decay exceeds the (fixed) emission level, and following equation (6-7) $dA_t / dt < 0$ and A hence decreases. On the contrary, if initially located to the left of A^1, $dA_t / dt > 0$ and the pollutant stock A increases. Using the same logic, we find that if initially located to the right of A^2, $dA_t / dt > 0$ and the stock increases, while it decreases when being to the left of this point (but above stock level A^1). Therefore, while A^1 is (locally) stable, A^2 is unstable. From this we can conclude that with fixed emission $\bar{E}$ and a zero growth economy, depending on the initial situation, the pollution damage can either settle down to the fixed level A^1 or the pollution stock will grow above all limits. The reason for this twosided outcome is the decay function where the amount regenerated declines with the accumulated amount A.

The economics of this pollution problem is now considered. In the above static problem in section 6.2, where we aimed to find the flow pollution level that maximised the difference between the profit of the polluting firm and the external polluting cost, this was in principle an easy task. The social surplus at time t is now given by equation (6-6), and because the time periods are linked together through a stock-flow relationship, the problem of finding the social desirably emission level is now more complicated. We will attack the problem in two ways. First, we study the economic *equilibrium* pollution problem, and next some elements of the *dynamics* of the stock problem are studied.

When formulated as an equilibrium stock pollution problem, the social planner aims to find an emission level that maximises net social surplus in equation (6-6) subject to (6-7), when the pollutant stock stays unchanged over time; that is, when $dA_t / dt = 0$ and hence $E = R(A)$ (the time subscript is again omitted). This problem may either be solved as a constrained maximization problem by using the Lagrange method, or by inserting the emission-decay relationship into the net benefit function. Using the inserting method, the problem may be formulated as to find the value of A that maximises $U = B(R(A)) - D(A)$. When using the composite differentiation rule, the condition for maximisation is $dU / dA = B'(E)R'(A) - D'(A) = 0$, or:

$$D'(A) = B'(E)R'(A) \tag{6-8}$$

This condition together with $E = R(A)$ then determines the socially desirable emission flow and production level, and pollutant stock. Condition (6-8) indicates that in optimum the marginal value of emission times the marginal amount of decay should be equal the marginal stock damage. In other words; the marginal production benefit, expressed as a marginal pollution stock benefit, should be equal the marginal stock damage. Because B' and D' are positive, R' will be positive as well, or $R'(A) = D'(A) / B'(E) > 0$. In the case of a logistic type decay function, it is therefore seen that the solution to the problem is to be found to the left hand side of the peak value of the function which means that it is beneficial with a ‘modest’ (or ‘small’) degree of accumulated pollution. The second order condition of the maximisation problem should also be controlled, and it reads $d^2U/dA^2 = B''(E)R'(A)^2 + B'(E)R''(A) - D''(A) < 0$. Therefore, a concave benefit function ($B'' \leq 0$) and a convex damage function ($D'' \geq 0$), together with the strictly concave logistic decay ($R'' < 0$) function will secure a meaningful interior solution to the problem. In the linear decay case, either the benefit function must be strictly concave or the damage function must be strictly convex ($D'' > 0$), or both, to secure a meaningful solution.

As production and emission is linked together with the production damage through the accumulated amount of the pollutant, the growth of production and pollution is hence involved in the more far reaching view of this problem. This dynamic problem is progressively more complicated than the above formulated equilibrium economic solution. One problem is how to evaluate different cost and benefit streams that occur at different points in time; one needs to assess the value of ‘one Euro today versus one Euro next year’. The common method for doing this is so-called *geometric* (or exponential) discounting. If, say, the discount rent is 7 percent, this means that 107 Euro next year is considered as having the same value as 100 Euro this year. Likewise, 107 Euro in 11 year is considered as having the same value as 100 Euro in 10 years. There are two issues here. First, is it reasonable to assume that the substitution in time today, i.e. between this year and next year, should be the same as the substitution in time in 10 years time? Recent research clearly indicates that this is not so, and when running into the distant future the discount rent should be smaller. However, in what follows, we apply a constant discount rent as assuming a falling discount rent over time gives additional complications of the model. Next, what discount rent should be used? Is 7 percent reasonable, or should it be higher, or perhaps lower? There are also several other problems present when framing the dynamic problem which we will not touch upon here.

When assuming that the social planner aims to maximise the present value net benefit stream using a constant discount rent, the planning problem is hence to find a sequence of emission streams E_t that maximizes

$$PV = \int_{t=0}^{t=\infty} [B(E_t) - D(A_t)]e^{-\delta t} dt \tag{6-9}$$

where the planning horizon is assumed to be infinite. δ is the (constant) discount rent and $e^{-\delta t}$ is the accompanying discount factor when time, as here, is measured in a continuous manner. The constraint of the problem is the stock-flow relationship of the pollutant, equation (6-7).

This problem may be solved by using optimal control theory (see Clark 1990 for applications in natural resource management). This technique is quite demanding and we will not go into the details here. However, it turns out that the solution may be written as:

$$dE_t / dt = [1/B''(E_t)][B'(E_t)(\delta + R'(A_t)) - D'(A_t)] \qquad (6\text{-}10)$$

together with the above stock-flow relationship (6-7) and a so-called transversality condition, in essence securing a steady-state (see below).

The solution to the problem is hence given by two first order nonlinear differential equations. There may be a multi equilibrium solution if the stock-flow equation (6-7) is of the logistic type. This will certainly not happen in the linear case. When we concentrate on this much simpler linear decay case and suggest that the benefit function is strictly concave (see also above), we find that the dynamics leading to a long-term equilibrium, or steady-state, will be characterized by a so-called saddle point path. In essence, a saddle point path means that the steady-state is approached along two optimal trajectories: either along a trajectory where the amount of the accumulated pollutant increases while the emission decreases, or the opposite; where the accumulated pollutant decreases while the emission decreases. These paths are depicted with arrows in Figure 6.4. Therefore, depending on the initial amount of accumulated pollution A_0, we find that either A_t will decrease and E_t will increase over time until the economy approaches the long term equilibrium, or the opposite. As a corollary, equation 6-6 then states that the instant surplus U_t will increase over time in the first case and decrease in the other case. Therefore, following the Brundtland commission's definition of sustainability as *non-declining* welfare over time (Brundland 1987), it is clear that the growth pattern in this simple economy is sustainable in the first case and non-sustainable in the other case.

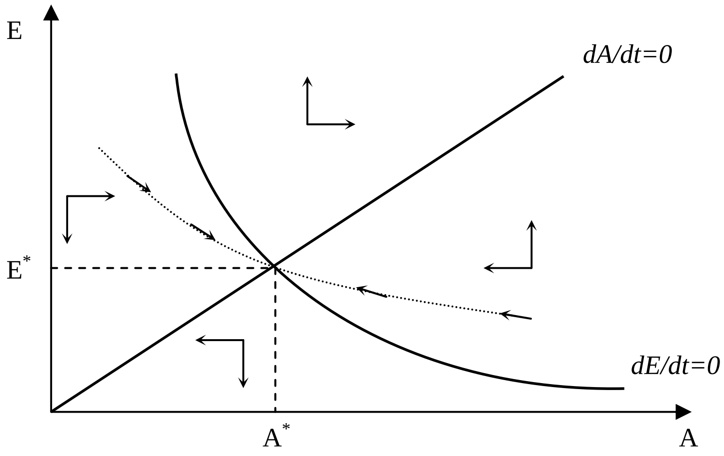

Figure 6.4: Phase diagram and steady-state dynamic pollution problem

In Figure 6.4 we have also depicted combinations of emission and accumulated pollution such that the stock growth is zero, $dA_t / dt = 0$ (equation 6-7), and combinations for zero growth emission, $dE_t / dt = 0$ (equation 6-10). When these equations hold at the same time we hence have the steady-state A^* and E^* characterized by:

$$D'(A) = B'(E)(\delta + R'(A)) \tag{6-11}$$

together with the stock-flow relationship $E = R(A)$. It is seen that the only difference compared to the above solution of the static problem (equation 6-8) is that the discount rent now is included. When explicitly taking the linear decay function $R(A) = \beta A$ into account, condition (6-11) may also be written as $D'(A) = B'(\beta A)(\delta + \beta)$. Therefore, as $D'' \geq 0$ and $B \leq 0$ (see above) it is recognized that the steady-state of the dynamic problem yields a higher amount of accumulated pollutant and hence also a higher emission flow and production level than in the static problem. A high discount rent makes this difference larger than a small one.

Therefore, one of the main conclusions from this highly abstract stock pollution model is that how to value the future versus the present matters for the socially desirable production level, emission flow and pollutant stock in the long term and less weight put on the future means more pollution and damage. Another general insight is that how the pollution stock decays may have important consequences. If the offsetting factors work in a manner where the cleansing fraction decreases with the amount of stock of pollution, as in the logistic function case, a socially desirable steady-state characterized by low emission flow and production level together with a highly polluted environment is a possible outcome. Even ’doomsday’ may be a possible outcome in the lake example considered. This simple stock pollution model also demonstrates how flow and stock relationships may be interconnected, and where the benefit is related to the flow while the cost is related to the stock. However, more generally and as demonstrated above, the cost of pollution may be related to not only to the accumulated stock, but also the emission flow. Stock magnitudes may also cover benefits. The above mentioned existence and bequest values (section 6.1) are typically such values which may easily be introduced in a more far reaching setting.

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