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Chapter 5

The Economics of Environmental Quality

Chapter 4 showed that the market system will generally not yield a socially efficient equilibrium when externalities, open-access resources, and public goods exist. Social efficiency is a ***normative concept*** in economics. It is a statement of what “ought to be.” The determination of public policies to deal with environmental problems is another example of normative economics. How much SO_2 in the air, phosphates in lakes, or toxic compounds in the soil should there be and how are these targets reached? ***Positive economics*** is the study of how events actually occur in the real world, how various outcomes come to pass. The quantity of output that actually occurs on a market and its price are matters of positive economics. Questions such as how much sulphur dioxide (SO_2) actually is produced from a group of power plants and what determines the fuel mix chosen by the power plants are matters of positive economics.

In normative policy analysis, a number of steps are generally taken:

1. Identify the target level of environmental quality to achieve. The target level can be in terms of either an ambient or emissions level of the pollutant.
2. Determine how to divide that target level among the many polluters that may contribute to the environmental problem.
3. Determine the set of policy instruments to use that will meet the target. Section 4 examines these policy instruments extensively.
4. Address the question of how the benefits and costs of environmental programs are distributed across society and whether this distribution is appropriate. Techniques for computing benefits and costs are covered in Section 3.

This chapter focuses on the first step—determining a target level of environmental quality.

The construction of effective public policy for the environment depends on having “correct” information about both economic and scientific variables. How do pollutants affect environmental quality? How do producers and consumers respond to policy initiatives a regulator could take? In many cases, we know more about how producers and consumers react to different policies than we do about the links between pollutants and environmental quality. While environmental sciences are uncovering more each day about these links, much uncertainty remains. Scientists do not yet fully understand the many diverse effects that specific pollutants (or combinations of pollutants) have on the environment. Debate over the causes of climate change, what exact compounds in pulp mill effluent are responsible for disease and mortality in shell fisheries, whether electric power transmission lines cause cancer—all are examples of scientific uncertainty.

The Target Level of Pollution—A General Model

There is no single public policy that can address all the diverse types of environmental problems. Nonetheless, a very simple model can be used to establish the fundamentals of any policy situation. The model presents a simple trade-off situation that characterizes all pollution-control activities. On the one hand, reducing emissions reduces the damages that people (and the ecosystem) incur from environmental pollution; on the other hand, reducing emissions takes resources that could have been used in some other way, to produce goods and services that people want. For example, the reduction of sulphur dioxide emissions from a coal-fired power plant will reduce air pollution and acid precipitation. Environmental quality will rise, benefiting people and the ecosystem. But to reduce emissions, the power plant will have to install abatement equipment or switch to a fuel input that contains less sulphur (e.g., natural gas). This increases its costs of production. If the plant can pass along these higher costs to consumers, electricity prices will rise. Consumers will then have less to spend on other goods. This trade-off is what is captured in the simple model developed in this chapter.

Pollution Damages

"Pollution damages" refers to all of the negative impacts that users of the environment experience as a result of the degradation of that environment.[1] There are many different examples. A factory that discharges its effluent into a river poisons fish stocks. Anglers no longer can eat any fish that they catch. The toxins in the fish may in turn enter the food chain, damaging other species that prey on them—for example, raptors such as hawks and eagles. The city downstream that uses the river for its water supply will incur higher treatment costs to remove the toxins from its drinking water, and so on. Air pollution produces damage through its impacts on human health. Excess deaths from diseases such as lung cancer, chronic bronchitis, and emphysema are related to elevated levels of various pollutants, such as sulphur dioxide, asbestos fibres, and radon emissions. Air pollution can cause damages through the degradation of materials (for example, outdoor sculptures in Florence, Italy dating from the Renaissance have had to be put indoors to protect them from air pollution) and the deterioration of the visual environment. Besides damage to human beings, environmental destruction can have important impacts on various elements of the nonhuman ecosystem. Some of these, such as destruction of genetic information in plant and animal species driven to extinction, will ultimately have important implications for humans. Estimating environmental damages is one of the primary tasks facing environmental scientists and economists; Chapter 7 addresses this problem.

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[1] Refer back to Table 2-2 for a synopsis of the major pollutants in Canada and their probable environmental impacts.

In general, the greater the pollution, the greater the damages it produces. To describe the relationship between pollution and damage, a ***damage function*** is introduced.

> ***A damage function shows the relationship between the quantity of a waste product and the value of its damages.***

There are different types of damage functions:

- ***Emission damage functions*** show the relationship between the wastes from a particular source or sources and the resulting damages to the environment.
- ***Ambient damage functions*** show how damages are related to the concentration of a waste product contained in the ambient environment.
- ***Marginal damage functions*** show the change in damages stemming from a unit change in emissions or ambient concentration.
- ***Total damages*** are the total amount of damage at each possible emission level.

The marginal damage function is the focus of the general model developed in this chapter.

Marginal Damage Functions: Possible Shapes

Examples of marginal damage functions are depicted in Figure 5-1.[2] The top two are marginal emission damage functions; the horizontal axes measure the quantity of an effluent emitted into the environment during some specified period of time. The exact units (kilograms, tonnes, etc.) used in any particular case depends on the specific pollutant involved. The vertical axes measure environmental damages in dollar terms. In physical terms, environmental damage can include many types of impacts: kilometres of coastline polluted, numbers of people contracting lung disease, numbers of animals wiped out, quantities of water contaminated, and so on. Every case of environmental pollution normally involves multiple types of impacts, the nature of which will depend on the pollutant involved and the time and place where it is emitted. To consider these impacts comprehensively we need to be able to aggregate them into a single dimension. For this purpose we use a monetary scale. It is sometimes easy to express damage in monetary units. For example, it is relatively straightforward to measure the dollars people spend on ***defensive expenditures*** to protect themselves against pollution (e.g., heavier insulation to protect against noise, more spent on sunscreen and protective clothing with the depletion of stratospheric ozone, expenditures on bottled water when municipal water supplies are contaminated). But in many situations, measurement of the value of marginal damages is a challenging exercise (as examined more fully in Chapter 7).

The Environmental Valuation and Cost–Benefit Website: www.damagevaluation.com

The marginal emission damage function in panel (a) of Figure 5-1 shows marginal damages increasing only modestly at the beginning but more rapidly as emissions increase. Work by environmental scientists and economists seems to suggest that this is a typical shape for a number of pollutants. At low levels of emissions marginal damages may be comparatively small; ambient concentrations are so modest that only the most sensitive people in the population are affected. But when emission levels

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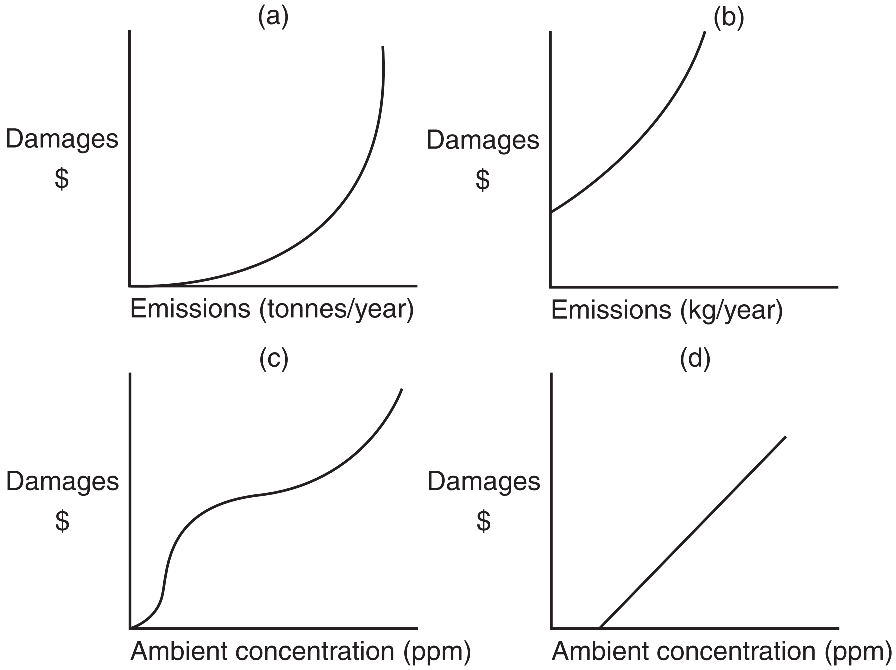
[2] For those with a calculus background, the marginal damage function can be derived from a total damage function. It is simply the first derivative of that function. For example, if total damages are a function such as $TD = .4E^2$, then $MD = .8E$.

Figure 5-1: Representative Marginal Damage Functions



Two types of marginal damage functions are shown for waste emissions and for ambient concentrations of a waste product. Panels (a) and (b) illustrate emissions functions, while (c) and (d) show ambient functions. The marginal damage functions shown illustrate the different slopes that may be possible depending on the type of pollutant and where it is released.

go higher, damages mount—at still higher levels of emissions, marginal damages become very elevated as environmental impacts become widespread and intense.

Panel (b) shows a marginal emission damage function that has the same general shape as panel (a) (i.e., it shows increasing marginal damage), but it begins much higher on the vertical axis and rises more sharply. It might represent a toxic substance that has a deadly effect even at very low levels of emission.

The two bottom relationships in Figure 5-1 are marginal ambient damage functions. While the vertical axes have a monetary index of damages, the horizontal axes have an index of ambient concentration, such as parts per million (ppm). Panel (c) shows a complicated function that increases at low concentrations, then tends to level off until much higher concentrations are reached, after which damages increase rapidly. This might apply, for example, to an air pollutant that causes marked damages among particularly sensitive members of society at relatively low concentrations, and among all people at very high concentrations, while in the middle ranges marginal damages do not increase rapidly. Panel (d) demonstrates an ambient marginal damage function that begins to the right of the origin and then increases linearly with ambient concentration.

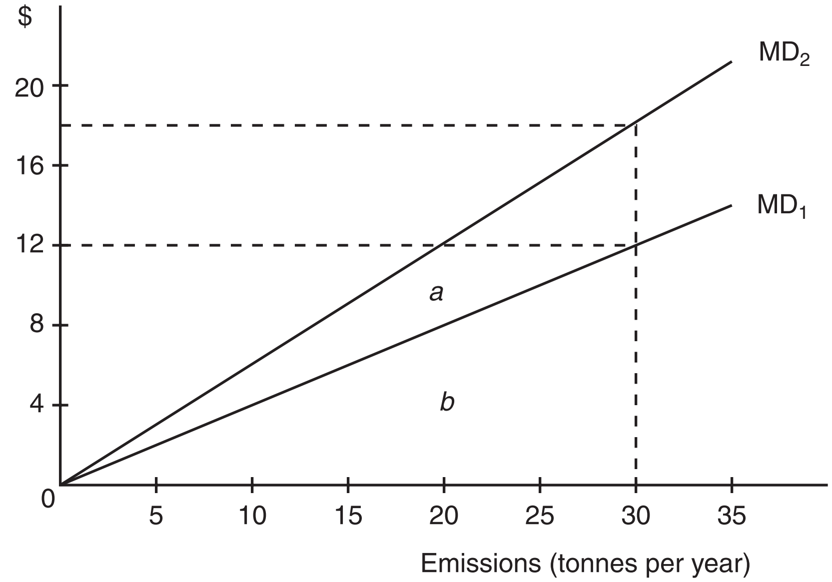
Panels (a) and (d) show a characteristic that is in fact quite controversial. The functions have a ***threshold***—a value of emissions or ambient concentration below which marginal damages are zero. The pollutant can increase to these threshold levels without causing any increase in damages. As we will see in chapters to come, the assumed existence or non-existence of a threshold in the damage functions for particular pollutants has had important impacts on real-world environmental control policies. There have been long, vigorous arguments about whether the damage functions of certain types of pollutants do or do not have thresholds.

Marginal Damage Functions: Properties and Analysis

The marginal damage function is a key ingredient to normative policy analysis. This section examines its properties. While either ambient or emissions functions could be used, we have chosen emissions relationships because it is easier to design pollution policies when one can identify specific sources of emissions. While Figure 5-1 illustrated non-linear marginal damage functions, linear functions are used for the remainder of the chapter (and in subsequent chapters) to facilitate numerical calculations and the use of simple algebra. Figure 5-2 shows two marginal emission damage functions that show emissions in physical terms per unit time. Two assumptions are made to keep analysis simple:

- This is a single, non-accumulative pollutant that is uniformly distributed.
- No threshold exists; that is, each marginal damage function begins at the origin.

Figure 5-2: Marginal Damage Functions for a Non-accumulative Pollutant with No Threshold



Two marginal damage functions are shown. Marginal damages for each emissions level are read off the vertical axis. If emissions are 30 tonnes, marginal damages for MD_1 are \$12, while for MD_2 they are \$18. Total damages are calculated as the area under the MD curves from the origin to the emission level in question. At 30 tonnes, total damages are area *b* = \$180 for MD_1 and areas (*a* + *b*) = \$270 for MD_2.

These assumptions are modified in Sections 4 and 5; while working through this section, think about how the results would change if the pollutant were accumulative or if a threshold did exist.

Marginal damage functions are labelled MD and emissions labelled E. Each can be described by a function:

$$MD_1 = .4E$$

$$MD_2 = .6E$$

Consider first MD_1. A key property is the relationship between marginal and total damages.

The height of the marginal damage curve shows how much total damages change if there is a small change in the quantity of emissions.

When the effluent level is at the point marked $E_1 = 30$, for example, marginal damages are $12. If emissions were to increase by one tonne, from 30 to 31 tonnes, the damages experienced by people exposed to those emissions would increase by $12; by the same token, if emissions decreased by a small amount at 30 tonnes, total damages would be reduced by $12. Since the height of the curve, as measured on the *y*-axis, shows marginal damages, the area under the curve between the point where it is zero and the emissions level in question shows the total damages associated with that level of emissions. In the case of marginal damage function MD_1 and 30 tonnes, total damages are shown by area *b*, which is a triangle equal to $180 (fi [30 times $12]). At the emission level of 30 tonnes, the marginal damages for MD_2 is $18 and total damages is area $(a + b) = \$270$. Thus,

total damages for a given level of emissions is the area under the MD curve from 0 to that level.

What factors might account for the difference between MD_1 and MD_2 in Figure 5-2? MD_2 might refer to a situation where there are many people who are affected by a pollutant, such as a large urban area, while MD_1 could be a more sparsely populated rural area; fewer people, smaller damage. Another possibility is that, although they apply to the same group of people, they refer to different time periods. Marginal damage function MD_2 might be the situation when there is a temperature inversion that traps a pollutant over the city and produces relatively high ambient concentrations. MD_1 would be the damage function when normal wind patterns prevail so that most of the effluent is blown downwind and out of the area. Thus the same emission levels at two different times could yield substantially different damage levels owing to the workings of the natural environment.

It is now time to develop the other side of the trade-off relationship—the costs of controlling emissions. Two questions to ponder: Why shouldn't the target pollution level be zero emissions? Do costs have to be considered at all?

Abatement Costs

The costs of reducing the quantity of residuals being emitted into the environment or of lowering ambient concentrations are called ***abatement costs***. Think of a pulp mill located on a river. It produces a large quantity of organic wastes. The cheapest way to get rid of these wastes is simply to pump them into the river. But the mill could reduce these emissions by using pollution-control technologies or changes in the production process (e.g., non-chlorine bleaching techniques). *Abatement costs* is the catch-all term that describes these costs of abating, or reducing, the quantity of wastes put in the river. It includes all the many ways there are of reducing emissions: changes in production technology, input switching, residuals recycling, treatment, abandonment of a site, and so on.

U.S. Census Bureau Survey of Pollution Abatement Costs and Expenditures: www.census.gov/econ/www/mu1100.html

Abatement costs will differ from one type of effluent to another. The costs of reducing emissions of SO_2 from electric power plants will obviously be different from the costs of reducing toxic fumes from chemical plants. Even for sources producing the same type of effluent the costs of abatement are likely to be different because of differences in the technological features of the operation. One source may be relatively new, using modern production technology, while another may be an old one using more highly polluting technology.

Abatement cost functions can be defined algebraically and graphed. The model works with ***marginal abatement costs***.[3] The units on the axes are the same as before: quantities of pollutants on the horizontal axis and monetary value on the vertical axis. Marginal emission abatement costs show the added costs of achieving a one-unit decrease in emission level, or alternatively the costs saved if emissions are increased by a unit. On the horizontal axis, marginal abatement cost curves originate at the uncontrolled emission levels (the emission levels prior to undertaking any abatement activities). In general they slope upward to the left, depicting rising marginal abatement costs. In Chapter 3, we showed marginal cost curves sloping upward to the right. The graph for marginal abatement costs goes in the opposite direction because the "thing" we are producing is a *reduction in emissions*. A key point to remember in all figures used in the general model is that

> ***emissions are read from left to right along the horizontal axis, while pollution abatement is measured from right to left.***

Figure 5-3 presents three non-linear marginal abatement cost functions that illustrate the types of relationships one might find in practice. Let MAC be the acronym for marginal abatement costs.

- ***Panel (a):*** The MAC curve rises very modestly as emissions are first reduced, but then rises rapidly as emissions become relatively small.
- ***Panel (b):*** The MAC curve rises continuously.
- ***Panel (c):*** The MAC curve initially declines, then rises again. This might characterize a situation where small reductions can be handled only with technical means that require substantial initial investment. For somewhat larger reductions, the marginal costs may actually decline as it becomes possible to use these techniques more fully. Ultimately, however, marginal abatement costs increase.

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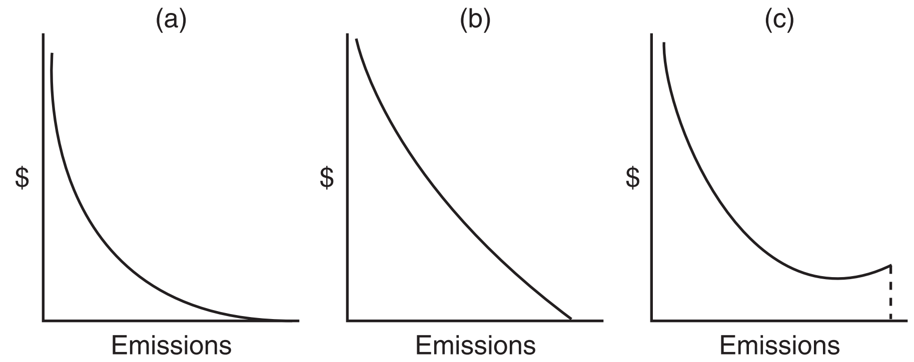
[3] Marginal abatement cost functions are the first derivative of a total abatement cost function.

Figure 5-3: Representative Marginal Abatement Cost Curves



Representative marginal abatement cost curves are shown. In panel (a), costs rise very slowly as emissions are reduced from their initial level then rise rapidly with further reductions in emissions. Panel (b) shows costs that rise relatively uniformly as emissions are reduced. Panel (c) shows marginal costs initially falling as emissions are reduced due to economies of scale in abatement. Marginal costs ultimately must rise as emissions are reduced toward zero.

Properties of Marginal Abatement Cost Functions

To investigate the properties of a marginal abatement cost consider Figure 5-4, which graphs two MAC curves derived from the following linear functions:

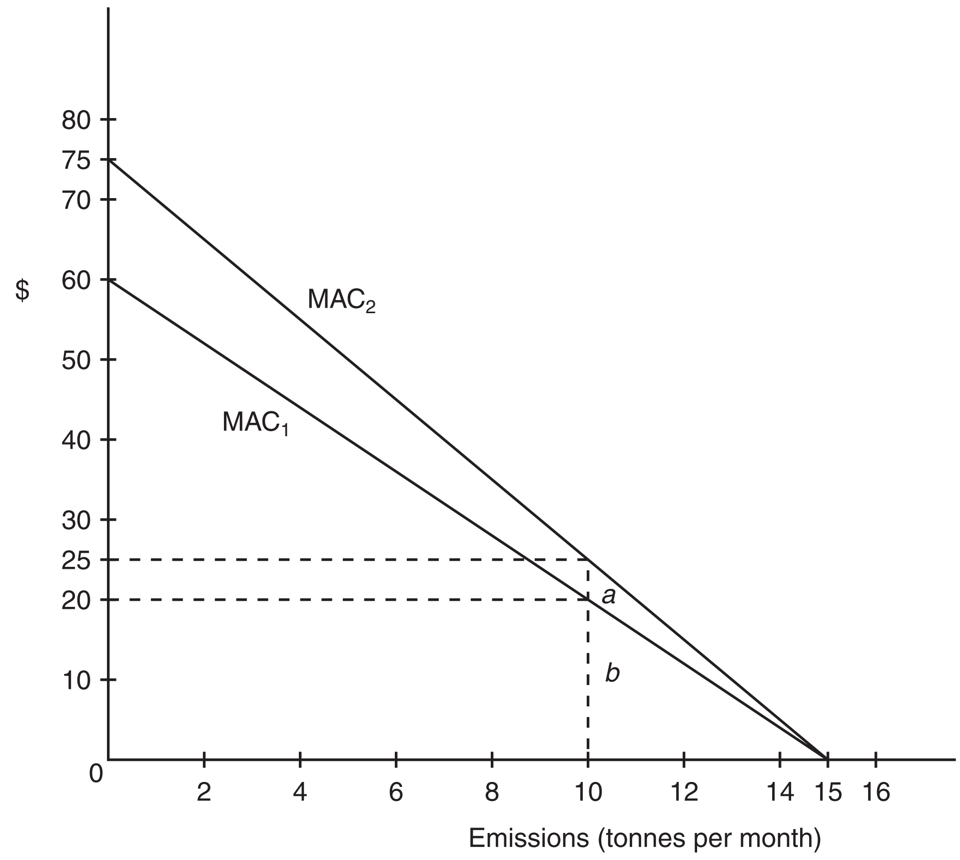
$$\text{MAC}_1 = 60 - 4E$$

$$\text{MAC}_2 = 75 - 5E$$

From the graph (or setting MAC = 0 for each equation and solving for E), we see that the uncontrolled emissions level for both sources is 15 tonnes per month. From 15 tonnes each MAC slopes upward to the left. This means that marginal costs of abatement rise as more and more emissions are controlled. At 10 tonnes per month of emissions, $\text{MAC}_1 = \$20$ while $\text{MAC}_2 = \$25$. When emissions are reduced to zero, the marginal cost of the last unit controlled is \$60 for polluter 1 and \$75 for polluter 2. Thus, the larger the reduction in emissions, the greater the marginal costs of producing further reductions. Note that by drawing these as linear functions with positive intercepts we are saying that the technology exists to reduce emissions to zero at a finite cost. If the MAC curve looks like panel (a) of Figure 5-3, it is technologically impossible to reduce emissions to zero.

It is also possible that the only way a polluter can reduce emissions to zero is to cease the activity that is generating the pollution. This may mean closing a plant or changing the good produced, which will have economic repercussions. If the polluter is one small plant within a large industry consisting of many such plants, the costs of actually closing it down may not be that great. In fact, it may have very little impact on, say, the price to consumers of whatever is being produced (paper in the pulp mill example), though the local impact on jobs and community welfare may be substantial. But if we are talking about the marginal abatement costs for an entire industry—the petrochemical industry in Ontario or Alberta, for example—the "shut-down" option, as a way of achieving zero emissions, would have enormous costs.

Figure 5-4: Marginal Abatement Costs for a Pollutant



MAC$_1$ and MAC$_2$ illustrate two sources of pollution (or one polluter at two different time periods) that are initially releasing 15 tonnes of pollution per month when no abatement occurs. At 10 tonnes of emissions (that is, abating five units each) MAC$_1$ = \$20 while MAC$_2$ = \$25. Total abatement costs for reducing emissions from 15 to 10 tonnes is area *b* for polluter 1 (\$50 per month) and areas *a* + *b* for polluter 2 (\$62.50 per month). Cost saving for adopting polluter 1's technology is area *a* (\$12.50 per month).

United Nations University's Zero Emissions Research Initiative: www.unu.edu/zef

As with any marginal graph, we can depict not only marginal but also total values. If emissions are currently at 10 tonnes per year, the value on the vertical axis shows the marginal cost of achieving one more unit of emission reduction. The area under the MAC curve, between its origin at 15 tonnes per month and any particular emission level, is equal to the total costs of abating emissions to that level. For MAC$_1$, the ***total abatement cost*** of achieving an emission level of 10 tonnes per month is equal to area *b* = \$50 (the area of the triangle = $\frac{1}{2}$ [5 times \$20]). The total abatement cost for polluter 2 is area *a* + *b* = \$62.50 (the area of triangle = $\frac{1}{2}$ [5 times \$25]).

The key to calculating total abatement costs (TAC) is to remember to read the graph from right to left.

What could account for the difference in the slopes of the two MAC curves when they pertain to the same pollutant? Often the reason is differences in ***pollution-control technology***. MAC_1 uses a cheaper technology to control its emissions than MAC_2. This could be because they are two different plants and MAC_2 was built many years ago, MAC_1 more recently.[4]

Technological change can therefore result in a lowering of the MAC curve for a given pollutant. We can readily measure the annual cost saving for a plant that adopts a new technology. Suppose again that emissions are 10 tonnes per month. The polluter would save area a if it adopts the new technology. We know from before that areas $a + b = \$62.50$ and area b equals \$50, so the cost saving is \$12.50 per month. This type of analysis will be important when we examine different types of pollution-control policies, because one of the criteria used to evaluate these policies is how much cost-saving incentive they offer to firms to engage in research and development to produce new pollution-control technologies.

Aggregate Marginal Abatement Costs

Most environmental policies, especially at provincial or federal levels, are aimed at controlling emissions from groups of pollution sources, not just single polluters. How are the marginal abatement costs of a group of firms (in the same industry or located in the same region) aggregated when their marginal abatement costs differ? The process of aggregation introduces an important concept in the design of effective environmental policy. The least costly way of achieving reductions in emissions for an individual firm is shown by its marginal abatement cost function; for a group of polluting sources, it is the aggregate marginal abatement cost function.

Panels (a) and (b) of Figure 5-5 redraw MAC_1 and MAC_2 from Figure 5-4. Panel (c) is the aggregate marginal abatement cost curve. When we have two (or any other number greater than one) sources with different abatement costs, the aggregate abatement cost will depend on how we allocate the total emissions among the different sources. The principle to follow is

> ***to aggregate marginal abatement costs, individual functions must be added horizontally to yield the lowest possible aggregate marginal abatement costs.***

Figure 5-5 provides an example of how to aggregate different marginal abatement costs. The steps are outlined below.

Example: How to aggregate MAC curves

1. Select a particular level of marginal abatement cost, for example \$40 per month.
2. Find how much each polluter will abate at this cost. At \$40, polluter 1 will want to abate to 5 tonnes per month, while polluter 2 will abate to 7 tonnes per month.
3. Add up these emission levels: 5 tonnes + 7 tonnes = 12 tonnes per month.
4. Repeat the process for a different abatement cost level.
5. Graph the aggregate curve as shown on panel (c) of Figure 5-5.

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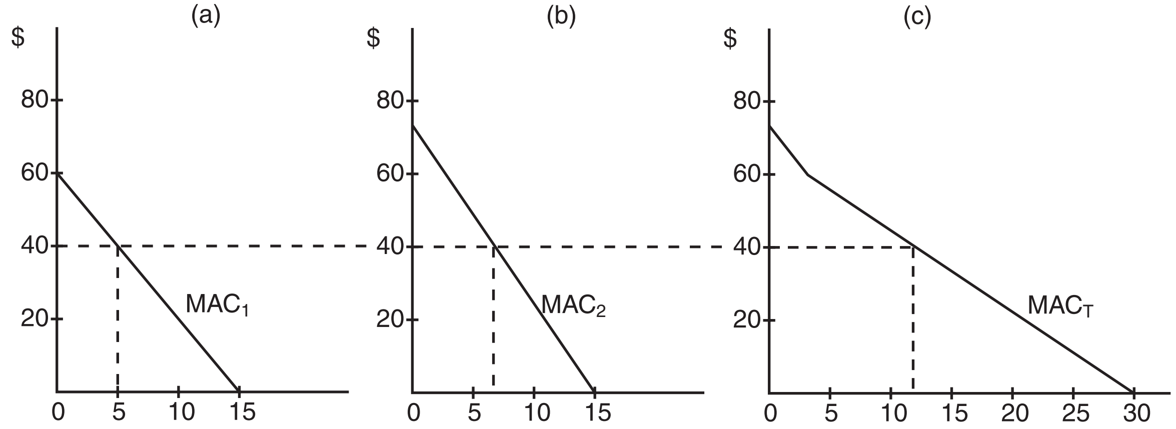
[4] The different MAC curves could also be for the same plant, but at different time periods in its existence.

Figure 5-5: Aggregation of Marginal Abatement Cost Curves



MAC curves are aggregated horizontally by picking a dollar value of marginal abatement costs and adding up each source's emission level at the MAC. For MAC = $40, panel (a) shows that polluter 1 releases 5 tonnes per month (abates 15–5 = 10 tonnes), while panel (b) shows that polluter 2 releases 7 tonnes (abates 15–7 = 8 tonnes). The aggregate MAC is shown in panel (c), where at a MAC of $40 total emissions are 12 tonnes per month. The aggregate MAC is derived by horizontally adding individual functions for different levels of MACs.

Aggregation of MACs invokes the equimarginal principle, an idea that was introduced in Chapter 4. To have the minimum aggregate marginal abatement cost curve, the aggregate level of emissions must be distributed among the different sources in such a way that they will all have the same marginal abatement costs. Start at the 12 tonnes/month point on the aggregate curve. Obviously, this 12-tonne total could be distributed between the two sources in any number of ways: 6 tonnes from each source, 10 tonnes from one and 2 tonnes from the other, and so on. But only one allocation will give the lowest aggregate marginal abatement costs; this is the allocation that leads the different sources to the point where they have exactly the same marginal abatement costs. The aggregate MAC has been constructed so that the equimarginal principle is satisfied.

The Socially Efficient Level of Emissions

For a particular pollutant being released at a particular place and time, the socially efficient level of emissions is found where the marginal damage function and the marginal abatement cost function are equated.

We illustrate this equilibrium concept graphically and algebraically.

Graphically: Figure 5-6 shows that the MAC intersects the MD at an emission level of 10 tonnes per month. Marginal abatement costs are equal to marginal damages at this emission level (both equal $20).

continued

Algebraically: *E* represents the level of emissions. E* is the socially efficient level of emissions. Assume both the MAC and MD are linear.[5] Let

$$MAC = 60 - 4E$$

$$MD = 2E.$$

Social efficiency requires MAC = MD. Substitute in for MAC and MD.

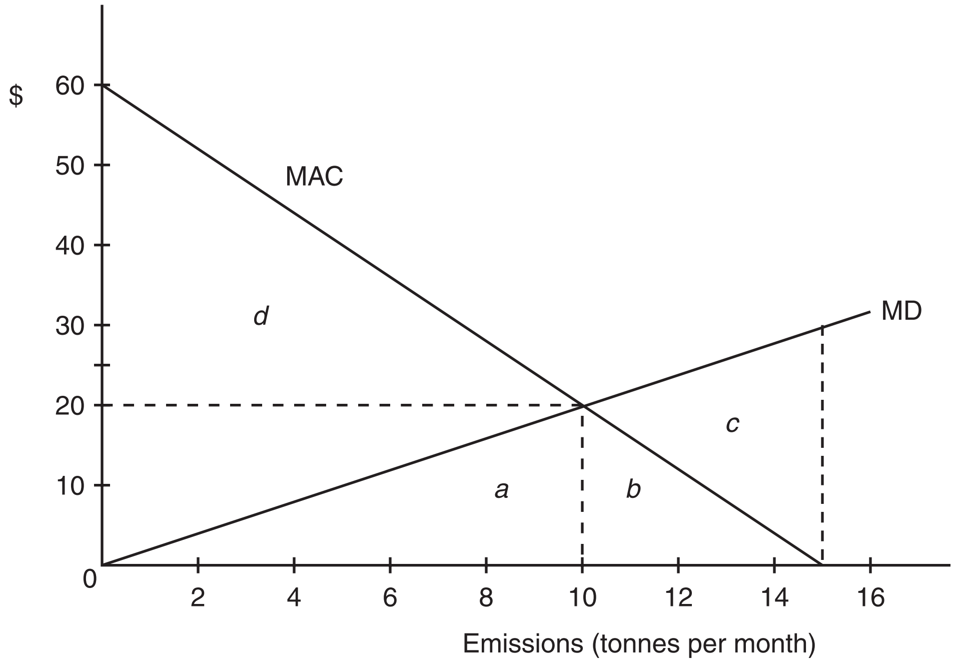
$$60 - 4E = 2E$$

Solve for E*: E* = 10 tonnes per month

Substitute E* back into either the MAC or MD to determine the “price” (marginal cost, marginal damage) that equates the two curves.

$$60 - 4(10) = \$20.$$

Figure 5-6: Determining the Socially Efficient Level of Emissions



The socially efficient equilibrium is found where the MAC curve intersects the MD curve. This occurs at E* = 10 tonnes of pollution per month. Area (*a* + *b* + *c*) = total damages at the initial emission level of 15 tonnes per month. At E*, total damages equal area *a* for a net gain of areas (*b* + *c*). At E*, total abatement costs equal area *b*. Therefore, the net social gain is areas (*b* + *c*) minus *b* = area *c*.

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[5] The MAC is the same used in the previous section for polluter 1 (MAC_1).

Why is E* socially efficient? Social efficiency means trading off a marginal increase in pollution damages against a marginal increase in pollution abatement costs. Higher emissions expose society to greater costs stemming from environmental damages. Lower emissions involve society in greater costs in the form of resources devoted to abatement activities. The socially efficient level of effluent is thus the level where these two types of costs exactly offset one another; that is, where marginal abatement costs equal marginal damage costs. Is the socially efficient level always positive? No. If the MD and MAC do not intersect at a positive level of emissions, the socially efficient level will be zero. The slopes and shape of the MAC and MD curves determine the equilibrium.

From an efficiency standpoint, E* is the best the economy can do; see the proof below.

Computing net social values: A proof that E* maximizes net social values

E* is the point where the net social benefits from reducing pollution are maximized (social costs from pollution control are minimized). This can be proven using Figure 5-6 and by computing total benefits and costs. The steps are as follows:

1. Suppose no emissions are controlled and are thus 15 tonnes per month.
2. Compute total damages (TD) at 15 tonnes per month.

   Graphically: Total damages are the area under the MD curve from 0 to 15 tonnes. This is shown in Figure 5-6 as area ($a + b + c$).

   Numerically: TD = \$225 ($^1/_2$ [15 times \$30]).[6]
3. Compute total abatement costs (TACs) at 15 units of output.

   TACs are zero; there is no abatement.
4. Compute net social costs.

   Net social costs are the difference between total damages and total abatement costs, which at 15 tonnes equal \$225.

Repeat the exercise assuming emissions are now at the socially efficient level of E* = 10 tonnes.

5. Total damages E* are area *a* and equal \$100.[7]
6. Total abatement costs are area *b* and equal \$50.
7. Total social costs are thus \$100 + \$50 = \$150.
8. Compute the difference in the total social costs between the two emission levels.

   \$150 is clearly less than \$225.

   The net saving is area c = \$75 compared to the case with zero pollution control.

Society saves \$75 by reducing emissions from 15 to 10 tonnes. This is the net social benefit of achieving the socially efficient level of emissions compared to no emission control. But how do we know that E* is the best society can do? Suppose

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[6] The height of the triangle is found by substituting 15 units into the MD function, MD = $2E$, the MD at 15 tonnes is \$30.

[7] Area a = ($^1/_2$ [10 times \$20]) = \$100.

emissions are reduced to zero. Total damages are then zero. Total abatement costs are areas (*a* + *b* + *d*) = ($^1/_2$ [$60 times 15]) = $450, which is considerably larger than $150. Pick any other emission level and compute the net social cost. It will be higher than that at E*.

The MAC–MD model is conceptual and allows us to examine a wide variety of cases. In the real world every pollution problem is different. This analysis provides a generalized way of framing the problem that obviously has to be adapted to the specifics of any particular case of environmental pollution. The real world is a dynamic place, and this is especially true of environmental pollution control. The level of emissions that was efficient last year, or last decade, is not necessarily the level that is efficient today, or that is likely to be in the future. Many different factors lie behind the marginal damage and marginal abatement cost functions, and when any of these underlying factors change, the functions themselves will shift and *E** will change.

Social efficiency is a normative concept. *E**, the level that balances abatement costs and damage costs, is presented as a desirable target for public policy. Will the actual economy be at *E**? This is unlikely without some form of government intervention. Unless persuaded to take into account the damages they inflict on society, polluters will have no incentive to incur any abatement costs. They will simply produce at the maximum pollution level. Section 4 examines in detail policies and actions that induce polluters to reduce emissions by whatever means possible to move toward a socially efficient equilibrium.

Addendum: Linking the MAC Curve to Profit Maximization[8]

The simple model in this chapter focuses on the realistic situation in which polluters can invest in abatement technologies that reduce the emissions from their operation. A MAC curve was assumed to exist for polluters. Let's back up for a moment and look more generally at the trade-offs facing polluters to see how the MAC curve can be linked to a firm's profit-maximizing behaviour.

Firms operating in a perfectly competitive industry maximize profits where the market price, P, equals their marginal costs of production, MC. Setting P = MC determines the firm's output level, Q. This is shown in the top half of Figure 5-7. But the firm also produces pollution. For simplicity, assume that one unit of output produces one unit of pollution. The bottom half of Figure 5-7 maps output into emissions of pollution (E). When there are no environmental regulations, the polluter is free to dispose of as much pollution as it wishes. What is the maximum amount of emissions? In Figure 5-7 the profit-maximizing firm produces Q_0 units of output, which means that it also produces E_{MAX} units of pollution.

With a rising MC curve, the firm earns profits on all units of output up to Q_0, the marginal unit of output produced where price is just equal to MC. The firm's marginal profits equal (P – MC), and are greatest for the first unit of the good sold at the constant price of P, then fall until P = MC at the competitive equilibrium. These marginal profits are what the firm would give up if it had to reduce its output below Q_0 because it must reduce its emissions. The MAC curve can then be thought of as the forgone

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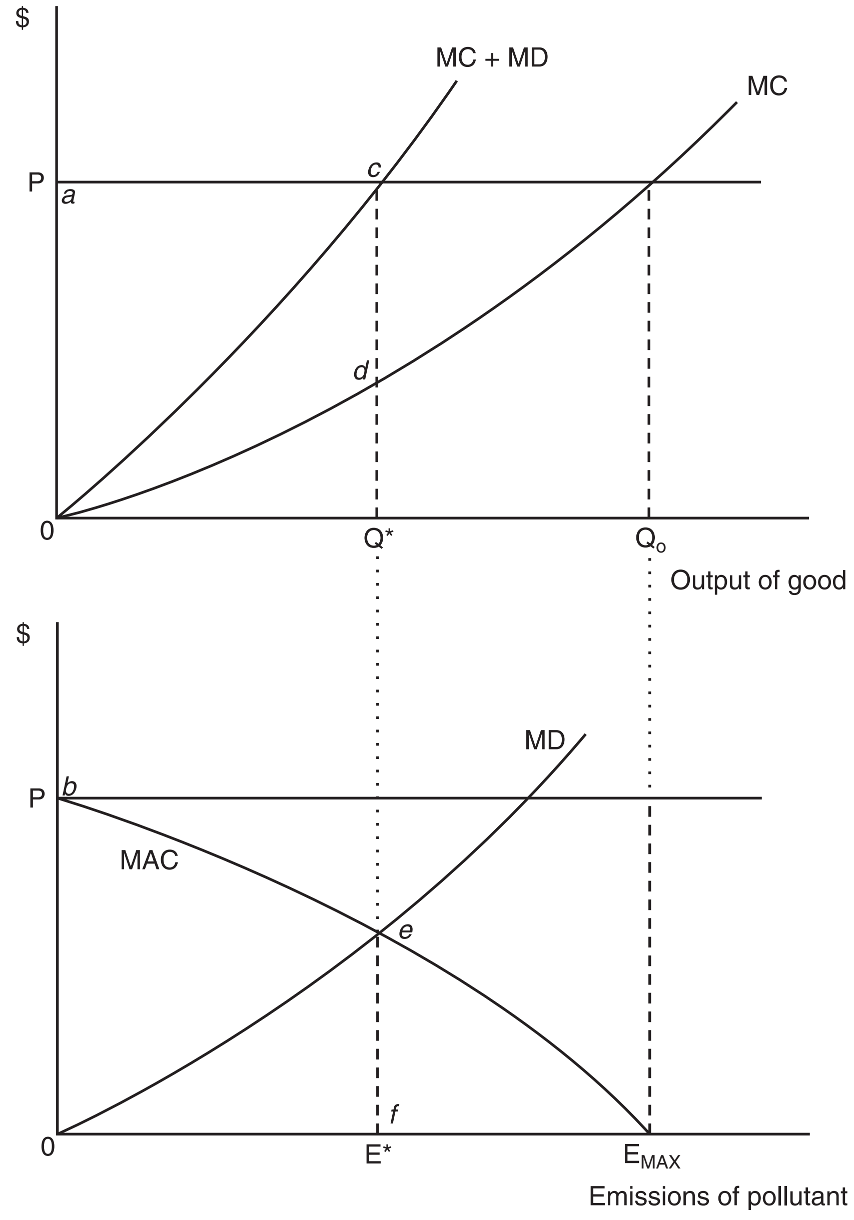
[8] The material in this section can be omitted, as it need not be used in subsequent chapters.

Figure 5-7: Linking the MAC Curve to Profit Maximization



A competitive firm ignoring the damages caused by its emissions of pollution maximizes profit where the price of the good it produces equals its marginal costs of production. For all units of output between 0 and Q_0, the firm earns marginal profits graphed in the lower panel as the downward sloping function. Assuming one unit of output generates one unit of pollution, these marginal profits represent the firm's MAC curve. If it must reduce emissions, the costs it incurs are forgone profits. When the firm is required to incorporate pollution damages as one of its costs of production, the MD curve is added to MC and the firm produces E* units of pollution.

profits the firm incurs due to reductions in emissions. The lower panel of Figure 5-7 graphs (P – MC) for all levels of output between 0 and Q_0. The distance $a0$ in the top panel equals $b0$ in the bottom. The MAC function thus has the same shape as the MC curve for the firm's output, but is inverted.

Suppose now that the firm is required by environmental policy to include the marginal damages due to its pollution as one of its costs of production. The marginal damage curve (MD) from the lower panel represents these costs. The MD curve is thus added to the firm's MC curve. The firm's marginal social costs now equal MC + MD.[9] Given these costs, the firm maximizes profits where P = MC + MD. Output of Q* produces E* emissions.[10] A socially efficient equilibrium in the goods market equates market prices of goods to the social costs of production on the margin, where these social costs include marginal costs of production plus marginal damages from production.

SUMMARY

This chapter develops a simple model of pollution control. It is based on the notion of a trade-off of environmental damages and pollution abatement costs. The marginal damage function is introduced. It shows the marginal social damages resulting from varying levels of residual emissions or ambient pollutant levels. Marginal abatement cost relationships are then shown, first for an individual pollution source and then for a group of such sources. By bringing together these two types of relationships a socially efficient level of emissions is found. The socially efficient level of pollution is where marginal damages and marginal abatement costs are equal. At this level of emissions, net social costs—the total of abatement costs and damages—are minimized.

A word of caution is appropriate. The model presented in this chapter is very general, and risks giving an overly simplistic impression of pollution problems in the real world. In fact, there are very few actual instances of environmental pollution where we know the marginal damage and marginal abatement functions with certainty. The natural world is too complex, and human and non-human responses are too difficult to identify with complete clarity. Furthermore, polluters come in all types and sizes and economic circumstances and it takes enormous resources to learn even simple things about the costs of pollution abatement in concrete instances. Pollution-control technology is changing rapidly, so what is efficient today will not necessarily be so tomorrow. Nevertheless, the simple model is useful for thinking about the basic problem of pollution control, and it will be useful in our later chapters on the various approaches to environmental policy. Before discussing complicated policy issues, it is appropriate to study the ways economists have tried to measure and make visible marginal abatement costs and marginal damages in specific cases of environmental quality changes.

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[9] This definition of social costs was also covered in Chapter 4: see Figure 4-3. This addendum links the marginal social costs to the MAC – MD diagram.

[10] Note too that distance *cd* in the top panel is equal to distance *ef* in the bottom panel, both indicating the difference between marginal costs and marginal damages at the socially efficient equilibrium of E* emissions and Q* of the good.

KEY TERMS

Abatement costs, 91
Ambient damage functions, 87
Damage function, 87
Defensive expenditures, 87
Emission damage functions, 87
Marginal abatement costs, 91
Marginal damage functions, 87
Normative concept, 85
Pollution-control technology, 94
Positive economics, 85
Threshold, 88
Total abatement cost, 93
Total damages, 87

ANALYTICAL PROBLEMS

1. Let $\text{MAC}_1 = 100 - 10E$ and $\text{MAC}_2 = 50 - 10E$. Graph each function and compute the aggregate MAC curve. Let $\text{MD} = 30E$, compute the socially efficient equilibrium. For the equations given above, suppose the government sets the pollution level at four units. What are the net social costs of this policy?
2. Suppose a technological change occurs that reduces the marginal costs of abatement for polluter 1 in the above equation to that of polluter 2. How does this affect the socially efficient level of pollution? Solve numerically and graphically.
3. When pollution regulations are imposed, governments incur enforcement costs that are part of social costs. Assume that enforcement costs are a constant amount, independent of the amount of pollution reduced. How would this change the location of the socially efficient equilibrium? Show graphically and explain.

DISCUSSION QUESTIONS

1. Scientists discover that marginal damages rise exponentially with emissions. How would this change the computation of total damages when there is no pollution abatement?
2. How is the equimarginal principle related to the socially efficient level of output?
3. Explain why society wants to minimize net social costs (maximize net social value) when choosing a target level of pollution.