Environmental Economics

Ross McKitrick
Associate Professor
University of Guelph
Department of Economics

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Environmental Economics

Chapter 1: Issues, Instruments, Institutions and Ideas

1.1 Environmental Issues

The term “Environment” is too broad to be meaningful—we will try to specify whether we are talking about air or water quality, land use etc. For air quality, the six main contaminants are as follows, though there are hundreds of compounds that can potentially be of concern.

1.1.1 Types of Air Pollution

Particulate Matter (PM)

These are small particles of smoke that get into the lungs and can cause disease or discomfort. The term “PM_{10}” refers to particulate matter smaller than 10 microns; similarly $PM_{2.5}$ refers to particulates under 2.5 microns diameter. The aggregate measure is sometimes abbreviated TSP for Total Suspended Particulates.

Oxides of Sulphur (SOx)

Suphur Oxide (SO) and Sulphur Dioxide (SO_2) are by-product of burning fossil fuels that contain Sulphur. SO_2 is a component of acid rain and in high concentrations can cause air to smell.

Oxides of Nitrogen (NOx)

These gases are collectively referred to as “NOx”. Nitrous Oxide (N_2O) is also called “laughing gas” and is used as a mild anesthetic. It breaks down in the atmosphere quickly so it is not counted in air quality statistics but it does have infrared-absorptive properties so it is listed as a “greenhouse” gas—see below. Nitrogen oxide (NO) and nitrogen dioxide (NO_2) are smog precursors. They contribute to the discolouring haze sometimes observed in urban air and the formation of ozone.

Volatile Organic Compounds (VOCs)

VOCs includes a large class of carbon-based compounds that contribute to smog. They are tied to fossil fuel use but there are also many natural sources, including trees.

Carbon Monoxide (CO)

CO is a byproduct of incomplete combustion of fossil fuels. It interferes with the blood’s absorption of oxygen. In high concentrations it is dangerous and even fatal.

Ground-level Ozone (O_3)

Ozone is formed in the air when NOx and VOCs mix under the intense ultraviolet (UV) radiation of summer days. It makes breathing difficult and the air stale. It is not an emission but is formed when the precursor emissions are already present in the air.

The next section shows some time series and cross-sectional graphs of air quality in Canada and around the world.

Water quality is more of a local issue than air quality, in the sense that water in one river doesn't typically affect quality of other river systems unless they are connected. But water pollution can accumulate when flows into lakes or into the ocean. The Great Lakes has had some problems over the years with this (see data below). Some issues of concern for water quality are as follows.

Drinking water quality

Cities usually draw water from lakes, rivers and/or underground aquifers, then filter and treat the water with chlorine or UV radiation to kill micro-organisms before piping it to homes. Dangerous contaminants may include fecal coliform bacteria, giardia, E. Coli and other germs. These must be killed by the treatment process or public health will be placed at risk. The water may have a high mineral content ("hardness") and the usual remedy for this is to have individual homeowners to use a water softener.

General water quality

Some contaminants affect water other than that intended for drinking. Agricultural run-off, including nitrogen and phosphorous from fertilizers and inorganic pesticide residues, can enter river systems and accumulate where those rivers empty into lakes, affecting the appearance and suitability of water for recreation and aquatic life. The fertilizer residues (also called "nutrients") stimulate growth of algae and underwater plants that deplete the water's oxygen levels, in turn making it hard for fish to survive. The algae can also make the water unsuitable for recreation since it can cause rashes and sometimes sickness for swimmers. Industrial effluent can include, depending on location, dioxins and furans from pulp mills and mercury from mines. These are toxic and need to be carefully controlled.

Other issues include land use and global environmental problems.

Land use

While urban and suburban areas make up only a very small amount of land space (less than 3 percent in North America) the conversion of forests and grassland to agriculture has had a large impact on our geography. It also affects habitat for wild species. Deforestation is also a concern in the tropics, especially the Amazon area of Brazil, and other places around the world including China and Africa. Large-scale hydroelectric projects, such as the James Bay dam in northern Quebec and the Three Gorges dam in China flood large valleys and thereby change the regional geography.

Global Environmental Problems

Use of freons, or chlorofluorocarbons (CFCs) is believed to have led to a build-up of chlorine in the stratosphere (above 12 km), where it catalytically destroys ozone. While we consider O_3 a nuisance at the ground level, it is important in the upper atmosphere since it filters UV radiation. Actually it filters UV at the ground level too, so the accumulation below the stratosphere could serve to make up for the loss in the stratosphere. However concern over stratospheric ozone loss led to an agreement called the Montreal Protocol which banned CFC production and use around the world.

The atmosphere consists of several distinct layers: the boundary layer (up to about 1 km), the troposphere (1 to about 15 km), the stratosphere above that, the mesosphere, then infinity and beyond. The troposphere experiences continual turbulent mixing due to convection of warm air from the surface. The stratosphere is more stable, but undergoes continual changes in chemistry due to variations in the level of solar ultraviolet radiation (UV) with the seasons. UV acts on gases naturally present in the stratosphere to produce ozone (O3), which then filters some of the UV that would otherwise reach the Earth's surface. This is called the "ozone layer," although ozone is produced at all levels of the atmosphere. We need protection from UV since it can cause damage to skin and eyes. At the Earth's surface the major variations in UV are experienced by changes in the seasons and by North-South travel: UV flux peaks at the height of summer, and is much stronger at the equator than at the poles. But some variation is also experienced due to changes in the density of ozone in the stratosphere, which is sometimes referred to euphemistically as the "thickness of the ozone layer."

Variations in ozone density happens naturally, since ozone is an unstable molecule that must be continually produced to be present in the atmosphere. But man-made chemicals are believed to be having an effect on atmospheric levels. We mentioned above that at the ground level, urban air pollutants like NOx and VOCs cause ozone levels to increase. In the stratosphere certain chlorine-based gases (halogens) are believed to be depleting ozone. It is not as simple as, say, cutting a hole in a roof. While ozone levels dropped in the stratosphere, for instance, they have grown in the troposphere (see World Meteorological Organization Ozone Assessment Report, 2002).

At the South Pole, the intense cold in the stratosphere causes a unique chemical reaction in which nitric acid, water and sulphuric acid condense to form what are called Polar Stratospheric Clouds. When chlorine contacts the molecules in these clouds it forms chlorine-oxygen pairs. In the presence of UV light these molecules react with ozone to break the O_3 molecule up, thus reducing the density of ozone in the stratosphere. That is why in the Antarctic spring (i.e. September and October) as the sun is rising over the South Pole, the density of stratospheric ozone drops for a few months, then rebuilds as sunlight acts on the gases in the atmosphere to produce new ozone. This is an annual phenomenon unique to the South Pole, and only happens in the stratosphere.[1]

There have been fears that humans are also causing a systematic thinning of the ozone layer, by the use of chlorine-based chemicals called chlorofluorocarbons (CFC's). These are inert gases that were developed for use in refrigeration condensers and in the manufacture of foam. Because they are so stable they are ideal for industrial use, but their stability means they can cause long-lasting environmental effects. Some of these

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[1] Essex, Chris (2001) "Radiation and Radiative Transfer" *Encyclopedia of Environmetrics*, John Wiley&Sons.

gases seem to have passed upwards into the stratosphere and have destroyed ozone. Figure 14 shows the global average density of ozone in the stratosphere since 1965, based on data collected from satellites by the World Meteorological Organization. There were two discrete drops in ozone levels from 1980 to 1985, and from 1990 to 1995. The peak thinning was about six percent as of 1994, but ozone levels have since recovered to about 96 percent of their original levels.

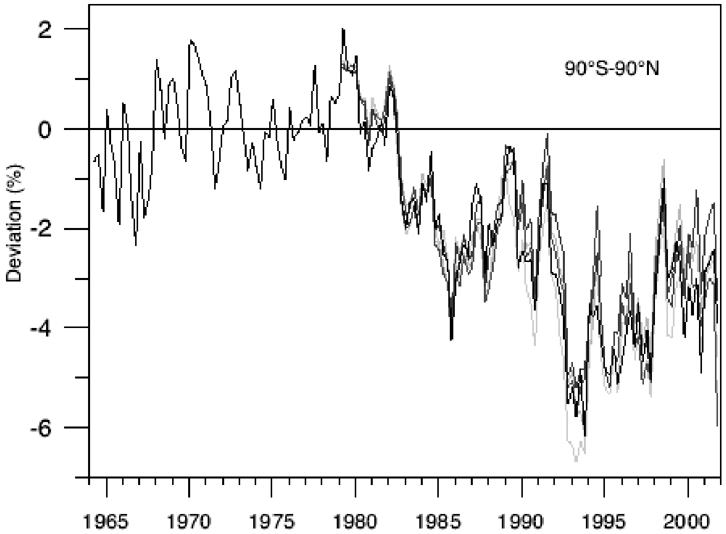

Figure 1.1: Total % Deviation in Global Average Ozone Layer Density 1965-2002. Source: World Meteorological Organization Ozone Assessment Report, 2002.

But looking at a global average only tells part of the story. The thinning is not evenly distributed in time and space. The next Figure shows that the thinning has been concentrated in the polar regions in winter. The vertical axis refers to latitude, going from the North Pole (top) to the South Pole (bottom). From left to right along the top (North Pole) shows January to December, and along the bottom (South Pole) it shows July to June: in other words the diagram shows the Winter-Spring-Summer-Fall sequence from left to right. The pattern looks like two big islands in a sea of smooth grey. The smooth grey represents areas where the change in ozone is statistically insignificant: in other words where the change is not distinguishable from natural variability. This covers the equatorial zone (latitude 30N to 30S) all year round, which is fortuitous since it is the equatorial zone where UV radiation is most intense anyway. In the northern midlatitudes (30N to 60N, covering Europe and North America) the thinning is insignificant in the summer and fall, and only becomes detectable from January to May. This too is fortuitous: in Winter and early Spring there is relatively little sun and people tend to be indoors or wearing longsleeves. During the months of intense UV exposure (July and August) there is no significant ozone loss.

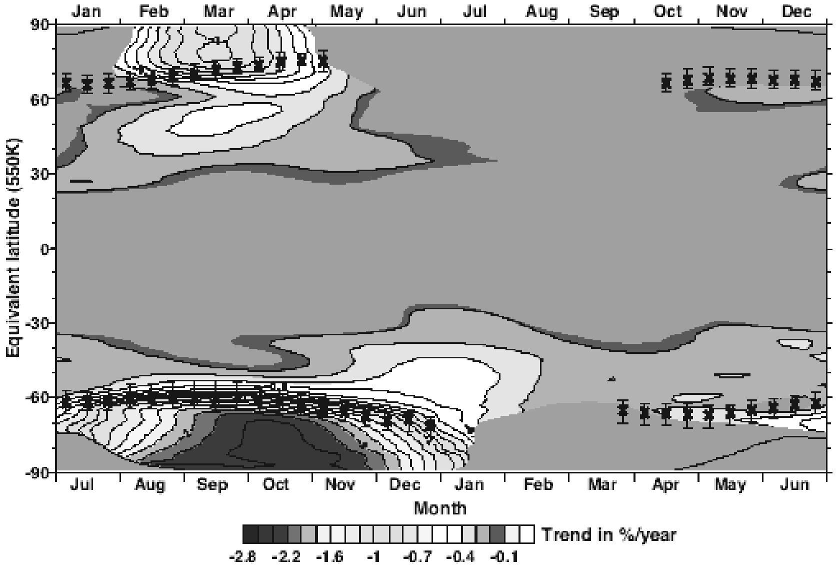

Figure 1.2 Variations in ozone density trends (Nov 1978 to Dec 2000) by season and latitude. Source: World Meteorological Organization.

The next Figure shows more detail for the Northern midlatitudes. The current thinning during the December to May season is about 4 percent. Thinning ozone increases the amount of UV reaching the Earth's surface You also experience more UV as you move towards the equator. A one percent thinning of the ozone layer causes about as much increase in surface UV flux as moving 10 miles towards the equator.[2] So the four percent thinning in the winter changes the UV flux at the surface for someone in the Northern Hemisphere by an amount equivalent to the extra UV experienced by traveling about 60 km south, roughly the distance from Guelph to St. Catharines.

Concern about the effect of CFCs on the ozone layer led countries around the world to sign the Montreal Protocol, which bans production and use of these compounds. Since non ozone-depleting substitutes were readily available the treaty has been successful in radically reducing global CFC use. The World Meteorological Organization forecasts that the ozone layer will have recovered to 100 percent of its natural density within about 40 years.

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[2] Ellsaesser, Hugh (2000) "The Ozone Layer" Chapter 20.4 in Lehr&Lehr (eds) *Standard Handbook of Environmental Science, Health and Technology*, San Francisco, McGraw-Hill. Page 20.33.

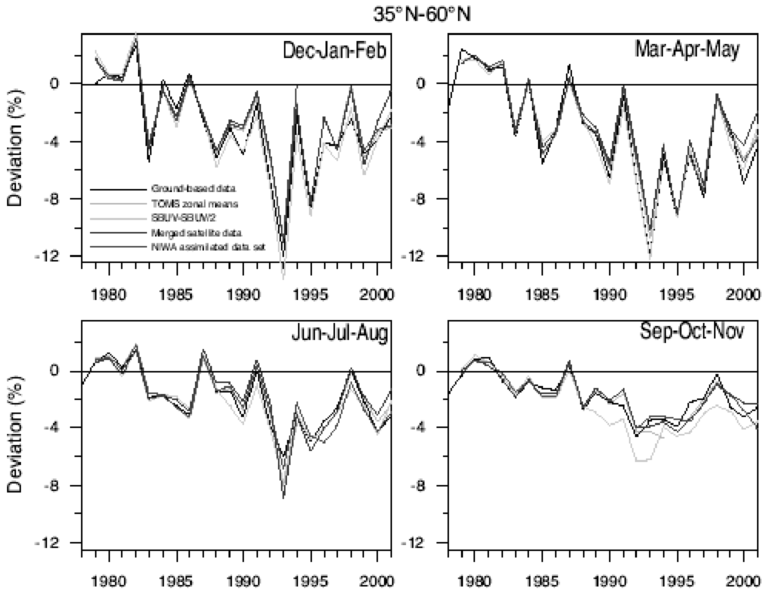


Figure 1.3 Seasonal variations in ozone layer density in Northern midlatitudes (35N to 60N). Source: World Meteorological Organization.

Another big global environmental issue is global warming. Fossil fuel consumption releases carbon dioxide (CO_2) and N_2O, among other things. Also, land-use changes can cause emissions of methane (CH_4) to go up. These gases are not air "pollutants" per se, but they do have in common that they filter small bands of infrared (IR) light. There is a constant "shine" of IR off the surface of the Earth. This radiation is part of the process by which energy from the sun, after absorption by the Earth is transported back to space, to maintain the balance of incoming and outgoing energy. The other major energy transport mechanism is convection, or fluid dynamics, which gives us our weather by the turbulent motions of air and water in the lower atmosphere (troposphere) and boundary layer. Most IR absorption is by water vapour, which is abundant throughout the lower atmosphere. The addition of CO_2 to the air enhances the IR absorption, slowing the radiative energy transport somewhat. Depending on how the fluid dynamics adjusts, there may be an increase in temperatures experienced at the ground level over time.

1.1.2 Air Pollution and Economic Growth over Time

There is a common perception that economic growth causes increased pollution. Many people would conjecture a relationship like this:

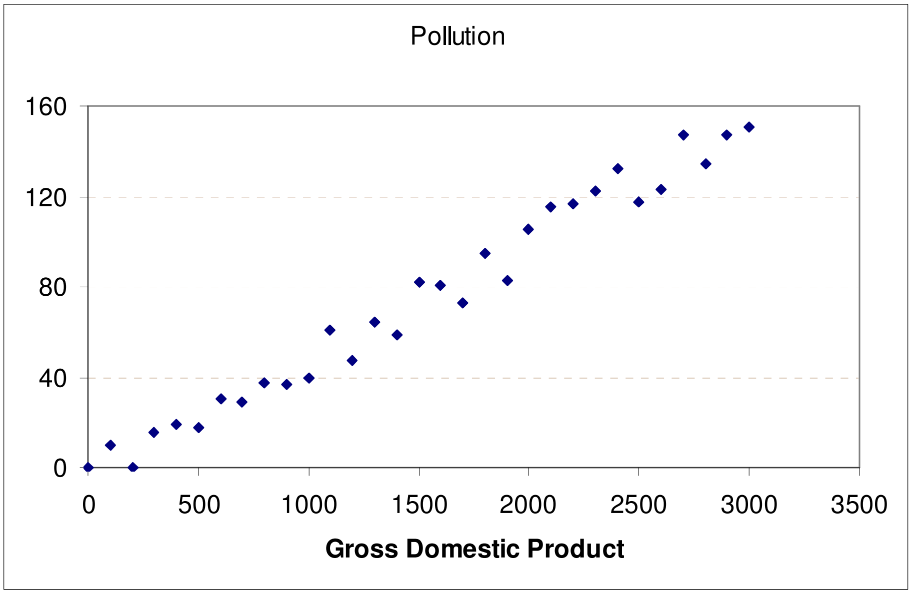


Figure 1.4: Hypothetical relationship between GDP and pollution

Actual data show that the situation is more complicated. For instance, a scatterplot of postwar US per capita income and particulate emissions shows the relationship is actually downward-sloping:

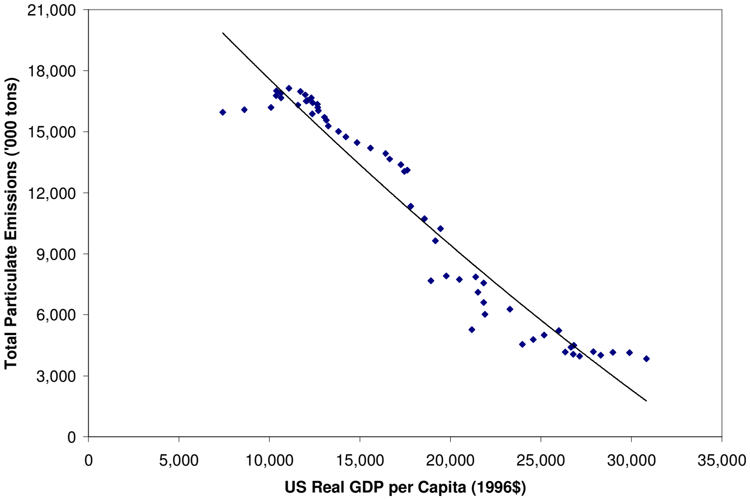


Figure 1.5: US Real GDP and total particulate emissions. Source: EPEQ data base http://www.uoguelph.ca/~rmckitri/epeq/epeq.html.

On the other hand, American CO emissions show an upside-down-U shaped pattern:

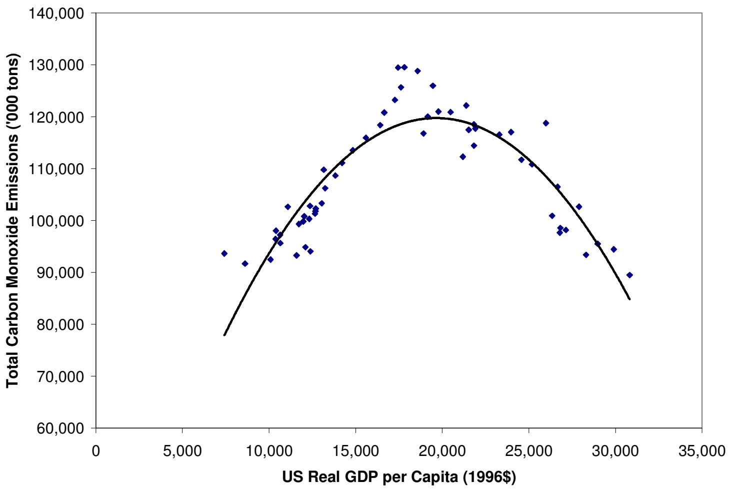


Figure 1.6: US Real GDP and total CO emissions. Source: EPEQ.

A surprising feature of postwar US economic growth is that most air contaminant emissions are at or below where they were at the end of WWII:

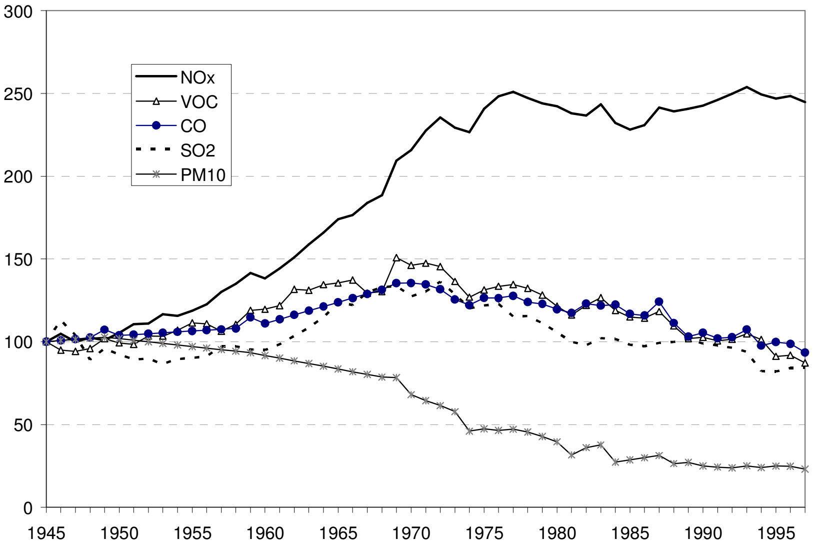


Figure 1.7: US Emissions by type, 1945-1998. Source: EPEQ

The data have all been scaled so the 1945 value equals 100. NOx grew until about 1975 and leveled off thereafter. Otherwise total air pollution emissions today in the US are below where they were in 1945, despite the overall economy growing more than 8-fold in size. The following graph shows the number of violations of air quality standards per monitoring station per year in the US, for CO and Ozone.

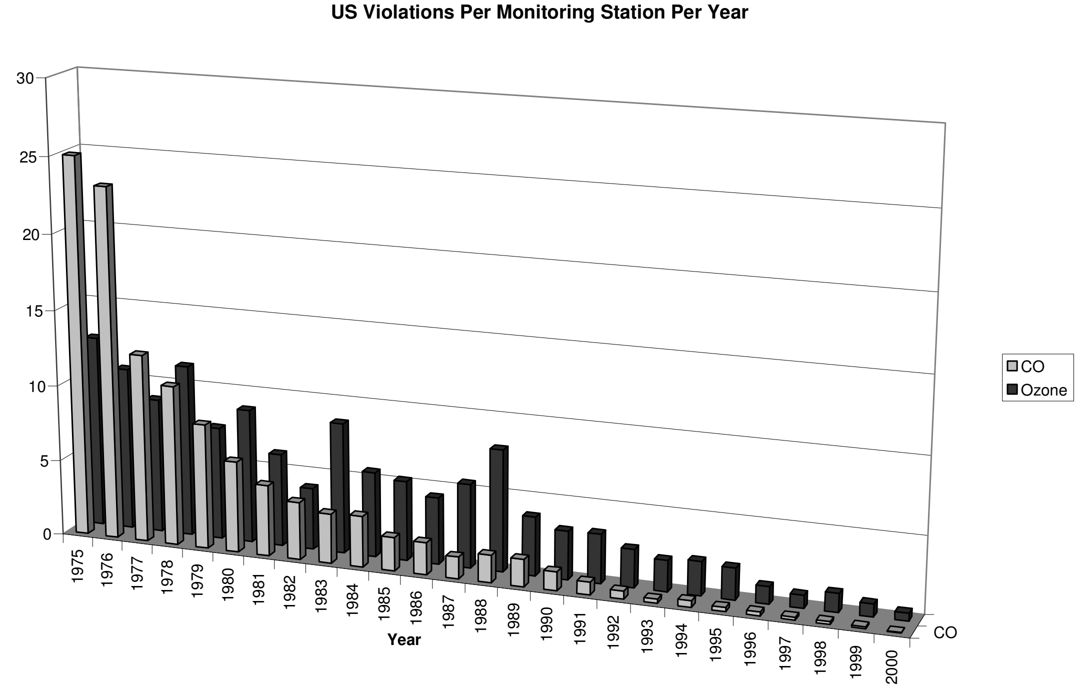


Figure 1.8: US Air Monitoring Violations per station per year, CO and O3. Source: EPEQ.

The improvement in air quality can, at least in part, be attributed to tightening standards on factories and automobiles. The following Table shows the US federal motor vehicle standards since 1966 for the three main air contaminants that come out the tailpipe: VOCs, NOx and CO. Each standard is indexed to equal 100 in 1966 to allow easier comparison over time (the actual standards in 1966, in grams per mile, for autos were 10.6, 4.1 and 80 respectively; for trucks 8, 3.6 and 102.) By the year 2000 all these standards had been reduced by approximately 90 to 95 percent. Cars today must emit about 4 percent of the carbon monoxide (per mile) they were allowed to emit in the mid-1960s. Note that in 2005 the NOx standards for cars and trucks, and the VOC standards for trucks, will be tightened yet again. This will yield little additional benefit to air quality, but will add a lot to the purchase price of cars, so if you plan to buy a new car do it in 2004.

	VOC grams per mile		NOx grams per mile		CO grams per mile	
Year	Autos	Light Truck	Autos	Light Truck	Autos	Light Trucks
1966	100.00	100.00	100.00	100.00	100.00	
1967	38.68	100.00	100.00	100.00	42.50	100.00
1971	38.68	100.00	100.00	100.00	42.50	100.00
1972	32.08	100.00	75.61	100.00	35.00	100.00
1974	32.08	100.00	75.61	100.00	35.00	100.00
1975	14.15	25.00	75.61	86.11	18.75	19.61
1976	14.15	25.00	75.61	86.11	18.75	19.61
1977	14.15	25.00	48.78	86.11	18.75	19.61
1979	14.15	21.25	48.78	63.89	18.75	17.65
1980	3.87	21.25	48.78	63.89	8.75	17.65
1981	3.87	21.25	24.39	63.89	4.25	17.65
1983	3.87	21.25	24.39	63.89	4.25	17.65
1984	3.87	10.00	24.39	63.89	4.25	9.80
1987	3.87	10.00	24.39	63.89	4.25	9.80
1988	3.87	10.00	24.39	33.33	4.25	9.80
1993	3.87	10.00	24.39	33.33	4.25	9.80
1994	2.36	4.00	9.76	33.33	4.25	3.33
1995	2.36	4.00	9.76	11.11	4.25	3.33
2001	2.36	4.00	9.76	11.11	4.25	3.33
2002	2.36	4.00	9.76	11.11	4.25	3.33
2003	2.36	4.00	9.76	11.11	4.25	3.33
2004	0.66	4.00	9.76	11.11	4.25	3.33
2005	0.66	0.88	1.71	1.94		
2006	0.66	0.88	1.71	1.94		
2007	0.66	0.88	1.71	1.94		

TABLE 1.1: Federal emissions control standards for all new cars and light trucks sold in the United States, indexed to 1966 = 100. Source: US Federal Highway Administration - http://www.fhwa.dot.gov////environment/aqfactbk/factbk12.htm#t26.

Looking internationally it turns out that high-income countries are also ones with relatively low levels of urban air pollution. This graph compares average TSP levels in major cities with national real income in 1995 $US:

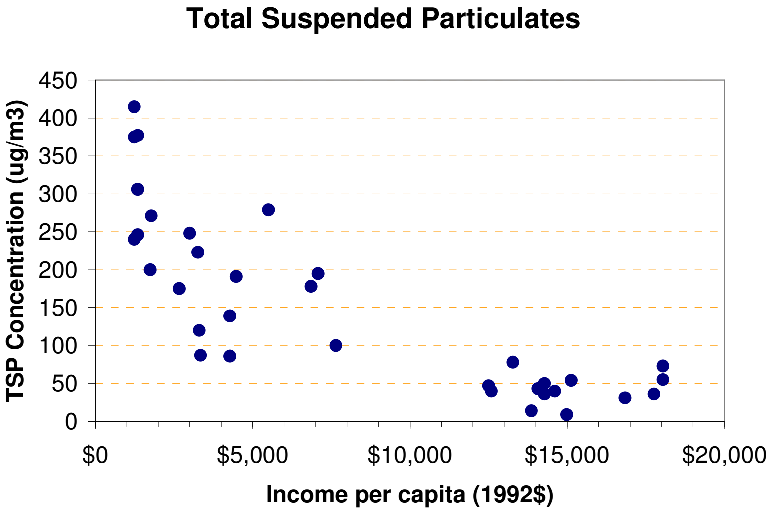


Figure 1.9: International income vs. TSP concentrations. Source: EPEQ.

Clearly the cluster of high-income countries enjoy better urban air quality than the group of low-income countries. A similar pattern is observed for SO_2:

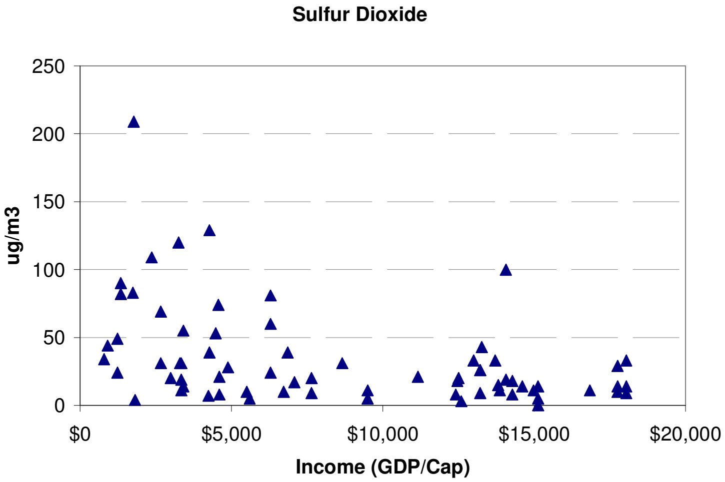


Figure 1.10: International income vs. SO_2 concentrations. Source: EPEQ.

For NOx the pattern is not clear: income growth seems to have little effect one way or the other:

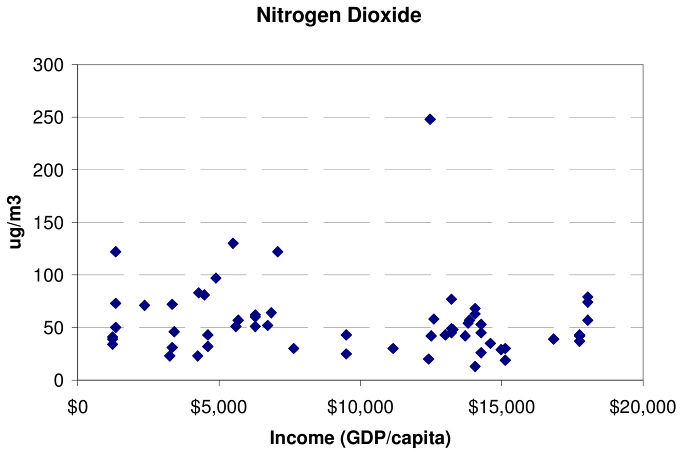
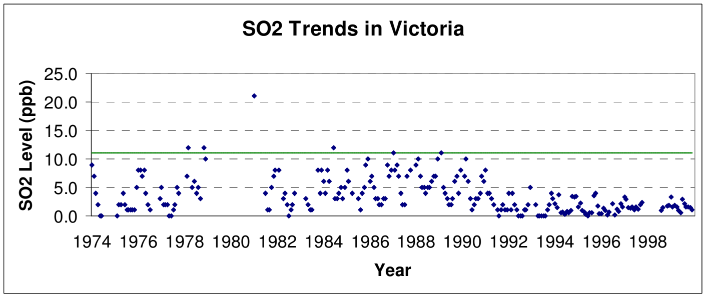
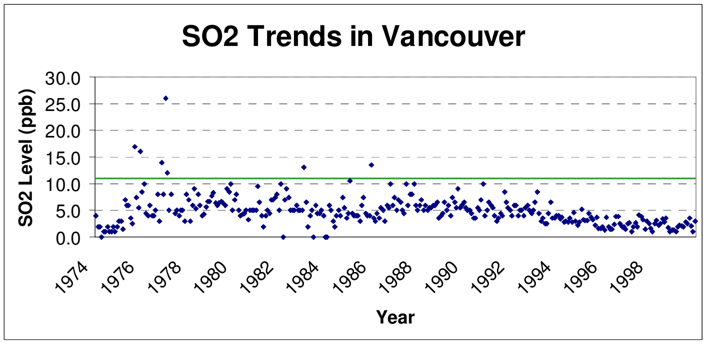
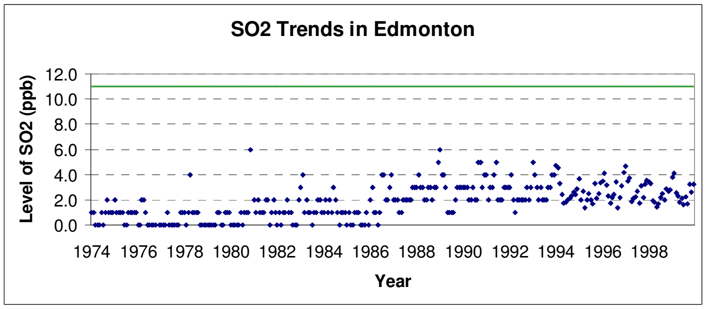


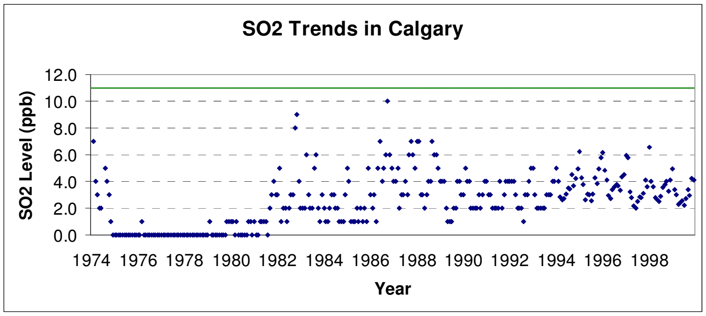
Figure 1.11: International income vs. NOx concentrations. Source: EPEQ.

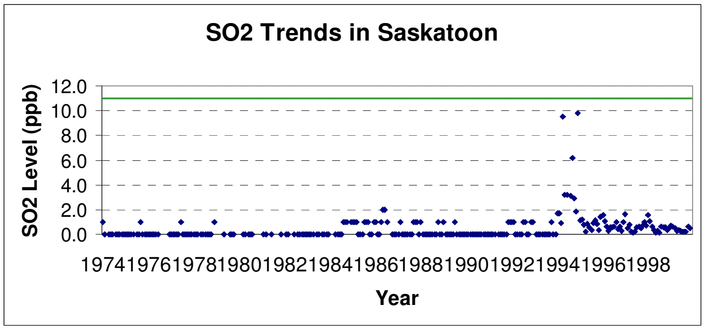
In the 1980s a lot of work was done to control SO_2 emissions. The following graphs present concentrations of SO_2 in 10 major Canadian cities since 1974. The horizontal line shows the Environment Canada standard for air quality, while each dot represents the average monthly concentration.








SO2 Trends in Calgary
SO2 Level (ppb)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
Year


SO2 Trends in Saskatoon
SO2 Level (ppb)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1974
1976
1978
1980
1982
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1986
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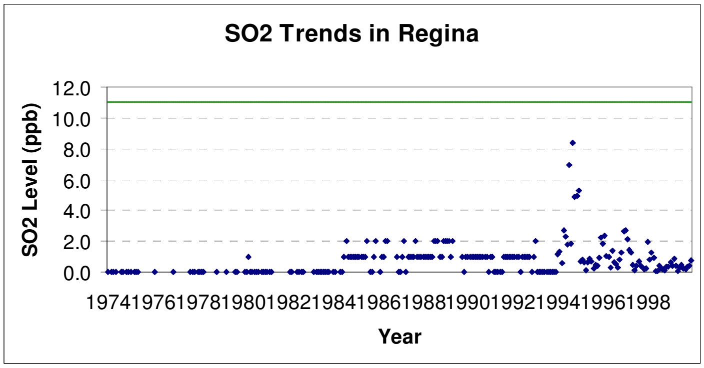
1992
1994
1996
1998
Year


SO2 Trends in Regina
SO2 Level (ppb)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1974
1976
1978
1980
1982
1984
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1988
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1992
1994
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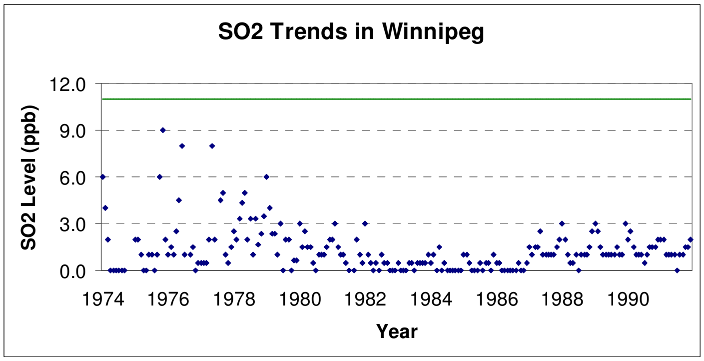
Year


SO2 Trends in Winnipeg
SO2 Level (ppb)
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9.0
6.0
3.0
0.0
1974
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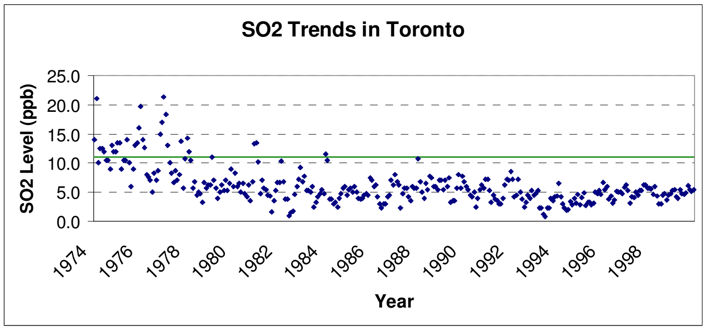
1978
1980
1982
1984
1986
1988
1990
Year


SO2 Trends in Toronto
SO2 Level (ppb)
25.0
20.0
15.0
10.0
5.0
0.0
1974
1976
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1980
1982
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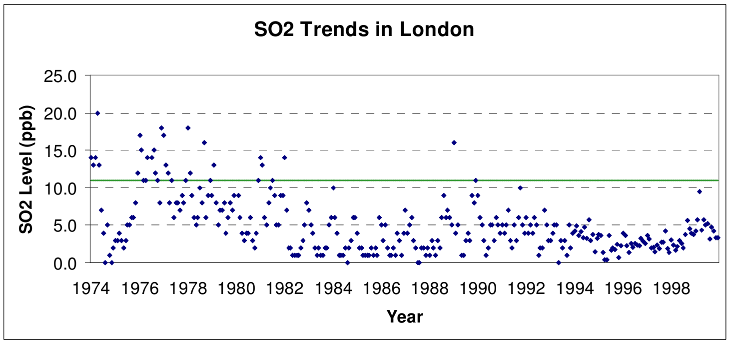
1996
1998
Year


SO2 Trends in London
SO2 Level (ppb)
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20.0
15.0
10.0
5.0
0.0
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1976
1978
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1994
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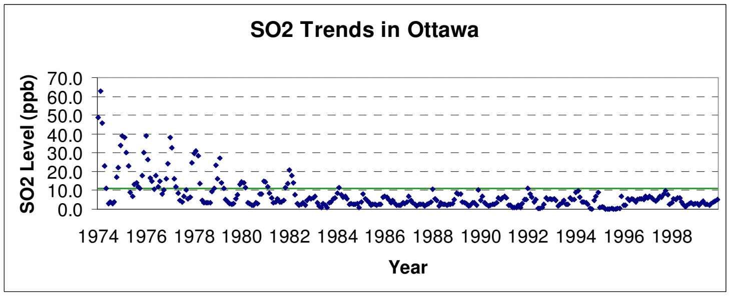
Year


SO2 Trends in Ottawa
SO2 Level (ppb)
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60.0
50.0
40.0
30.0
20.0
10.0
0.0
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1978
1980
1982
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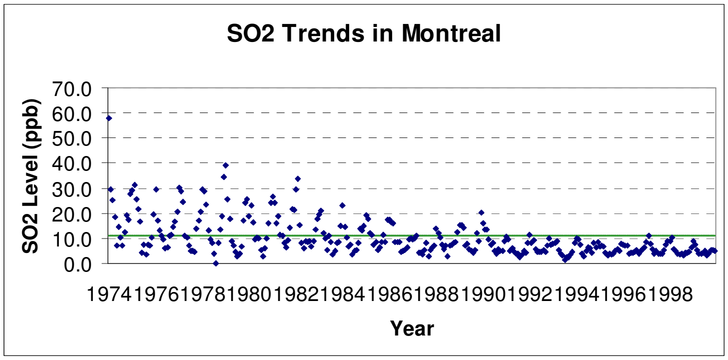
Year


SO2 Trends in Montreal
SO2 Level (ppb)
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50.0
40.0
30.0
20.0
10.0
0.0
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1992
1994
1996
1998
Year

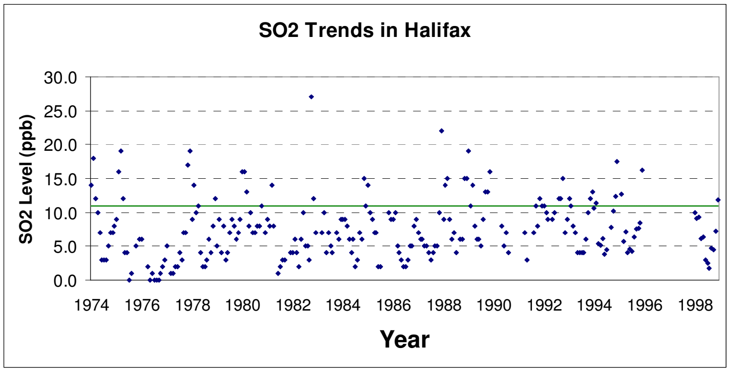
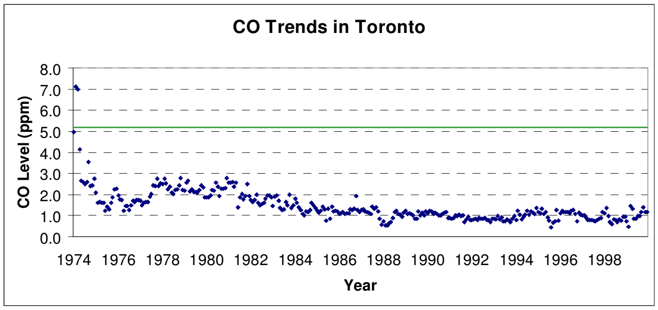
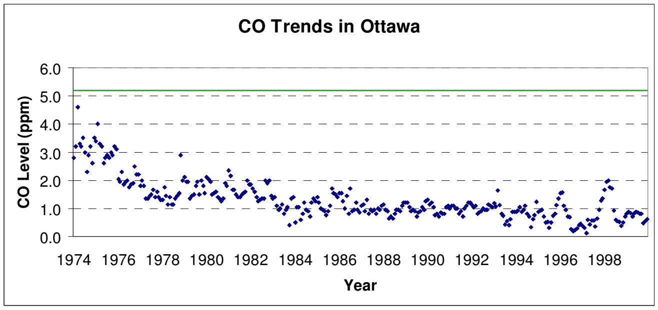
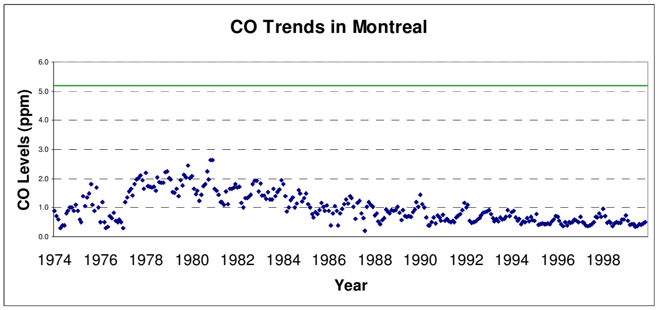


Figure 1.12: SO_2 Concentrations by Year, Canadian Cities. Source: EPEQ.

Except for Prairie cities, SO_2 levels were persistently above the acceptable level in the 1970s. Today they are trivial. Compare the Canadian cities, with concentrations below 11 ppb for the most part, with low-income cities where the annual average is around 50 ppb. Carbon monoxide (CO) is also a non-issue in Canadian cities. The following charts illustrate that monthly concentrations are extremely low.







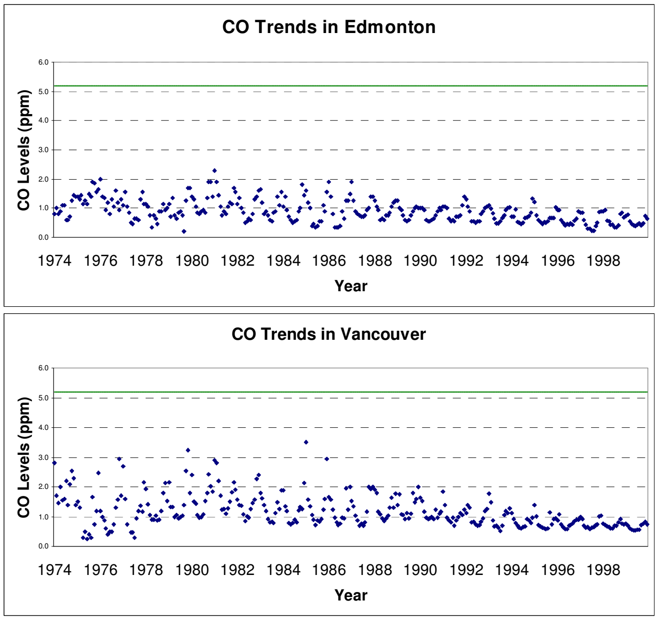


Figure 1.13: CO Concentrations by Year, Canadian Cities. Source: EPEQ.

Other cities show similar trends—CO just isn't an issue in Canadian urban air, and hasn't been for a long time. TSP levels have also dropped considerably, as the following graph from Toronto shows:

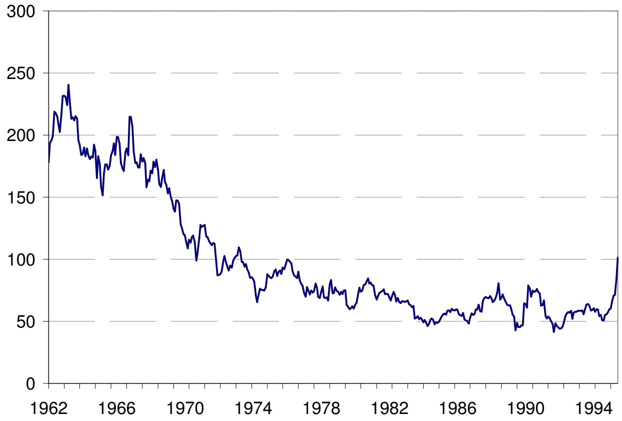


Figure 1.14: TSP Levels (ug/m3), Bay and Wellesley, 1962 to 1997, Toronto. Source: EPEQ.

Monthly ozone levels at the same location are extremely variable, but have trended down slightly.

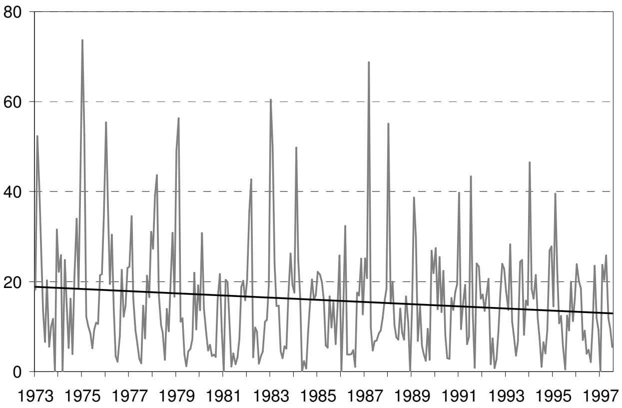


Figure 1.15: Ozone Levels (ug/m3), Bay and Wellesley, 1973 to 1997, Toronto. Source: EPEQ.

1.1.3 Water Pollution

The upside-down-U shape seen in US CO emissions is also observed in water pollution data. The following diagram plot s organic water pollution per worker, in Kg per day per worker, against national real income per capita (in 1985 $US), based on 2 surveys by the World Bank in 1980 and 1993:

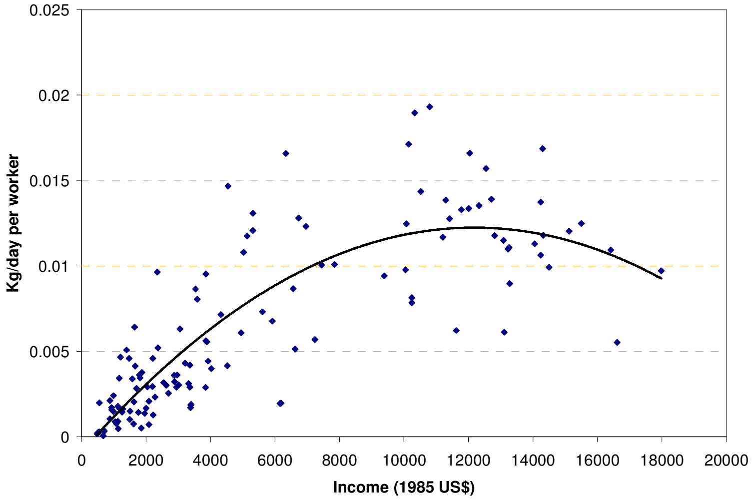
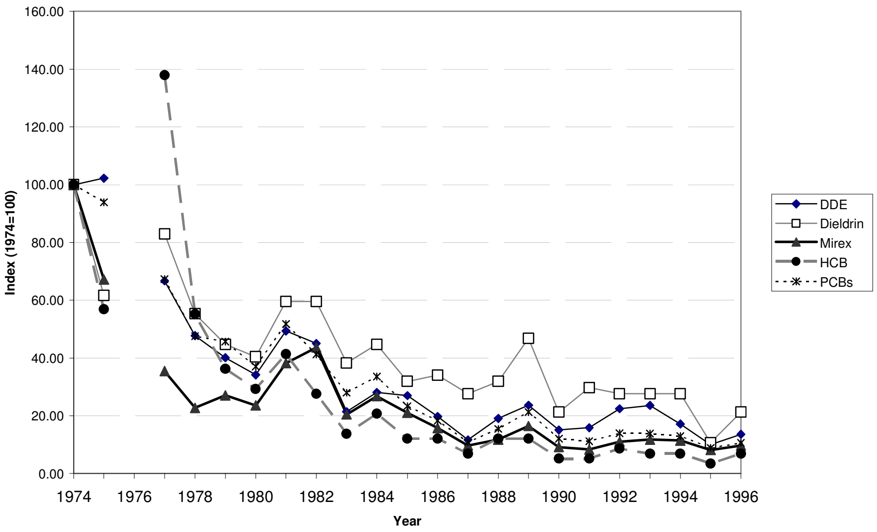


Figure 1.16: International income vs. water pollution. Source: EPEQ.

In the low-income setting, income growth seems to accompany emissions growth, but in the high-income group the opposite pattern emerges.

The fact that water quality improves with economic growth in high income economies might seem surprising but the same picture is borne out when looking at the Great Lakes.

The following picture shows the changes in concentrations of organic toxins in herring gull eggs from sites around Lake Ontario (1974-1996) and Lake Erie (1974-1999).


Contaminant Levels in Herring Gull Eggs, Lake Ontario

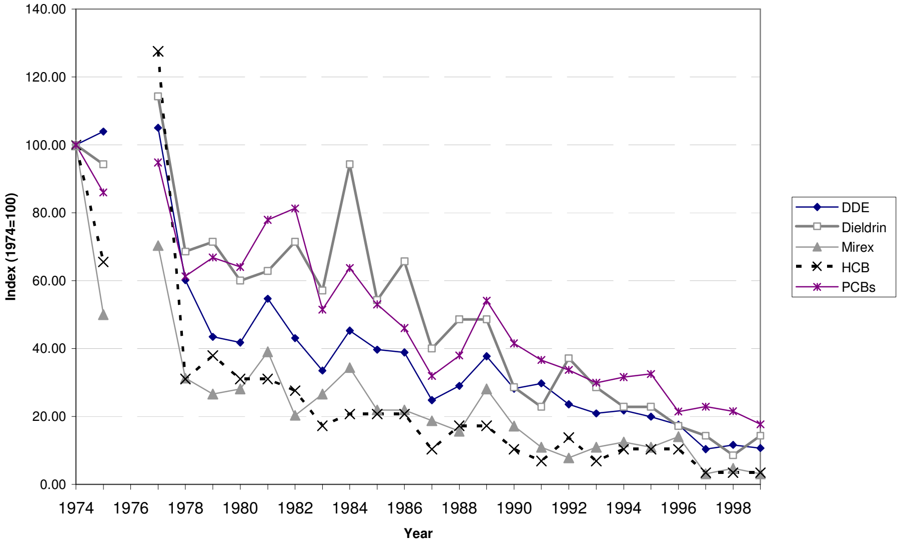

Contaminant Levels in Herring Gull Eggs, Lake Erie

Figure 1.17: Great Lakes Water Pollution by Year. Source: EPEQ.

All the series start at 1974=100, and by 1996 they have all fallen by 80 percent or more. DDE is the compound that the pesticide DDT breaks down into once in the environment.

There is a lot more that could be said about environmental quality: air and water pollution, land use, etc. This is just a smattering of the available evidence. But one pattern is clear. In high-growth economies there is no clear connection between economic growth and pollution, nor does pollution inexorably rise with time. The worst air and water quality problems are in low-income countries. Hence economic growth may actually help them clean up.

1.2 Policy Instruments: A Brief Introduction

1.2.1 Standards

Standards can take many forms, but at heart each one is a 'command-and-control' mechanism to directly influence pollution levels. A *level* standard requires a source to keep total emissions below a certain level. A *ratio* standard requires a source to maintain emissions per unit of something to below a certain target. For instance, the standard may permit smoke from a chimney to contain no more than 100 parts per billion of benzene. If a standard is adjusted based on a firm's output it may, in effect, be a ratio standard. For instance if a firm is allowed to emit 10 tons of SO_2 for every 1000 tons of steel it produces, it faces a ratio standard of 0.01 tons SO_2/unit output. A *process* or *technology* standard does not prescribe emissions, instead it requires installation of certain pollution control equipment. For example, cars must have devices called catalytic converters installed, regardless of how much they are driven. Some process standards only stipulate that firms must use the 'Best Available Technology', and regulators then decide what the standard means in light of currently available abatement equipment options.

1.2.2 Emission Taxes

An emissions tax is simply a charge per unit of emissions. The term 'Pigovian' tax originally referred to a charge on a commodity based on the externalized social cost associated with it. However, taxing the output of a firm only equates to a tax on its emissions in the special case where emissions and output vary linearly. Since this is not generally true in the models we examine herein, we will avoid using the term 'Prigovian' tax, and refer instead to *emissions* taxes.

1.2.3 Emission Permits

Another way of putting a price on emissions is to require firms to hold a permit for each unit of pollution they release, while allowing them to buy and sell the permits. This system is called *Tradable Emission Permits* or some similar term (e.g. tradable quotas, tradable credits, etc.) The best-known system of tradable permits is the US SO_2 market. Large emitters of sulfur dioxide in the US must by permits to cover their emissions, and there is an active market in permits for both current and future emissions. You can see information about the US program at http://cfpub.epa.gov/gdm/ and Ontario's permit trading system is described at http://www.ene.gov.on.ca/envision/air/etr/.

1.2.4 Liability Law

The use of courts to control pollution pre-dates modern environmental laws. The British common law has long recognized the right of property owners to be protected against *nuisance* and *trespass*. A *nuisance* is an interfering action which prevents a person from using or enjoying his or her property. It can take the form of noise, smell or other interference. A *trespass* is an invasion of one's property, including pollution deposition, with damaging consequences. Another area of law that has mitigated pollution is *tort* law, which is the branch of civil law dealing with harmful actions for which monetary damages (and, usually, an injunction preventing further harm) are sought. Finally, where damage to waterways occurs, courts have historically been asked to intervene based on the *riparian* rights of landowners adjacent to the waterway.

1.3 Institutions and Rule-Makers

1.3.1 Federal Government

In Canada, the federal body primarily responsible for environmental regulation is Environment Canada. However, under the Canadian constitution, primary responsibility for air and water quality protection rests with the provincial governments. The federal government coordinates provincial action through the Canadian Council of Ministers of the Environment, including devising targets and sharing policy initiatives. The federal government exercises direct authority in some areas, however. First, it has sole jurisdiction for signing international treaties, including agreements like the Canada-US Acid Rain treaty and the Kyoto Protocol. Second, federal transport regulations establish standards for automobiles and trucks. Third, the federal government exercises control over some water quality issues because they have authority over fisheries and navigable waterways. Fourth, the federal government has passed laws like the Species at Risk Act, which give it some authority over habitat protection, and the Environmental Protection Act, which give it authority over some pollutants, chiefly those designated ‘toxic.’ Also the federal government has established legislation requiring environmental assessments for large projects.

In the USA the federal Environmental Protection Agency (EPA) exerts considerably more direct authority than Environment Canada does here. The EPA sets national air quality standards and has the power to enforce stringent remedial measures on counties determined to be out of compliance. It established emission limits for SO_2 and NOx and runs a tradable permits system for these. It oversees the ‘Superfund’ program for cleaning up contaminated waste sites. Other US federal agencies are also important, for instance the Department of the Interior which controls habitat protection programs under the Endangered Species Act, and the Department of Transport which sets motor vehicle emission standards and abatement technology requirements.

1.3.2 Provincial and State Governments

In Canada, provinces have authority over air and water regulation, as well as most resource management issues like forestry and mining. In the USA, states have authority over mining but the federal government controls much of the public forestry since it is federal, rather than provincial, land. US states have less independence in air and water pollution regulation, and if they are out of compliance with federal standards they can be compelled to implement federally-mandated remedies.

1.3.3 Municipalities

In both Canada and the USA, municipal governments control issues like garbage and recycling facilities, land-use zoning and some resource management issues, like groundwater use.

1.3.4 Courts

The jurisdiction of courts in Canada and the USA has diminished over the postwar era as governments have introduced regulations and placed matters previously subject to common law under direct government control. However, tort and property law continue to serve as instruments for individuals affected by pollution to press claims for compensation and to assert their rights to not suffer the damages due to pollution.

1.4 Growth and the Environment: Theoretical Ideas

Many people express worries about the earth's ability to bear up under the pressure of such development. Will economic growth inevitably lead to more pollution? Many economists would give a two-handed answer.

(i) On the one hand, growth involves increased output, resource use, pollution, garbage, etc. This is the "substitution" effect: a society gives up some environmental assets to obtain more consumption goods

(ii) On the other hand, growth means consumers have more money and more leisure time, which translates into demand for a cleaner environment and the resources to achieve it. This is the "income" effect: since environmental quality is a normal good, as national income rises, people demand more of it and put resources into its production (or conservation as the case may be).

Which effect is the stronger of the two? There is good evidence that, at low income levels, the substitution effect dominates the income effect, and growth leads to worsening environmental quality. But as income continues to rise, a turn-around point is reached, after which the income effect dominates, and growth begins to support improved environmental conditions. This effect is called the "Environmental Kuznets Curve," after the "Kuznets" curve in the study of income distribution, where inequality is sometimes observed to behave the same way during the growth process.

It is easy to illustrate a mechanism behind Kuznets curve found in some data. Consider a simple economy with a fixed population producing consumption goods C from its environmental endowment E. At an early stage of development, the production frontier is linear, reflecting the fact that production primarily takes the form of extraction and consumption of what is found in nature with very little value-added through secondary production. As the economy's capital stock grows, the production possibility boundary pivots upwards along the C axis, since the maximum endowment of E, denoted E^M, remains more or less fixed. Also, since capital is used to add value to what is extracted from nature, the PPB displays more and more curvature, indicating the diminishing returns to scale inherent in secondary and tertiary processing. So the sequence of PPB's under technological advance look like Figure 1.18:

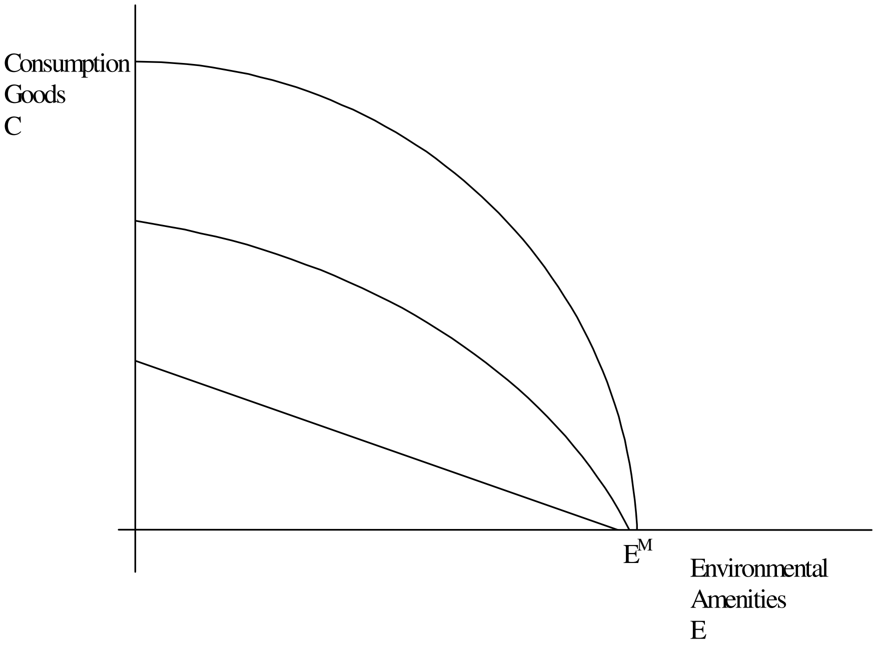


Figure 1.18 Production Possibility Boundaries Between Consumption and Environment

Social preferences are illustrated by indifference curves between E and C. They have the usual quasi-concave shape, although at very high levels of E they might begin to bend back upwards, since people don't necessarily like to rough it in the wilds all the time. So a group of indifference curves would look like Figure 1.19:

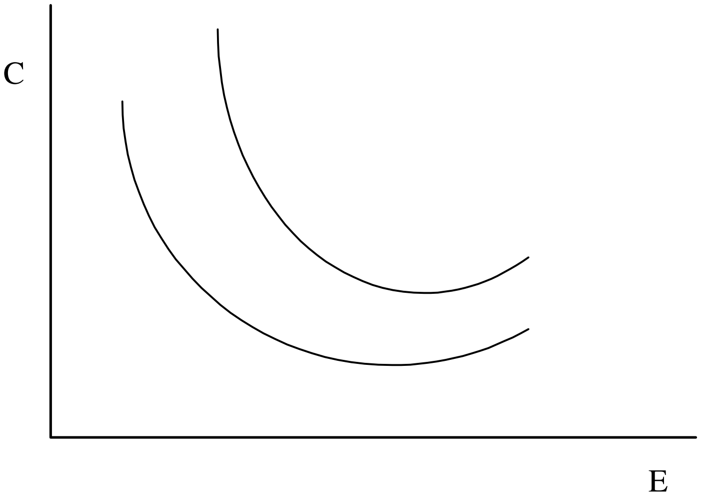


Figure 1.19 Indifference Curves Between Consumption and Environmental Quality

If we combine the two diagrams we can get Figure 1.20:

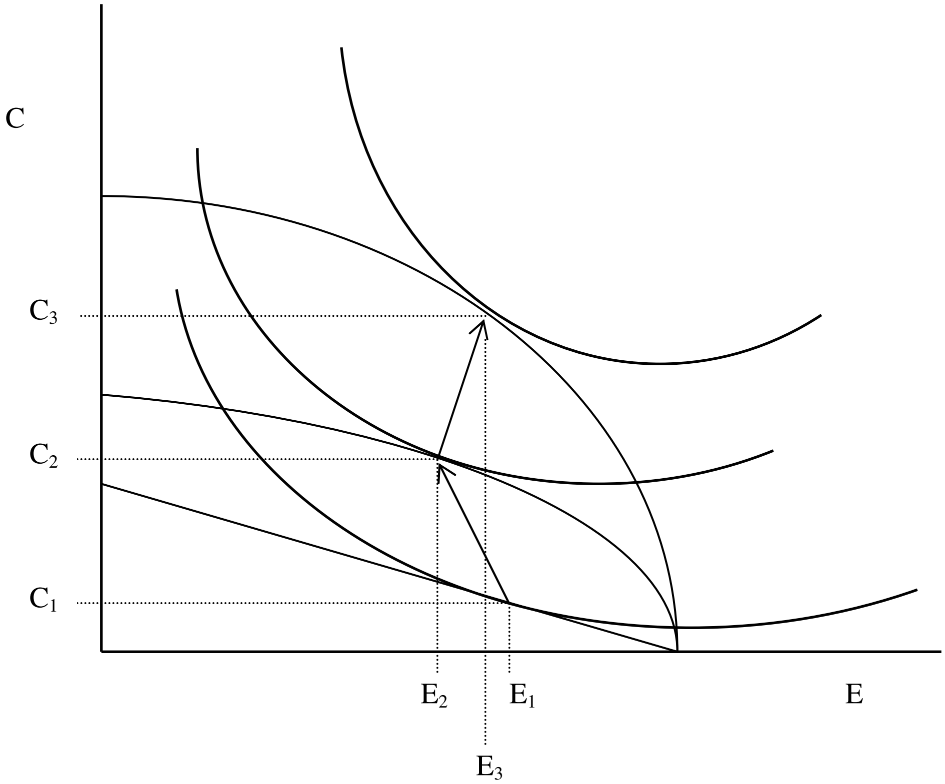


Figure 1.20 Optimal Path Between Consumption and Environmental Quality

We assume that the economy chooses optimal pairs of E and C, denoted (E_i, C_i) i=1, 2, 3, etc.. At low levels of development and consumption, the country is willing to trade off a lot of E to get relatively small increments of C. Where survival is at issue, i.e. if the question is whether one lives another six months, the loss of environmental amenities is clearly not going to stop people harvesting trees for fuel and shelter, or hunting and fishing endangered species. In addition, people will accept more pollution and ecological degradation in exchange for economic development and enhanced consumption possibilities. As development proceeds, and the society moves to higher PPB's and indifference curves, the relative cost of consumption (in terms of lost E) goes up, and the tradeoff becomes less and less attractive. At some point, further increases in C are paired with increases in E, since income is now high enough that resources can be put into both increased consumption and environmental preservation. So from the first to second indifference curve we observe increased income and consumption paired with decreasing environmental quality, but from the second to third, and beyond, income growth supports increased environmental quality.

A long-standing literature uses neoclassical optimal growth models to examine the question: what is the optimal allocation of income among consumption, investment and pollution control, to maximize the discounted present value of utility over an infinite horizon? Forster (*Southern Econ. Jnl.* 1973) solves a basic form of the optimal growth problem and finds that the steady-state values of capital (*K*) and consumption (*C*) with optimal pollution growth were strictly lower than the steady-state values of *K* and *C* without optimal pollution control. This is intuitively clear enough: if income is not devoted to environmental preservation, too much growth occurs and welfare falls. Forster treats pollution as a flow variable. By contrast, Keeler, Spence and Zeckhauser (*Journal of Economic Theory* 1971) treat pollution as a cumulative stock variable. They find that two steady-states exist, one with no money spent on pollution control and one with money allocated to both consumption and pollution control. Utility is lower in the first steady state. Unfortunately stability is not analysed. Also, pollution in both these papers is treated as a fixed proportion of production or consumption. Other studies tend to do the same, and focus on proving the existence and stability of resulting equilibria. Brock (1977) examined growth and pollution and concluded that zero discounting is a sufficient condition for the existence of a saddle point optimum.

More recently, the question of growth and the environment has been taken up again. Tahvonen and Kuuluvainen (*JEEM* 1993) and others have explored models with stock pollution effects, renewable resources, etc. This paper shows that an optimal path can be attained through the use of emission taxes. But these papers continue to examine existence and stability issues, whereas the question we tend to be more interested in is: Will economic growth inevitably lead to unbearable pollution levels? This question wasn't examined again until some recent empirical work associated with the debate in the US about the possible environmental side effects of the North American Free Tade Agreement. Grossman and Kreuger's paper is the most famous of these (*Quarterly Journal of Economics* 1995). They gathered evidence from a UN-sponsored emissions monitoring project, which reported air and water pollution levels for cities all over the world from 1972 onwards. They used a simple reduced-form regression to examine the link between total emissions and per-capita income. They found evidence that, for many pollutants, there is an inverted-U shaped function relating income to pollution for some kinds of air pollution (smoke, heavy particulates), organic water pollutants (nitrates, BOD and COD) and some heavy metal water contaminants. They found that the turn-around point occurs by about $6-8,000 US per capita income for many pollutants. A similar study (Selden and Song, *JEEM* 1994) found the turn-around point came somewhat later (8-10,000 US), however they were using indirectly estimated national air pollution emissions, rather than actual ambient concentrations.

While the empirical results are certainly suggestive, there are a number of problems with them. The curves which have been estimated appear to be very sensitive to model specification (also noted by Galeotti and Lanza 1998). Fitting a curve requires ad hoc decisions about the data (levels, logs, differences, etc) and the number of terms in the polynomial equation to be estimated. Regardless of the actual pattern in the data, using a 2nd-degree polynomial forces it to "reveal" either a ∪ -shape or a ∩-shape, while a cubic polynomial forces a 'sideways-S' shape. Since the most interesting inferences from such models pertain to inflection points and limits, this sensitivity to modeling assumptions would warrant care in drawing conclusions. But such care is not always observed. For instance, Hilton and Levinson (1998) estimate polynomials relating atmospheric lead levels to per capita GDP. They readily conclude that the 'true' relationship is inverted-U, yet their parameter estimates yield a variety of patterns depending on the specification: ∪, ∩, ~, etc (see their Figure 3).

Notwithstanding such problems, the empirical results have prompted a burst of theoretical models aimed at rationalizing structural interpretations of the EKC. But rather than explain the inverted-U path, they have apparently established that models which are rich enough to generate nonlinear pollution dynamics can rationalize *any* pollution path. Andreoni and Levinson (1998) show that, in a simple model with preferences over consumption and environmental quality, income effects (by which increases in environmental quality become marginally more valuable as income grows) can dominate substitution effects (the trading off of environmental quality to obtain more consumption and investment), if the pollution abatement technology exhibits increasing returns to scale. Under other plausible assumptions, the pollution-income path can be linear in income or U-shaped.

Beltratti (1996) develops a simple dynamic model as follows. Preferences between consumption c and environmental quality E are given by the simple Cobb-Douglas utility function $U = \frac{1}{1-\eta}(cE)^{1-\eta}$. Production is by a linear production function $y = \beta K$. Environmental quality evolves according to $\dot{E} = R(E) - yv(K)$ where R is the "recovery" function and v is the function which relates the stock of capital to the factor by which output deteriorates environmental quality. Capital evolves according to the investment equation $\dot{K} = y - c$. The optimal path for the economy can be found using the Hamiltonian equation:

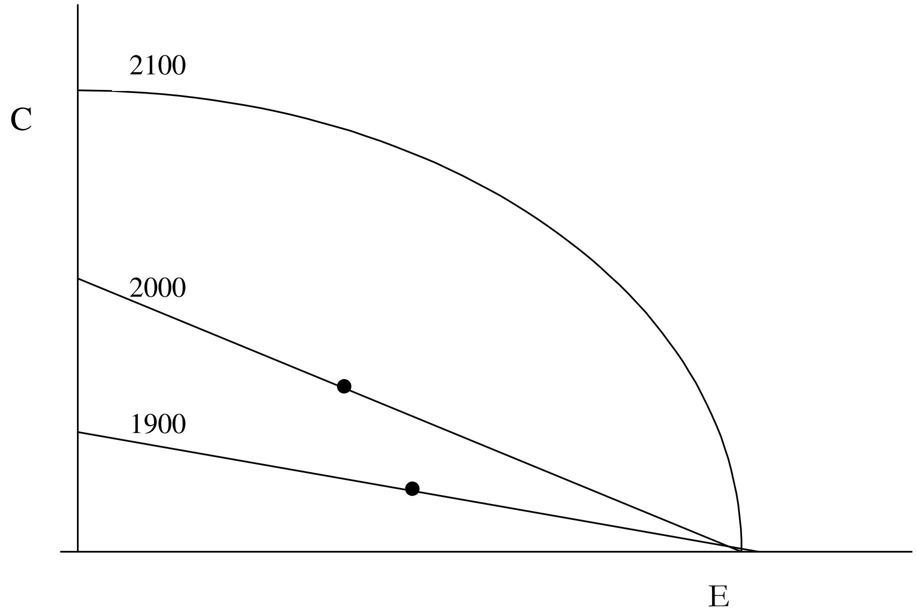
$$H = \frac{(cE)^{1-\eta}}{1-\eta} + \lambda_1(\beta K - c) + \lambda_2(R(E) - \beta K v(K)).$$

A simple version would use $v(K) = GK$ where G is a constant. However this would not generate the kind of nonlinearities we are looking for, so a more complex version must be used. Suppose that we define $v(K) = \frac{G}{K} + K^{\alpha-1}e^{-\gamma K}$. This is a specification that allows for a variety of plausible nonlinear relationships between $\dot{E}$ and K, depending on the parameter values, yet is tractable enough to solve. It has the attractive features that as $K \to 0$, $v(K) \to \infty$ and $v'(K) \to -\infty$, so output is extremely damaging at low capital levels, but as $K \to \infty$ both v and v' tend to zero, so output is asymptotically benign. This matches our intuition about the Kuznets curve dynamics. The model thus specified is as simple as one can get without assuming away the nonlinear growth-pollution relationship.

It turns out (see Beltratti pp. 49-52) that this model exhibits quite unexpected dynamics. First, it has no steady state. Second, for a plausible set of parameters, the relationship between production y and the state of the environment, E, is $\cup$-shaped, with the *worst* environmental effects associated with the *highest* levels of output. This is not what intuition or data would have led us to expect. But to tweak the model in order to get rid of these results calls into question the whole exercize: if we're just writing down a model to give us results we already decided upon on other grounds, it is pointless.

The lesson here is that pure growth theory is unlikely to settle the deeper questions about the relationship between growth and the environment. While economists continue to explore dynamic models, the need at present is for a better link between empirical work and existing theory. This is an important opening for current research. We will discuss some recent work on this by Copeland and Taylor later when we look at trade and the environment.

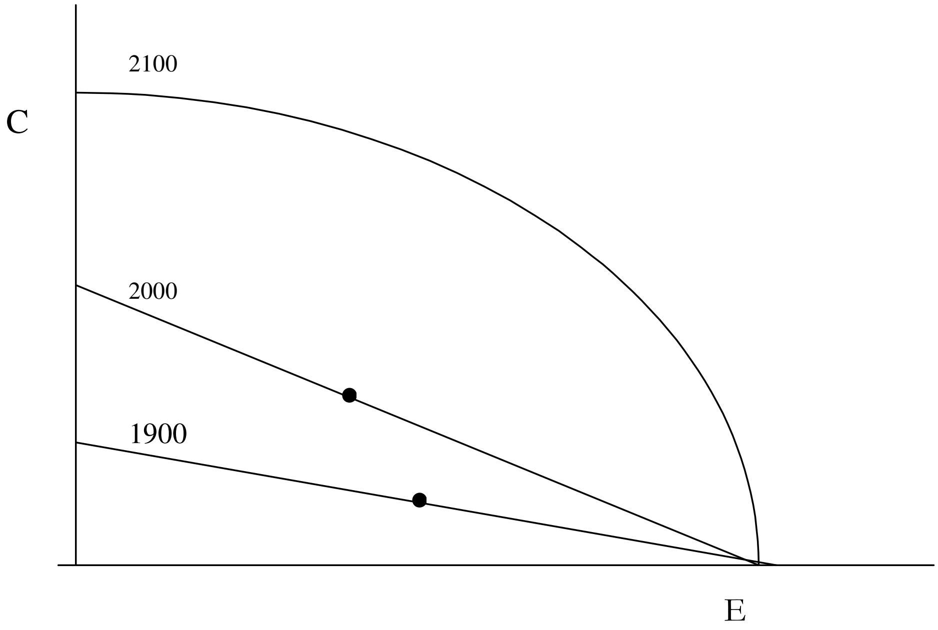
Practice Questions



The diagram shows the PPB for each year. The dots show the observed outcome. The indifference curves are not drawn, but you will need to draw them in to answer the questions. The outcome represented by a dot is not necessarily a tangency.

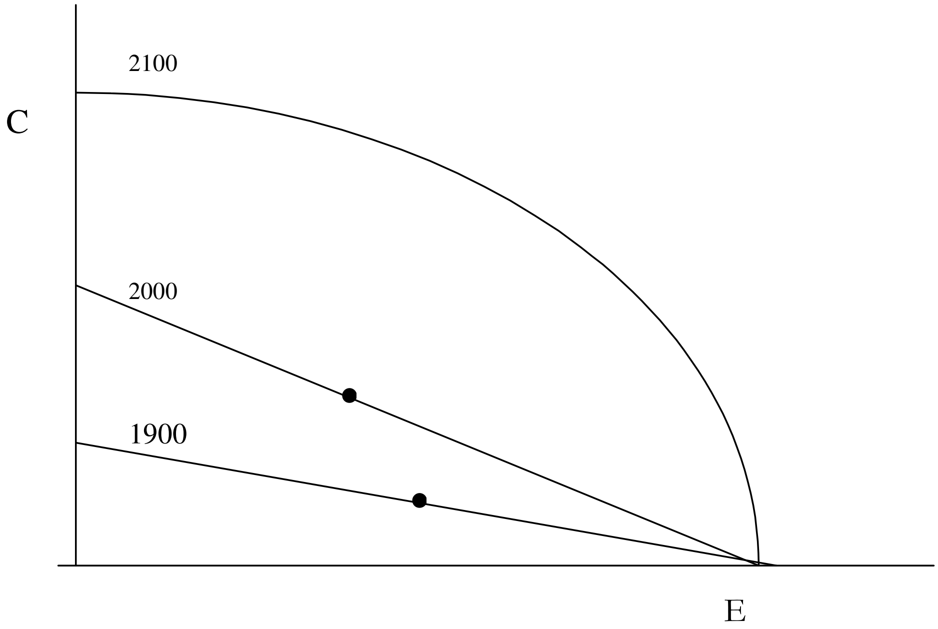
1. Suppose consumption C and environmental quality E are perfect complements and 1900 is an efficient outcome. Are we better off in 1900 or 2000?

2. Suppose preferences are not complements, and are such that we are better off in 2000 than in 1900. If we got better off by reducing E, does that mean environmental quality will be even lower in 2100?



3. Assume C and E are substitutes, but not perfect substitutes. Also suppose that the outcome in 1900 was efficient, and that we are no better off in 2000. Show that the outcome in 2000 is not efficient. What will happen to C and E if we move to a tangency point in 2000?

4. Suppose we are at an efficient outcome in 2000. Are we better off than we were in 1900?



5. Is environmental quality costlier in 2000 than in 1900? (define your cost measure carefully)

6. Show the level of environmental quality which would have been attained in 2000 if there had been an income effect but no substitution effect over the previous 100 years.

7. What must the public's attitude towards consumption be if we are worse off in 2000 compared to 1900?

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Chapter 2: Microeconomic Fundamentals of Environmental Economics

2.1 Externalities

We are concerned with situations in which one person's actions affect the welfare of another, such that 'external costs', or 'externalities', are imposed. There are two important aspects to an externality, as highlighted by the following definition:

Externality: When one agent's activities affect the utility or productivity of another agent or agents, without the former paying the price for the damages incurred by the latter, and without the latter having any control over the level of the activity.

There must be an imposition from one agent to another in which the former does not pay the cost and the latter does not have complete control over the magnitude of it. If Jane's stereo is interfering with Jill's sleep, that is an externality, unless Jill has climbed in Jane's apartment and is trying to sleep on Jane's couch without her permission. In this case Jill could go elsewhere to sleep, so the 'damage' she is suffering has a voluntary element to it. If a smelter emits a lot of smoke and fouls the air in a town, that would be an externality, unless the firm were paying the townspeople an agreed-upon sum of money for their suffering, in which case it is bearing the cost of its actions internally.

The situations we have in mind can be described in economics terms with some examples. Consider first a firm-on-firm externality. Suppose there are 2 firms with production functions defined over labour *L* and capital *K*:

$$\begin{aligned} Q_1 &= f^1(L_1, K_1) \\ Q_2 &= f^2(L_2, K_2, Q_1) \end{aligned}$$

In this case the productivity of the second firm is affected by the output of the first firm. The effect may be beneficial or harmful. Suppose it is beneficial (i.e. if the bees from the honey-producer help pollinate the orchard next door). In that case the owner of firm 1 is not receiving a payment to reflect his contribution to the operations of the orchard. This is not necessarily a boon for the orchard-grower, since he might be even better served if the beekeeper had twice as many bees, but the only way the beekeeper would do that would be on receipt of financial inducement.

Of more importance is the case where the effect is harmful. If a smoky factory ruins the quality of the pies at the bakery next door, so that the bakery has to put time and effort into installing air-cleaners and ventilation equipment, the factory is not paying the full costs of its production. Hence it will tend to produce more than would be socially desirable.

Another example is that of a firm-on-consumer externality, for example:

$$Q_1 = f^1(L_1, K_1)$$
$$U = U(x_1, ..., x_n, Q_1)$$

Here the consumer's utility U is a function not only of the consumption of the n goods $x_1, \ldots x_n$, but also of the output level of firm 1. Firm 1 might, for example, emit some air pollution that is a nuisance, annoyance or hazard for the person. In this case it is a negative externality.

Another distinction is between 'Public' and 'Private' externalities. A public externality is not depleted when one person suffers its effects. For instance, the noise pollution endured by a group is not diminished if another person moves within hearing range. By contrast, if a truck spills oil on one person's property, that oil can not also then be spilled out of the truck again, elsewhere. So it is a 'private' externality. Another term for a private externality is a 'depletable' externality, since the more is inflicted upon one recipient, the less there is to inflict on other recipients. In this course we will primarily be concerned with public, firm-on-consumer externalities.

Pollution concerns us both as a stock and as a flow. The stock of pollution is the level of contamination in the environment. The flow of pollution is the level of new emissions. Suppose the stock of pollution at time t is Z_t, and the emissions level at time t is e_t. The simplest type of pollution is one for which

$$Z_t = e_t$$

i.e. there is no accumulation of the pollutant over time. It disperses instantly. An example of this is noise pollution.

If the pollution does accumulate, but breaks down at a percentage rate δ each period, the relation between the stock and flow is

$$Z_t = Z_{t-1}(1-\delta) + e_t .$$

An example of this type is smoke, which builds up as emissions are added, but disperses and breaks down over time. A more complex dynamic case is one in which the dispersion rate δ is a function of the stock of pollution:

$$Z_t = Z_{t-1}(1-\delta(Z_{t-1})) + e_t$$

such as when the build-up of pollution in a lake detracts from the lake's ability to naturally regenerate itself. In this case δ gets smaller as Z gets larger. This case received some attention by theorists many years ago, and is now being reexamined in studies of economic growth and pollution.

For the most part in this course we will confine our attention to the simplest case. This reflects the fact that most of the environmental economics literature assumes pollution is a pure flow variable, as do most policies, but by contrast some of the more interesting and pressing problems of our time are pollution stock problems.

2.2. Some Results from Microeconomics and Welfare Economics

Most of the arguments we will generate in this course pertain to economic welfare. Consequently we need to set forth some basic ideas that will be essential for supporting the normative conclusions we will want to advance. We cannot take time to prove the following assertions here, but the technical arguments behind them can be found in any number of advanced texts on microeconomic theory, including Varian (1995).

1. Firms maximize profits.

This is a standard behavioural assumption about firms, and it generates a number of helpful corollaries. Suppose output y is a function of labour L and capital K, and it sells for price p. The wage rate on labour is w and the rental rate on capital is r. Then profits are:

$$\pi(w,r,p) = \arg\max\left\{pF(L,K) - wL - rK\right\}$$

where the term 'argmax' means the value of the expression in braces when L and K are chosen optimally. The first-order conditions from the firm's optimization problem yield the familiar rules that the firm choose labour and capital such that the value-marginal product of each equals its variable cost:

$$pF_L = w$$

$$pF_K = r\ .$$

Thus we have

1a: Factors are hired until their respective value marginal products just equals the variable costs.

An alternate approach is to express profits as the difference between revenue py and the production costs, as defined by a cost function $c(w,r,y)$. That is,

$$\pi(w,r,p) = \arg\max\left\{py - c(w,r,y)\right\}$$

Here the firm chooses the optimum output level by setting price equal to marginal cost:

$$p = c_y$$

Thus we have

1b: Output is produced up to the point where marginal cost just equals price.

2. In a competitive equilibrium, economic profits are zero.

Economic profits include a charge for the opportunity cost of capital. If, after making such an adjustment, the firm is still earning profits, this will attract entry by other firms into that market, driving down the price and raising input costs until the economic profits have gone to zero. Alternatively, if economic losses are incurred, firms will exit until the output price rises and input costs fall sufficiently to bring economic profits to zero. This assumption always holds true if firms have a constant-returns to scale technology. It is not true if technology is everywhere decreasing-returns or increasing-returns. But if it has a region of initially increasing-returns which gives way to a region of decreasing returns, an intermediate point will exhibit locally constant-returns, which will coincide with the minimum average costs; and at that point the firm will have zero economic profits in the long run.

3. Consumers maximize utility.

This behavioural assumption yields a number of important points regarding the social value of consumption and the meaning of prices. If utility is described by a function $U(x_1,\ldots,x_n)$ defined over *n* goods, each with a price p_i, and if consumer income is *M*, the consumer solves:

$$\max_{\mathbf{x}} U(x_1,\ldots,x_n) \text{ subject to } \mathbf{p}\cdot\mathbf{x} \le M$$

where characters in bold face are vectors. This yields the familiar first-order conditions:

$$\frac{\partial U}{\partial x_i} = \lambda p_i \qquad (2.1)$$

where λ is a Lagrange multiplier. (2.1) can be re-written:

$$\frac{\partial U}{\partial x_i}\Big/ p_i = \lambda$$

which implies

3a. The marginal utility of the last dollar spent on each good is equal across all goods.

Alternatively we can write (2.1) as

$$\frac{\partial U}{\partial x_i}\Big/\frac{\partial U}{\partial x_j} = p_i / p_j$$

which implies

3b. Price ratios indicate ratios of marginal values of consumption to consumers.

Since economic theory tells us that we can always normalize one price to take the value 1, and we can normalize the marginal utility of that good to equal 1, we can assert that

3c. The price of a good in a competitive market indicates the marginal social benefit of consumption of that good.

Therefore

3d. A rise in price indicates a rise in the marginal social value of that good, and vice-versa.

And

> *3e. Economic profits indicate that the marginal social value of the production of the good exceeds the marginal social value of the resources and inputs used in its production.*

From 3e, an increase in economic profits in one sector indicates that increased production of that good would be socially beneficial at the margin, and vice-versa. When all firms earn zero economic profits, the market price of each good is that which equates the Marginal Social Value of consumption to the Marginal Cost of production. Thus we have

> *4. In a competitive market, the socially optimal amount of each good is produced, and the socially optimal amount of each factor is employed.*

This leads directly to the First Theorem of Welfare Economics:

> *5. A Competitive Equilibrium is Pareto Optimal.*

In other words, starting from a Competitive Equilibrium, we cannot make any one person better off without making at least one other person worse off. Equivalent terminology is: no 'Pareto-Improvement' is possible. Furthermore:

> *6. A competitive equilibrium is efficient.*

In other words, output of one good cannot be increased without decreasing the production of another good.

We can illustrate these postulates through the use of a Utility Possibility Frontier as shown in Figure 2.1. It shows the possible distributions of utility between persons in a 2-person economy.

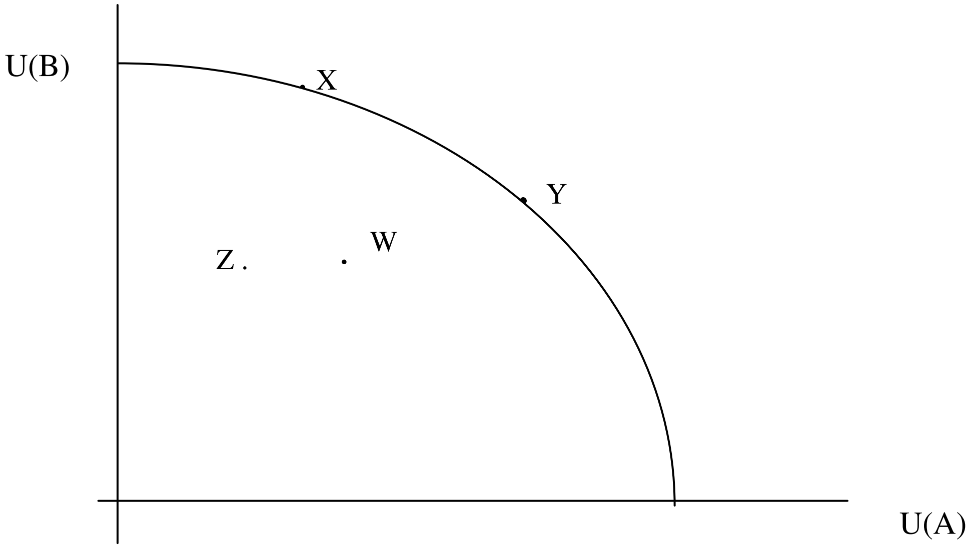


Figure 2.1: Pareto Optimal and Sub-optimal Allocations

Start at point Z. This is neither Pareto Optimal nor efficient. The move from Z to W makes person A better off and person B no worse off. A move from Z to X or Y makes both better off. So both of these moves are Pareto-Improving, i.e. at least one person is made better off and no one is made worse off. At point W, a Pareto Improvement is still possible by moving to Y. The move from W to X is not a Pareto Improvement, because A is made worse off.

Points X and Y are both Pareto Optimal. The move from either one to the other improves welfare for one but reduces it for the other. From point X it is impossible to move in either direction without reducing the welfare of another person, and similarly for point Y.

This analysis says nothing about whether point X would be ‘socially’ preferred to point Y. If person B has some aversion to inequality it is quite likely that both may prefer outcome Y to X. In this case we could postulate some social indifference curve that would rank Y ahead of X on equity grounds.

2.3 Pollution Damages in Utility Terms

At this point we make an important assumption:

The damages due to pollution can be measured in monetary terms.

There are some respects in which this statement is not controversial. Contaminated land must be cleaned up, which is costly. Air and water pollution may necessitate expenditures on averting damages (i.e. by buying bottled water and using ventilation equipment) or avoiding damages, by moving away from a polluted area. But in other respects this assumption is controversial. Suppose pollution destroys the ecology of a group of lakes. We might conceivably estimate a dollar amount in compensation for the local property owners for the loss of recreational amenities. But does this measure the ‘damage’ done? The damage is aesthetic, among other things: especially if the natural asset was in some sense unique. It might have been the habitat for a rare fish or bird, it might have had important historical and cultural associations, and it might have been intended as a preserve for future generations. One naturally resists the notion that such losses can be measured in dollars.

But the assumption does not need to be considered unusual. If the damages really matter, they must matter to people, and if something really matters to people that means they are willing, in principle, to pay for it (i.e., in this case, to pay to prevent the environmental damage).

So we will make use of the convention that all costs and benefits can be translated into commensurable monetary terms. Represent the (aggregate) consumer’s preferences by a utility function $U(x,e)$ where x is a vector of consumption goods and e is the level of emissions. The consumer faces a price vector p for x, and has income m. Solving the utility maximization problem yields continuous demand functions $x^*(p,e,m)$ defined implicitly by

$$U_x(x^*,e)-\lambda p=0 \qquad (2.2)$$

where λ is the Lagrange multiplier. Note that pollution level e is an argument in the demand functions x^*.

Denote by u^o the household's optimized utility in the absence of any pollution, i.e. when $e=0$. Denote the household's expenditure function as $m(p,e,u)=h$, showing the minimum amount h the household must spend to achieve utility u, given prices p and pollution level e. The Total Damages function TD is defined by:

$$m(p,e,u^o)=m(p,0,u^o)+TD(p,e) \qquad (2.3).$$

This shows the amount the household would need to receive to be as well off in the presence of pollution e (assuming optimal choices on x) as it would have been in the absence of pollution (at $e = 0$). Note we are defining total damages as a function of e.

Rearrange (2.3) to get

$$TD(p,e,u^o)=m(p,e,u^o)-m_o \qquad (2.4)$$

where $m_o \equiv m(p,0,u^o)$, which is a constant. Marginal damages MD are defined (suppressing unnecessary arguments):

$$MD(p,e,u^o)=TD_e=m_e \qquad (2.5).$$

MD is continuous with respect to e, by construction.

Suppose we compare two emission levels $e_2 > e_1$. Since emissions are a 'bad' as opposed to a 'good', it must be the case that

$$m(p,e_2,u^o) \geq m(p,e_1,u^o).$$

Then if we express the differences using Δ,

$$MD=\frac{\Delta m}{\Delta e} \geq 0;$$

i.e. marginal damages are positive. They are not necessarily increasing in e: they might be flat or (in unusual cases) downward-sloping, but we will usually draw them as upward-sloping.

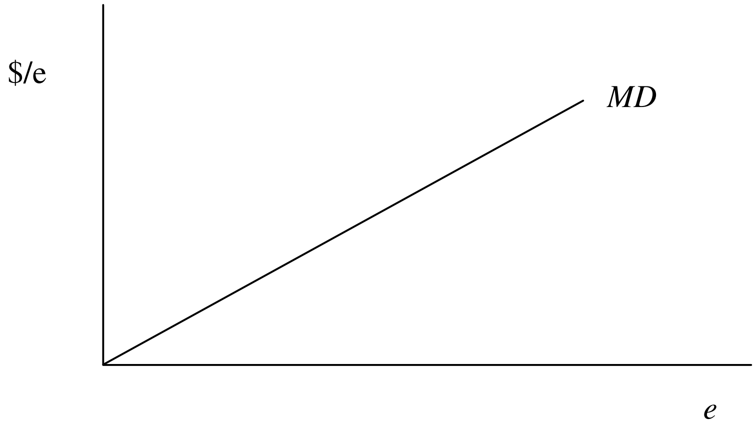


Figure 2.2: Marginal Damages

Chapter 3: Firms, Emissions and Abatement

3.1 The Optimal Output-Abatement Choice

A firm or industry produces output *y* using inputs with a cost vector *w*, and engages in non-negative levels of pollution abatement *a*. Output sells for *p* per unit. Emissions *e* are generated based on the level of output and abatement. Thus profits are

$$\pi(p, y, w, a) = py - c(w, y, a) \qquad (3.1)$$

and emissions are

$$e = e(y, a) \qquad (3.2).$$

Here "profits" denote value-added by the firm, or the excess of the value of what is produced and the cost of its production after inputs, energy and variable factors have been paid their opportunity costs. As such it indicates the social value of the productive activity behind the emissions.

Assume $e_y > 0, e_{yy} > 0, e_a < 0,$ and $e_{aa} > 0$. That is, emissions are increasing in output at an increasing rate, and emissions are decreasing in abatement activity at a diminishing rate. Assume also that $c_y > 0$, $c_{yy} > 0$, $c_a \geq 0$ and

$$c_a(w, y, 0) = 0 \qquad (3.3).$$

In the absence of controls on emissions, the firm chooses (*y*,*a*) such that price equals marginal cost: $p = c_y$, and $c_a = 0$, which imply the unregulated optimum (*y**,0), and emissions *e**.

We can graph the firm's decision problem using iso-profit lines in (*y*,*a*) space. Differentiating (5), and setting $d\pi$ =0, yields

$$d\pi(p, y, w, a) = p\partial y - c_y \partial y - c_a \partial a = 0$$

which can be rearranged to get

$$\frac{\partial a}{\partial y} = \frac{p - c_y}{c_a} \qquad (3.4).$$

We are interested in graphing the lines that show constant profits ($d\pi$ =0) in the (*y*,*a*) axes. We can infer the slope of any one such line as follows.

For a>0, we have:

$$y < y^* \Rightarrow \partial a/\partial y > 0\,;$$

$$y = y^* \Rightarrow \partial a/\partial y = 0\,;$$

and $$y > y^* \Rightarrow \partial a/\partial y < 0\,.$$

At a=0,

$$y <> y^* \Rightarrow \partial a/\partial y = \infty$$

and $$y = y^* \Rightarrow \partial a/\partial y = 0/0\,.$$

Thus, the iso-profit lines are semi-circles which cut the y-axis vertically and which converge concentrically to a single point at (y*,0). A group of iso-profit lines is shown in Figure One (labeled π_1, π_2, π_3.) Since, for a given output level, increases in a decrease profits, the direction of increasing profits is towards the centre, as shown.

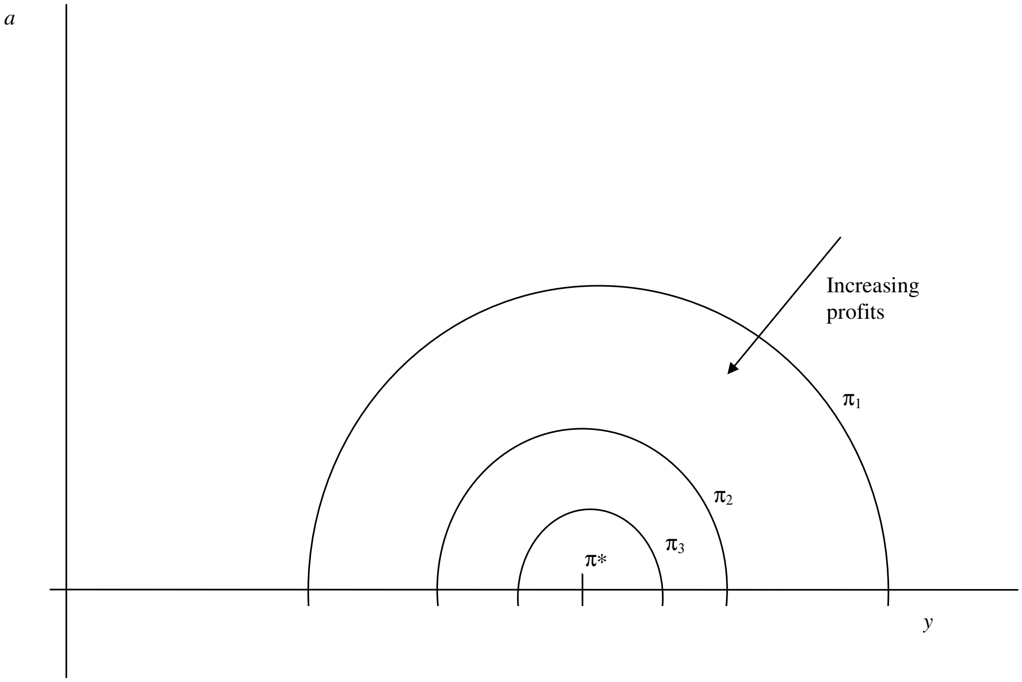


Figure 3.1: Iso-profit Lines

Suppose that, instead of being allowed to emit whatever it wants, the firm faces an emissions control policy which takes the form of an upper limit on emissions:

$$e(y,a) \le e_1 \qquad (3.5).$$

Since the policy reduces pollution below what was observed in the unregulated case, we will assume the constraint is binding. The total differential of the constraint is $e_y dy + e_a da = de_1$, which for a fixed target (i.e. $de_1 = 0$) yields an iso-emission line in (y,a) space with the (positive) slope

$$\frac{\partial a}{\partial y} = \frac{-e_y}{e_a} > 0 \qquad (3.6).$$

That is, the locus of combinations of output and abatement which yields the same emissions level is an upward sloping line when output is graphed against abatement. If we assume that

$$e_{ay} > e_a e_{yy} / e_y ,$$

then

$$\frac{\partial^2 a}{\partial y^2} = \frac{-e_a e_{yy} + e_y e_{ay}}{e_a{}^2} > 0 .$$

So the line is convex upwards, i.e. it is increasing at an increasing rate. The line labeled e_1 in Figure 3.2 is the graph of this line, showing combinations of a and y which yield emissions e_1. For a given level of output, emissions rise as abatement falls, and for a given level of abatement, emissions rise as output rises, so movement to points below and to the right of the line indicates higher emissions.

To maximize profits subject to the emission constraint (3.5), the firm will maximize the Lagrangian expression

$$L = py - c(w, y, a) - \lambda\big(e(y, a) - e_1\big)$$

with respect to y and a. Graphically, the firm wants to move onto the lowest iso-profit line it can, subject to the restriction that it must still be touching (or above) the iso-emissions line e_1. In Figure 3.2 this is drawn for e_2 such that this occurs on π_2. The higher iso-profit line π_1 satisfies the constraint but does not maximize profits. The lower iso-profit line π_3 gives higher profits but does not satisfy the constraint.

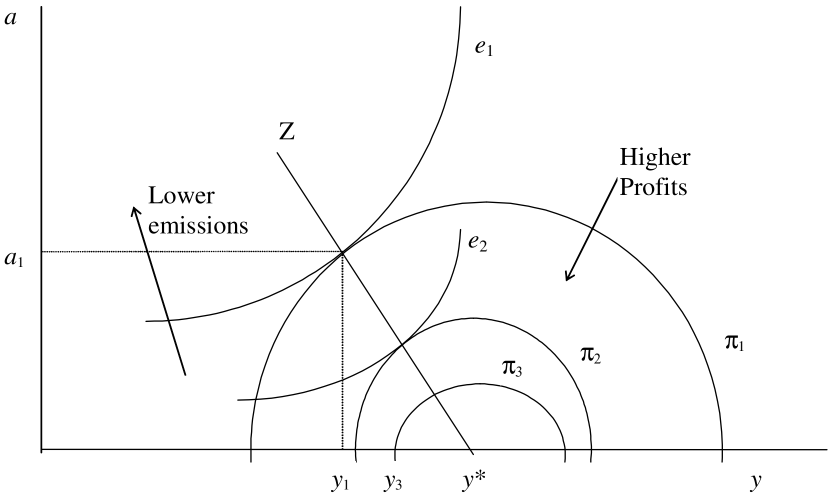


Figure 3.2: Iso-profit, iso-emission lines with optimal tangency path

The first order conditions for the firm's problem are

$$p - c_y = \lambda e_y$$

and

$$-c_a = \lambda e_a,$$

and dividing the first by the second yields

$$\frac{p - c_y}{-c_a} = \frac{e_y}{e_a} \tag{3.7}$$

Compare (3.7) with (3.4) and (3.6): the slope of the iso-profit line equals the slope of the iso-emissions line whenever firms are maximizing profits under the emissions constraint. This defines a locus of tangency's drawn as the line $Z\pi^*$ in Figure Three. The optimal choice of output and abatement given the constraint e_1 is the point labeled (y_1,a_1).

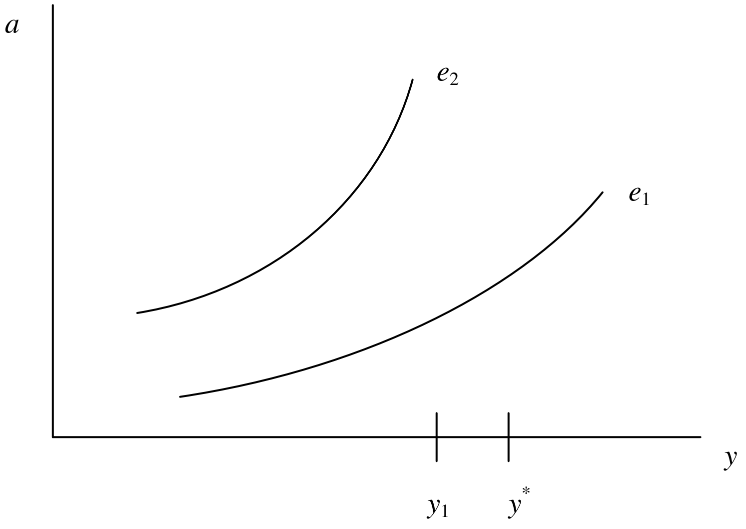
The firm meets the constraint not simply by installing abatement equipment, but by combining abatement equipment (a_1) with a reduction in output. In trying to estimate the 'cost' to the firm of meeting the emission constraint it would be incorrect to simply add up the cost of the abatement equipment. The firm also bears a cost by changing its output level. The *actual* cost to the firm of meeting the emissions constraint is the loss in profits between π^* and π_2.

A technical point: The importance of assumption (3.3) is that by assuming $c_a(w, y, 0) = 0$ we ensure that the iso-profit lines cross the y-axis vertically, therefore an upward-sloping emissions constraint will always be tangent to an iso-profit line at interior points in the

(y,a) space, ruling out corner solutions. That is, (3.7) can only be satisfied when $a>0$: the firm will use combinations of output reduction and abatement equipment, rather than abatement equipment alone or output reductions alone, to respond to even very low levels of required emissions reductions. If $c_a > 0$ at $a=0$ then (3.7) might not hold near the a axis. The firm might use output reductions alone to control emissions at first, and only use abatement equipment to handle large emission reductions.

Practice Questions

1. Use the iso-profits-iso-emissions diagram to illustrate the firm's optimal output-abatement combinations when emissions are strictly a function of output, and abatement effort has no effect.



2. In the above diagram, what would be the cost to the firm if it reduced emissions from E_1 to E_2 but it was also required to keep output at level y_1? What is the cost to the firm of the output constraint?

3. Suppose the firm is told that it must reduce emissions from E_1 to E_2, but the regulator will now subsidize all its abatement costs. What, if anything, will happen to the firm's output level?

4. Compare the amount of pollution abatement equipment (a) the firm will purchase under this arrangement to the amount it would buy if it had to pay for its own equipment.

3.2 The Marginal Abatement Cost Function.

We can now explain the relationship between the 'marginal costs of abatement activity', c_a, and the marginal abatement cost (MAC) function. First assume that *e*(*y*,*a*) can be inverted to yield a function $a = a(y,e)$, showing the level of abatement required to achieve emissions *e* given output level *y*. Note that $a_y > 0$ and $a_e < 0$. Substituting into the profit function for *a* gives

$$\pi(p, y, w, a) = py - c(w, y, a(y,e))$$

and taking partial derivatives yields

$$\pi_y = p - c_y - c_a \frac{\partial a}{\partial y}$$

and

$$\pi_e = -c_a \frac{\partial a}{\partial e}.$$

The second equation is the partial derivative of profits with respect to emissions. The envelope theorem tells us that it also (approximately) equals the total derivative.

{The total derivative of π is $d\pi = \pi_y dy + \pi_e de$. This can be rearranged to yield $\frac{d\pi}{de} = \pi_y \frac{dy}{de} - \pi_e$. Then substitute in the partial derivatives to get

$$\frac{d\pi}{de} = \left(p - c_y - c_a \frac{\partial a}{\partial y} \right) \frac{dy}{de} - c_a \frac{\partial a}{\partial e}.$$

Along the tangency locus (3.7) we have $(p - c_y) = -c_a e_y / e_a$. This plus (3.6) implies that the term in the brackets is zero}

Thus, when the firm is adjusting output optimally in response to changes in emissions:

$$\frac{d\pi}{de} = -c_a \frac{\partial a}{\partial e} \qquad (3.8).$$

(3.8) is the Marginal Abatement Cost curve corresponding to the locus of optimal output-abatement pairs in (3.7). This is what is often drawn in textbooks and articles as the marginal abatement cost function, showing the change in profits due to a policy-driven change in *e*, with *y* adjusted optimally in the background. Intuitively we would suppose that (3.8) is positive, since the constraint reduced the firm's emissions below the level they were at in the absence of regulations, so an increase in allowable emissions should lead to higher profits. Indeed, since $a_e < 0$ and $c_a > 0$ the function is positive along $a > 0$.

At $a=0$, i.e. when the firm engages in no abatement, assumption (3.3) implies that the MAC curve must be also be zero, i.e. it hits the horizontal axis.

The slope of the MAC curve can be characterized by differentiating (3.8) with respect to *e*, yielding:

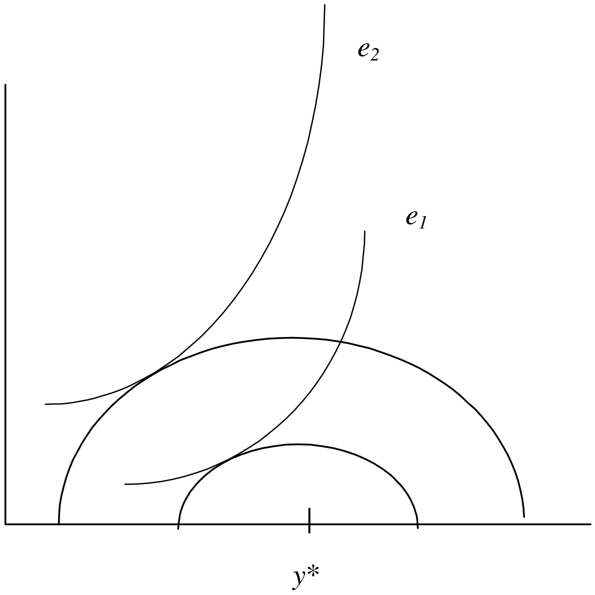
$$\frac{d^2\pi}{de^2} = -\left(a_e c_{ae} + c_a a_{ee}\right).$$

Since marginal costs of abatement are lower at higher emission levels, $c_{ae} < 0$. Also, since abatement activity has diminishing effectiveness, $a_{ee} > 0$. Thus $\frac{d^2\pi}{de^2} < 0$, i.e. the MAC curve is downward sloping.

Practice Questions

1. Suppose the regulator has constrained a firm to some emissions level e_1. If the standard is reduced further, to e_2, show on a single diagram the difference between: (i) the cost of the abatement equipment required if the firm does not adjust output; (ii) the cost of the abatement equipment if the firm optimally adjusts output; and (iii) the firm's actual abatement cost (i.e. the area under the MAC).

2. Put the letters on the diagram in the correct location.



a The unregulated output level.
b The output level under emission standard e_2
c The abatement level under emission standard e_2
d The value to the firm of being allowed to increase emissions from e_2 to e_1
f The change in abatement if emissions increase from e_2 to e_1
g The abatement used if emissions fall from e_1 to e_2 but y stays constant
h The abatement used if emissions fall from e_1 to e_2 but the regulator subsidizes all abatement costs (y can adjust)
i The output level if emissions fall from e_1 to e_2 but the regulator used a tax to control emissions

j The abatement level if emissions fall to e_2 but the regulator used a tax to control emissions

k The unregulated abatement level

3. A firm has a cost function $c(w, y, a)$ where w is the wage rate, y is the output level and a is abatement effort. Output sells at price p. The firm's profits are $\pi = py - c(w, y, a)$. Emissions are given by the function $e(y, a)$. Prove that the firm will choose the same combination of output and abatement under the following two policy scenarios:

   (i) An emissions constraint of the form $e(y, a) \leq \hat{e}$.

   (ii) A tax τ on emissions set at a level high enough that total emissions fall to $\hat{e}$.

Chapter 4: Optimal Emissions and Static Efficiency in Partial Equilibrium

4.1 The Optimal Emissions Level

We are mostly interested in the analysis of firm-generated pollution, although there are many interesting and important examples of consumer-generated pollution, such as motor vehicle emissions. A competitive firm's production process generates emissions *e*, which can be offset with abatement activity *a*. Since units of abatement are costly, the firm wants to force *a* to be as low as possible, by setting it equal to zero if possible. If the firm must meet some emissions target other than the level of emissions it would choose in the absence of regulation, it will face reduced profits. The loss of profits at the margin, as a function of the level of emissions, is shown by the marginal abatement cost (*MAC*) function. If the firm can increase emissions slightly, the benefit to the firm is the amount of profit it did not have to forego by holding emissions down.

Note that the firm's profits reflect the total value (from society's point of view) of the production activity generating the pollution, in the sense that when a firm is earning positive profits, the marginal value to consumers of what is produced exceeds the marginal value of the resources and factors used in its production. So by illustrating the reduction in profits due to an emissions cut, the MAC captures the marginal social costs of reducing emissions (when read from right to left); and since it shows the marginal increase in profits if emissions increase slightly, the MAC shows the marginal social benefit of emissions (when read from left to right).

The marginal damage curve captures the benefits to society of reducing pollution. Consequently, where it intersects the MAC is an optimum for society, while the polluting firm's private optimum is where marginal benefits are zero, i.e. where the MAC reaches the horizontal axis.

We can illustrate the social gain to pollution control as follows.

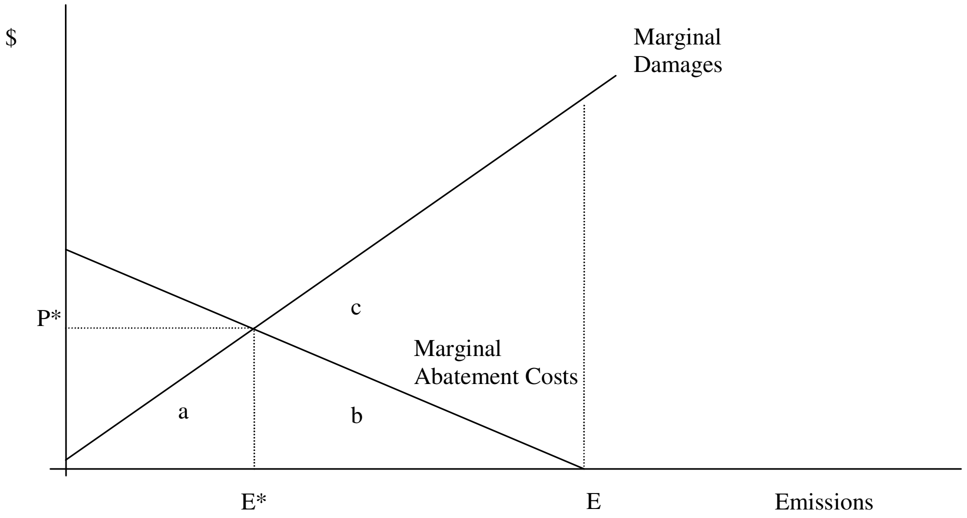


Figure 4.1: Marginal Damages and Marginal Abatement Costs

If emissions are initially at point E, the total social damages equals the area under the marginal damages curve, which is a+b+c. If emissions are reduced from E to E*, the costs of doing so is represented by the area under the Marginal Abatement Cost function between E and E*, which is b. The gain to society is the reduction in damages, equal to the area b+c. Consequently, the net gain of reducing emissions is area c. If emissions were reduced further, the marginal cost of doing so (shown along the MAC curve) would exceed the marginal reduction in damages (shown along the MD curve), so such a move would be welfare-reducing. And if emissions were not reduced as far as E*, the foregone benefits of emission reduction would exceed the cost savings. Consequently, at the optimal emissions level E*, the net social gain (=c) of pollution reduction is maximized.

The relationship between Figures 4.1 and 3.2 is as follows:

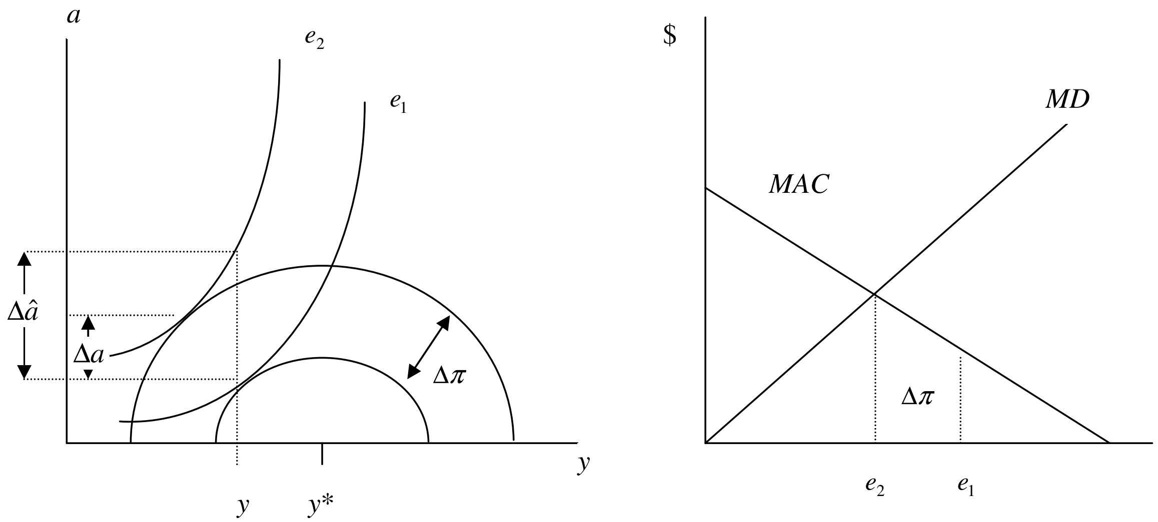
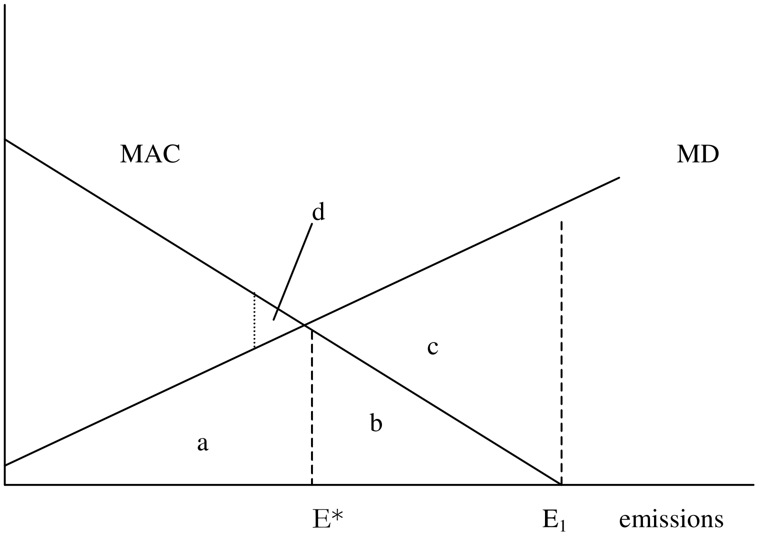


Figure 4.2 Relationship Between Iso-profits model and MAC model

In the diagram on the left, the emissions constraint is reduced from e_1 to e_2. As a result the firm drops to a lower iso-profits line and the change in profits is $\Delta\pi$. This quantity corresponds to the area under the marginal abatement cost curve in the diagram on the right. The amount $\Delta\hat{a}$ shows how much extra abatement effort would be required to reduce emissions if output were held constant. The cost of this change is unobserved and does not appear in the diagram on the right. Nor does the cost of the actual change in a. The cost of Δa ($\partial c/\partial a$) is not the same as the marginal abatement cost since $-c_a \neq \frac{d\pi}{de}$.

An important point to stress here is that the MAC on the right is defined for the particular policy situation in which firms are able to meet an emissions constraint without any restriction on how they do so. If the move from e_1 to e_2 also had to respect output constraints, or if the regulator promised to cover some or all of the abatement costs then the MAC would change shape.

Practice Questions



1. What is the definition of the optimal level of pollution?
2. What 2 things are measured by the area under the Marginal Abatement Cost Curve?
3. What is measured by the area under the Marginal Damages Curve?
4. Suppose emissions are unregulated. Why does the firm emit at E_1?
5. In terms of the above diagram, what is the magnitude of the benefit to society of reducing emissions to E*?
6. What is the cost to society of the same reduction?
7. What is the net benefit?
8. What is the meaning attached to area d?

9. Suppose that instead of imposing an emissions constraint as in Figure 2.2 the regulator leaves emissions unconstrained but charges the firm a tax T per unit of e.

Show how the first order conditions from maximizing profits $\pi(p, y, w, a) = py - c(w, y, a) - Te(y, a)$ compare to equation (4.11).

10. Suppose there is a firm that has two factories, both of which produce tables. The first has a marginal cost curve written:

    $MC_1 = 10 + 10y_1$

    and the second has a marginal cost curve written

    $MC_2 = 15y_2$

    where y_i is the number of tables produced per month at factor *i*. If the selling price is 300 dollars per table, how many tables should be produced in total, and how many should be produced at each factory?

    Answer

    Each factory should produce tables up to the point where price equals marginal cost (can you recall why? *To maximize profits, that's why.*) Set $MC_1 = 300$ and solve to get $y_1 = 29$. Set $MC_2 = 300$ and solve to get $y_2 = 20$. Total output is 49.

11. Suppose marginal damages due to industrial chlorine emissions into a river system are defined by the equation

    $MD = 2E$.

    where *E* is the measure of pollution. Marginal abatement costs are defined by the equation

    $MAC = 1000 - \frac{1}{2}E$.

    (i) Calculate the pollution level in the absence of any regulation. If you were a policy maker and were asked to set a target for emissions reduction, how large a reduction would you guess ought to be pursued?

    (ii) Calculate the optimal level of pollution. How good was your guess?

    Answer.

    (i) In the absence of any pollution, the firm will pollute up to the point where $MAC = 0$. The MAC curve shows the marginal benefit of pollution to the firm, and as long as it is positive it pays for the firm to pollute more. Set $1000 - \frac{1}{2}E = 0$ and solve to get $E = 2000$ units.

(ii) The optimal pollution level (E^*)occurs where MD = MAC. Set $2E = 1000 - ½E$ and solve for E, to get $E^* = 400$. Pollution should be reduced in this case by 80 per cent (1600 units).

12. Now suppose that scientific evidence arises showing that the chlorine release is twice as damaging as previously thought: so the MD curve is actually

    $MD = 4E$.

    Should you order emissions be cut in half (from 400 down to 200)? Or more? Why or why not?

    Answer.
    Set $4E = 1000 - ½E$ and solve for E, to get $E^* = 222$. Emissions should be cut by 44.5 per cent (178 out of 400). While marginal damages have doubled, further cuts in emissions increase the marginal cost of pollution abatement. Hence it is not desirable to cut emissions by half, even though marginal damages have "doubled".

4.2 Static Short-Run Efficiency

We have already considered the notion of optimality in setting a maximum level of pollution. The optimal, or *efficient* level is one at which the marginal damages just equals the marginal benefit of pollution, where the marginal benefit is equivalent to the marginal abatement cost. In this lecture we consider a related concept in policy design, that of cost-effectiveness. A policy which is cost-effective in a static sense is one such that, for a given total emissions level, the cost of abatement activity is minimized, or equivalently, the benefits of pollution are maximized. Cost-efficiency is a necessary, but not sufficient, condition for optimality. It is possible that a cost-efficient policy still achieves an overall emissions level that exceeds the socially optimal level. However, a policy which is optimal cannot simultaneously be cost-inefficient. This will be made clear in the discussion below.

The key to cost-efficient pollution policy is that marginal abatement costs across all polluters must be equal. This is called the 'equimarginal' principle. To prove it, first note that we are assuming emissions mix uniformly in the environment, so all polluters face a common marginal damages curve. Each polluter i gets (decreasing marginal) benefits from generating emissions e_i so its profits can be written as a function of emissions, $\pi^i(e_i)$, and its marginal benefits of emissions, a.k.a. its marginal abatement cost curve, can be written $\frac{\partial \pi^i}{\partial e_i}$.

The regulator wants to achieve some overall emissions level $E = \sum_i e_i$. The policy challenge is to do this in such a way as to minimize the economic costs, or equivalently, to maximize the economic benefits from the allowed emission levels:

$$\max w.r.t.\{e_i\} \quad \sum_i \pi^i(e_i) \text{ subject to } \sum_i e_i = E.$$

The Lagrangian function for this constrained optimization problem is:

$$L = \sum_i \pi^i(e_i) - \lambda\left[\sum_i e_i - E\right]. \tag{4.1}$$

The first order conditions, with respect to the e_i's are each written

$$\frac{\partial L}{\partial e_i} = \frac{\partial \pi^i(e_i)}{\partial e_i} - \lambda = 0 \tag{4.2}$$

and since the λ's are constant this implies that

$$\frac{\partial \pi^i(e_i)}{\partial e_i} = \frac{\partial \pi^j(e_j)}{\partial e_j} \tag{4.3}$$

for any pair of polluters *i,j*; or in other words, the MAC's across all pollution sources should be equal.

To see the intuition of this result, suppose that as a result of a pollution control policy, two firms must reduce their emissions a certain amount each. The last unit of emissions reduction cost firm A \$1200, and the last unit of emission reduction cost firm B \$200. If A had paid firm B, say, \$300, to cut its emissions by one more unit, and A had cut its emissions one less unit, A would save (1200-300)=900, while B would earn 300 for an action that cost it 200, for a net gain of 100. Consequently, while the overall emissions would have been identical, both firms would have been better off. As long as MAC's differ at the margin, the possibility for a mutually-advantageous rearrangement of abatement activity exists. That is why (4.3) is a necessary condition for cost-efficiency. Moreover, cost-efficiency is a necessary condition for optimality, since if the MAC's differ at the margin, they cannot all have abated to the point where marginal damages equal marginal abatement costs, which defines the optimal level of emissions for each source.

The main policy instruments at the disposal of a pollution regulator are standards (e.g. ambient, emission or process standards), pricing instruments (emission taxes, tradable permits) and legal liability. It turns out that only some of the instruments are inherently cost-efficient, namely taxes and tradable permits. Because of this, they are referred to as "economic instruments". Standards by contrast are referred to as "Command and Control" instruments. Liability laws are potentially optimal in cases where a single polluter and a single victim can negotiate, but when there are multiple parties the outcome is unlikely to be cost-efficient.

Consider first a pollution standard imposed on two firms, A and B, whose marginal abatement costs are as shown in Figure 4.3.

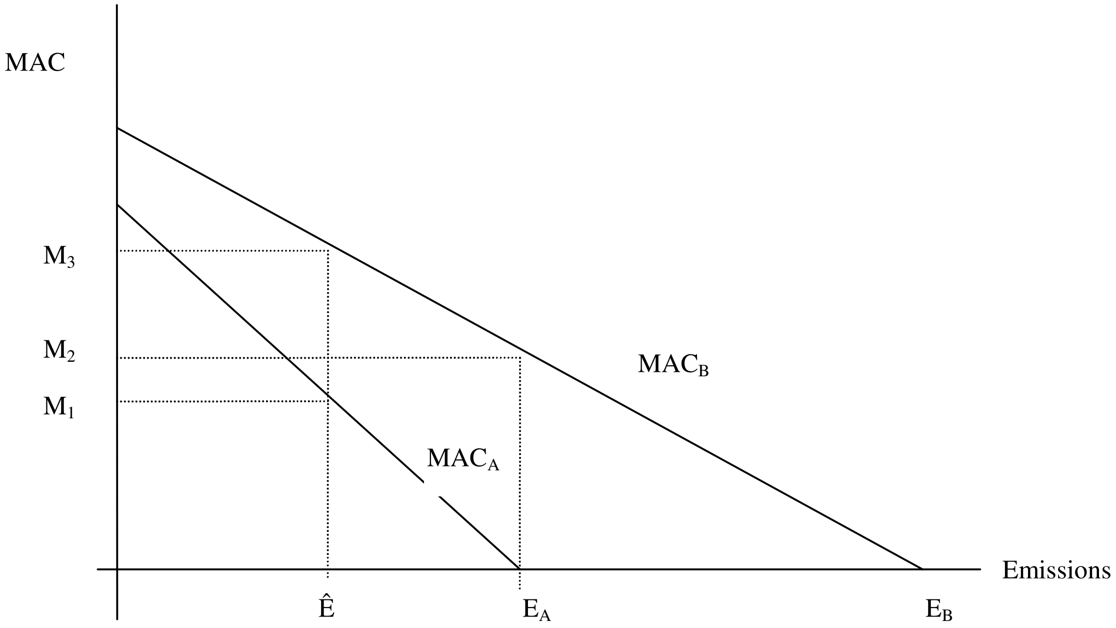


Figure 4.3: Two firms subject to a uniform standard

Firms A and B start at differing pollution levels prior to regulation, namely at E_A and E_B respectively. The regulation requires both firms to cut back emissions to Ê. Clearly, at this level, the marginal abatement costs are different between the firms: M_1 for firm A and M_3 for firm B. In practice it is more common to specify equal percentage reductions for each firm. If each firm must reduce its emissions by half against a base case, this would require (in Figure One) firm B to cut back to E_A and firm A to cut back to Ê. This reduces the discrepancy between the firms in their MAC's, but only by exceptional coincidence would they be equal following such a policy.

As mentioned, standards are called "Command and Control" pollution policies. Pollution liability laws can also have the same efficiency (or inefficiency) properties as standards, if the chief way for a firm to avoid exposure to liability is to be in compliance with legal standards.

Economic instruments do achieve cost-efficiency, by confronting firms with a common price for pollution activity. This is illustrated in Figure 4.4.

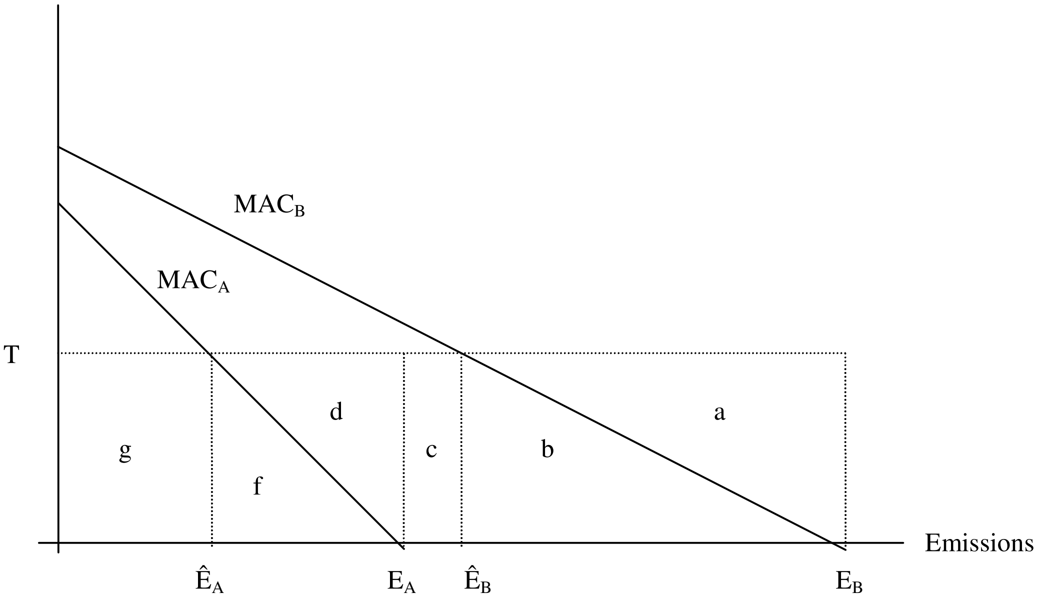


Figure 4.4: Two firms subject to an emissions pricing rule

Firms A and B initially pollute at E_A and E_B respectively, where their MAC's are zero. Now suppose the government imposes a tax T on each unit of emissions. Consider firm A first. If it continues to pollute as before, it will pay g+d+f in taxes. By reducing emissions one unit, its tax burden falls by T, but its abatement costs are nearly zero. So it is in the firm's interest to reduce emissions. It continues to be in the firm's interest to reduce emissions until the cost of one more unit of emissions reduction has risen to equal the tax rate, which occurs at $\hat{E}_A$. The firm's tax bill falls by d+f, but it only incurs abatement costs f, for a net savings of d. Similarly, firm B finds it worthwhile to reduce emissions to $\hat{E}_B$. At this point it saves a+b on its tax bill, while incurring costs b in abatement, for a net savings of a.

At the resulting emissions level, both firms are polluting at a level where their respective MAC's equals the tax rate T. We can easily reiterate mathematically the point made diagrammatically; each firm looks at the net benefit of polluting as the profits from polluting, $\pi^i(e_i)$, less the tax bill Te_i. If these benefits are maximized,

$$\frac{\partial(\pi^i(e_i) - Te_i)}{\partial e_i} = 0 \Rightarrow MAC^i = T$$

for all *i*. Since the tax rate is the same for all firms, this policy leads to an outcome consistent with the equimarginal principle.

If instead of a tax, the government pays each firm a subsidy T for each unit by which it reduces emissions below its initial level, the same outcome is attained. In Figure 4.4, firm A finds it advantageous to reduce its emissions one unit, which earns it T in subsidy but costs it nearly zero in abatement costs. This same reasoning applies up to the point where the marginal abatement cost equals the subsidy rate. Consequently firm A reduces pollution to (again) $\hat{E}_A$, earning d+f in subsidies, spending f in abatement costs, and pocketing d, the difference. Similarly firm B earns a+b in subsidies, and its net gain is a. While the result in this case is the same as under the tax, there are important long run differences in outcomes between taxes and subsidies, since the subsidy creates a different incentive to enter this industry than does the tax. We will consider this contrast in a later lecture.

The use of tradable permits can also be illustrated in Figure 4.4. Suppose a market for such permits exists and the going price is T. We are assuming for simplicity that firms do not have market power in the permits market, which not always a realistic assumption, but will do for the moment. Firm A finds it worthwhile to buy its first permit, because the cost is T but the benefit of the first unit of pollution is higher, where the MAC intersects the vertical axis. Similarly the firm finds it worthwhile to buy more and more permits, until the point $\hat{E}_A$, where the MAC dips below the price T. Beyond this, the marginal benefit of polluting is lower than the marginal cost of buying permits. Similarly, firm B wishes to buy $\hat{E}_B$ permits, at the market price T. Notice that the MAC defines the quantity of permits a firm wishes to buy at each price, hence we can also use the MAC as the firm's demand curve for permits in a tradable pollution permits market. (By similar reasoning we can use the marginal damages curve as society's "supply" function for pollution). Since both firms face a common price, they will choose to pollute at levels which satisfy the equimarginal criterion.

It is not always the case that firms have to buy all their permits. In some cases the government distributes a number of permits freely, then allows firms to trade them. If in this case the regulator distributed $\hat{E} = \hat{E}_a + \hat{E}_B$ permits we would expect the same outcome to prevail. In the example given after deriving the equimarginal criterion, it was clear that as long as MAC's differ between firms, they have an incentive to reallocate abatement activity between themselves. The tradable permit system allows them to do this, and the outcome is the equality of their MAC's at a price where their total emissions equal the aggregate set by the regulator.

Continuing with our 2-firm example, we can now illustrate the relationship between a policy which is cost-efficient and one which is optimal.

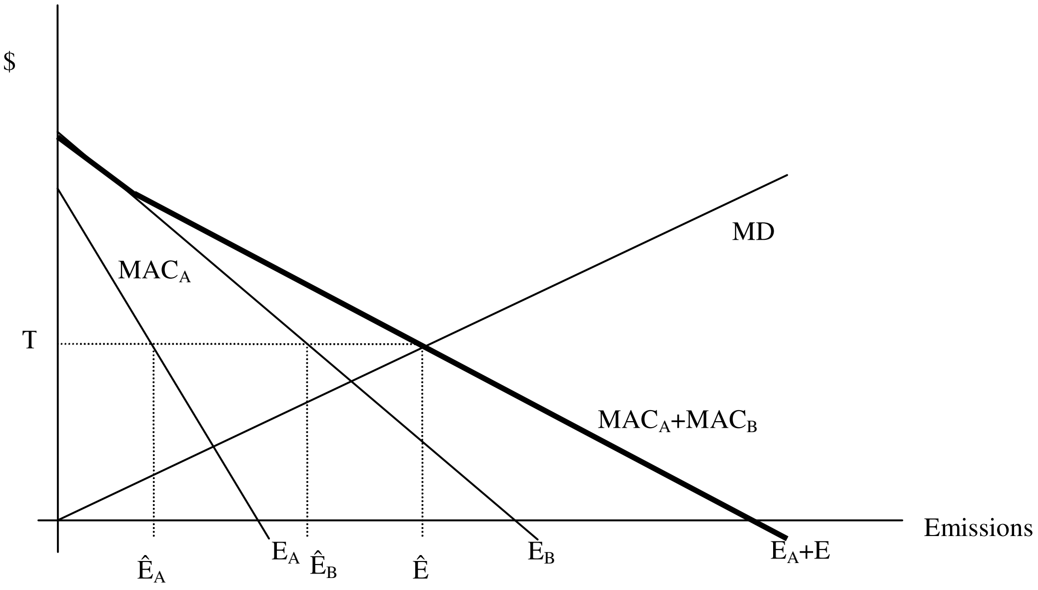


Figure 4.5: Two firms subject to an emissions tax that is set at the optimal level

The heavy black line is the aggregate MAC curve, defined as MAC_A+MAC_B, the horizontal summation of the two firms' own MAC curves. This crosses the MD curve at a price level T. This defines the optimal total emissions level Ê and the tax rate T. By charging the tax rate T, the firms choose emission levels which sum to Ê, and at which their MAC's are equal. Consequently this policy is both *cost-efficient* and *optimal*. Had the tax rate been set at a different level, the resulting total emissions level would be different, so the policy would not be *optimal*, even though it would still be *cost-efficient* since the tax yields identical MAC's. By similar reasoning a subsidy or tradable permit policy could achieve cost-efficiency alone, or cost-efficiency and optimality. The latter case would correspond with the outcome if the regulator auctioned off a total of Ê permits and the firms each paid the same price T. But a system of standards could not achieve cost-efficiency or optimality, except in the lucky case where the standards for the firms are set exactly at the outcome generated under the optimal tax policy. This is true whether the standards are enforced using conventional methods or through liability laws or information strategies.

Efficiency is not the only criterion we need to be concerned about in examining pollution policy. We need also pay attention to administrative ease, monitoring and enforcement costs, and the dynamic incentives created by the policy. With respect to the first, some of the economic instruments are at a disadvantage. It is certainly easier to impose a technology standard than administer a new tax or establish a permits system. However, administrative expedience should not be an over-riding concern if there are large costs due to an inefficient policy. Efficiency losses not only mean wastage of resources, but also mean that less pollution control is ultimately achieved than would have been under an efficient policy. The issues of monitoring and enforcement are closely related, and are pertinent to all policies which attempt to control the volume of emissions directly. The question of dynamic incentives is also important, since the polluters themselves are often in the best position to develop innovative and cost-saving methods to reduce pollution.

Practice Questions

1. Suppose two firms, 1 and 2, have the following marginal abatement cost curves:

   $MAC_1 = 100 - 3e_1 \qquad MAC_2 = 50 - 2e_2$

   Find the least-cost allocation of emissions between the two firms that controls total emissions to 20 units.

   Answer: We know that aggregate abatement costs between the two firms is minimized when their marginal abatement costs are equal (the equi-marginal principle). Therefore, we want

   $100 - 3e_1 = 50 - 2e_2$

   We also want $e_1 + e_2 = 200$. Therefore, $e_2 = 200 - e_1$. Making this substitution gives

   $100 - 3e_1 = 50 - 2(20 - e_1)$

   Solving gives $e_1 = 90$. Therefore, $e_2 = 110$. Firm 1 should emit 90 units and Firm 2 should emit 110 units - this minimizes the aggregate cost of abatement of the two firms combined.

2. Suppose the marginal damages function is defined by

   $MD = 2e$

   and the industry MAC function is defined by

   $MAC = 20 - 3e$.

   Calculate the optimal emissions level and the pollution tax which would implement it.

   Answer.
   Set MD = MAC:
   $2e = 20 - 3e$.

   This rearranges to

   $5e = 20$

   which implies $e^*=4$. At $e = 4$, MD = MAC = 8. Since the tax should charge firms their marginal damages, the optimal pollution tax in this case is 8.

3. Suppose there are 2 firms. The first has an MAC curve given by

$MAC_1 = 10 - e_1$

The second has an MAC curve given by

$MAC_2 = 30 - 3e_2$

Suppose the regulator wants to reduce emissions by half compared to the unregulated level. What emissions tax is needed? How much does each firm emit? Does each firm cut emissions by the same amount?

Answer: First, the unregulated emission levels are found where the MAC equals zero. For the first firm, this occurs where $e_1 = 10$, and for the second firm this occurs where $e_2 = 10$. The total emissions level is 20, and so the regulator wants to reduce emissions to 10.
Each firm responds to the tax, which we call t, by setting MAC = t. So for firm 1, its emissions are at the level

$10 - e_1 = t$

which implies

$e_1 = 10 - t.$

Similarly, for firm 2,

$30 - 3e_2 = t$

so

$e_2 = 10 - t/3.$

Total emissions in the presence of the tax are

$e_1 + e_2 = (10 - t) + (10 - t/3) = 20 - 4t/3.$

We want total emission to equal 10, so we solve

$10 = 20 - 4t/3$

which gives us

$t = 7.5.$

Then $e_1 = 10 - t = 2.5$, and $e_2 = 10 - t/3 = 7.5$. These sum to 10, as they should. Note that firm 2 cuts back its emissions by 25 per cent, but firm 1 cuts back by 75 per cent. If you draw the MAC curves you will see why it is much more costly for firm 2 to reduce emissions compared to firm 1.

4. Suppose there are two firms with marginal abatement cost functions, $MAC_1 = 100 - 3e_1$ and $MAC_2 = 50 - 2e_2$. If the government wishes to control total emissions so that $e_1 + e_2 = 20$ using a TDP system, find the equilibrium price and allocation of permits.

   Answer: Firms 1 and 2 will continue to trade permits from one to the other as long as their MACs differ. (The firm with the higher MAC will buy permits from the firm with the lower MAC.) Trading will stop only when the MACs have become equal. Thus, in equilibrium, $MAC_1 = MAC_2$. This implies
   $100 - 3e_1 = 50 - 2(20 - e_1)$

   Solving gives $e_1 = 18$ and $e_2 = 2$. Therefore MAC = 50 - 2(2) = $46 = price.

5. Suppose there are 2 firms with *MAC*'s

   $$MAC_1 = 1000 - E_1$$

   $$MAC_2 = 1200 - 2E_2$$

   and Marginal Damages $MD = \frac{2}{3}E$ where $E = E_1 + E_2$

   Find optimal level of emissions (E^*), plus firm-specific optimal emissions and the level of marginal damages at the optimum.

   Solution
   2 things must be true at the optimum:

the *equimarginal condition* must hold, $MAC_1 = MAC_2$
the optimality condition must hold, $MAC = MD$

I. Set $MAC_1 = MAC_2 = M$ and get the market *MAC* curve:

$$MAC_1 = M = 1000 - E_1 \Rightarrow \quad E_1 = 1000 - M$$
$$MAC_2 = M = 1200 - 2E_2 \Rightarrow \quad E_2 = 600 - \tfrac{1}{2}M$$

Add up to get $E = E_1 + E_2$
$\Rightarrow E = 1600 - \frac{3}{2}M$.

Note that unregulated emissions $\overline{E}$ occur where M=0, so $\overline{E} = 1600$.

II. Set MD=M which implies $M = \frac{2}{3}E$. Substitute into the expression for E to get

$$E = 1600 - \tfrac{3}{2}(\tfrac{2}{3}E)$$
$$\Rightarrow E = 1600 - E$$

$\Rightarrow E^* = 800$. Optimal emissions are 800.

MD at *E**=800 is $\dfrac{2\times 800}{3} = \dfrac{1600}{3}$

Then $E_1^* = 1000 - \dfrac{1600}{3} = 466\tfrac{2}{3}$

and $E_2^* = 600 - \tfrac{1}{2}\tfrac{1600}{3} = 333\tfrac{1}{3}$.

6. Suppose that $MAC_1 = 1000 - 2E_1$

$MAC_2 = 1200 - 2E_2$

$MD = 3E$ where $E = E_1 + E_2$

Derive - the market (or aggregate) *MAC* curve
- the optimal emissions level
- the optimal level of emissions for firm 1 and firm 2
- the value of an emissions tax that would achieve the optimum.

7. Suppose a firm has a factory that will operate for 2 periods before closing permanently. It currently has an MAC of

$MAC = 1400 - 2e$.

But next period, because of some equipment upgrades it will have an MAC of

$MAC = 1000 - 2e$.

The government would like the firm to restrict emissions to 300 each period. The firm offers to keep its total emissions to 600 across the 2 periods but would like to emit different amounts in each. If the government allows this how much will the firm emit in period 1 and how much in period 2?

8. Consider a situation in which there are 15 polluters all emitting the same pollutant in some region. Suppose a regulator knows the total damage function $TD(E)$ defined over emissions E in that region, but not the aggregate marginal abatement cost function $MAC(E)$. In particular,

$$TD(E) = 5000E + 6.1E^2$$

where E is kilotons per year and TD is measured in dollars per year.

The current level of emissions is 1000 kilotons annually. Assume the emissions of each firm can be accurately measured.

(i) If the regulator imposes a pollution tax of \$10,000 per kiloton, what level of resulting emissions would leave her satisfied that this is an optimal policy? Explain your answer carefully. Hint: derive the MD curve and draw a picture of the situation.

(ii) Suppose after a few years emissions have settled down to 600 Kt per year. Political constraints arise such that only one further revision to the tax rate can be made. Suggest what the new rate should be.

4.3 Static Long-Run Efficiency

Another condition we need to examine is the question of long-run versus short-run optimality. Most studies of pollution policy assume the number of regulated firms is fixed. However, since policies change firms' profits, we would expect entry and exit to occur. There is a literature examining the implications of this observation for the optimality of different regulatory mechanisms (see, especially, Spulber, "Effluent Regulation and Long-Run Optimality", *JEEM* 1985). Entry and exit are especially important in comparing subsidies and taxes, which we will do later. For now, we will explore a basic model showing the long-run efficiency properties of pollution taxes.

As before, consider an economy in which a group of firms indexed by i=1,…,n emit a homogeneous pollutant denoted e_i, with $E = \sum_{i=1}^{n} e_i$. We will assume that each firm sells its output x_i into a perfectly competitive market at price p.

Each firm's cost function is of the form $c^i(x_i, e_i)$ with $c_x^i > 0, c_{xx}^i > 0, c_e^i < 0$, $c_{ee}^i > 0$, and $c^i(0,0) = c_e^i(x_i, 0) = 0$. Denote $E_{-i} \equiv e_1 + \cdots + e_{i-1} + e_{i+1} + \cdots + e_n$ and thus $E = E_{-i} + e_i$. The social planner's objective function is

$$W = \sum_{i=1}^{n} [px_i - c^i(x_i, e_i)] - D(E) \qquad (4.4)$$

where D is a convex aggregate damage function, with D' >0 and D''>0. The planner optimizes (17) by choosing outputs and emissions to solve:

$$\frac{\partial W}{\partial x_i} = p - \frac{\partial c_i}{\partial x_i} = 0 \tag{4.5}$$

and

$$\frac{\partial W}{\partial e_i} = -\frac{\partial c_i}{\partial e_i} - D'(E)\frac{\partial E}{\partial e_i} = 0 \tag{4.6}$$

Assume that $\partial E/\partial e_i$ =1. The firms draw from a common local factor market, and with increasing costs there is an endogenous market size at which the last firm to enter earns zero profits. From the planner's perspective, the producer surplus of the last firm to enter should just offset the pollution damages. We will assume an integer value of the optimal *n* exists which is defined by:

$$W(n) - W(n-1) = 0 \text{ and } W(n+1) - W(n) < 0$$

or

$$px_n - c^n(x_n, e_n) - (D(E) - D(E_{-n})) = 0 \tag{4.7}$$

Equations (4.5)-(4.7) define the social planner's optimum, which we will denote $(\{\hat{x}_i, \hat{e}_i\}, \hat{n})$.

Suppose the regulator imposes a pollution tax equal to marginal social damages at the optimal emissions level,

$$t = D'(\hat{E}) \tag{4.8}$$

In response to (4.8), firm *i* solves

$$\max \text{ (w.r.t. } x_i, e_i) \ \pi_i = px_i - c_i(x_i, e_i) - D'(\hat{E})e_i .$$

The resulting privately output level x_i^* and emissions level e_i^* solve

$$p - c_x^i(x_i^*, e_i^*) = 0 \tag{4.9}$$

and

$$c_e^i(x_i^*, e_i^*) - D'(\hat{E}) = 0 \tag{4.10}$$

Assume that the last firm to enter this economy will earn exactly zero profits, so n^* occurs where

$$px_n^* - c^i(x_n^*, e_n^*) - D(\hat{E})e_n^* = 0 \tag{4.11}$$

It is clear that the tax rule (4.8) causes (4.5) and (4.6) to correspond with (4.9) and (4.10). Equation (4.7) will match (4.11) only if

$$D'(\hat{E})e_n = D(\hat{E}) - D(\hat{E}_{-n}) \qquad (4.12).$$

Equation (4.12) will hold if D is linear. It also holds if there are many small firms such that $e_n \to 0$, since a derivative is defined (by Newton's quotient) as

$$D'(\hat{E}) = \lim_{e_n \to 0} \frac{D(\hat{E}) - D(\hat{E}_{-n})}{e_n} \Rightarrow \lim_{e_n \to 0} \quad D(\hat{E}) - D(\hat{E}_{-n}) = D'(\hat{E})e_n .$$

Consider the following diagram showing D'. Area $a = D(\hat{E}) - D(\hat{E}_{-n})$. Area $a+b = D'(\hat{E})e_n$. Thus area $b = D'(\hat{E})e_n - (D(\hat{E}) - D(\hat{E}_{-n}))$. This is sometimes referred to as a quasi-rent or inframarginal rent on the environmental good. The socially optimal entry condition (4.7) requires that the firm pay *a* for its emissions. The optimizing firm confronting the tax (4.8) pays *a*+*b*. Thus, unless each firm makes a negligible contribution to marginal damages, or the total damage function is linear, the pollution tax (4.8) will cause excessive exit. This can be remedied if each firm receives a lump-sum payment equal to *b*, but it will be more or less impossible to calculate such an amount. Alternative mechanisms which charge firms only *a* include the rental emission permits system suggested in Collinge and Oates (*CJE* 1982) and the differential damages tax to be discussed later under the topic of asymmetric information.

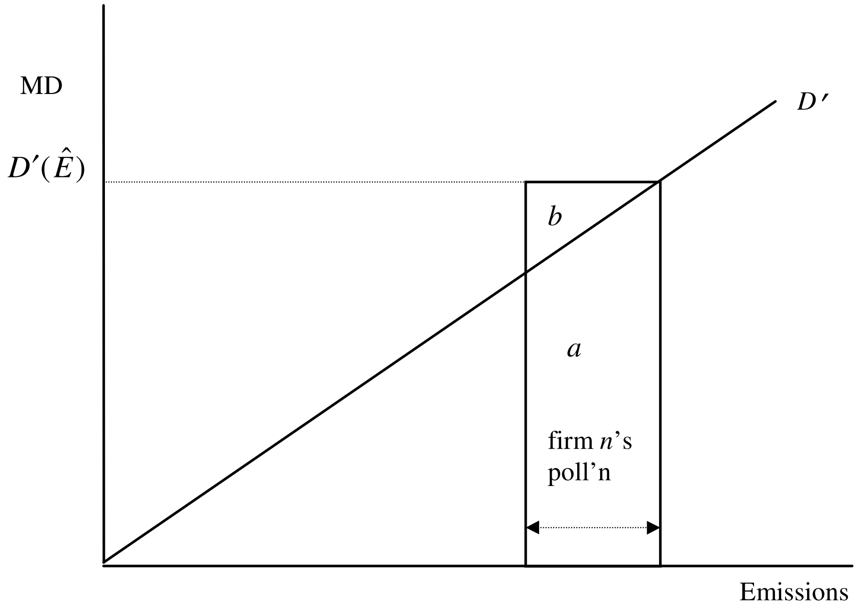


Figure 4.6: Entry of a new polluting firm

In sum, policies which yield short-run optimality must give each firm the correct marginal incentives, that is, they must price emissions at the rate of aggregate marginal damages evaluated at the optimal emissions level. Long-run optimality requires that firms pay the value of incremental damages, i.e. that the marginal firm earns profits just equal to its marginal contribution to social damages. For further on this topic, see Spulber (*JEEM*, 1985).

4.4 Dynamic Efficiency

Firms which generate pollution need incentives not only to use *existing* abatement technology, but also to help improve it and to adopt better versions as they become available. If a policy provides the correct incentives for firms to innovate and adopt new technologies, it is said to achieve *dynamic* efficiency. To see how it works, consider the following diagram. It shows a firm which can choose between two abatement technology options.

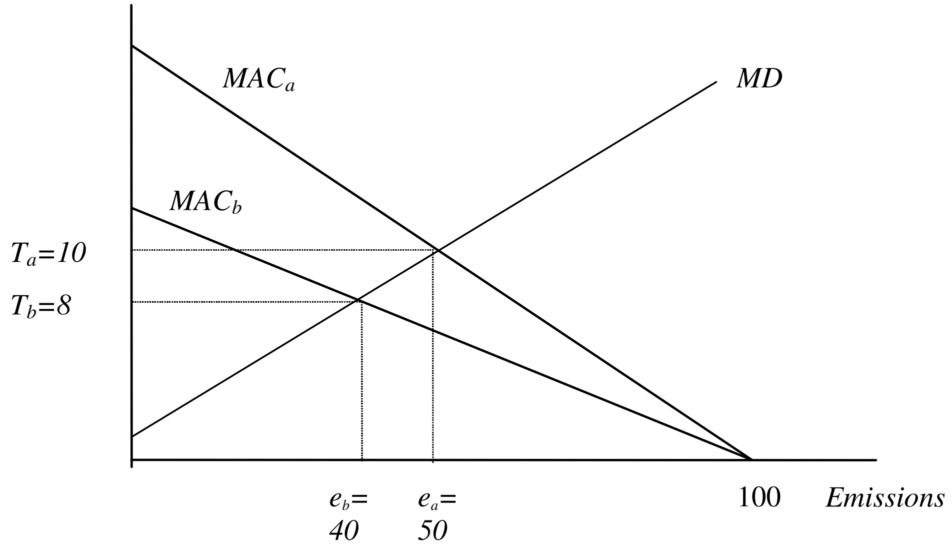


Figure 4.7: Assessing the benefits of adopting a new technology

The firm currently employs technology *a*, represented by the higher MAC line. It can innovate by switching to technology *b* at a resource cost of X=25 dollars. The innovation allows for emission control at a lower cost to the firm and hence to society. Using technology *a* the standard the firm would face is at e_a, which is at 50 units. Using technology *b* the standard would be set at 40 units, reflecting the lower optimal emissions level. If instead the regulator uses taxes to control emissions, the tax rate would be 10 under technology *a* and 8 under technology *b*. We want to know under what circumstances the firm *would* switch from *a* to *b*, and when it *should* switch.

Consider the situation under emission standards. When technology *a* is used the firm incurs abatement costs equal to the area under the MAC_{a} curve, which equals 250. When technology *b* is used the abatement costs are 240. The firm would not pay 25 to adopt the innovation because it only saves 10. But from society's point of view this is not necessarily the desirable outcome. The switch from technology *a* to *b* means that emissions 50 through 100 are now abated more cheaply, which is a resource savings. The reduction in emissions is also a net welfare gain. The resource savings is the area under MAC_{a} minus the area under MAC_{b} between 50 and 100, which in this case equals $83^{1}/_{3}$ (you should be able to verify this). The reduction in emissions from 50 to 40 yields a reduction in total damages net of the additional abatement cost (under MAC_{b}) of $11^{2}/_{3}$. So the social welfare gain of the technology change is 95 in total, less a resource cost of 25, for a net value of 70. So society would have preferred the firm to adopt the new technology. Clearly, emission standards do not provide adequate dynamic incentives. This inefficiency is not related to the lack of cost-effectiveness across multiple emitters.

Consider the outcome under taxes. The total compliance cost to the firm under tax T_a is the abatement cost 250 plus the tax of 500 on emissions for a total compliance cost of 750. Under tax T_b the abatement costs are 240 and the tax bill is 320 for a total compliance cost of 560. The firm will save 190 minus 25 by switching technology, so it will choose to do so. Clearly a tax system creates stronger incentives to adopt cost-saving technologies.

Practice Questions

1. Assume *MAC*'s are linear. Suppose a new technology can be adopted at zero cost, which causes the *MAC* to swing downwards. Also assume that if the firm adopts the technology, the regulator automatically adjusts the standard or tax rate to its new optimal level. Prove that under an emissions tax system, the firm will *always* adopt the new technology, but under a standards system the firm may or may not do so.

2. Consider the same situation as above, but assume now that the regulator is expected to leave the emissions tax or standard constant after the firm adopts the new technology. Will the firm always adopt the innovation under taxes or standards or both?

In the example above, the tax led to the socially-preferred outcome. But notice in this example that the savings to the firm exceed the social benefit of the technological change. For instance, if X=100, the net benefit to society of the adoption of the new technology would be –5, so society would be better off without the innovation. In this case, taxes led to the wrong outcome.

What can we say about the propensity of economic instruments and regulations to generate correct incentives for dynamic efficiency? This is a question which has not been extensively studied. Milliman and Prince (JEEM 1986) were the first to show that neither standards nor emission taxes consistently generate the correct incentives for innovation. Not much progress has been made since then in designing instruments which do provide proper incentives. It is an important area of research which would benefit from more attention.

Chapter 5: Information, Uncertainty and Instrument Choice

5.1 Incentives to Report Truthfully

In a situation of uncertain or incomplete information, regulators often negotiate standards with the party being regulated. The first step in this process is to find out from the polluter, "what are you capable of doing?" The regulator often does not know what the firms' MAC curve looks like, and it must take seriously the firm's report of its abatement costs. What incentives does the polluting firm have to tell the truth? The answer depends on the type of policy that will be implemented.

If the regulator is going to set a standard based on the firm's report of its own marginal abatement cost function, the firm has an incentive to exaggerate its control costs. In the diagram below, MAC_T is the true MAC function, while MAC_R is what the firm reports. The regulator picks the emissions level where MD equals MAC. The compliance cost to the firm is the area under the MAC curve.

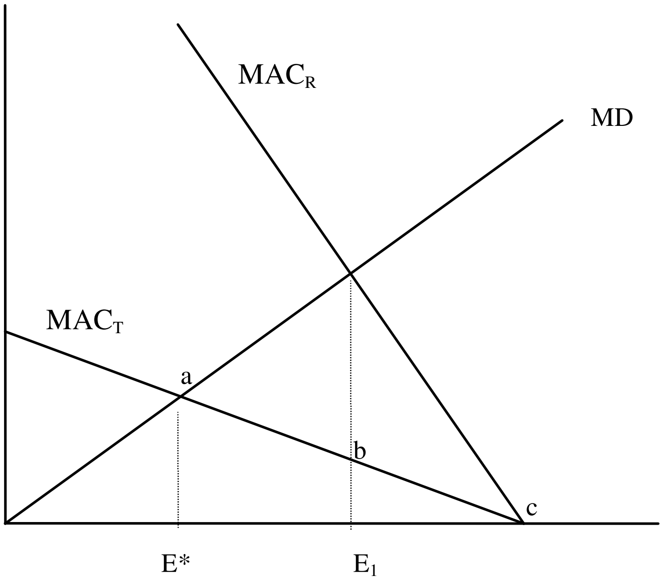


Figure 5.1: Incentives to exaggerate costs under a standard

If the firm reports MAC_T it pays compliance costs shown as the triangle E*ac. If it reports MAC_R it only pays compliance costs E_1bc because the regulator sets the standard at E_1 rather than E*. Hence the fact that the firm knows a regulatory standard will be set based on the information it gives to the regulator gives the firm the incentive to misrepresent its control costs, leading to a higher-than-optimal pollution level. An important point here is that once the policy is implemented based on the firm's report, no information concerning marginal abatement costs is generated that would signal to the regulator that control costs were exaggerated.

Suppose instead the regulator is going to impose a tax based on what the firm says. It will set the tax rate where MD=MAC. Interestingly, in this case, the firm never has an incentive to over-report its MAC, and in fact may under-report its MAC. Consider the diagram below.

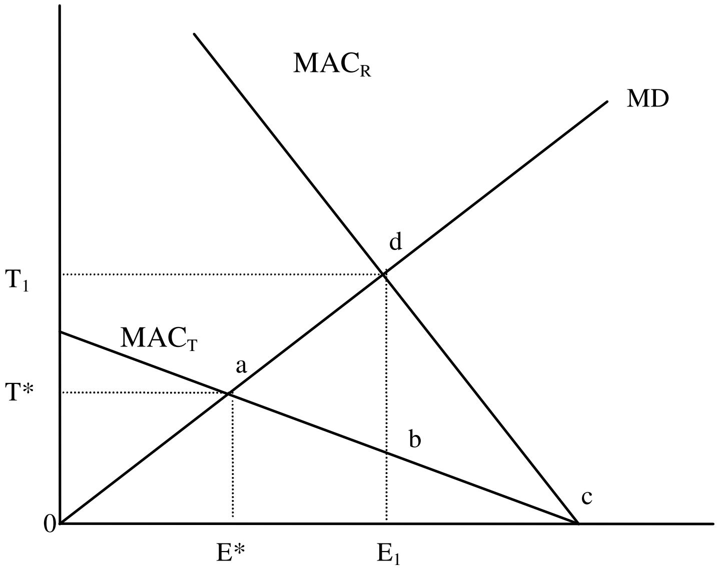


Figure 5.2: Incentives to report costs under an emissions tax

Under a pollution tax the firm's compliance costs are the sum of its tax payments plus the area under the MAC. If the firm reports MAC$_T$ it pays the area 0T*aE* in tax payments on emissions E*, plus the area E*ac in abatement costs, for a total of 0T*ac. But look what happens if it reports MAC$_R$ instead. If the tax rate is set at T$_1$ it can't very well shut down or it would give away the fact that it overstated its MAC. Instead it must go along with the MAC it reported by emitting at E$_1$. Here its compliance costs have dropped to E$_1$bc, but it must pay taxes at the rate T$_1$ on all its emissions, shown by the area 0T$_1$dE$_1$. So its total compliance costs are now 0T$_1$dbc, which exceeds 0T$_1$ac. Hence the firm is worse off by exaggerating its compliance costs.

It can be shown that the firm will in fact have an incentive to under-report its abatement costs in the presence of a tax. It will find it profitable to have a lower tax rate and a lower emissions level than E*, even at the cost of slightly higher abatement costs. Define $v = E_1 - E^*$ and $d = T_1 - T^*$. If the firm files a truthful report its total compliance costs are

$$TCC_T = T^*E^* + \pi(\overline{E}) - \pi(E^*)$$

where $\overline{E}$ is the unregulated emissions level and π is the profits function, i.e. $\pi_E = MAC$. The firm, by filing a false report about its MAC and then playing along by responding to the tax rate as if its reported MAC is true, would have total compliance costs

$$TCC_R = (T^* + d)(E^* + v) + \pi(\overline{E}) - \pi(E^* + v)\,.$$

Note that $d = MD(E^* + v) - MD(E^*)$. If the firm chooses v to minimize TCC_R we have the first order condition

$$(E^* + v)MD'(E_1) + T^* + MD(E_1) - MD(E^*) - \pi_E(E_1) = 0$$

where $\frac{\partial MD(E_1)}{\partial v} \equiv MD'(E_1)$. The above condition reduces to

$$MD(E_1) - \pi_E(E_1) = -E_1 MD'(E_1)\,.$$

Since the term on the right is negative this implies that the optimal value of E_1 is where $MD < MAC$, which is to the left of *E**.

If there are many small firms and each one is considering whether to exaggerate or not, if each perceives its influence on the tax rate to be negligible (so $MD' = 0$) the optimal report can be shown to coincide with the truthful one. Suppose all other firms have made reports such that the tax rate is set at $\tilde{T}$. At this tax level firm *i*'s privately optimal emissions level is $\tilde{e}_i$, but it considers changing its report to an MAC that implies optimal emissions $\hat{e}_i = \tilde{e}_i + v$. Assuming it has to follow through on this claim its total compliance costs are

$$TCC_R^i = \tilde{T}(\tilde{e}_i + v) + \pi^i(\overline{e}_i) - \pi^i(\tilde{e}_i + v)$$

where $\overline{e}_i$ is firm *i*'s unregulated emissions level. The first order condition is

$$\frac{\partial TCC_R^i}{\partial v} = \tilde{T} - \pi_e^i(\hat{e}_i) = 0$$

and this implies $\hat{e}_i = \tilde{e}_i$ or $v = 0$. Since this is the case for all firms regardless of how $\tilde{T}$ is defined (i.e. it does not assume all other firms tell the truth) the Nash equilibrium involves truth-telling.

In the case of emission reduction subsidies, the picture is not as good. It turns out that the firm has an incentive to exaggerate its control costs once again. Try to draw out the diagram which demonstrates why this is so. Draw the MD-MAC diagram with the ‘true’ and the ‘reported’ MAC curves and compare the firm’s net compliance costs. Assume that the firm will be paid a subsidy for each unit by which its emissions fall below the base level. By reporting an artificially high MAC, it raises the equilibrium subsidy rate and reduces the amount of emissions reduction it must do.

5.2 Prices v. Quantities

5.2.1 Equivalence under certainty

If we had the luxury of knowing exactly where the MD and MAC curves sit, we would have a relatively easy task in setting pollution policy. However, this information is not necessarily available. In this lecture we examine two aspects of working under uncertainty. First, which variable should we target, and second, which policies will give polluters the incentives to truthfully reveal what they know?

We can broadly classify policy instruments into ones that target prices (including taxes and subsidies) and ones that target quantities (include permits and standards). To achieve an optimal pollution level, if all the relevant curves are known with certainty it does not matter which variable we control.

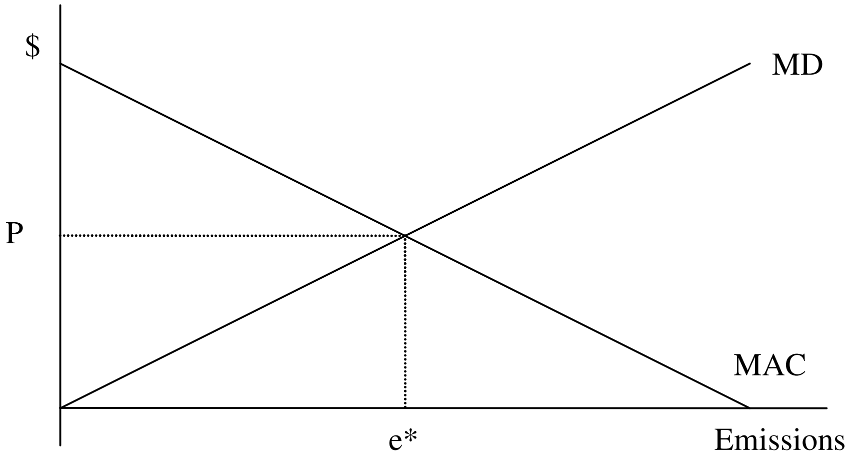


Figure 5.3: Equivalence of Price and Quantity Instruments

In Figure 5.3, which shows the aggregate MAC and MD curves, we attain the optimum either by setting the quantity of emissions at e*, using fixed standards or tradable permits (assuming the fixed standards are efficiently distributed), or by setting a tax at P*. There is an evident symmetry between the policies.

But it is often the case that we do not know the MD and/or the MAC curves with certainty. In such cases we have to make do with an estimate of one or both functions. Since we are sure of making an error of some magnitude in such an exercise, we can also be sure we will experience some social welfare loss, compared to the full-information optimum. How does this affect the symmetry between price and quantity instruments? When we examine the expected social welfare losses due to mismeasurement of pollution damages or abatement costs, it turns out that, in some cases, price controls are preferred to quantity controls, and vice-versa in others. In this lecture we characterize such situations.

The classic analysis of regulation under uncertainty is Weitzman (1974). This lecture follows Baumol and Oates (1988, chapter 6). Another recent survey is Cropper and Oates (1992). Throughout this lecture we will assume that the lack of information takes a very specific form. We assume that the relevant curves are linear, and that their slopes are known (at least locally in the neighbourhood of the optimum), but that the position of one or the other curve is unknown. Later we will examine policy options when the MAC cost function is completely unknown to the regulator (i.e. when policy is set under asymmetric information.)

5.2.2. Policy Choice when Damages are Uncertain.
Suppose that the MAC function is known with certainty, but the MD function is not known. The situation is illustrated in Figure 5.4.

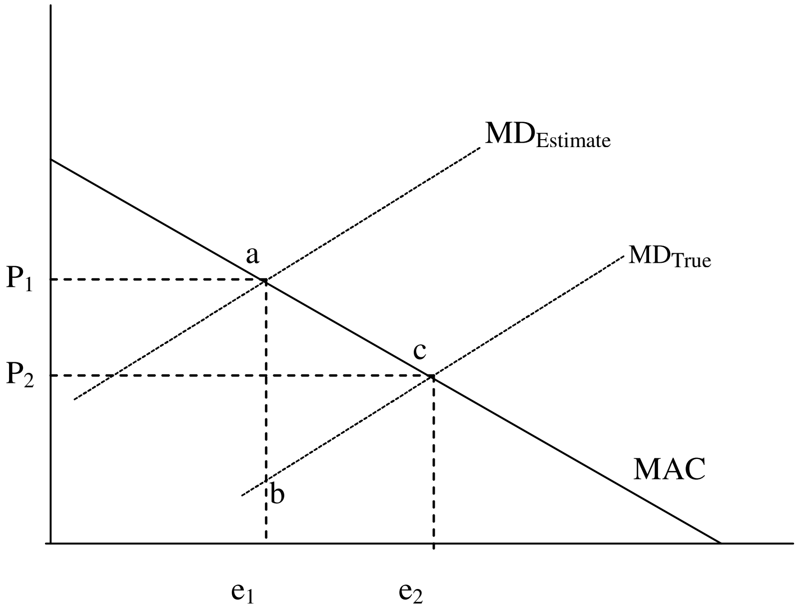


Figure 5.4 Situation in which Marginal Damages are incorrectly estimated

The regulator believes that the marginal damages are represented by the curve MD_1, while in fact the true damages are shown by MD_2. What are the consequences of setting policy under such conditions?

If the regulator uses a permits policy, she will force emissions back to the level e_1, which is below the true social optimum at e_2. The social welfare loss compared to the full-information optimum is illustrated by the area between the true MD and the MAC curves from e_1 to e_2, which is triangle abc. On the other hand, if the regulator uses a tax (price) instrument, she will compute the optimal tax rate as P_1, instead of P_2, the true optimal emissions price. In this case the social welfare loss is also triangle abc. Thus, when the MAC function is known but the MD function is unknown, the social welfare losses due to incorrect estimation are the same regardless of whether the regulator uses a price or a quantity instrument.

The reason the symmetry is maintained in this case is that the response of polluters to either type of policy is determined by the MAC curve, which is known with certainty. Consequently, both price and quantity instruments generate the same, predictable outcome. What the MD curve tells us is the social costs of the emissions. We are uncertain about the magnitude of the social costs at the policy-induced outcome, but not about where the outcome itself will be. The gap between marginal damages and marginal abatement costs is identical regardless of which instrument got us to the targeted emissions level. In the next example however, the MAC function is uncertain, so the response of firms is not predictable *a priori*. This will cause the welfare loss due to an incorrect policy target to differ between instrument types.

5.2.3. Policy Choice when the Marginal Abatement Cost is Uncertain.

Suppose that the regulator's information is as illustrated in Figure 5.5.

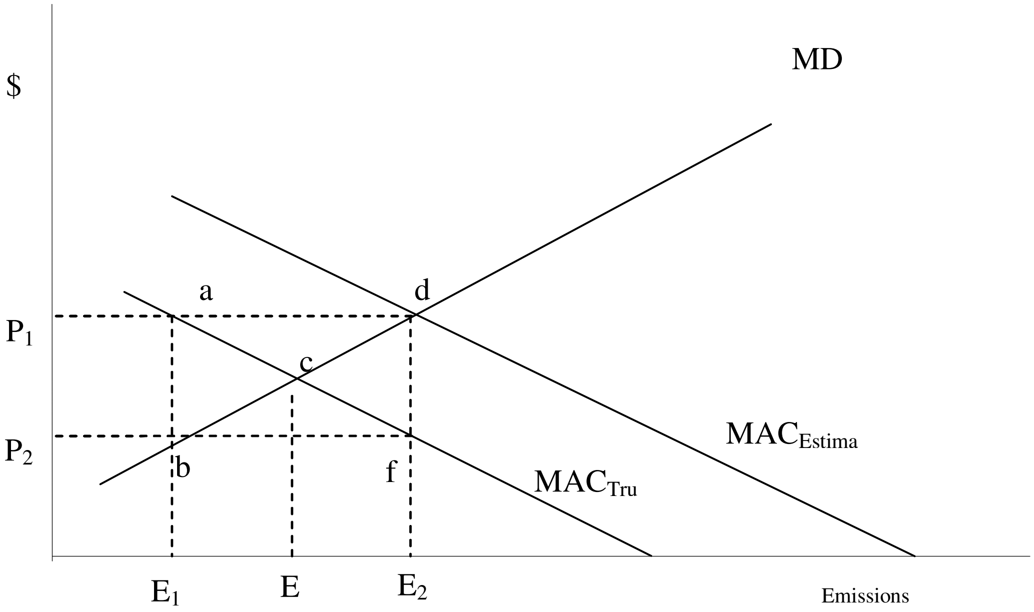


Figure 5.5 Situation in which MAC is incorrectly estimated.

In this case the regulator estimates the $MAC_{Estimate}$ curve while the true control costs are represented by the MAC_{True} curve. If the regulator uses a tax policy, he will set it equal to P_1, and firms respond by emitting E_1. Thus firms overshoot the optimum and implement too much abatement. The welfare losses of this policy are in the triangle abc. If instead

the regulator uses a quantity instrument, such as a permits auction, he will set the total quantity at E_2, for which firms will bid an equilibrium price P_2. In this case there is too little abatement, and the social welfare costs are in the triangle cdf.
Which outcome is worse? As drawn, abc is a bit bigger than cdf, so the mistake under the tax policy is worse than the mistake under the permits policy. That is, given the above situation, a regulator can expect to cause a smaller loss in social welfare due to mis-measurement of the MAC curve under a permits policy than under a tax policy. Is this always the case? No, it depends on the relative slopes of the MD and MAC curves.

5.2.4. Instrument Choice under Uncertainty

Given an uncertain MAC curve, suppose the MD curve is perfectly flat. This would be associated with a linear total damages function. If Marginal Damages are perfectly flat, we know exactly what the optimum emissions price must be, regardless of where the MAC function lies. Consequently, a tax instrument would be the better option for emissions control. Conversely, if the MD function were vertical, we would know the optimum quantity of emissions, regardless of where the MAC curve crosses the MD curve. Consequently a quantity instrument would be preferable. So in general, as the MD curve gets steeper, for a given MAC curve slope, our preference moves towards quantity control.

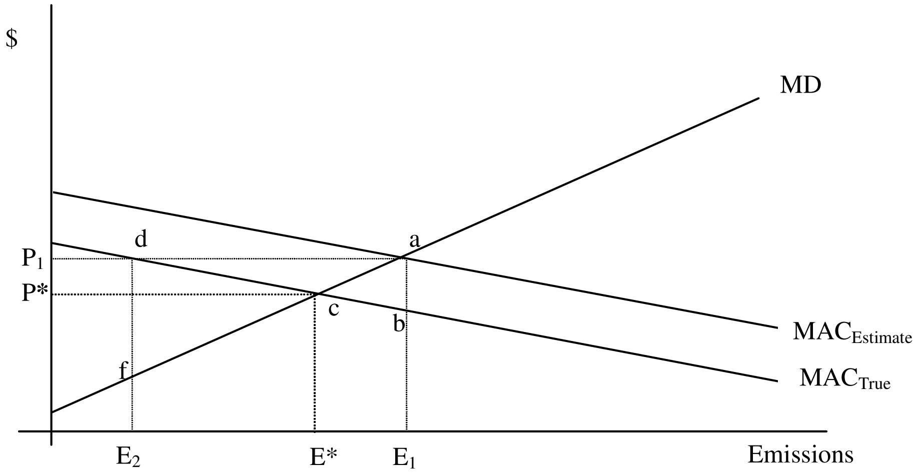


Figure 5.6 Welfare analysis of making a mistake when the MAC is flat

We have drawn a general conclusion from considering the slope of the MD curve, but what about variations in the slope of the MAC curve? Suppose the MAC curve is almost flat. If we pick the quantity E_1 and in so doing make a mistake, the implied price P_1 (i.e. the equilibrium in an emissions trading market) will nevertheless not be far off from the optimal emissions price P*. But if we pick the price P_1 and in so doing get it wrong, even small mistakes will result in a quantity relatively far off from the optimum, in this case at E_2. Consequently we are better off picking the quantity when the MAC is flat. In Figure 5.6, suppose $MAC_{Estimate}$ is estimated, but MAC_{True} is the true location of the curve. The diagram shows that the welfare loss associated with an incorrectly chosen quantity is small (area abc) compared to the welfare loss associated with an incorrectly chosen price (area dcf).

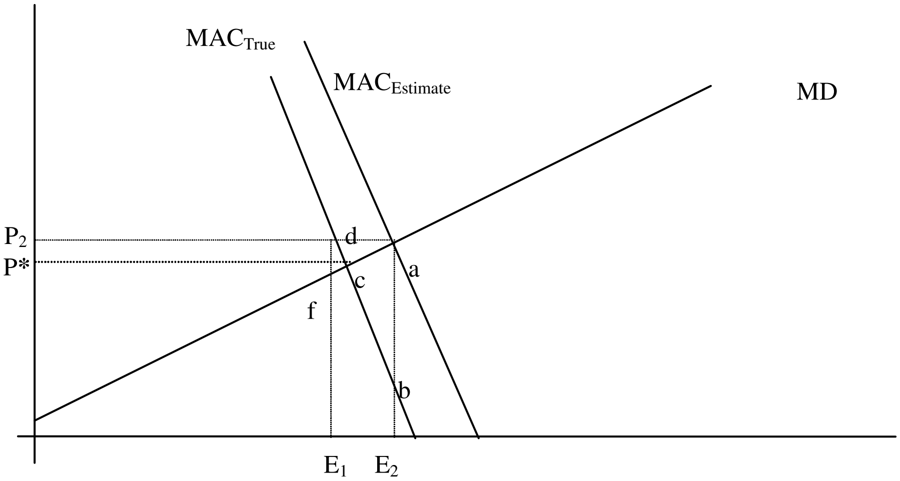


Figure 5.7 Welfare analysis of making a mistake when the MAC is steep

Now suppose the MAC curve is almost vertical. In Figure 5.7, again suppose MAC$_{Estimate}$ is estimated, but MAC$_{True}$ is the true location of the curve. If we pick a price (i.e. set a tax at P$_2$) and make a mistake, the resulting quantity (E$_1$) will nevertheless not be far off the optimal emissions level. But if we pick the quantity E$_2$ and get it wrong, even small mistakes will result in an implied price relatively far from the optimum P*. Consequently we are probably better off picking the price in this case. The diagram shows that the welfare loss associated with an incorrectly chosen price is small (area cdf) compared to the welfare loss associated with an incorrectly chosen quantity (area abc).

These two results can be summarized as follows. Denote the absolute slope of the functions in the neighbourhood of the optimum as $|MD'|$ and $|MAC'|$ respectively. As $|MD'|$ falls or $|MAC'|$ rises, price instruments (taxes) are preferred. As $|MD'|$ rises or $|MAC'|$ falls, quantity controls (permits) are preferred. We can combine the results by defining the ratio:

$$R = \frac{|MD'|}{|MAC'|}$$

If $R = 1$ then neither curve is 'steep' compared to the other, and we would be indifferent between price and quantity instruments. If $R<1$, and as $R \rightarrow 0$ (i.e. $|MD'|$ falls and/or $|MAC'|$ rises), price measures are the preferred instrument. If $R>1$, and as $R \rightarrow \infty$ (i.e. $|MD'|$ rises and/or $|MAC'|$ falls), quantity measures are preferred. Note that (1) defines the preferred instrument when the position of the MAC curve is stochastic but the MD curve is known.

5.3 Asymmetric Information Models

We had a look earlier at the problem of selecting a policy instrument under uncertainty, i.e. when the position of the MAC or MD curve is known with an additive error. We also looked at the issue of what sort of information firms will reveal to the regulator when different policies are being proposed. In this lecture we examine the related problem of asymmetric information. In the case of uncertainty, the decision makers need information which *no one* knows exactly. In the case of asymmetric information, one party lacks some information which other parties possess. We are interested in the case where the regulator and the firms being regulated all know the MD function, but only the firms know the MAC functions, since they contain information held privately by the firms being regulated. Hence, the asymmetry is that firms know something which the regulator doesn't, but which the regulator needs in order to implement the correct policy. The 'trick' will be to present the firms with a menu of policy choices which will induce them to implement the socially optimal outcome. If the menu is designed correctly the regulator needn't know in advance how the firms will respond in order to guarantee that, no matter how they responded, the policy will have yielded the optimal outcome.

Recall that in the case of uncertainty, randomness in the position of the MD function has no implications for the choice of taxes versus permits. Randomness in location of the MAC function does lead to a preference for one over the other. However, our 'solution' to the policy problem under uncertainty is only an *expected* optimum, and if there is a large error in the estimate of the location of the MAC then the welfare loss will be large as well. A solution to the asymmetric information problem (if one exists) is potentially more helpful than a solution to the uncertainty problem, because here we are proceeding with no information at all about the MAC curve, yet we nevertheless hope to achieve an exact solution.

This is an ambitious hope, but one which has actually been realized (on paper at least). In the next section I will review asymmetric information models in general and how they have been applied to pollution regulation. I will suggest why this approach has not yielded satisfactory solutions. In the third section I will outline some alternative mechanisms which lie outside the standard asymmetric information literature, but which actually provide potentially implementable and practical solutions to the asymmetric information problem.

5.3.1. Asymmetric Information Models and Pollution Control

Much of the literature on policy making under asymmetric information (AI) arose from considering the problem of government procurement. The central AI results are usually expressed in these terms, so we will present a simple procurement problem, then discuss how it is translated it into pollution control situations. (The example here is from Kreps, *A Course in Microeconomics* ch. 18.2) Suppose the government needs to buy 100 airplanes, and it seeks bids from 2 potential suppliers. Each firm might be either a low cost producer (with costs of 1 per unit) or a high cost producer (with costs of 2 per unit), with probability of ½ either way. Firms can only reveal one of those two costs. The government does not know the firms' costs, nor do the firms know each others' costs. The problem for the government is to get the planes built at the lowest possible cost.

There are four possible distributions of costs in this industry: (1,1), (1,2), (2,1) or (2,2). Suppose each has a probability of ¼. If the government knew the firms' costs, and it were certain that both potential suppliers would participate in the procurement once the project begins, it could identify the low cost producer (if there were one) and give it the contract, or if both firms have the same costs, give each one half the contract. Suppose the government announces the following contract:

(C1) If both firms bid *i*, each produces 50 and is paid *i* per unit.
If one bids 1 and one bids 2, the low bidder gets the contract and is paid 1 per unit.

In this case the government's expected costs of getting the planes built would be

$$100(\tfrac{1}{4}[1] + \tfrac{1}{4}[1] + \tfrac{1}{4}[1] + \tfrac{1}{4}[2]) = 125.$$

But the government does not know the firms' costs, so it can't count on identifying the low cost firm. Nor can it necessarily count on firms participating in the project. Because of these uncertainties, the government needs to modify its contract, or it may find it has brought about an unintended and undesirable outcome. Suppose for the moment that it went ahead with the announcement (C1). Firm 1 would reason:

Costs=2:
If I have costs of 2, I won't say my costs are 1, since I might win the contract and have to produce at a loss of (1-2) on each unit. Thus if I have costs of 2 I will bid 2.

Costs=1:
If I have costs of 1, if I win the contract I earn zero per unit; if I split the contract I also earn zero per unit. So regardless of what the other firm bids I earn zero if I bid 1 when my costs are 1.
If I have costs of 1, but I bid 2, I earn zero if the other firm bids 1 and wins the contract, but if the other firm also bids 2 we split the contract and I earn 50(2-1) = 50. So I have a chance of getting 50 if I bid 2.
So I earn nothing if I bid 1, but maybe I get 50 if I bid 2. Therefore, I will bid 2.

Thus, regardless of what the other firm does, and regardless of its own actual costs, firm 1 will bid 2 in response to (C1). Since both firms reason in an identical fashion, we are certain that the only bid the government can expect to receive is (2,2). So the true expected cost to the government of contract (C1) is not 125, but 200.

Because each firm bids (2,2) regardless of what the other does, this is a Nash equilibrium. It would be a good exercise to write out a payoff matrix and see how the quadrant (2,2) is indeed the Nash equilibrium. In this case the Nash equilibrium is the worst outcome for the regulator: is maximizes the cost of the procurement contract.

So let's suppose the government designs a better contract. Kreps (p. 681-2) goes over several possible options. It is helpful to look at the general structure of the contract (or *mechanism*) design problem. The general contract takes the form:

(C2) Each firm will get $e>0$ for participating (submitting a bid and filling the contract if selected).
If both firms bid 1, each gets to produce 50 and is paid x per unit, where $1<x<2$.
If both firms bid 2, each gets to produce 50 and is paid 2 per unit
If one firm bids 1 and the other bids 2, the lower bid gets the contract and is paid $1<y<2$ per unit.

Since e>0, both firms have an incentive to participate, since even if they don't make money on the production they earn money on the bid.

Now suppose that a firm has costs of 2. It won't bid 1, because it might just win the contract and be paid less than 2 per unit. So we only need to consider what happens when a firm has costs of 1. When will a firm tell the truth? Only if its expected payoff from bidding 1 exceeds that from bidding 2.

Expected payoff from bidding 1: $\frac{1}{2}50(x-1) + \frac{1}{2}100(y-1)$
Expected payoff from bidding 2: $\frac{1}{2}(0) + \frac{1}{2}(50) = 25$

So the contract must satisfy the 'truth-telling' constraint:

$$\tfrac{1}{2}50(x-1) + \tfrac{1}{2}100(y-1) \geq 25 \quad (5.1)$$

or

$$25x + 50y \geq 100. \qquad (5.2)$$

The government's expected costs (call this G) of the contract are $100(x/4 + y/2 + 2/4) +2e$, which can be written:

$$G = 25x + 50y + 50 +2e. \qquad (5.3)$$

Compare (5.1) and (5.2). Any pair x and y which satisfy (5.1) implies, from (5.2), $G \geq 150+2e$. That is, *any contract which induces truth-telling must have an expected cost for the government of at least 150+2e*.

As long as e is very small (it can be arbitrarily close to zero) this contract is an improvement on the naïve version (C1). But note that it must be costlier than the full information (expected) cost of 125. This increased cost is due to the fact that firms have private information, and they must be 'bribed' in some way to tell the truth. The bribe here has an expected value of 25+2e. This sum is sometimes referred to as 'information rents'. These are payments which firms get only because they start the day with some private information which is useful to the government, and which the government cannot obtain without payment.

We worked out the incentive-compatible contract for the government which minimizes the information rents required to induce truth telling. But is this the same as working out the minimum cost for the government of procuring the airplanes under the AI problem? As it turns out, it is. An important theorem in information economics is the "revelation principle", which states that, given a general AI contract design problem where the goal of the contract is to secure some transaction, the contract which minimizes the cost of ensuring participation and truth-telling (i.e. features these things in a dominant strategy Nash equilibrium) also minimizes the expected cost across the class of all outcomes in which fulfilling the contract is a dominant strategy Nash equilibrium. In the context of the current model, we want to buy airplanes at the lowest cost. Because the firms respond strategically, we need to ensure that the outcome we are interested in is a Nash equilibrium. There may be many such equilibria. Ignore for a moment the procurement problem, and instead concentrate on designing contracts which induce participation and which lead to a Nash equilibrium with truth-telling behaviour (i.e. each firm reveals its true costs). It will turn out that the least costly of these 'truth-telling' contracts is also the least-cost solution to the procurement problem. The great usefulness of this result is that it allows us to concentrate on a smaller class of policy problems without losing any generality.

This is a simple version of the general problem of *mechanism design*, in which one party offers another party a menu of contracts and the other party selects among them, and in so doing reveals its private information. This structure of model has been applied to pollution policy. The general form of such a policy can be thought of as a set of regulations and fees:

$$\{(e_1,t_1),...,(e_m,t_m)\}.$$

The regulator 'offers' this menu to firms: you may choose any pair (e_j,t_j) which obliges you to emit no more than e_j and pay the fee t_j for doing so. A more compact notation is

$$\{E(\theta),T(\theta)\}$$

where θ is distributed across some interval $(\underline{\theta},\overline{\theta})$, and *E* and *T* are functions which, respectively, define allowable emissions and required tax payments, given firm *j*'s announcement that its 'type' is θ^j. Each firm is assumed to have a MAC function $c^j(\theta^j)$. The regulator knows the function c^j but does not know the parameter values θ^j. However it also knows the distribution of the θ^j's, which is assumed to be independent and identical across firms. By designing appropriate policies (i.e. functions *E* and *T*) it is possible to induce truth-telling behaviour and participation in a dominant strategy Nash equilibrium, however it is not possible to achieve the 'first-best' outcome, as the regulator must pay information rents to firms. For a formal proof see Spulber (1988).

This is how the pollution policy literature has made use of information-revealing models as developed elsewhere. But the solution presented above really isn't quite satisfactory, for a number of reasons.

(1) The regulator actually needs to have a lot of information. Namely, it knows the form of the c^j functions, lacking only the parameters θ^j. In an econometric sense, to know the true functional form, and lack only the parameter values, is still more information than we usually expect to have. Moreover, the regulator is assumed to know the exact distribution of the θ^j's. How is this distribution function to be estimated? In advance of the introduction of the policy there would be no data on which to base such an estimation.

(2) The assumption that the θ^j's are independent is not very realistic. If one firm reveals that it could meet a policy target at a very low cost, it would be reasonable for the government to condition its expectation of the other firms' cost parameters on this knowledge. Or at least it would seem unreasonable to suppose that this information is of no relevance to predicting other firms' costs.

(3) Throughout these models we assume that there are a fixed number of firms *n*. But the kinds of tax rules that are proposed in this literature involve potentially enormous costs to firms, and hence may induce exit. Hence the solutions are at best short-run.

(4) There is a dynamic inconsistency problem with all these models. We saw that the government cannot induce truthful reporting of firms' cost types without proposing tax/fee schedules which pay information rents to firms, which is a costly burden for the regulator. Now suppose the regulator has implemented a truth-revealing mechanism. Having obtained the true parameter values, why should the regulator follow through on the payments? Conceivably, if the model were a one-shot affair the government could make a credible commitment because the firms might have recourse to legal action if the regulator did not carry out the announced policy. But as in the case with enforcement under asymmetric information, the government must commit to implementing policy which it (and everyone else) knows, when the time comes, it would rather deviate from. Also, suppose the regulator is dealing with a regular pollution problem that persists period after period. After one round of play, the regulator knows each firms' θ^j parameters, and it can implement the first-best solution. If the firms anticipate this, they may have additional incentives to misrepresent their true costs.

These are problems with regulation models under asymmetric information in general. Nevertheless, there has been much written applying such models to the design of pollution policy in the last two decades. For a review, see Lewis, *Rand Journal of Economics*, Dec. 1997.

5.3.2. Alternative Approaches

Various other approaches to setting pollution policy under asymmetric information have been explored. Iterative mechanisms have been studied by Conrad (1991) and Karp and Livernois (1994). These authors model a situation in which the regulator periodically adjusts the pollution tax rate up or down until an optimum is achieved where all the MAC's equal the MD's. When firms anticipate that the regulator will adjust the tax rate in this way, these studies show the shortcoming of these mechanisms to be that convergence and optimality of the steady state are typically incompatible objectives, except under restrictive conditions.

A simple, practical and effective mechanism which deftly solves both the long-run entry-exit problem and the AI problem was proposed by Robert Collinge and Wallace Oates ("Efficiency in Pollution Control in the Short and Long Runs: A System of Rental Emission Permits." *Canadian Journal of Economics* XV(2) 1981, pp. 346-354. Unfortunately this paper was largely ignored after publication, not least by Oates himself, who mentions it in his book (Baumol and Oates) and his review paper (Cropper and Oates) only in connection with the entry-exit problem, but not in connection with the

AI problem. The paper is widely cited but rarely read, and its central point is quite simple.

The Rental Emission Permits (REP) system would work as follows.

1. Print permits, each allowing one unit of pollution per period (say a year).
2. Number the permits and order them sequentially (1,…,*n*).
3. Assign a rental price to each permit, equal to the total pollution damages if all the permits up to that one were being used, less the total damages if only the previous permits were in use. That is, for permit *i*, its rental price would be:

   $$D(E_i) - D(E_{i-1})$$

   where D is the total damage function, and $E_i = \sum_{j=1}^{i} e_j$.
4. Distribute these permits in some fashion, subject to the condition that the holder pays the rental fee each period. After the initial distribution, remaining permits would be available to any firm prepared to pay the rental on them.
5. Allow firms to buy and sell these permits, as long as each holder pays the appropriate rental.

As shown in their article, this system presents each firm with the appropriate incentives to abate such that a social optimum is achieved. Step 4 can take the form either of an auction, a lottery, or some other method.

The REP system works by confronting each firm with an upward sloping supply curve which corresponds with the marginal damages curve. Implemented in this way, the regulator only needs to know the MD function in order to price the sequence of permits: firms will automatically implement the first-best solution in response. Moreover, there is no scope for collusion or strategic behaviour on the part of firms, since the rental prices of the permits are fixed. Hence the REP system is an apparently practical and attractive method for yielding a first-best outcome under AI.

An alternative approach which employs a nonlinear tax rule is outlined in my paper "A Cournot Mechanism for Pollution Control under Asymmetric Information." (*Environmental and Resource Economics* 1999). It turns out to have a lot of features in common with the Collinge and Oates approach, in that it presents firms with an upward-sloping cost function for emissions which leads to correct short run and long run behaviour without the regulator needing to know the MAC functions.

Consider an economy in which a group of firms indexed by i=1,…,n emit a homogeneous pollutant denoted e_i, with $E = \sum_{i=1}^{n} e_i$. We will assume that each firm sells its output x_i into a perfectly competitive market at price p.[3]

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[3] The analysis is unchanged if we assume the outputs are distinct so that each firm receives a different price.

Each firm's cost function is of the form $c^i(x_i, e_i)$ with $c_x^i > 0, c_{xx}^i > 0, c_e^i < 0$, $c_{ee}^i > 0$, and $c^i(0,0) = c_e^i(x_i, 0) = 0$. Denote $E_{-i} \equiv e_1 + \cdots + e_{i-1} + e_{i+1} + \cdots + e_n$ and thus $E = E_{-i} + e_i$. The social planner's objective function is

$$W = \sum_{i=1}^{n} [px_i - c^i(x_i, e_i)] - D(E) \tag{5.4}$$

where D is a convex aggregate damage function, with D_E >0 and D_{EE}>0. The planner optimizes (4) by choosing outputs and emissions to solve:

$$\frac{\partial W}{\partial x_i} = p - \frac{\partial c_i}{\partial x_i} = 0 \tag{5.5}$$

and

$$\frac{\partial W}{\partial e_i} = -\frac{\partial c_i}{\partial e_i} - \frac{\partial D}{\partial E}\frac{\partial E}{\partial e_i} = 0 \qquad (5.6).$$

We employ the standard Cournot assumption that firms do not believe their current emissions will simultaneously change other firms' emission levels, and consequently $\partial E / \partial e_i$ =1. The firms draw from a common local factor market, and with increasing costs there is an endogenous market size at which the last firm to enter earns zero profits. From the planner's perspective, the producer surplus of the last firm to enter should just offset the pollution damages. We will assume an integer value of the optimal n exists which is defined by:

$$W(n) - W(n-1) = 0 \text{ and } W(n+1) - W(n) < 0$$

or

$$px_n - c^n(x_n, e_n) - (D(E) - D(E_{-n})) = 0 \qquad (5.7).$$

Equations (5.5)-(5.7) define the social planner's optimum, which we will denote $(\{\hat{x}_i, \hat{e}_i\}, \hat{n})$.

Consider a rule which levies the following charge on a firm's emissions e_i:

$$T_i = D(E) - D(E_{-i}) \qquad (5.8).$$

This rule says to charge firm i total damages *D(E)* less the damages that would have resulted had the firm produced nothing, i.e. the damages due to other firms' observed emissions. In the case of monopoly, $D(E_{-i})$=0 and (5.5) corresponds to the single-firm tax rule (which says to charge the firm total damages D). For $n \geq 2$, the tax burden on a single firm is the shaded area shown in Figure 5.8. Figure 5.9 shows the tax burden faced by three firms all subject to (5.8). As n rises, each firm becomes a negligible contributor to total damages and the shaded areas form a saw-tooth pattern which geometrically converges to a rectangle corresponding to the full-information Pigovian tax burden $D'(E^*)E^*$.

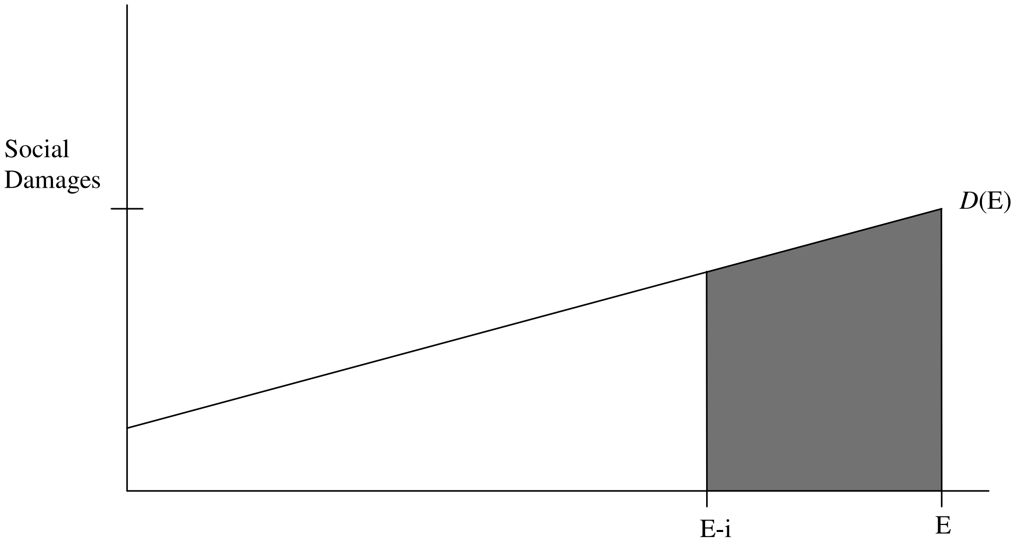

Figure 5.8. Differential Damages Tax Burden for 1 firm.

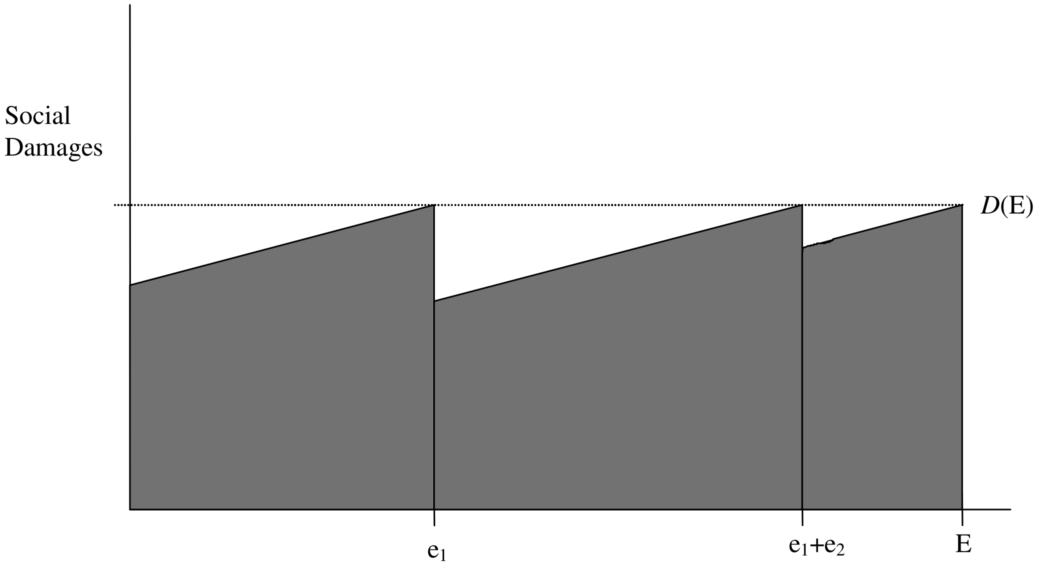

Figure 5.9. Differential Damages tax for 3 firms.

In response to (5.8), firm *i* solves

$$\max \text{ (w.r.t. } x_i, e_i) \ \pi_i = px_i - c_i(x_i, e_i) - (D(E) - D(E_{-i})).$$

The resulting output level x_i^* and emissions level e_i^* solve

$$p - c_x^i(x_i^*, e_i^*) = 0 \qquad (5.9)$$

and

$$c_e^i(x_i^*, e_i^*) - D'(E_{-i}^* + e_i^*) = 0 \qquad (5.10)$$

where $E_{-i}^* = \sum_{j \neq i} e_j^*$. Assuming an integer entry condition, the last firm to enter this economy will just earn zero profits, i.e. n^* occurs where[4]

$$px_n^* - c^i(x_n^*, e_n^*) - (D(E^*) - D(E_{-n}^*)) = 0 \qquad (5.11).$$

By comparing (5.5)-(5.7) with (5.9)-(5.11) we have

Proposition 1. Given E_{-i}, tax rule (8) yields the long-run socially optimal level of output and pollution.

Furthermore the convexity of D implies:

Proposition 2. The tax burden that an industry will face under (5.8) is always less than or equal to that which would be faced under the full information Pigovian approach.

Proposition 2 ensures that the asymmetric information mechanism does not require an unrealistically large tax burden be imposed on polluting firms, or at least no larger than under the full information case. The lower limit is the value of social damages, and as n increases the regulator captures progressively more of the inframarginal rents on the use of environmental services.

Of course it is unrealistic to suppose that E_{-i} is known by the firm. Instead, the firm must act based on its conjectures about other firms' aggregate emissions, which we will denote E_{-i}^c. From (9) we have $x_i^* = y^i(p, e_i^*)$, so (5.7) can be rewritten

$$\tilde{e}_i = e_i(p, E_{-i}^c) \ (5.12)$$

where the ~ denotes an optimum given the conjecture E_{-i}^c. As p is a constant we will suppress it as an argument henceforth. Since $\tilde{e}_i$ is the realized emission level, i.e. the

---

[4] The analysis here confirms earlier results (e.g. Spulber 1985) that a constant Pigovian tax "overcharges" polluters and hence causes excessive exit from the industry in the long run. The differential damages approach here produces an exact correction for this effect and consequently yields a long run optimum.

firm's profit maximizing choice, $\tilde{e}_i(\tilde{E}_{-i}) = e_i^*$. Total differentiation of (5.10) with price p held constant yields

$$\frac{\partial e_i(E_{-i}, p)}{\partial E_{-i}} = -\frac{D''}{c_{ee}^i + D''} < 0 \tag{5.13}$$

which implies that $\tilde{e}_i$ is unique given E_{-i}^c. The realized aggregate output level is $\tilde{E}$. A Cournot-Nash equilibrium occurs where each firm's conjectures are realized, i.e. $\tilde{E} = \sum_i \tilde{e}_i\left(E_{-i}^c\right) = \tilde{e}_i + E_{-i}^c$. The following proposition establishes such an equilibrium exists, by showing that when conjectures are correct, the outcome coincides with the planner's optimum, the existence of which is assured by the structure of the model.

Proposition 3. $\tilde{e}_i(E_{-i}^c) + E_{-i}^c = \tilde{E} \Leftrightarrow \tilde{e}_i = \hat{e}_i$

In words, this proposition states: ($\Rightarrow$) if all firms have correct conjectures, the equilibrium emissions level must correspond with the social planner's optimum; and ($\Leftarrow$) if all firms' privately optimal emissions levels are socially optimal, their conjectures had to have been correct (necessity). The proof is in the Appendix of my paper. In addition I present theorems showing that the Nash equilibrium in conjectures is stable and can be reached by myopic iterations from an arbitrary starting point.

Chapter 5 References.

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Chapter 6: Pollution Standards, Monitoring and Enforcement

6.1. Standards vs. Standards

A famous paper in 1991 by Gloria Helfand ("Standards versus Standards", *AER*) showed that many environmental regulations take the form, not of caps on emission *levels*, but of *ratios* of emissions to inputs or outputs. But even when the regulation is designed to achieve the same emissions level, using a ratio (or 'concentration' or 'intensity') standard is a more costly approach. In the Helfand paper this result was derived by analyzing a firm with two inputs, one 'dirty' and one 'clean'. However the same result can be shown using the basic iso-profits, iso-emissions line model as developed in Chapter 3.

6.1.1 Level Standard versus Emissions Intensity Rule

The first step is to consider the contrast between a 'level' standard, i.e.

$$e(y,a) \le e_1 \qquad (6.1)$$

and an emissions intensity rule, specifying that emissions per unit of output must be below some level

$$\frac{e(y,a)}{y} \le z_1 \qquad (6.2).$$

To examine the shape of (6.2), totally differentiate it and set equal to zero:

$$\frac{y(e_y \partial y + e_a \partial a) - e\partial y}{y^2} = 0 .$$

This rearranges to

$$\frac{\partial a}{\partial y} = -\frac{e_y}{e_a} + \frac{e}{ye_a} \qquad (6.3).$$

The first term in (6.3) is the slope of (6.1) (see equation 3.6). The second term is negative, since $e_a < 0$. Hence the slope of (6.2) at every level of y is less than the slope of (6.1). The locus of points representing equivalent ratios of emissions to output is shallower than the locus of points representing equivalent emissions. However the iso-intensity line is still upward sloping.

$$-\frac{e_y}{e_a}+\frac{e}{ye_a}>0 \Leftrightarrow \frac{e}{y}<e_y .$$

The second inequality states that average emissions are less than marginal emissions (with respect to output), and since we have assumed $e_{yy}>0$ this must be true.

Putting the two types of constraints together we have the following comparison.

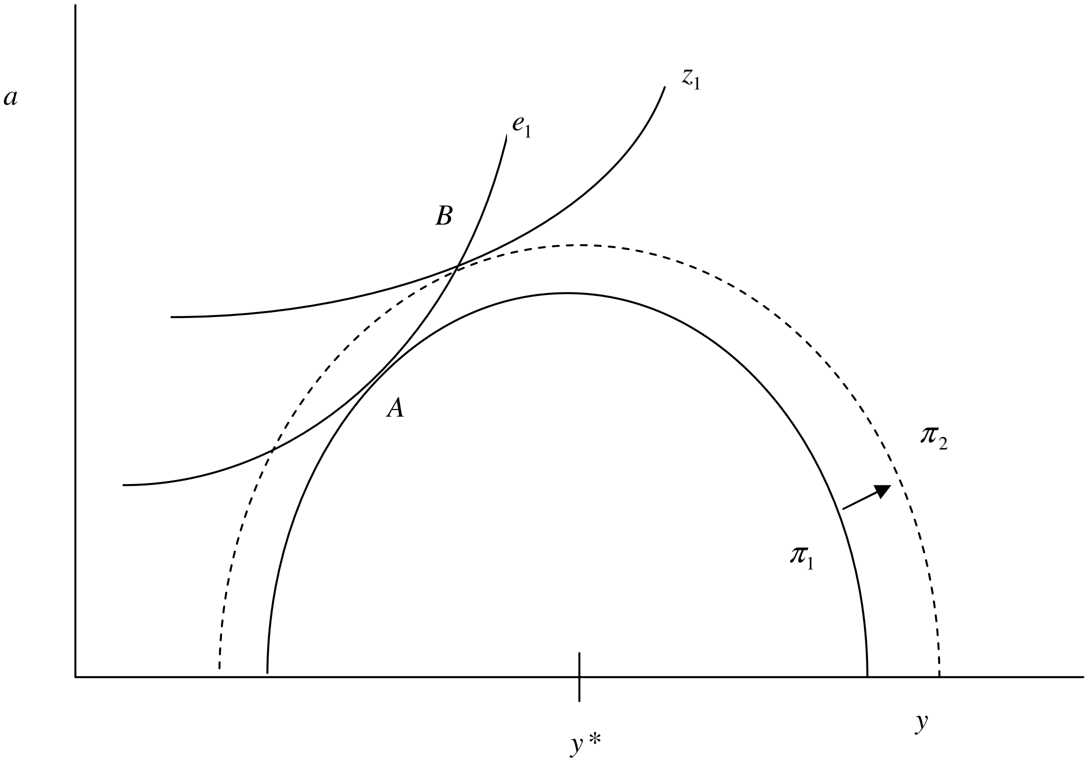


Figure 6.1. Comparison of a level standard and an intensity standard that achieves the same emissions level.

Figure 6.1 shows the conventional result when a firm complies with a level standard (point *A*), by finding the tangency point between the iso-profits line π_1 and the iso-emissions line e_1. Now suppose the firm is instead presented with the intensity standard (6.2). To make the outcome comparable we set the condition that emissions must remain at e_1. So we need to find a point where the iso-profit line is tangent to z_1 but the tangency sits on the line e_1. This occurs at point *B*, and is associated with profits π_2. It is apparent in Figure 6.1 that by using the intensity standard to get emissions down to e_1, output increases, abatement increases and profits decrease.

Now suppose we want to compare a level standard to one that mandates a minimum abatement level

$$a \geq a_z \qquad (6.4).$$

This sort of standard is represented as a horizontal line, and if we again require that the firm operate with emissions e_1 the outcome is as follows.

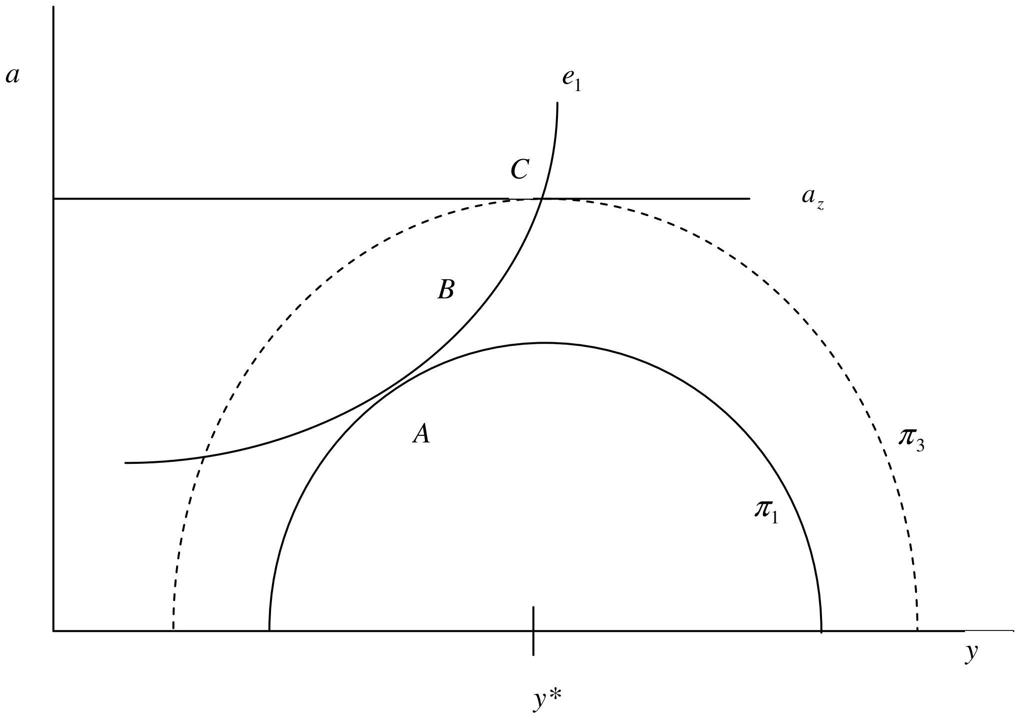


Figure 6.2. Comparison of a level standard with a minimum abatement standard.

In Figure 6.2, the minimum abatement level is set sufficiently high that a tangency between it and the iso-profit line (which must occur where the slope of the iso-profit line is zero) occurs on the e_1 line. This is at point *C*, which implies lower profits (at π_3), higher output and higher abatement. Point *B* is indicated as well, indicating that the minimum abatement standard is not only costlier than the level standard, but also costlier than the intensity standard, and while it forces more abatement effort it also induces more output and lower profits.

The comparison of points *A*, *B* and *C* reveals that the cost of a target depends not merely on how stringent it is, but also on the specific form it takes. In the case of the intensity target and the abatement requirement, the firm is being told not only how much it needs to reduce emissions by, but also *how* to reduce emissions. By adding redundant constraints in this way the cost of the policy goes up. For the purpose of achieving a certain emissions level, the simple level standard is the lowest-cost form of command-and-control, because it gives the firm the maximum freedom in responding to the target.

This analysis also shows that the shape of the marginal abatement cost function depends on the nature of the policy. The area under the *MAC* between the unregulated emissions level and e_1 is equal to the difference between the unrestricted profits π^* and the profits realized under the policy. For *A* this is $(\pi^* - \pi_1)$, for *B* it is $(\pi^* - \pi_2)$ and for *C* it is $(\pi^* - \pi_3)$. Since these are different amounts, the areas under the *MAC*'s must differ, and hence so must the *MAC*'s themselves.

6.2. Concentration Standards with Many Firms

The Helfand model only examines a single firm. We can extend the analysis to look at multiple firms, as follows (see McKitrick 2001). Consider a regulator confronting *n* firms, each indexed by *i*, each emitting a pollutant x_i in an airflow a_i. The concentration ratio is

$$r_i = x_i / a_i$$

and the emissions level can therefore be written $x_i = r_i a_i$. The aggregate concentration ratio *R* for all *n* firms is given by

$$R = \frac{\Sigma x_i}{\Sigma a_i}$$

where the summation is over *i*=1,…,*n*. The cost to the firm of abating output to a specific concentration ratio is $c^i(r)$,a U-shaped function with a minimum of zero at the value of *r* which the firm would choose without regulation. The regulator typically sets a uniform standard of

$$r_i \le r^* \text{ for all } i=1,\ldots,n$$

so as to achieve a given total concentration of the pollutant in the environment.

But suppose the regulator instead solves an optimization problem, namely, minimize the aggregate cost of achieving an aggregate concentration rate *R**. The outcome is as follows. Define $s_i = \frac{a_i}{\Sigma a_i}$, i.e. the firm's share in the aggregate airflow of all the regulated firms. Also, note that

$$R = \frac{\Sigma x_i}{\Sigma a_i} = \Sigma r_i \frac{a_i}{\Sigma a_i} = \Sigma r_i s_i .$$

The Lagrangian function is

$$L = \Sigma c^i(r_i) - \lambda(\Sigma r_i s_i - R^*)$$

Differentiating with respect to each r_i gives first order conditions:

$$\frac{\partial c^i}{\partial r_i} = \lambda s_i \qquad (6.5).$$

The left hand side can be interpreted as the firm's marginal abatement cost function defined over the concentration of pollution emissions. Note first that (6.5) implies that marginal abatement costs (defined over r_i not x_i) should *not* be equal across firms. Consequently if the regulator wishes to target the aggregate emissions concentration *R*, an economic instrument, such as a tax or tradable permits, which puts a common price on emission concentrations, will not yield the correct outcome. But a tax based on the relative shares (the s_i's) will be efficient (see McKitrick 2005). Second, note that a uniform concentration standard will not yield an efficient outcome. Since c^i is downward-sloping to the left of the minimum point, larger firms (those with large shares s_i) should operate at a higher *MAC* level, which implies a lower concentration standard; conversely firms with a small airflow should be allowed a higher concentration of contaminant in their emissions.

An anecdote reported to me by an environmental engineer will illustrate the intuition of the above result. In Ontario, incinerators are restricted to having a total hydrocarbon (THC) concentration of no more than 100 parts per million in the exhaust airflow. In a certain municipality, the garbage incinerator releases approximately 50,000 litres per minute of smoke, with the THC concentration kept within the standard. Nearby, a recycling firm developed a microwave-based process to convert used tires into useable compounds without requiring fuel-based combustion. The process generated a trivial exhaust airflow of about 2 litres per minute (about the rate of an adult breathing). But an inspection showed that the THC concentration in this flow was at least ten times the legal standard. Consequently, the recycling plant was denied a permit to operate. The consultant's intuition was that this was rather ridiculous, considering the minute volume of emissions involved. The above result confirms that an efficient set of standards would allow higher concentrations in smaller airflows, if the target is the aggregate concentration of contaminants.

6.3 Monitoring and Enforcement.

If everyone were honest all the time, or if monitoring pollution emissions were cheap and easy, we would not have a problem implementing pollution policy. Unfortunately, monitoring may be costly and/or difficult. This leads to a decision problem for the regulator: how to obtain maximum compliance subject to a budget constraint. A regulator faced with this problem soon finds it breaks down into two separate but related issues: getting firms to comply with regulations, and getting them to tell the truth about what they do.

The second challenge arises because a regulator usually needs firms to report on their own activities, just as the tax department relies on people filing honest tax returns. Any time someone fills in a form, they are reporting their activities to the government, and the presumption is that they are doing so truthfully. For that matter, any time one does *not* fill in a form, that is a kind of reporting as well. In Ontario, firms are required to report any ‘spills’ or accidental releases of controlled chemicals in the air or water. If a firm does not report a spill on any particular day, that is a kind of report, and the regulator needs to decide if it is a true report. But to inspect all firms, all the time, would require an inspection bureaucracy as large as the private sector itself, and moreover the regulator would then need to somehow ensure that the inspector makes a truthful report, which would require the inspectors themselves be monitored against bribe-taking or favouritism. Since this is both infeasible and an undesirable waste of society’s resources, we need to consider how the regulator might structure some economic incentives to encourage truthful reporting and compliance. This is a subject of ongoing research, and is one of the most interesting areas of environmental economics.

One thing we can observe right at the outset is that if the regulator finds a way to ensure truthful reporting, it also has the compliance problem licked. If firms all report their activity truthfully, they know that they will be caught and punished for any infractions, and if the penalties are severe enough, they will prefer to comply with the regulations. The tricky part is to induce truthful reporting. To accomplish the twin objectives of ensuring truth-telling and compliance the regulator needs to structure the rewards and punishments in a way that can sometime looks odd from the outside. We will see, for instance, that it sometimes may make “sense” to *punish* firms which actually are in compliance, and to *reward* firms that break the law!

6.3.1 Standard Enforcement Model

To begin modeling the problem of law enforcement, we develop a very standard crime-and-punishment model. Suppose the payoff from some crime is y, the probability of detection is π, and the fine if caught is F. The expected value of the crime is denoted V, and equals

$$V = (1-\pi)y - \pi F .$$

The crook has a $(1-\pi)$ chance of getting away with the crime and pocketing the proceeds y, and a π chance of being caught and fined F. The regulator wants to ensure that the crook does not commit the crime, so she must find a way to make the expected value negative. We can rearrange the above to show that

$$V < 0 \quad \Leftrightarrow \quad F > \frac{1-\pi}{\pi} y .$$

So the regulator wants to make F as large as possible, and π as close to 1 as possible. But from the regulator’s point of view, it is costly to raise π, and relatively cheap to raise F. Therefore the optimal strategy to control crime at the lowest possible cost is to set

$$\left.\begin{array}{r} F \to \infty \\ \pi \to 0 \end{array}\right\} s.t. \quad F > \frac{1-\pi}{\pi} y .$$

In other words, set very high fines along with a low probability of detection. However, while this might have been observed historically it is not the typical strategy today. We tend to observe the punishment variable F to be rather low and trending down over time, and a lot of resources being spent raising π. This is true in pollution policy as well, and as we will see can be explained by considering the uncertainty involved in proving guilt.

Evidence on pollution regulation has indicated that while the level of fines (or whatever measure of punishment we use), is rather low, actual rates of compliance are quite high. Inspections of firms and audits of emissions routinely show the vast majority comply with stated regulations. But those who are out of compliance tend not to be fined too heavily. Why do firms comply as much as they do, even if penalties are low?

There have been a number of recent explanations. Winston Harrington (*Journal of Public Economics* 1988) worked out a model in which firms are tagged as 'dirty' or 'clean'. Dirty firms are inspected more and fined more heavily. Clean firms are inspected less and fined less heavily, but thereafter they are considered 'dirty' until they pass a number of subsequent inspections. Under such a system, firms have an incentive to be considered 'clean'. Apart from good public relations, it is cheaper for them to face fewer inspections and expect lower fines for noncompliance. So most firms attempt to get, and stay, in the 'clean' category. As a result, when such firms are found out of compliance, they pay a small fine, but then move into the other category. This model does succeed in explaining how it could be that firms largely comply but pay small fines if they break the law. However, it has a number of problems, including the fact that, in practice, regulators have not been observed to actually use this sort of 'experience rating' system.

An alternative explanation was proposed by several other authors (Kaplow and Shavell NBER WP 3822, 1991; Malik *JEEM* 1993). They argue that regulators want to encourage truthful self-reporting by firms in order to cut down on their inspection costs. So they set two different fines: F_1, for firms that truthfully report noncompliance, and F_2 for firms that report compliance but are found to have actually been out of compliance. If the probability of detection is π, the regulator the fine system such that

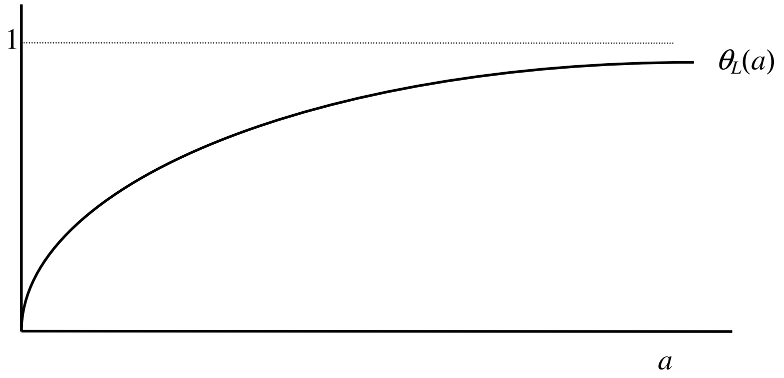
$$F_1 \le \pi F_2$$

so that truth-telling is the better strategy. In this case it is better to make F_1 very small, so that π does not have to be so big. In fact, if the regulator wants to maximize the chance that firms will tell the truth, it should set F_1 equal to zero, or even negative. Then it would be rewarding firms who break the law but confess afterwards. This may turn out to ensure greater compliance and lower enforcement costs.

6.3.2. Regulation with Random Pollution and Uncertain Inspections

There are other complications that need to be considered. Firms may not have complete control over their emissions, i.e. there is still a possibility of random noncompliance, and inspections are not entirely accurate. Examining these issues requires some additional notation. The following section is based on Malik's 1993 JEEM paper.

Suppose a firm can have one of two emission levels: low (e_L) or high (e_H). The firm puts abatement efforts a into keeping its emissions low, but can only affect the probability of having low emissions, which is called $\theta_L(a)$. The probability of maintaining low emissions is a concave function of effort *a*:



The firm files a report *r* indicating it had either low emissions (*r* = *L*) or high emissions (*r* = *H*). The regulator takes action as follows.

- If the firm reports high emissions it pays a fine F_H .
- If the firm reports low emissions it pays a fine F_L , and it is selected with probability π for an audit. Audits are assumed to be expensive so the regulator would like to keep the audit frequency as low as possible. The outcome of the audit is a report indicating either low or high emissions, and depends on the firm's true emissions:
    - If the firm truly has low emissions, there is a probability q_L that the audit will report this, and a probability (1-q_L) that the audit will report high emissions.
    - If the firm truly has high emissions, there is a probability q_H that the audit will report this, and a probability (1-q_H) that the audit will report low emissions.
- If the audit reports low emissions the firm pays no additional fine.
- If the audit reports high emissions the firm pays an additional fine F_X for having cheated on its report.

The policy problem is to induce truth-telling. If firms who know themselves to have high emissions are to prefer telling the truth, it must be the case that the expected fine for reporting *L* is reported is greater than the certain fine of reporting *H*. This requires:

[fine for reporting *L*] + [expected fine from being audited and found in state *H*] > F_H

which works out to be

$$F_L + \pi q_H F_X > F_H \qquad (6.6).$$

Also, if firms who know themselves to have emissions *L* are to prefer saying so, it must be that:

[fine for reporting *H*] > [F_L] + [expected fine if audit mistakenly reports *H*]

which is written out as

$$F_H > (1-\pi)F_L + \pi(F_L + q_L \cdot 0 + (1-q_L)F_X)$$

or

$$F_H > F_L + \pi(1-q_L)F_X \qquad (6.7).$$

Suppose both (6.6) and (6.7) hold. Then firms will prefer to tell the truth no matter whether their emissions are low or high. What is the cost for the firm of making a unit of abatement effort under this condition? Suppose the abatement cost function is $C(a)$. Expected total costs will be:

$C(a) +\ \theta(a)$ [expected fine under *L*] + $(1-\theta(a))$ [fine under *H*]

which is written as

$$C(a) + \theta(a)\left[F_L + \pi(1-q_L)F_X\right] + (1-\theta(a))F_H\ .$$

The firm wants to choose *a* to minimize this, which yields a first order condition:

$$C'(a) = \theta'(a)\left[F_H - (F_L + \pi(1-q_L)F_X)\right].$$

If this yields an interior solution (*a*>0), it must be the case that the term in the square brackets is positive. This in turn implies

$$F_H > F_L + \pi(1-q_L)F_X$$

which is equation (6.7) again. So as long as the firm is engaging in positive levels of abatement effort we are certain (6.7) holds, which means that the firm will tell the truth if it has emissions *L*. The only reason it would lie about having low emissions is if there was such a high chance of a false accusation about lying that it would prefer to just pay the fine F_H and avoid being audited. In this case it won't bother with abatement effort.

It is a trickier matter to ensure (6.6) holds, i.e. that the firm always tells the truth when in state *H*. We can rearrange the expression to yield

$$\pi > \frac{(F_H - F_L)}{q_H F_X} \qquad (6.8).$$

Notice that the higher the regulator sets F_H, the higher the probability of audit π must be set. This is a consequence of the need to induce firms to tell the truth. Thus we expect fines for firms telling the truth about noncompliance not to go 'too high'. The higher F_L is set (assuming it is less than F_H) the lower we can set the audit probability π, but we also need (6.7) to hold, and it is less likely to hold the higher is F_L. Hence the fines for truthfully reporting low emissions should also be kept small. The penalty for being caught cheating, F_X, should be set as high as possible in order to minimize the need to audit firms. Finally, the less accurate are the audits of firms with high emissions the lower will q_H be, and consequently the audit probability must be higher.

At this point we have shown that the regulator should set only modest penalties for firms that tell the truth, which is why one occasionally hears complaints about how polluters are paying rather small fines for accidental spills and other forms of noncompliance. As long as the truth-telling constraints are working, we should expect to observe low fines: the key is whether we also observe high compliance and self-reporting of non-compliance.

One additional, and unexpected result, is the problem of 'credible commitment'. It arises because the audits are not entirely accurate. Suppose a regulator implements the scheme outlined above, and ensures that conditions (6.6) and (6.7) hold. Then a firm reports *L*. It is audited, and the audit comes back *H*. What to do? The regulator is caught in a dilemma:

- The structure of the policy guarantees that the firm was telling the truth
- The audits are known to make mistakes sometimes.

Therefore the regulator should ignore the audit and let the firm off the hook.

But if she does this, *she will change the structure of the policy in such a way as to destroy the incentives that got the firms to tell the truth in the first place*. Therefore,

- She must impose the fine, even though she knows the firm is innocent!

Did you follow that? The policy design induces truthful reporting. So why bother auditing? Because without the threat of the audit ($\pi > 0$) firms will not tell the truth. But the audit is not precise. So the regulator may occasionally have to knowingly fine an innocent firm. This raises the problem of credible commitment: can the regulator *really* commit to such a policy? It is hard to say, but it is not likely that the regulator could stay permanently committed to such a policy.

Is there a way around the commitment dilemma? One suggestion might be to increase the accuracy of the audit, for instance by ordering a second one. Suppose the regulator sets an audit probability π using equation (6.8):

$$\pi = \frac{(F_H - F_L)}{q_H F_X}.$$

Then one day a firm reporting low emissions ($r = L$) is audited and the result comes back H. Knowing the audit is probably wrong the regulator orders a second audit. But that departs from the policy structure that originally implied equation (6.6). If a second audit is ordered in the event of a finding of H for a firm reporting L, we could show equation (6.6) should read

$$F_L + \pi(q_H)^2 F_X > F_H \qquad (6.9).$$

This implies the audit probability should be

$$\hat{\pi} > \frac{(F_H - F_L)}{(q_H)^2 F_X} > \frac{(F_H - F_L)}{q_H F_X} = \pi$$

As long as $q_H < 1$ we will have $\hat{\pi} > \pi$. That is, if the regulator plans to use a second audit to verify the first one, then the probability of being audited in the first place must be higher, or else the truth-telling constraints will not hold. If firms merely *expect* that the regulator will go to a second audit, truth-telling constraints may not hold. Also, the two-audit structure increases costs for the regulator. Not only do more firms need to be audited, but there is also the cost of the second audits.

So there isn’t an easy answer here. If audits are not 100% accurate, the regulator will eventually run into the credible commitment dilemma. The outcome will either be a weakening of the truth-telling incentives or an attempt to prosecute a firm that the regulator does not think is guilty. If a firm truly has L emissions then the expected fine for reporting L is (writing it out in long form):

$$(1-\pi)F_L + \pi(F_L + q_L \cdot 0 + (1-q_L)(q_L \cdot 0 + (1-q_L)F_X))$$

which means equation (6.7) changes to

$$F_H > F_L + \pi(1-q_L)^2 F_X.$$

The expected size of the unfair fine drops at the rate $(1-q_L)^2$. If audits are 80% accurate then instead of a 20% chance of an unfair fine there will only be 4% chance. However this improvement in the system comes at the cost of more audits.

We noted earlier on that a simple crime and punishment model suggests the cheapest regulatory strategy would be a low probability of detection and very high penalties. But now we can begin to see why legal systems have tended in the opposite direction. Courts try to minimize the chance of a false conviction. Knowing that investigations are not 100% accurate, the 'audit' process (which can be viewed as the investigation/prosecution process) tends to get more thorough over time. As in the above model, the result is relatively high compliance rates, relatively low penalties with severe penalties reserved for those who deny being out of compliance but are convicted anyway, increasing 'audit' probabilities (i.e. increased policing and investigation activity), and occasionally the need for a prosecutor to press charges against individuals he or she is not really sure are guilty.

Chapter 7: Tradable Permits and Quotas

7.1. The Competitive Case

In much of the discussion so far we have treated environmental policy as a pricing problem in which we put a tax τ on emissions. If τ is set equal to marginal damages (evaluated at the optimal emissions level) then the result is cost-effective (the equimarginal criterion holds) and efficient (marginal damages equals marginal abatement costs). A firm paying a tax τ on each unit of emissions e will choose emissions to maximize net profits

$$\pi(e) - \tau e$$

which occurs at a point $\hat{e}$ where

$$\pi'(\hat{e}) = \tau \qquad (7.1)$$

i.e. where the tax equals marginal abatement costs (see Sct. 4.2). Now suppose the firm does not pay a tax τ, but instead has to hold a permit Q for each unit of emissions, and permits can be bought and sold for a price P. This ought, in principle, to yield a symmetrical result. The firms' problem now is

$$\max_{e} \pi(e) - PQ \text{ subject to } Q=e.$$

Substituting e for Q gives us the same result as (7.1):

$$\pi' = P\,. \qquad (7.2)$$

The symmetry between the instruments is expressed as $Q = \hat{e} \Leftrightarrow P = \tau$. Hence the policymaker can control either price (i.e. set a tax on emissions) and let the market determine the quantity, or control the quantity (by issuing a set number of permits) and let the market determine the price, and either method can generate the same outcome.

Tradable permits yield an equimarginal outcome because if any two firms have differing *MAC*'s then they have an incentive to exchange permits. For instance, suppose firm *A* has an *MAC* of \$100, and firm *B* has an *MAC* of \$50, then it would be mutually beneficial for *A* to purchase an emissions permit from *B* for, say, \$75. This requires *B* to reduce emissions by one unit, but it is getting paid \$75 to do something that costs it \$50, so it comes out ahead. The extra credit means firm *A* can increase emissions, earning \$100 to do so, at a cost of \$75 for the permit, so it too comes out ahead. As long as *MAC*'s differ between them, any two firms will be able to find a mutually-beneficial trade. Thus, market equilibrium implies the equimarginal criterion must hold: *MAC*'s are equal across emission sources. If the number of permits Q is set equal to the optimal emission level E^* the outcome will be efficient as well.

The outcome of a permits market also provides important information since it reveals firms' *MAC*'s. If the regulator knows the *MD* curve then the market price of permits can be used to assess whether the supply of permits is too high (*MD*>*MAC*) or too low (*MAC*>*MD*).

7.1.1 The US Sulfur Market

The most famous tradable permit system in the world is the US sulfur dioxide market. Its first phase began as a provision of the 1991 US Clean Air Act Amendments. As of 2000 it covered all power generating plants over 25 Megawatts.[5] For many years permit prices were rather low, at around \$100/ton. But as shown in Figure 7.1, that has changed dramatically in recent years, with prices running over \$1,000 per ton as of November 2005 (today's price is \$1,380 per ton—Nov 30 2005).

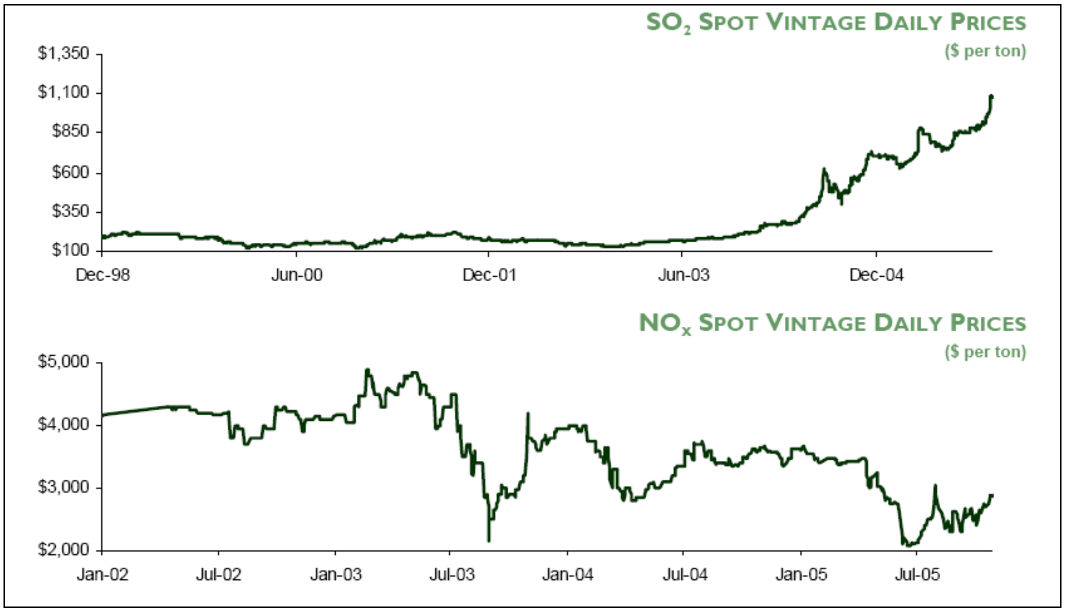


Figure 7.1. Top: Sulfur Dioxide permit prices in US market. Bottom: Nitrogen Oxides permit prices in US market.
Source (accessed November 30 2005):
http://www.chicagoclimatex.com/news/publications/pdf/CCXQ_Fal05.pdf.

The EPA runs an annual auction in which 150,000 permits are sold (the EPA calls them 'allowances'), each one allowing 1 ton of emissions. Most permits (currently just under 9 million tons) are given away free to established emitters. Joskow *et. al* (1998) took the auction data from some of the permit auctions and drew bid-ask curves, showing how many allowances were bid for at a descending menu of prices. These reveal the marginal abatement cost (*MAC*) curves for polluters. As long as bidding for permits is competitive, it can be expected that firms will be willing to pay for permits only up to the

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[5] http://www.epa.gov/airmarkets/arp/allfact.html#how.

point where the cost of an additional permit is equal to the marginal benefit of the permit (which is the cost of marginal emissions abatement).

In 1997 a total of approximately 10.6 million permits were issued, of which 150,000 were auctioned and the rest were given to existing emitters. This is shown in Figure 7.2 as the Initial Supply curve. The backstop price is $2,000, which point firms can pay as an emissions tax in lieu of holding permits, making it an effective cap on the permits price.

The market clearing price in the 1997 auction was $106.75. The EPA estimates that in the absence of the SO_2 emission controls, 15.1 million tons of sulfur would have been emitted in 1997 (EPA 1995, Table 3-1). Presumably, in the absence of a control requirement, the price of permits would be zero. This gives us two points on the market *MAC* curve. A straight line joining (15.1, 0) and (10.6, 106.75) has the (approximate) equation

$$MAC_1 = 359 - 23.8E \tag{7.3}$$

where *E* measures sulfur emissions in million tons and *MAC* is measured in US dollars. Equation (7.3) is graphed in Figure 7.2 as the blue dashed line ("Initial Demand").

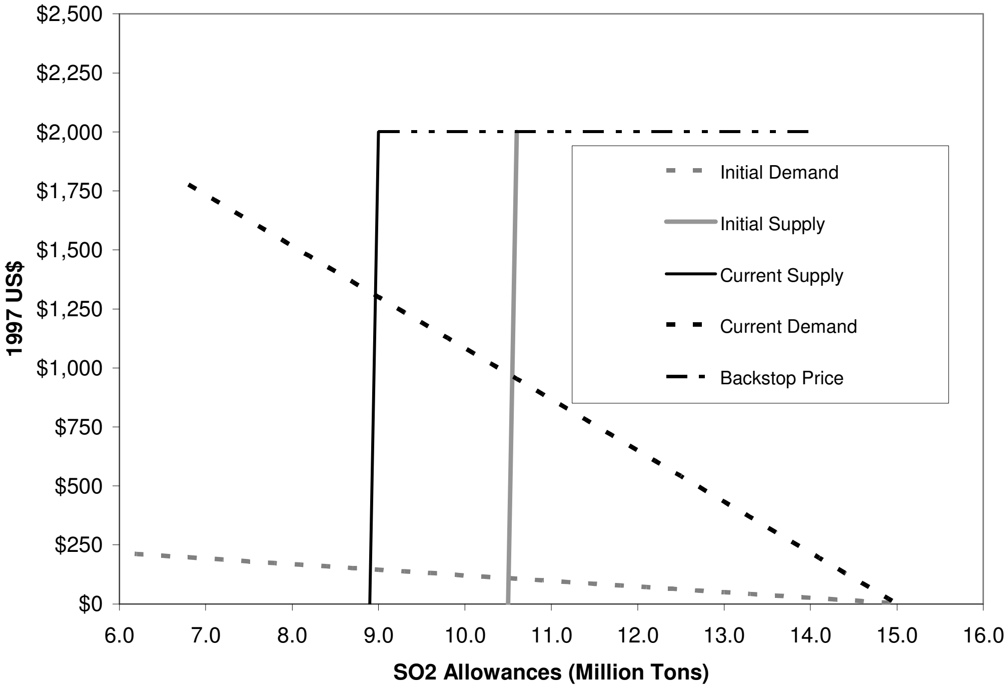

Figure 7.2 Estimated MAC for US sulfur emissions from plants covered by EPA SO2 Allowance market.

Industry and EPA forecasts were for permit prices between $750-1,000 per ton, so the low prices observed in the initial years of the market were unexpected. It turned out that switching to low-sulfur coal and improving abatement technology was less costly than had been anticipated.[6]

In Phase II of the program, starting in 2000, allowable emissions were reduced to approximately 9 million tons annually ("Current Supply", solid black line). The *MAC* curve ("Initial Demand") implies a market price of about $150, which remained the case for several years.

Some of the smoothness of the price at the 2000 supply shift was due to "banking" of permits. Firms are permitted to buy permits for use up to 7 years ahead. By the year 2000 firms had banked 11.4 million tons of permits.[7] In effect they were emitting less than they held allowances for, and in the years to follow they emitted more than they had (current) permits for, thus drawing down their permit reserves.

However since early 2003 the *MAC* has swung upwards to the "Current Demand" line, where the market price is getting close to $1,400, approaching the backstop price at $2,000. This is due to several factors. In 2003 the US EPA began discussing measures to further reduce air emissions and in January 2004 released what would later be entitled the Clean Air Interstate Rule, requiring emission reductions of up to 70 percent in many eastern states by 2015. Firms have begun buying up permits already in anticipation of tighter market conditions in years ahead. Also, strong demand for energy has caused an expansion of the demand for permits. Some market analysts forecast that prices will drop in the years ahead, as many firms are working quickly to build and install new scrubbers.

One lesson from the US market is that the MAC curve is not static. Regulators must have some idea of what market price they consider reasonable before writing down rules for tradable permits markets. In the case of the US system, the backstop price of $2,000 means that the permits supply function becomes horizontal. But it is worth questioning whether marginal damages really are as high as even half that.

The combination of a permits supply plus a backstop tax is sometimes called a "hybrid" instrument. In Section 5.2 we looked at the choice between taxes and permits when the MAC and MD curves are uncertain. As shown in an analysis many years ago by Roberts and Spence (1977), a combination of tax, subsidy and permits can provide a better option than one instrument alone.

Suppose the regulator offers permits for sale with the following rules:

- L permits will be sold
- Firms can opt to pay the tax τ instead of holding a permit for a ton of emissions
- The regulator will buy back permits at the price s.

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[6] See http://yosemite.epa.gov/ee/epa/incsave.nsf/0/e8448f37d3eeb89b85256636004f926e?OpenDocument (accessed Nov 30 2005).

[7] See http://www.emissionstrategies.com/SO2/SO2MarketEconomics.htm (accessed Nov 30 2005).

The outcome of this arrangement is illustrated in Figure 7.3. The (vertical) supply curve is at emissions *L*. No one will bid more than τ per unit of emissions since they can pay that as a tax instead. And no one will sell permits for less than *s* since they can sell them back to the government for that amount. So the supply function is capped, top and bottom, as shown.

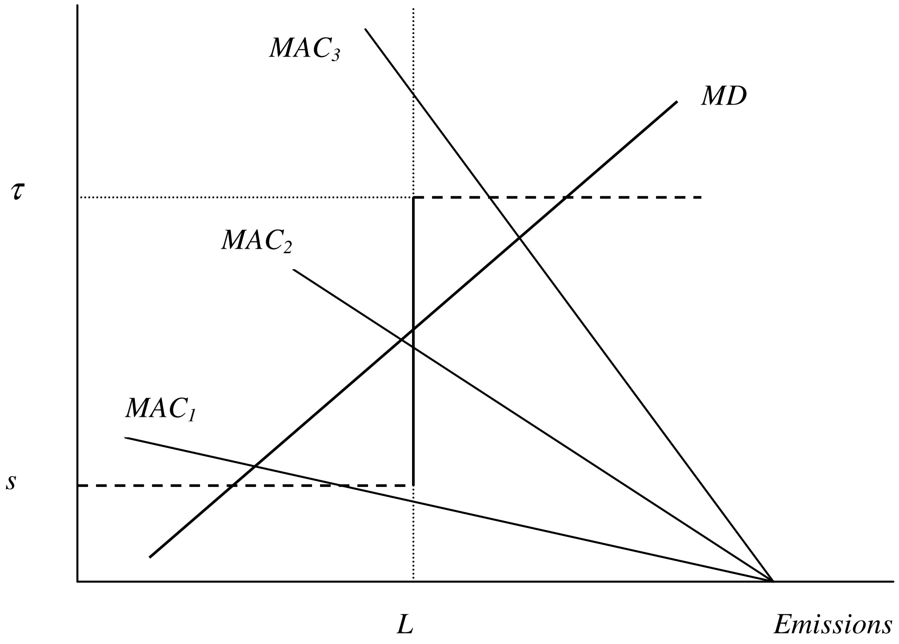

Figure 7.3: Hybrid Instrument

Now suppose we don't know which MAC curve it the right one, or we might have an estimate of MAC_2 at the moment but we anticipate it may change up or down depending on economic and technology changes in years ahead. If we are committed to emissions at *L*, the market equilibrium is pretty close to the optimum, given the position of the *MD* curve. But we run two risks. If abatement becomes much cheaper, falling to MAC_1, we would want to have emissions go down below *L*. If abatement becomes more expensive, rising to MAC_3, we would want emissions to rise above *L*. But in practice it may be legally difficult for a regulator to adjust the volume of permits or the tax rate on emissions. That's where the tax/subsidy hybrid policy can help. By offering to buy emission permits back at a price *s* firms have an incentive to reduce emissions below *L* when abatement costs fall. And by offering to let firms pay the tax τ instead of holding a permit, it allows emissions to grow if the *MAC* curve moves far enough out to justify it. In Figure 7.3 you can identify the optimum emission levels associated with the MD curve and MAC_1 – MAC_3, and see how the hybrid instrument yields tracks the optimum more closely than would a pure permits auction at a quantity of *L* or an emissions tax of τ, each of which could, on their own, cause very large departures from efficiency.

Practice Questions

1. Suppose $MD = 2E$
   and $MAC = 20 - E$.

   The government sells Q = 10 emission permits. It also sets a 'backstop' emissions tax at $T = 7$. That is, firms can either hold a permit or pay the fee to emit. What will be the outcome of this policy, and how would it compare to the optimal outcome?

ANSWER

The optimum is given by $MD = MAC$

$$20 - E = 2E$$

which implies $E^* = 6\tfrac{2}{3}$. At this emission level the MAC is $13\tfrac{1}{3}$. But firms won't pay this much for a permit since they can pay the tax instead. So they emit where MAC = 7, which is E= 13.

Hence firms buy 10 permits at $7 and emit 3 more units, paying the price of $7 per unit. Emissions are approximately double the optimum. The social welfare loss can be shown to be $6\tfrac{1}{3}\times 6\tfrac{1}{3}+\tfrac{1}{2}\times 6\tfrac{1}{3}\times 6\tfrac{1}{3}$ (from looking at the areas of the relevant triangles).

2. Suppose the $MD = \tfrac{1}{3}E$ and there are two firms with MAC's of $MAC_1 = 100 - \tfrac{1}{2}e_1$ and $MAC_2 = 150 - e_2$. Note that $E = e_1 + e_2$. Prove that the unregulated emissions level is 350. Prove that the optimal emissions level is 175, and that if an optimal tradable permits system were in place, firm 1 would emit 250/3 units and firm 2 would emit 275/3 units.

ANSWER:

Since the solution involves $MAC_1 = MAC_2 = MD$ set all three equal to m. Then invert the MACs and add them:

$$\begin{array}{l} e_1 = 200 - 2m \\ \underline{e_2 = 150 - m} \\ E = 350 - 3m \end{array}$$

Now substitute in the MD curve to get

$$E = 350 - E \Rightarrow E^* = 175.$$

Sub 175 into the MD curve to get m = 175/3. Then sub this into the expressions for e_1 and e_2 to get the answers.

3. One important application of tradable permits is called *banking*, in which a firm can purchase permits today to be used at some point in the future. Suppose there is an industry which releases a pollutant *e*. In 4 years the pollutant will be banned entirely and no emissions will be allowed (with or without a permit). At present, emissions are unregulated. The firm's profit function with respect to emissions is

   $$\pi(e) = 100 + 100e - \tfrac{1}{2}e^2 .$$

   The regulator announces a plan to phase out emissions according to the following schedule.

Year	Total Allowable Emissions
1	75
2	50
3	25
4	10

   and 0 thereafter.

   So, for instance: for 1 year starting today, the firm can emit 75 units. Then in the year after that, the firm can emit 50 units. And so forth.

   Consider the discount rate to be zero. Banking would allow the firm to emit less than the allowable limit in one year, and save the unused allowances in order to emit more than the allowable limit in another year. Assume that emissions after year 4 are not permitted even if the firm holds a permit. Calculate the optimal banking strategy for this firm, and the amount it saves compared to the no-banking case. Explain your answer.

4. Suppose we have $MD = 2E$ and $MAC = 200 - 2E$. If we are uncertain about the positions of the MD and MAC curves, would a price instrument be preferred to a quantity instrument in order to minimize the social welfare costs of making a mistake?

   Now suppose the government auctions 50 permits, and also sets a backstop price of \$80, meaning that firms could pay the fee of \$80 per unit of emissions rather than hold a permit. What will be the outcome? Contrast it graphically with the optimum.

5. Suppose a firm has an MAC given by $MAC = 1000 - E$. Currently, emissions are unregulated. The government plans to phase out all emissions over the next 4 years. It announces a schedule of annual allowable emissions, but the firm is permitted to bank permits, meaning that if it emits less in one year than it holds permits for, it can save the unused permits for use in a subsequent year. The schedule is as follows:

Year 1	Year 2	Year 3	Year 4
1,000	700	400	0

   After Year 4 the pollutant is banned outright and permits from earlier years cannot be used.

Also, the regulator announces a "backstop price" of \$600, meaning that if in years 1—4 the firm wants to emit more than it holds permits for it can do so at a cost of \$600 per unit.

Derive the firm's optimal banking strategy, its level of emissions in years 1—4, and the amount paid in "backstop" charges, if any. Assume the firm uses a discount rate of 0.

7.2 The Problem of Market Power

In settings where one or more firms may exert market power, the tradable permit system may have a disadvantage over emission taxes due to the ability of a large firm to manipulate the price. A uniform emissions tax is equivalent to a perfectly elastic permits supply function, which precludes price manipulation by the buyers unless the policymaker has previously committed to a pricing rule that ties price to quantity. But if permits are sold in the market then a large buyer can potentially crowd out other firms in order to gain financially. This problem was explored by Hahn (1984) in a model of a dominant player-competitive fringe.

Suppose there are m firms and all firms but one (indexed #1) are price takers. The regulator distributes L permits. Firm i gets Q_i^0 permits where the superscript *0* denotes the initial holdings. The firm buys or sells permits, and after trading holds Q_i permits. The market price of permits is denoted P.

Each firm has a profit function $\pi^i(e_i)$, which is expressed as a function of emissions. Since firms must hold one unit of permits for each unit of emissions we can rewrite it as $\pi^i(Q_i)$. Firms 2,…,m are price takers, so by (7.2) they operate where

$$\frac{\partial \pi^i}{\partial Q_i} = P \qquad (7.4),$$

which implies that there are $m - 1$ permit demand functions of the form

$$Q_i(P),\ i = 2,\ldots,m.$$

The dominant player does not choose an emissions quantity in this case, it choose the optimal permits *price*. Recognizing its influence on the market price it solves

$$\max_P \pi^1(Q_1) - P(Q_1 - Q_1^0)$$

subject to the market clearing constraint

$$L - \sum_{i=2}^{m} Q_i(P) = Q_1 \qquad (7.5).$$

Substituting the constraint into the objective function and differentiating yields first order conditions

$$-\frac{\partial \pi^1}{\partial Q_1}\sum_{i=2}^{m}\frac{\partial Q_i}{\partial P} + P\sum_{i=2}^{m}\frac{\partial Q_i}{\partial P} - \left(L - \sum_{i=2}^{m} Q_i - Q_1^0\right) = 0 \qquad (7.6).$$

We will denote the firm's privately optimal price $\tilde{P}$. Collecting terms in (7.6) gives us

$$\frac{\partial \pi^1}{\partial Q_1} = P \Leftrightarrow Q_1^0 = L - \sum Q_i(P) \qquad (7.7).$$

This tells us that if the dominant player's initial allocation (Q_1^0) equals the amount it would choose to buy under a trading system in which it controls the price, then its *MAC* will equal *P*, and since, by (7.4), this is also true of all the other firms then the outcome satisfies the equimarginal criterion. We will denote the price in a competitive, equimarginal outcome *P**.

That means the presence of the dominant player does not preclude a cost-effective outcome, but only if the regulator is able to forecast the exact right number of permits to give the large firm. If the large firm ends up buying or selling permits, that indicates that it did not receive its *ex post* optimal number of permits and the cost-effective outcome will not be attained.

In that case, we can ask what would happen if the amount of permits assigned to the dominant player goes up or down. Note that firm 1's optimal profits depend on its choice of *P*, its permit endowment Q_1^0 and the total number of permits *L*, hence we can write it as $\pi^1(P, Q_1^0, L)$. It optimizes profits at the point where $\pi_P^1 = 0$ (the subscript denotes a derivative), and we can differentiate the first order condition to obtain

$$\pi_{PP}^1 \partial P + \pi_{PQ}^1 \partial Q_1^0 + \pi_{PL}^1 \partial L = 0 \qquad (7.8).$$

We can assume *L* is constant. Also, note that π_{PQ}^1 is the derivative of (7.6) with respect to Q_1^0, which equals 1. Using these and rearranging (7.8) yields

$$\frac{\partial P}{\partial Q_1^0} = -\frac{1}{\pi_{PP}^1} \qquad (7.9).$$

Since the firm is optimizing profits $\pi_{PP}^1 < 0$, so (7.9) implies that the higher the initial endowment to firm 1, the higher will be the equilibrium price.

The total benefit of emission is the sum of the profit functions. For firms 2,…,*m*, their permit usage is a function of *P*, as implied by (7.4). The policy objective is to maximize this subject to the emissions constraint (7.5). Suppose firm 1 considered all firms' profits along with its own. It would then choose *P* to maximize the total industry profits subject to the emissions constraint. Substituting (7.5) into the objective function yields the unconstrained maximization problem

$$\max_P \pi^1(P, Q_1^0, Q_1 + \Sigma Q_i(P)) + \Sigma \pi^i(Q_i(P)) \qquad (7.10)$$

where the summation Σ is over firms 2,…,*m*. The first order condition is

$$\frac{\partial \pi^1}{\partial P} + \frac{\partial \pi^1}{\partial L}\sum \frac{\partial Q_i}{\partial P} + \sum \frac{\partial \pi^i}{\partial Q_i}\frac{\partial Q_i}{\partial P} = 0$$

$$\Rightarrow \frac{\partial \pi^1}{\partial P} = -\sum \frac{\partial Q_i}{\partial P}\left(\frac{\partial \pi^1}{\partial L} + \frac{\partial \pi^i}{\partial Q_i}\right) \qquad (7.11).$$

Since for each firm emissions are a decreasing function of permits price *P* and profits increase with emissions, the expression on the right side must be positive (noting the minus sign in front of the summation). Hence the competitive price *P** would be where

$$\frac{\partial \pi^1}{\partial P^*} > 0 \qquad (7.12).$$

If firm 1 did not optimize the profits of the rest of the industry it would choose a price $\tilde{P}$ where $\pi_P^1 = 0$. Since the profit function is concave, (7.12) implies the competitive price *P** is less than the distorted price $\tilde{P}$.

7.3 Auction versus Quotas

Looking back at Figure 7.2, the current volume of US sulfur permits is 9 million, and the price is about $1,250 per ton. This implies the total market value is around $11.3 billion and the Total Abatement Cost can be approximated as the area under the MAC up to 15 million tons, which is $3.75 billion (assuming a current market price of $1,250). Some advocates for tradable permits point to the $11.3 billion market as an argument for setting up tradable permits for other types of air emissions, such as CO_2. You might hear people say things like: "The market for CO_2 emission permits could be worth a trillion dollars globally by 2010. Unless the US ratifies the Kyoto Protocol it risks being shut out of this valuable market."

The statement doesn't actually make sense, since the market value of the permits only arises due to the limits on emissions, which are costly for society to impose. The $11.3 billion permits market represents the rental values of the permits. It is not new wealth, it is a transfer of capital valuation away from the shares of the firms doing the emitting, towards the holders of the emission permits.

In the absence of the emission limits imposed by the permits market, the MAC would be zero and the profits of the emitters would be higher. This would be reflected in their share prices. Now imaging imposing a tradable permits system in which 9 million permits trade at $1,250 each. Total Abatement Costs are $3.75 billion, which comes off the market value of the firms (ignoring for a moment the difference between the annual and the accrued-perpetual costs). $11.275 billion in share value is shifted away from the firms doing the emitting, towards the holders of the permits. If the owners of the firms are assigned the permits, this transfer leaves them no worse off. If the permit recipients are not the same as the emitters' shareholders, then wealth is transferred. But at no point is new wealth created by the policy.

If the reduction in emissions generates benefits that exceed the costs, then the policy would pass a social welfare cost-benefit test and would be worth implementing. But that is a different analysis than simply pointing to the volume of trading on the permits market and thinking that the $11.3 billion represents a "new" market, or an overall economic opportunity. If that were true, we could make ourselves arbitrarily wealthy by limiting all sorts of activities. We could issue tradable permits for eating in restaurants, buying books, owning a television, etc. Such permit markets would be worth many billions of dollars (assuming the limits could be enforced), but it would not be new wealth. It would be a reallocation of existing wealth into the hands of whoever received the initial allocation of permits, along with a deadweight loss reflecting the difference between the total cost of the reduction in (say) restaurant visits and the total value of the restaurant permits market.

By imposing an artificial scarcity on emissions, the tradable permit market creates "scarcity rents" which equal the permit price times the number of permits. However, scarcity rents are created by any policy that limits a valuable activity. If the emission limits were imposed in the form of standards, rents would still be created, it would just be harder to identify them because the policy does not create the data necessary to value them. In the case of the US sulfur dioxide market we know the price because it is observed in daily trading. This makes it easy to estimate the size of the scarcity rents, but it does not imply that scarcity rents are only created by a permits system.

The question of what happens to the scarcity rents is very important for evaluating the overall cost of emissions control policy. If the rents are not captured, they accrue to whoever gets the permits. If the government hands out the permits free of charge then the holders of permits get the rents. If the government auctions all the permits to the highest bidders, the government collects the rents and can use them to generate social welfare by lowering other taxes. In principle, the second approach should have a lower social cost than the first one, even though the outcome in terms of emissions control is the same.

Some authors distinguish these two cases by referring to freely-distributed permits as "quotas", as opposed to "permits" or "credits" which are auctioned off. In principle, the economic costs of quotas are higher than (auctioned) permits because the rents are not captured by the government, and hence cannot be used to improve welfare by reducing other taxes. The two systems are identical in economic terms if we compare quotas to auctioned permits where the proceeds from the auction are handed out as a lump-sum to households, or if the economy happens not to have any tax distortions. Barring these two unlikely situations, quotas are costlier to implement than auctioned permits or emission taxes. This is a relatively new topic in environmental economics, and to explore it further requires developing some models of tax policy, which is done in the next chapter.

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Chapter 8: Emission Taxes in Partial and General Equilibrium

8.1 Introduction: Deadweight Loss

It will be helpful to begin with a review the basic terminology of taxation and deadweight loss. In Figure 8.1 we have a standard demand-supply diagram.

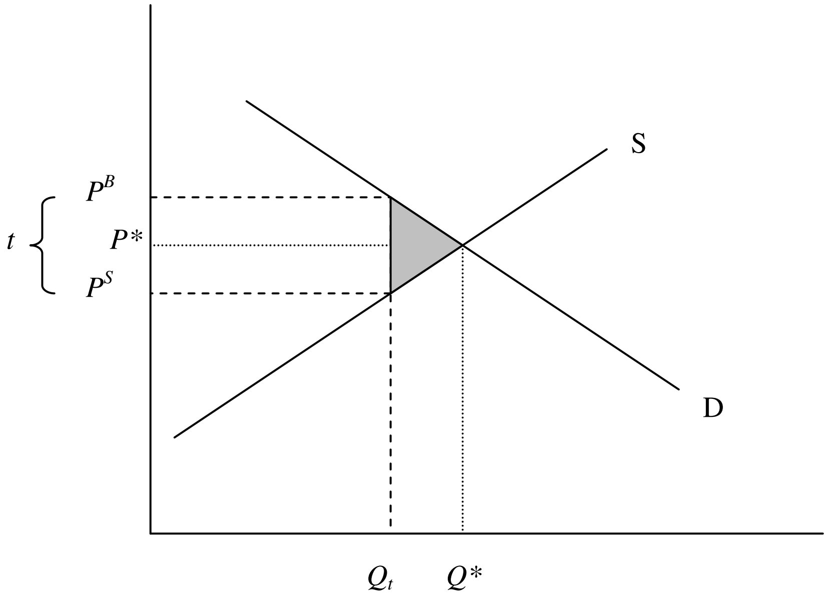

Figure 8.1 Deadweight Loss

The initial competitive equilibrium is at Q^*. Adding the unit tax t causes the buyer's price to rise from P^* to P^B and the seller's price to fall to P^S, and the new equilibrium is at Q_t. The deadweight loss is the shaded area, representing the loss in consumer surplus and producer surplus which does not accrue as revenue for the government. The deadweight loss is often referred to as the "excess burden" of the tax system, and if the tax rate is raised the additional deadweight loss is the "marginal excess burden" or MEB. It can be shown that with linear demand and supply lines, the MEB rises with the square of the tax rate. A related term is the "Marginal Cost of Public Funds" (MCPF). This is the welfare cost per dollar of additional revenue. Recent estimates of the MCPF in the US range from 1.2 to 4.0 for many of the principal revenue-raising taxes (see Browning *AER* 1987; Fullerton *AER* 1991). A MCPF of 1.2 implies that $1.20 of consumer and producer surplus must be destroyed for every $1 of public revenue at the margin.

8.2 Revenue Recycling and Tax Interaction Effects

That, more or less, is the standard public finance view: taxes cause welfare losses over and above the revenue they raise, by driving a wedge between buyers' and sellers' prices. But environmental economics offers an alternative story: a tax on marginal damages due to externalities *improves* welfare, by internalizing the social cost of emissions. It didn't take long before people suggested that these two results ought to be put together. Suppose we levy environmental taxes, which raise money and improve welfare. We could then use the money to reduce other, distorting taxes at the margin, which reduces the excess burden of the tax system and hence provides an additional increase in welfare. This is called the 'double dividend' argument: environmental taxes provide two benefits, one from reducing pollution, the other from reducing distortions in the tax system (assuming the revenue from pollution taxes is 'recycled' by reducing other tax rates). Applying this logic to a simple tax reform model, Lee and Misiolek (*JEEM* 1986) concluded that environmental taxes should typically be higher than marginal damages. In its more extreme form, the double dividend hypothesis was sometimes held to imply that *any* environmental tax is welfare improving, even if we don't know what are the benefits of reducing pollution, since the pollution tax reduces environmental damages while tax revenues allow for a reduction in the excess burden of the rest of the tax system.

The flaws in this argument were quickly discovered. It is not the case that *any* reduction in pollution improves net welfare (it depends on the MAC as well), and in addition, taxes on polluting goods exacerbate the excess burdens of other taxes. This latter point is rather subtle and was missed for a while. The so-called "tax interaction" effects may equal or exceed the "revenue recycling" benefit from reducing other taxes.

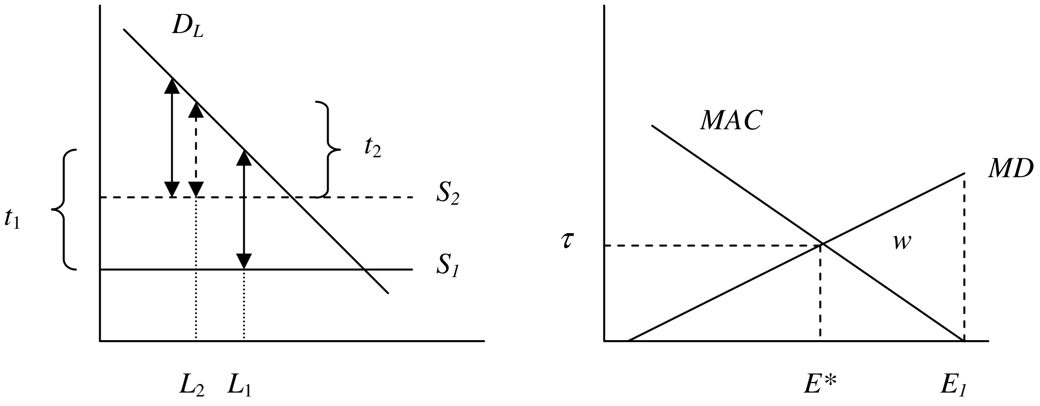

Figure 8.2 Tax Interaction and Revenue Recycling Effects

Figure 8.2 illustrates the point as follows. The labour market is in the left diagram and the pollution is in the right diagram. The story on the right side is the conventional one: an emissions tax τ is levied, causing emissions to fall from E_1 to E^*, increasing welfare by w and generating tax revenues τE^* for the government. The story on the left side begins with an elastic labour supply S_1, a downward-sloping demand for labour D_L, a labour tax t_1, and an equilibrium in the labour market at L_1. There is a deadweight loss associated with this outcome, though the triangle is not labeled to keep the diagram from getting too cluttered.

At first glance we might expect that the emissions tax revenue τE^* could be used to finance a reduction in the labour tax rate from t_1 to t_2. On its own this would generate an additional welfare gain. This is the “revenue recycling effect.” But the emissions control policy increases the cost of consumption, which reduces the real wage rate. Since the opportunity cost of leisure falls, the labour supply curve shifts up, indicating that a higher nominal wage must be offered to induce the same supply as before. So the labour supply curve shifts up from S_1 to S_2 and the new labour market equilibrium is below L_1. On its own (i.e. if the labour tax rate remained at t_1) this would reposition the excess burden triangle up and to the left, as shown by the solid arrow. Since the equilibrium labour supply is now lower and output prices are higher, government real revenue from the labour market would be lower. This “tax interaction effect” implies that, to maintain government revenue neutrality it might even be necessary to raise the labour tax rate, but we will assume that τE^* is enough to more than offset these changes so total real government revenue rises. Imposing government revenue neutrality implies a reduction in the labour tax rate to t_2 as shown by the dashed arrow. The new labour market equilibrium is at L_2.

As drawn, the net effect is to reduce the equilibrium employment level and the overall size of the labour market surplus. The loss of surplus must be counted against w when evaluating the total welfare gain of the emissions control policy. It might, in principle, be large enough to fully offset the welfare benefit of controlling emissions

Thus we find two offsetting effects are at work, the revenue recycling effect and the tax interaction effect. Parry (1995) applied a graphical analysis similar to Figure 8.2 and showed that the ratio of the revenue recycling effect (RE) to the tax interaction effect (IE) can be approximated as:

$$\frac{RE}{IE} = \frac{X^*}{X_1}\frac{\varepsilon}{\eta_{XL}} \tag{8.1}$$

where η_{XL} is the compensated elasticity of demand for the emissions-generating goods with respect to net wages, X_1 and X^* are the levels of emission-generating goods before and after the emission tax is imposed, and ε is the compensated labour supply elasticity. If the supply of labour and the demand for emissions-generating goods are equally responsive to changes in the net wage rate ($\varepsilon = \eta_{XL}$) then the ratio of the RE to the IE will equal the ratio of post-tax to pre-tax production of the emitting commodity. As long as consumption of the dirty good falls in response to an emissions tax, for the RE to completely offset the IE would require that $\varepsilon > \eta_{XL}$, i.e. that the labour supply elasticity is large relative to the income elasticity of emissions-intensive goods. This is certainly going to be true for the situation in Fig. 8.2 since the labour supply is assumed to be elastic. But, according to the parameter values tabulated in Parry’s article, it is unlikely to be true generally. If it is not true then the optimal tax on emissions should be lower than marginal damages, to take account of the economic costs of the tax interactions.

The key issue in this analysis is the presence of pre-existing distortions in the economy due to the structure of the rest of the tax system. In Figure 8.2, the fact that the emissions tax raises revenue τE^* for the government (as would a permits auction) allows offsetting tax reductions. But suppose the policy was a set of emission standards, or tradable permits subject to free distribution. If the permits are given away or 'grandfathered' (rather than being auctioned), as is the case in the US sulphur dioxide market, then the amount τE^* accrues as *scarcity rents* to the permit holders and the government does not raise as much additional revenue (the only additional revenue raised by the government is income taxation of the scarcity rents). Therefore it has less money to fund tax reductions to offset the IE. When tradable permits are grandfathered rather than auctioned they are sometimes called *quotas*. In the presence of a distorting tax system, a quota market is more expensive, from society's point of view, than an emissions tax or a permits auction, because the interaction effects are common in both policies, but the revenue recycling effect is much weaker under a quota system.

So the presence of other taxes in the economy makes two differences to the standard (partial equilibrium) analysis. First it breaks down the symmetry between taxes and tradable quotas because of the way the scarcity rents (τE^*) are distributed. Second, it implies that the conventional optimal pricing rule ($\tau = MD$) may not hold. We will show this latter point in the next section.

On the issue of the asymmetry between taxes and quotas, Parry, Williams and Goulder (1999) used analytical and numerical modeling to show that, in the case of US carbon dioxide emissions, at a labour tax rate of 40% the tax interaction effect was so strong that under tradable quotas the first unit of emissions reduction would cost at least \$18 (US) per ton. If quota rents are not themselves subject to taxation the marginal cost of the first unit of emissions reduction would be over \$29 per ton. But if emissions are taxed and the revenues are used to reduce labour taxes the marginal cost of emission reductions begin at zero. For a 20% reduction in emissions, an emissions tax would have a marginal cost of just over \$60 per ton whereas tradable quotas would have a marginal economic cost of over \$100 per ton.

These results suggest that, if marginal damages of CO_2 emissions were, say, \$10 per ton, any amount of emissions reduction would be welfare-reducing under a tradable quota scheme. This seems counterintuitive, since in Figure 8.2 the right side diagram shows the MAC reaching the horizontal axis at E_1, and it is clearly optimal to reduce emissions at that point, *ceteris paribus*. The point of the tax interaction literature is that the distortions in the economy due to the tax system create a hidden category of *policy costs*. If these are taken into account our standard MAC curve should be re-drawn as shown in Figure 8.3. If the marginal damages are MD_1, the diagram would imply emissions should be reduced to E_3 if we only consult the *MAC* curve. But if we do not achieve revenue-recycling we need to refer instead to *MAC+policy costs*, which implies that emissions should be reduced by a lesser amount, to E_2, and the tax rate necessary (which follows the *MAC* curve) would be less also. If marginal damages are MD_2, we would not be able to justify reducing emissions at all as long as we use an instrument that has policy costs associated with it.

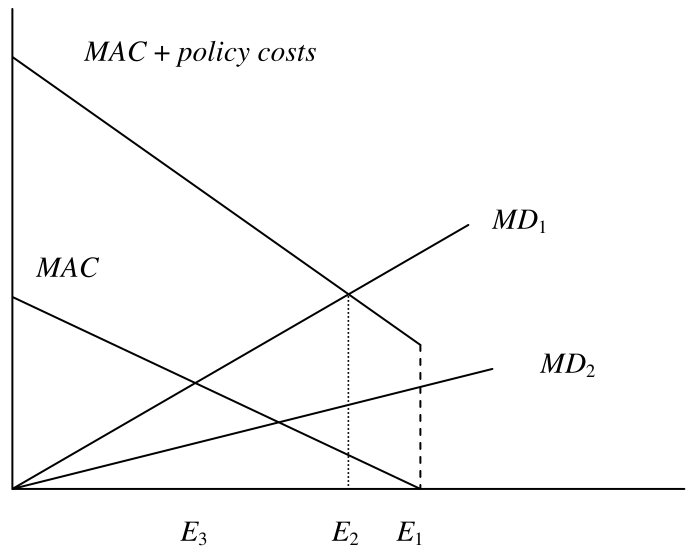

Figure 8.3 Optimal emissions control taking policy costs into account

The other question raised by considering the nature of the tax system is how externalities should be taxed in an economy in which there are pre-existing tax distortions. The recent writings on this have provided support for an elegant result first presented by Agnar Sandmo in the *Swedish Journal of Economics* in 1975.

8.3 The Sandmo Model of Optimal Taxation in the Presence of Extenalities

Suppose we get very good at measuring environmental damages and figure out that the marginal social cost of using gasoline is 5 cents per litre. Should we add 5 cents to the cost of gasoline? The petroleum industry would probably respond: but there are already existing taxes of about 30 cents per litre on gasoline. Should we reduce these to 5 cents? Surely that's not right either. Should we then just count 5 of the existing 30 cents per litre as the environmental taxes? But then why were taxes previously levied at 30 cents, not 25 cents? And apart from gasoline, should we should tax other goods, such as tires and garage door openers, the use of which is tied to gasoline consumption?

To unravel this puzzle, we need to back up a step and ask the global question: what is the optimal tax on a commodity whose consumption generates external costs, in an economy which already has distortionary taxes? This is the question Sandmo's model helps us answer.

Consider an economy with n consumers, all of whom are identical. There are m+1 consumer goods. The amount of good i consumed by each consumer is denoted x_i. The total consumption across n consumers is denoted X_i. x_0 is the amount of labour supplied. The total time endowment is normalized at unity, so leisure demand is $1\text{-}x_0$. Consumption of the mth good generates an externality in linear proportion to total consumption. The individual utility function is written

$$u^j = u(1 - x_0, x_1, ..., x_m, X_m) \qquad (8.2)$$

and the aggregate utility is nu^j. Production occurs through a linear technology frontier:

$$\sum_{i=1}^{m} a_i X_i = X_0 \qquad (8.3)$$

where the a_i's are input-output coefficients, showing the amount of labour required to produce a unit of the output of that commodity. The left-hand side shows the aggregate labour requirement to produce all m commodities and the right hand side shows the aggregate labour supply. Note there is no capital or savings in this model.

8.4.1 First-Best Allocation.

The Pareto-optimal allocation of production and consumption will solve the following constrained optimization (the "planner's problem"):

$$\max_{x_i} L = nu(1 - x_0, x_1, ..., x_m, X_m) - \alpha\left(-X_0 + \sum_{i=1}^{m} a_i X_i\right) \qquad (8.4).$$

The first order conditions are:

$$\frac{u_i}{u_0} = a_i \qquad (i = 1,\dots,m\text{-}1) \qquad (8.5)$$

and

$$\frac{u_m}{u_0}\left(1 + n\frac{u_{m+1}}{u_m}\right) = a_m \qquad (8.6).$$

(The equations here numbered 8.5 and 8.6 correspond to equations 5 and 6 in Sandmo's article). Equation (8.5) indicates that, for each good, the marginal rate of substitution in consumption should equal the marginal rate of transformation of labour into that commodity. Equation (8.6) is analogous to the familiar Samuelsonian rule for public goods. The second term in the brackets is the sum across individuals of the marginal rates of substitution between X_m, the public externality, and x_m, the private benefit from consuming good m. The marginal rate of substitution between labour and production of good m should exceed the marginal cost of producing good m (expressed in labour units) by an amount reflecting the aggregate disutility caused by consumption of good m.

These are the first-order conditions for an optimally-“planned” economy. What we now want to do is examine the first-order conditions in a competitive economy, i.e. one in which agents individually choose production and consumption levels in response to market prices. Then, we will see if there is a tax system that can cause the competitive outcome to correspond with the planner’s optimum.

8.4.2 Decentralized Competitive Outcome.

We first need to define price and tax terms *P*=*p*+*t*. Consumers pay prices $P=(P_0,P_1,...,P_m)$, firms receive prices $p=(p_0,p_1,...,p_m)$, and the difference is the set of unit taxes $t=(t_0,t_1,...,t_m)$. It is a feature of optimal taxation models that we can normalize one each of the consumer and producer prices to unity; by doing so we automatically set one tax rate to zero. We will make labour the numeraire good, hence $P_0=p_0=1$ and $t_0=0$. The consumer’s budget constraint is

$$\sum_{i=1}^{m} P_i x_i = S + x_0 \qquad (8.7)$$

where *S* is a lump-sum transfer from the government to each consumer. As price-takers, consumers solve their utility maximization problem at

$$\frac{u_i}{u_0} = P_i\,. \qquad (8.8)$$

Producers must operate where

$$p_i = a_i \qquad (8.9).$$

The left hand side of (8.9) shows the additional revenue from one more unit of production. The right hand side shows the marginal cost of production, in particular the additional units of labour needed to produce another unit of output, multiplied by the wage rate (in this case 1). If the selling price exceeded the marginal cost, the firm would expand production until the selling price falls, and if the selling price were below production the firm would reduce output until the selling price rises. Hence (8.9) is a zero-profit condition that describes the equilibrium production level.

For the outcome in the decentralized case to coincide with that Pareto-optimum, it must be the case that equations (8.8) and (8.9) correspond with (8.5) and (8.6). This requires:

$$P_i = p_i \text{ for all } i = 1,\ldots,m\text{-}1 \qquad (8.10),$$

and

$$P_m\left(1+n\frac{u_{m+1}}{u_m}\right) = p_m \qquad (8.11).$$

(8.10) implies that unit taxes on each good should be zero, except for the *m*-th good. (8.11) implies that the buyer's price should exceed the seller's price (since $u_{m+1} < 0$). Define

$$\theta_m = -n\frac{u_{m+1}}{u_m} \tag{8.12}$$

which is marginal social damages. Since, by (8.11), $P_m(1-\theta_m) = p_m$ we have

$$\theta_m P_m = P_m - p_m = t_m \tag{8.13}$$

Thus (8.13) implies that the unit tax on *m* should equal marginal social damages, converted into money at P_m the current relative price between (the consumer's cost of) *m* and labour.

The competitive outcome only coincides with the planner's outcome when all unit taxes are zero and the externality tax is equal to marginal damages. Lump-sum transfers *S* don't matter one way or the other. Also, there is no reason to subsidize other goods (i.e. set the tax rate *t*<0) due to the externality on good *m*, even if the other goods are substitutes for *m*. If X_{276} is total consumption of Toyota Prius-like hybrids, just because gasoline use generates an externality, it is still not optimal to subsidize a hybrid (or an alternate fuel vehicle). The right approach is to put a charge on the externality, not a subsidy on substitute commodities.

Another point that could easily be shown in this framework is that no compensation payments should be made to the household in response to the overall externality. If we added to the consumer's budget a payment cX_m, where *c* is a compensation payment for the total externality, the above analysis still implies the optimal level of $c = 0$. While this is not a feature of the Sandmo model itself, the extension is explored formally in Chapter 4 of Baumol and Oates (1988).

Setting the emissions tax equal to marginal damages is a *first best* outcome. But it may not be the case (and likely isn't) that emission taxes suffice to balance the government budget. The only other option in the above set-up is to use lump-sum taxes *S*, which are generally ruled out in practice. But once we allow taxes on labour or other commodities to increase we have changed the price structure under which the first best result was derived. So we must explore, from scratch, the design of the optimal 'second-best' tax system when we rule out ahead of time the possibility of using lump-sum taxes, and assume that taxes on commodities other than x_m are not zero. This is called a 'second-best' tax system.

8.4.3 Optimal Second-Best Tax System

It will facilitate the analysis to work with the indirect utility function rather than the direct utility function. This is the function we get if we substitute the Marshallian demand functions (which are functions of prices and income alone) back into the utility function. Hence we define $u(x(P)) \equiv v(P)$, where the absence of a subscript indicates a vector. Differentiate *v* with respect to price *k* to get

$$\frac{\partial v}{\partial P_k} = -u_0 \frac{\partial x_0}{\partial P_k} + \sum_{i=1}^{m} u_i \frac{\partial x_i}{\partial P_k} + nu_{m+1} \frac{\partial x_m}{\partial P_k} \qquad (8.14).$$

(Why? Just a minute.)

When the consumer solves the utility-maximization problem subject to a linear budget constraint the first order conditions are:

$$u_i = \lambda P_i$$

where λ is the Lagrange multiplier. Substitute these into (8.14) to get

$$\frac{\partial v}{\partial P_k} = -\lambda \frac{\partial x_0}{\partial P_k} + \lambda \sum_{i=1}^{m} P_i \frac{\partial x_i}{\partial P_k} + nu_{m+1} \frac{\partial x_m}{\partial P_k} \qquad (8.15).$$

Now note that the total differential of the consumer's budget constraint with respect to the *k*-th price is

$$-\frac{\partial x_0}{\partial P_k} + \sum_{i=1}^{m} P_i \frac{\partial x_i}{\partial P_k} + x_k = 0 \qquad (8.16).$$

Rearrange this as follows:

$$x_k = \frac{\partial x_0}{\partial P_k} + \sum_{i=1}^{m} P_i \frac{\partial x_i}{\partial P_k}$$

and substitute into (8.16) to get

$$\frac{\partial v}{\partial P_k} = -\lambda x_k + nu_{m+1} \frac{\partial x_m}{\partial P_k} \qquad (8.17).$$

(Why? Hold on.)

Now let's introduce the government. Suppose the government needs to raise revenue *T*. Its budget constraint is

$$\sum_{i=1}^{m} t_i X_i = n \sum_{i=1}^{m} (P_i - p_i) x_i = T \qquad (8.18).$$

We will suppose a utilitarian social welfare function, which is written

$$W = nv(P) \qquad (8.19).$$

The government's tax design problem is to max W subject to (16). Rather than doing the maximization with respect to the tax rates it will turn out to be easier to do it with respect to the consumer price P. (Since the producer prices are determined by the input-output coefficients the choice of P automatically determines t as well.) The Lagrange function is

$$L = nv(P) - \beta\left[n\sum (P_i - p_i)x_i - T\right].$$

The foc's (with respect to P_k) are:

$$n\frac{\partial v}{\partial P_k} - \beta\left[n\sum (P_i - p_i)\frac{\partial x_i}{\partial P_k} + nx_k\right] = 0.$$

The n's cancel out. Also, we can replace $\frac{\partial v}{\partial P_k}$ with (8.17) and $(P_i - p_i)$ with t_i. This yields:

$$-\lambda x_k + nu_{m+1}\frac{\partial x_m}{\partial P_k} - \beta\left[n\sum t_i \frac{\partial x_i}{\partial P_k} + x_k\right] = 0 \qquad (8.20)$$

for (k= 1,…,m).

Buried in this series of equations is the optimal tax system. We want to solve it for the t's. We will need to use matrix notation to do this. Re-write (8.20) as

$$-\lambda\mathbf{x} + nu_{m+1}\nabla_p x_m - \beta\mathbf{J}^* t - \beta\mathbf{x} = \mathbf{0}$$

where $\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_m \end{bmatrix}$, $\nabla_p x_m = \begin{bmatrix} \frac{\partial x_m}{\partial P_1} \\ \vdots \\ \frac{\partial x_m}{\partial P_M} \end{bmatrix}$, $\mathbf{J}^* = \begin{bmatrix} \frac{\partial x_1}{\partial P_1} & \cdots & \frac{\partial x_m}{\partial P_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial x_1}{\partial P_m} & \cdots & \frac{\partial x_m}{\partial P_m} \end{bmatrix}$, and t is the vector of tax rates. Then

$$-(\lambda + \beta)\mathbf{x} + nu_{m+1}\nabla_p x_m = \beta\mathbf{J}^* t$$

or

$$\mathbf{J}^* t = \tfrac{-(\lambda+\beta)}{\beta}\mathbf{x} + \tfrac{1}{\beta} nu_{m+1}\nabla_p x_m.$$

Denote the determinant of $\mathbf{J}^*$ as $\mathbf{J}$ and let J_{ik} be the co-factor of element j_{ik}. Then by Cramer's rule,

$$t_k = -\left(\tfrac{\lambda+\beta}{\beta}\right)\frac{\sum x_i J_{ik}}{\mathbf{J}} + \tfrac{1}{\beta} n u_{m+1} \frac{\sum \frac{\partial x_i}{\partial P_i}}{\mathbf{J}}$$

which further reduces to

$$\theta_k = (1-\mu)\left[-\frac{1}{P_k}\frac{\sum x_i J_{ik}}{\mathbf{J}}\right] \qquad (8.21)$$

for k=1,…,m-1; and

$$\theta_m = (1-\mu)\left[-\frac{1}{P_m}\frac{\sum x_i J_{im}}{\mathbf{J}}\right] + \mu\left[-n\frac{u_{m+1}}{u_m}\right] \qquad (8.22),$$

where θ_k is the *ad valorem* tax rate, i.e. $\theta_k = \dfrac{t_k}{P_k}$, and $\mu = -\lambda / \beta$.

Equation (8.22) tells us that the externality component of the tax is additive, and moreover that it only enters the formula for the m-th good, not for any of the others. These are helpful insights. For instance, even if good m is complementary with some other good k, the externality associated with m does not justify an environmental tax on k. If good m is, for instance, gasoline, then policy should be directed at gasoline, not at complementary goods like cars; nor should policy take the form of subsidies for substitutes (e.g. ethanol). If there are social costs associated with gasoline, then put the tax on gasoline.

What does the weighting parameter μ signify? Recall that $\mu = -\lambda / \beta$. The variable λ is the Lagrange multiplier from the consumer's optimization problem, and hence shows the marginal utility of (private) income. The variable β is the Lagrange multiplier from the social welfare maximization problem. It shows the social welfare change from raising the government's revenue requirement, or in other words, the aggregate marginal disutility of adding one dollar to public income. Thus

$$-\frac{\lambda}{\beta} = -\frac{\partial u / \partial[\text{Private Income}]}{\partial u / \partial[\text{Public Income}]} \qquad (8.23)$$

In words, μ = the Marginal Rate of Substitution between Public and Private income. It indicates the amount of income the public would have to earn to offset the welfare loss of a dollar to the private sector while leaving overall welfare constant. In an economy with no tax distortions, the value of a dollar lost to the private sector exactly equals the value of the dollar gained by the public sector. In this case we would have μ=1. The only non-lump sum tax would be the one on good m, and it would be equal to marginal social damages.

This, as we saw earlier, corresponds to the case where there is no excess burden in the tax system. The classic prescription of $\tau = MD$ applies in the ideal world where there are no distortions to the existing tax system. But if there are distorting taxes, the marginal value of private income must exceed the marginal value of public income. That is, the value of a dollar given up to taxation exceeds the (social) value of the additional public income, because of the deadweight loss triangle. Hence $\mu<1$ when there are tax distortions in the economy, and the optimal environmental tax should be smaller than it otherwise would be. This completes a point introduced in Section 8.2, where we said that the presence of other taxes in the economy causes the classical rule $\tau = MD$ to not apply any longer.

The parameter μ is very close to the concept of the marginal cost of public funds mentioned in the introduction since it is approximately true that $\mu = 1/MCPF$. If the MCPF rises towards infinity (taxes get extremely distorting and burdensome), then μ approaches 0. By (8.22), the efficient tax system would be based only on revenue-raising components, and the environmental component would on good *m* would vanish. This is somewhat counter-intuitive, and indeed goes against the double-dividend argument that in economies with very distorting tax systems we should raise pollution taxes and lower other taxes. It turns out the opposite is true: in very distorting tax systems we should not raise pollution taxes, other things being equal we should lower them. The reason is that as the level of distortions in the tax system rise, all public goods—including environmental protection—get more costly and subject to lower levels of optimal provision. Suppose the externality in this case were a benefit, rather than a cost. Then the 'tax' would be negative—i.e. a subsidy. But if the tax system were heavily distorting, we would intuitively expect the subsidy for provision of the external benefit must be scaled back. In the same way, the tax places a cost on the externality and in that sense provides a public good, namely environmental cleanliness. But in doing so it increases the distortions in the market for the *m*-th good, and if these distortions are already severe, we will not want to exacerbate them, even to improve environmental quality. The focus of the tax system would shift to raising revenue.

If we make one further simplification we can generate a but more insight. Suppose the cross-price derivatives are zero, i.e. $\frac{\partial x_i}{\partial P_j} = 0$ for all $i \neq j$. Define $\varepsilon_k = \frac{\partial x_k}{\partial P_k}\frac{P_k}{x_k}$. Then

$$\theta_k = (1-\mu)\left[-\frac{1}{\varepsilon_k}\right] \tag{8.24}$$

for $k=1,\ldots,m-1$; and

$$\theta_m = (1-\mu)\left[-\frac{1}{\varepsilon_m}\right] + \mu\left[-n\frac{u_{m+1}}{u_m}\right] \tag{8.25}$$

Equation (8.24) is a standard optimal tax equation showing that the tax rate on a good should be higher, the smaller is the magnitude of its own-price elasticity. Equation (8.25) shows that the optimal tax on a good which generates an externality is a weighted sum of two components: the first 'Ramsey' type revenue-raising component, and the second externality component.

8.4.4. Pollution Taxes and Deadweight Loss

Estimates of the marginal cost of public funds are quite variable depending on rather obscure differences between definitions, and can easily range from 1.1 to 1.8 (Mayshar 1991). Suppose we take a central estimate to be around 1.3. Hence we can go back to the question posed earlier, what to do with fuel taxes if marginal environmental damages are discovered to be 5 cents per litre. First, we do not want to put an environmental tax (or subsidy) on any other commodities except the fuel itself: this is obvious from equations (8.21) and (8.22). But the point seems to be easy to miss, since so many countries subsidize alternate energy sources out of concern about the environmental impacts of fuel use.

Second, the environmental component will be additive on top of the revenue-raising component. If the government had previously determined that the existing taxes are the necessary 'revenue-raising' taxes, and the externality were 'newly-discovered', then we would add to the existing fuel tax an amount approximately equal to

$$\frac{5¢}{\mu} = \frac{5}{1.3} \approx 3.8¢ .$$

The denominator is our current estimate of the MCPF in this economy (say, 1.3). This analysis is reasonable to a first approximation, but a proper analysis would note that the environmental tax may induce price changes throughout the economy, changing labour supplies, etc., and these in turn may change both the MCPF and the government's optimal revenue-requirement. Such matters could be investigated in a computable general equilibrium framework, but for our purposes we find the 'first-order' answer helpful in thinking through the questions posed in the introduction.

Many recent papers on the double dividend have likewise concluded that an environmental tax, in a distorted economy, should not quite equal the value of marginal damages, but should be reduced by a proportion reflecting the excess burden of taxation. This by no means takes away from the idea that environmental taxes are good tools for dealing with externalities. Recall that distortions in the tax system raise the cost of all forms of environmental protection, whether achieved through pricing or non-price instruments. In the case of non-price instruments, such as standards, no revenue is contributed to the government except indirectly through taxation of the scarcity rents generated by emissions controls, as discussed in Section 8.2.

8.5 Subsidies

In a simple sense, subsidies should work just the same as taxes do, except for the presence of a constant term. Suppose that in the absence of regulation a firm emits $\bar{e}$. If the firm is confronted with an emission tax t its profits are $\pi(e) - \tau e$. The optimal emissions level occurs where

$$\pi'(e) = \tau\ .$$

Suppose instead that the regulator promises to pay the firm s for each unit by which its emissions fall below $\bar{e}$. Then the firm's profits are:

$$\pi(e) + s(\bar{e} - e) \qquad (8.26).$$

But this rearranges to

$$\pi(e) - se + s\bar{e}\ .$$

The last term, $s\bar{e}$, is a lump-sum. So when the firm chooses its optimal emissions under (8.26), it goes to where

$$\pi'(e) = s\ .$$

If $s = \tau$, the first order condition is identical to that for an emissions tax. Hence the outcome for the individual firm will be the same.

For the *industry* however, the outcome may not be the same. At the optimal emissions level under the tax system (call it e^{τ}), the firm earns

$$\pi(e^{\tau}) - \tau e^{\tau}\ .$$

Under the subsidy system, the firms earns

$$\pi(e^{s}) - se^{s} + s\bar{e}\ .$$

The policy which yields identical emissions for each firm sets $s = \tau$. But this policy yields different profits for each firm in the industry because firms earn more under the subsidy scheme. Since profits attract entrants, there will be more firms in the industry under the subsidy scheme than under the tax scheme. If each firm emits the same amount under either policy, but there are more firms under the subsidy policy, total emissions are higher under the subsidy scheme than under the tax scheme.

It is even possible that the subsidy plan can increase total emissions. Suppose there are n firms and that all firms are identical. The total emissions are

$$E = ne\ .$$

The effect of the subsidy s is

$$\frac{dE}{ds} = n\frac{\partial e}{\partial s} + e\frac{\partial n}{\partial s}\ .$$

We know that $\frac{\partial e}{\partial s}$ is negative, but $\frac{\partial n}{\partial s}$ is non-negative. Hence $\frac{dE}{ds}$ may be positive or negative.

The only way to avoid attracting entrants is to offer the subsidy only to existing firms. But this creates an advantage for incumbents which can be used strategically to keep out potential competitors. The way to avoid this, in turn, is to give the subsidy to all current and future firms regardless of whether they enter or exit. But this is computationally impossible, and would be infeasible to implement. There may be cases in which entry is ruled out just by circumstance. For instance, emissions might be tied to the operation of gas or oil wells, or mines, and the total number of these fixed by extraction permits. In this case the subsidy system can still yield an efficient outcome.

8.6 Chapter 8 References

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Chapter 9: Bargaining and Tort Law as Solutions to Externalities

1. Introduction

Up to now we have primarily looked at regulatory interventions for externalities, such as taxes, permits and standards. A relevant category of policy that involves courts, rather than legislators, is *tort law*. This is a branch of civil law which addresses torts, or harm done by one party (the "tortfeasor") against a victim, where there is no contract between them to govern the payment of costs. Several types of tort law can be applied in cases of pollution.

If one person's activity interferes with another's right to reasonable enjoyment of his or her property this may be considered a *nuisance*, which would constitute a tort. This can take the form of smells, smoke, obstruction of view, etc. If one person's actions cause an invasion of another's property, for instance by waste runoff or heavy air emissions, this may be considered a *trespass*, which is also a form of tort. There does not need to be a specific law prohibiting nuisance or trespass for them to be considered torts, since the categories exist under longstanding common law traditions.

If a victim sues a tortfeasor and the court upholds the complaint, the tortfeasor is said to be *liable*. Liability may arise because the tortfeasor failed to meet a *negligence* standard, which means he or she failed to exercise a sufficient level of *due care*. Under a negligence rule, if damages occurred but the tortfeasor can show he or she exercized due care, he or she is not liable for damages. Alternatively, if a *strict liability* standard holds, the court will find the tortfeasor liable if any damages can be proven to have occurred, regardless of the care taken by the tortfeasor to prevent them.

Remedies may include an *injunction* that forbids the action causing the tort, and/or the court may order the tortfeasor to pay *damages* to the victim to compensate for the loss of welfare. By issuing a ruling the court also assigns rights. If the complaint is upheld the court effectively assigns rights to the victim. If the complaint is dismissed the court effectively assigns rights to the tortfeasor.

Suppose a farmer observes that a neighboring garbage incinerator is spraying soot and waste on his fields. He goes to court and sues for an injunction. The court agrees that the soot constitutes a nuisance and orders the incinerator to shut down. In this case an externality was dealt with and no law was required, beyond the common law of torts.

However the story does not necessarily end there. The court has assigned the right to the farmer not to have soot blow onto his field. But the incinerator may try to negotiate a contract with the farmer, and begin bargaining over the situation. After all, it would be very expensive for the incinerator to shut down, and it might not cost very much for the farmer to simply leave the section of his farm uncultivated. Or the incinerator may be able to reduce the emissions somewhat by spending money on abatement, but not eliminate them entirely. In that case it might be better (from an overall efficiency point of view) for the incinerator to continue operating while paying the farmer for the smoke damages.

The situation is illustrated in Figure 9.1.

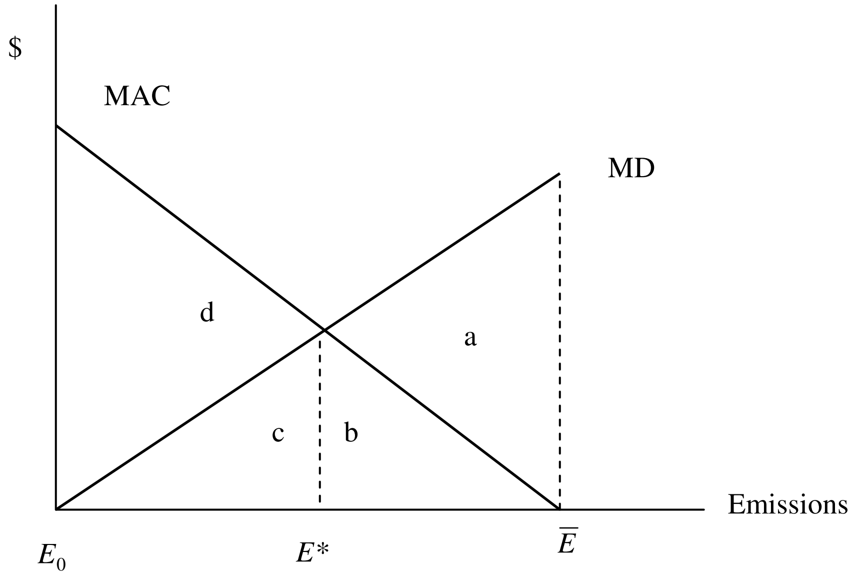

Figure 9.1 Bargaining directly over the level of an externality

Initially emissions at $\overline{E}$. Total damages are given by the area under the marginal damages curve, which add up to a+b+c. Now the court issues an injunction forbidding the emissions, so they fall to zero (E_0). The farmer is better off but the garbage incinerator is worse off. Suppose the incinerator goes to the farmer and offers the following deal. Allow us to increase emissions to E^*, in exchange for compensation of

c+ ½d.

From the farmer's perspective, he gets c+ ½d and incurs a cost of c in damages, so he is better off by ½d. From the firm's perspective it pays c+ ½d for the right to emission that earn it profits of c+d, so it is also better off by ½d.

This proposal yields the optimal emissions level at E^*. Would they bargain to a different target? Not in this example. If the firm wants to increase emissions further, it has to offer a payment at least as high as the MD curve, but it only earns an amount down on the MAC curve, so no mutually-beneficial bargain is possible. If the farmer wants the firm to reduce emissions below E^*, he knows the firm would incur the cost according to the MAC line, and so would be willing to bid up to that amount for the right to increase emissions again, while the compensation required is below that, on the MD line. So they will tend to arrive at E^* after bargaining.

But now back up and suppose the court had decided in favour of the incinerator. Suppose it held that the farmer did not establish that the smoke is a nuisance or trespass and refused to issue an injunction. Now the firm has the rights, and it emits at $\overline{E}$. The farmer could then go to the incinerator and offer to pay it to reduce emissions. By similar reasoning, suppose the farmer offers b+ ½a for the firm to cut emissions to E^*. You can verify that this makes each party better off (relative to where they started from) by ½a. Also, they would arrive at emissions E^* and would not have an incentive to bargain away from this point.

What we have shown is that the initial assignment of rights determines the flow of payments under a bargaining phase, but does not affect the eventual outcome. In this example we end up with emissions at E^* either way.

This result is popularly known as the “Coase Theorem.” Some authors, notably George Stigler, re-stated it in a very strong form by saying that in a competitive economy, direct bargaining will result in the elimination of all externalities and hence there will be no difference between private and social costs. This, however, goes further than the theory supports, and further than Coase’s own argument. Coase did argue that if there are no costs to bargaining and information is perfect, then one-on-one externalities will be resolved by direct negotiation, there will be no need for regulation or pollution taxes and the outcome will be optimal regardless of who has the initial rights. But he also added the corollary that not all externalities are dealt with by direct bargaining, therefore transaction costs are not zero and information is not perfect in all the instances that matter.

Coase’s article was published in 1961. There has been a lot of discussion in the years since about what he really meant, and what it means for environmental policy. Where externalities involve one injurer and one victim it is quite reasonable to argue that government regulation is not a good strategy, instead the individuals should work out a solution under the supervision of the courts in a context of clear property rights and liability law. In practice that is precisely what happens every day. There is a nice advantage of this, namely that the regulator does not need to have any prior information about damages, abatement costs, etc. The two parties involved have that information and will bring it to bear on the problem themselves. Hence liability law as a means of protecting the environment is sometimes motivated on the grounds that the regulator does not have the information necessary to achieve as good an outcome as can be achieved by direct bargaining.

However the role of property rights as a means of protecting the environment has been limited, for several reasons. First, in cases the matter there are multiple victims and/or multiple tortfeasors, coordinating litigation is difficult. Second, pollution damages are often uncertain and courts may have difficulty identifying efficient outcomes. Third, where victims are paid compensation directly there is a potential problem of deliberate over-exposure. We will look at each of these issues in turn. A further issue that comes up in environmental policy is when liability law is used in conjunction with direct regulation, which we will also look at briefly.

9.2 Multiple Victims and Joint Tortfeasors.

9.2.1 Multiple Victims

If there are multiple victims of a tort, for instance if a factory pollutes the water supply of a large region and causes injury to m households, the victims have to coordinate their efforts at suing the polluter. Because of the free-riding problem they may be unable to engage in the collective action needed to bring a suit to court on behalf of all victims.

In principle, courts do not need to hear from all victims. A single plaintiff would suffice to initiate a lawsuit, and if the connection between cause and effect is clear enough each victim would face a private incentive to sue. However, in order to facilitate joint cases, which are more efficient for the court and may result in a more accurate summation of damages, courts can certify *class actions*, in which a single plaintiff acts on behalf of a larger, identifiable group, and the lawyers are paid on the basis of the expectation of an award that covers all the group members rather than just one.

9.2.2 Joint Tortfeasors

One of the most interesting—and difficult—challenges confronting civil courts over the past few centuries has been the adjudication of cases involving *joint tortfeasors*, in which two or more individuals are jointly responsible for an injury. Examples include: a group of firms collectively polluting an airshed or watershed; a succession of landowners each of which contaminates the site and groundwater; a hazardous workplace at which employees work for a hierarchy of subcontractors, subsidiaries, firms and holding companies; etc. In each case, liability for damages is not obviously confined to one party. Since the injury is often indivisible, the court must decide which of the injurers should be held liable, under what circumstances, and for how much of the value of the damages, and it must apportion responsibility in a way that is fair *ex post* and which provides a deterrent *ex ante* to future potential injurers. Courts have thus far failed to determine a universally-satisfactory rule for adjudicating such disputes. Different doctrines, each one giving rise to different *ex ante* incentives, have been tried and discarded over time. Rules have changed when those in use are found to be manifestly unfair or impractical. Nor are economists entirely satisfied with the current approaches to joint tortfeasor cases.[8]

Negligence and strict liability doctrines developed where one party is wholly responsible for damages. One of the earliest complications to arise came about from recognizing that sometimes the victim is partly responsible for the extent of the injury. An early case (in which a drunken man fell from a horse upon running over some debris left in the road by a neighbour) led to a ruling that *contributory negligence* (in which the victim's carelessness or activities contributes to the injury) is a *bar to recovery*, i.e. it rules out any right of the victim to be paid damages by the tortfeasor. This constituted a severe restriction on plaintiffs. Courts soon began to weaken the doctrine. A later modification

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[8] The discussion here draws on Cooter and Ulen (1988) and Miceli and Segerson (1991).

assigned responsibility to the party who had the "last clear chance" to avoid the accident, and shielded from liability a party whose portion of blame was trivially small.

Common-law courts in the 20th century have moved away from the rule of contributory negligence towards a doctrine of *comparative fault*. This is the rule that if two or more individuals are responsible for the injury, the court should apportion blame and divide up the damage claim respectively. Since the victim may bear some percentage of the responsibility, the total which can be claimed from the tortfeasor may be reduced, but the contributory negligence does not make a complete bar to recovery.[9]

Where comparative fault has been applied, the courts have had a difficult time deciding on an appropriate rule for apportioning liability. Sometimes the division is arbitrary, and sometimes it is based on comparisons of associated activity levels. A famous case involved the anti-miscarriage drug DES, which was shown to be carcinogenic in the children of its users two decades after its ingestion (Cooter and Ulen, 1988 p. 339-40). Victims sued the manufacturers after the symptoms appeared. The court found the pharmaceutical firms jointly liable, and they were ordered to pay claims according to their respective shares of sales at the time that the drug was being taken.

Comparative fault can place an onerous burden on a victim however, since he or she may have to sue dozens or hundreds of individuals to collect the full value of damages, depending on the number of tortfeasors. And if any of the injurers is insolvent or if their portion of the blame is so small that the award will not cover litigation costs, some of the damages may never be recovered. Consequently, many legislatures have implemented a rule of *joint and several liability*, under which a victim can sue any *one* of the injurers for the *entire* amount of the damages. This allows the victim to go after the injurer with the 'deep pockets', increasing the chance of full recovery of damages. Under an early version of joint and several liability, the defendant found liable for the damages caused jointly by all the tortfeasors could *not* sue the other parties to make them contribute to the cost of paying the claim. But many jurisdictions have since begun to allow such litigation, called *contribution actions*.

Other cases have led courts to use other rules, and new rules are regularly proposed to deal with emerging case law, such as environmental damages (see, e.g., Pardy 1998). But the situation is in flux, with no clear agreement as to whether a universally correct rule for joint tortfeasor liability exists. Nor is it clear whether the new "rule of contribution" is more or less efficient than the old rule of joint and several liability without contribution, although it strikes most observers as being more fair.

It is possible to show that joint and several liability without contribution *can* lead to efficiency under very specific circumstances, but generally will not. Joint and several liability with contribution, if implemented in a way to be described below, can approach efficiency depending on the tortfeasors' ability to correctly conjecture one another's actions.

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[9] Some places have added stipulations that comparative fault cases are dismissed if the victim is fifty per cent or more responsible: see North (1996).

9.2.2.1 Negligence

It is customary (Cooter and Ulen, 1988; Shavell, 1987) to model damages and costs as functions of the level of precaution taken by agents. It is easier to relate the liability problem to the environmental literature by focusing on the level of the activity (or emissions) in which agents engage, which gives rise to the external damages. The activity level of agent *i* will be denoted e_i. Total emissions $\Sigma_i e_i$ are denoted *E*. Denote the total emissions of all firms except those of firm *i* as E_{-i}, that is, $E_{-i} = E - e_i$. The gross private benefit to each firm of producing e_i is given by a profit function $\pi_i(e_i)$. Social costs associated with the activity are summarized by the convex, increasing damage function $D(E)$. The planner's social welfare function is the sum of private benefits minus the social costs of the activity:

$$W(e_1,...,e_n,n) = \Sigma_i \pi_i(e_i) - D(E). \qquad (9.1)$$

The optimal emission levels (denoted with *) are determined by the set of *n* first-order conditions:

$$\frac{\partial \pi_i(e_i^*)}{\partial e_i} = D'(E^*), \qquad (9.2)$$

which should be familiar by now. The optimal number of firms, *n**, is defined where the last firm to enter the externality-generating industry adds nothing to social net welfare *W*. Assume for simplicity that this occurs at an integer value of *n*, hence

$$W(\cdot,n^*) - W(\cdot,n^*-1) = \pi_n(e_n^*) - [D(E^*) - D(E_{-n}^*)] = 0 \qquad (9.3)$$

Equations (9.2) and (9.3) implicitly define the long-run socially optimal level of emissions per firm and the optimal number of firms.

The private optimum will be denoted throughout by ^. Firms weigh the benefits of their activity against the liability costs $L_i(e_i)$ which determined by the particular rules courts (and/or legislators) impose. Expected profits are

$$\pi_i(e_i) - L(e_i) \qquad (9.4).$$

Each firm chooses an activity level where

$$\frac{\partial \pi_i(\hat{e}_i)}{\partial e_i} = L'(\hat{e}_i) \qquad (9.5).$$

The last firm to enter earns zero expected profits:

$$\pi_m(\hat{e}_m) - L(\hat{e}_m) = 0 \qquad (9.6).$$

The letter *m* will be reserved throughout to denote that firm which earns zero profits upon entering under liability rule *L*, when all other firms are emitting according to (9.5). In general it will be the case that $\hat{m} \neq n^*$.

A negligence rule imposes a requirement of reasonable care to shield a firm from liability. Assume the rule stipulates an emissions level of e_i^R as the reasonable care threshold. Then the firm's expected profits are:

$$\pi_i(e_i) = \begin{cases} \pi_i(\hat{e}_i), & \hat{e}_i \leq e_i^R \\ \pi_i(\hat{e}_i) - L(\hat{e}_i), & \hat{e}_i > e_i^R \end{cases} \qquad (9.7).$$

If it were possible to set firm-specific due care requirements, a negligence rule that would yield efficiency would involve setting

$$e_i^R = e_i^*$$

and

$$L(e_i) > \pi_i(e_i) \text{ for all firms.}$$

This, in effect, presents firms with no penalty up to e_i^*, and a sufficiently expensive penalty above e_i^* that firms do not exceed that level. But to implement this solution the regulator must have absolute knowledge of all the functions in (9.7). Use of liability law as a regulatory tool is often motivated by the belief that the regulator does *not* have this information. If it did, it could implement the correct outcome through direct regulation, or through emission taxes. Otherwise, negligence standards are not much help if we are trying to achieve an optimal distribution of emission levels.

9.2.2.2 Strict Liability with Apportionment

A famous case of liability with apportionment is the litigation over the damaging side effects of the drug DES (see Cooter and Ulen 1988, pp. 339-40). In that case, the court apportioned responsibility based on each firm's market share over the time of the drug's use. Apportionment here will be assumed to be based on proportionate emissions levels. Each firm expects that the court will assign it the share e_i / E of total damages, hence it will maximize:

$$\pi_i(e_i) - \frac{e_i}{e_i + E_{-i}} D(E). \qquad (9.8).$$

The first order condition for (4) is

$$\frac{\partial \pi_i(\hat{e}_i)}{\partial e_i} - \frac{\hat{e}_i}{\hat{E}} D'(\hat{E}) - \frac{\hat{E}_{-i}}{\hat{E}^2} D(\hat{E}) = 0 \tag{9.9}$$

This shows that the firm takes two considerations into account when deciding its emission levels. First, it only expects to pay a fraction (e_i/E) of the actual damages. On this basis it would aim to operate where $\pi_i'(e_i) > D'(E)$, i.e. it would over-emit. But at the same time, it expects all other firms to choose their emission levels subject to the same condition. To the extent that other firms increase their emissions, the damages for which firm *i* increase also, and it will tend to scale back its emissions to limit this. Hence there are incentives which both raise and lower the firm's emissions. To compare the private optimum $\hat{e}_i$ to the social optimum e_i^*, re-write (9.9) as

$$\frac{\partial \pi_i(\hat{e}_i)}{\partial e_i} - D'(\hat{E}) = \frac{\hat{E}_{-i}}{\hat{E}} \left(\overline{D}(\hat{E}) - D'(\hat{E}) \right) \tag{9.10}$$

where $\overline{D}(\hat{E}) = D(\hat{E}) \big/ \hat{E}$, i.e. average damages. Suppose that the damage function is a straight line out of the origin. Then average damages always equal marginal damages, and right hand side of (9.10) equals zero. In that case, (9.10) corresponds to (9.2), implying $e_i^* = \hat{e}_i$. This is a well-known result first derived in Polinsky (1980). Now suppose instead that the damage function is convex, so marginal damages exceed average damages. Then the right side of (10) is negative, so at $\hat{e}_i$, marginal benefits are less than marginal damages. This implies that privately-optimal emissions by each firm exceed the socially optimal level as defined in (9.2), i.e. $\hat{e}_i > e_i^*$.

To summarize, if there are multiple contributors to an externality, assigning liability according to proportionate emissions will only lead to efficient behaviour by each source if the damage function is linear and passes through the origin. In the case of convex damages, where marginal damages are increasing, firms will generate excess emissions.

Moreover, only if damages are linear will the average-contribution rule lead to the correct number of firms in the industry. Under the strict liability rule, the last firm wishing to enter (denoted as firm *m*) will just earn zero profits:

$$\pi_m(e_m) - e_m \overline{D}(\hat{E}) = 0 . \tag{9.11}$$

The change in the social welfare function at this point is

$$\Delta_m W_m = \pi_m(e_m) - D(\hat{E}) + D(\hat{E}_{-m}) . \tag{9.12}$$

(9.11) and (9.12) together imply

$$\Delta_m W_m = -\hat{E}_{-m} \left(\overline{D}(\hat{E}) - \overline{D}(\hat{E}_{-m}) \right). \tag{9.13}$$

This expression can only equal zero if average damages are constant. Otherwise, increasing average damages implies the right hand side of (9.13) is negative, hence at *m* the social welfare function is sloping downwards. This implies that a greater-than optimal number of firms will enter the industry, each one emitting greater-than-optimal levels of pollution.

One way of dealing with the propensity for firms to over-emit under an apportionment liability rule is to have legislatures instruct courts to apply *punitive damages*. If the law stipulates a version of the so-called 'rule of the reciprocal' (Cooter 1991), the ratio of the plaintiff's total award to the value of damages would be, in this case, E/e_i. This will cause each firm's private profit function (9.4) to correspond to net social benefits, and each firm that operates will generate the optimal emissions. However, the last firm to enter will be the one that earns

$$\pi_m(\hat{e}_m) - D(\hat{E}_m) = 0 \qquad (9.14).$$

But where (9.14) holds, $\Delta_m W_m = D(\hat{E}_{-m}) > 0$. If the social welfare function is upward sloping this implies the equilibrium number of firms is too low. Hence punitive damages might correct the short run (firm-specific) incentives under the proportionate damage system, but too many firms will exit the industry and overall emissions will be too low. That firms undertaking efficient levels of the damaging activity may nevertheless exit due to the threat of punitive liability is a concern among analysts of contemporary tort liability. A striking example is the decision by the G.D. Searle company in the 1980's to withdraw its intrauterine birth control device from the market, even though independent experts considered it a safe product, after a competitor (the A.H. Robins Company) was bankrupted by liability proceedings over the Dalkon Shield.[10] The above result explains how the use of punitive damages to induce efficient firm-specific behaviour simultaneously creates long run inefficiency by inducing the exit of efficient firms.

It is possible to extend this framework to consider joint and several liability with contribution actions. In that case the model requires some tools of game theory to account for the interactions among firms. A firm has to decide how likely it is to be sued directly, and if it is either launching or facing a contribution action it has to apportion amounts across other firms. At that point it again becomes difficult to ensure efficient levels of emissions unless the damage function is linear, or unless the court is able to impose rather complicated cost burden formulae. Some additional development is in Miceli and Segerson (1991).

9.3 Uncertainty over Damages.

In the previous section we ignored the fact that court trials involve uncertain outcomes. Scholars in the economics of law have modeled the court process using *contest success functions* (Skaperdas 1992).

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[10] Cooter and Ulen (1988, p.373). Other examples of withdrawal of apparently safe medical services and products under the threat of tort liability are given in the same source.

Suppose that by hiring legal counsel at a unit cost *w*, the firm *i* can reduce the expected value of the damages by some factor $\rho_i(L_p, L_i)$, where L_p is the amount of legal services employed by the plaintiff and L_i is the amount of legal services hired by the defendant. A reduction in the expected value of the damages can come about in several ways. First, defence counsel may cast sufficient doubt on the plaintiff's evidence, or the defendant's own direct culpability, as to make it uncertain once the suit is underway that the plaintiff can pass the 'balance of probabilities' test. Second, the lawyer for the defendant may use procedural delays to postpone well into the future the date at which the actual damages must be paid, reducing their present value to the defendant. Third, the defendant's counsel may aggressively move against the plaintiff, through counter-suits or threats of legal action, and intimidate the plaintiff into either withdrawing or settling out-of-court for a reduced amount.[11] Finally, legal counsel can shelter or hide the defendant's assets so that only a limited amount of money remains accessible to the court to make good on a damage award.[12]

The success of these strategies can be summarized by the function $\rho_i(L_p, L_i)$. Its properties are:

(C.1) $0 \le \rho_i \le 1$; $L_p > 0, L_i > 0 \Rightarrow 0 < \rho_i < 1$

(ρ_i is bounded between 0 and 1, with the inequalities strict for positive amounts of plaintiff and defendant effort);

(C.2) $\rho_i(0, L_i) = 0$;

(C.3) $\rho_i(L_p, 0) = 1$

(failure to hire any legal counsel in the court ensures one's defeat);

(C.4) $\dfrac{\partial \rho_i(L_p, L_i)}{\partial L_i} < 0$; $\dfrac{\partial^2 \rho_i(L_p, L_i)}{\partial L_i^{\,2}} > 0$

(decreasing returns to the defendant's use of legal services. An analogous condition, not shown, would apply to the plaintiff).

The damages attributable to the defendant, if it is found liable, are

$$D(E) - D(E_{-i}).$$

Which we denote $\Delta_i D$. Hence its expected profits are

$$\pi_i - wL_i - \rho_i(\Delta_i D) \qquad (9.15).$$

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[11] On the use of counter-suits for intimidation see Hurley and Shogren, (1997), and Cooter and Rubinfeld (1989) on out-of-court settlements.

[12] On judgment-proofness in environmental contamination cases see Pitchford (1995).

This assumes the "American Rule", where each party to the lawsuit pays his or her own expenses. (The alternative is the British Rule, where the loser pays all court costs). We will ignore the negligence rule, since as we saw above there is no way to construct a uniform due care requirement that achieves long run efficiency in this kind of model (Polinsky 1980) and the regulator cannot be expected to have enough information to implement efficient firm-specific negligence rules. In the strict liability setting, we are interested in two issues. First, do the firms that operate generate the optimal emissions level, and, second, does the right number of firms continue to operate?

We can show that with uncertainty in the trial process, such that ρ_i<1, there will be too many firms, each emitting too much. The firm (i.e. the defendant) optimizes over e_i and L_i, taking the legal expenditures of potential plaintiffs as given, yielding first order conditions,

$$\pi_i'(e_i) - \rho_i D'(E) = 0 \tag{9.16}$$

and

$$-\frac{\partial \rho_i}{\partial L_i} = w / \Delta_i D \qquad (9.17),$$

where w is the unit cost of legal services. Since w>0, any firm which generates positive emissions will have a positive demand for legal representation, and consequently the expected value of the plaintiff's proportionate recovery of damages will be less than unity. As w increases (counsel gets costlier) or $\left(D(E) - D(E_{-i})\right)$ decreases (the value of damages declines), the firm moves to a point on $\rho_i(L_p, L_i)$ with a steeper (negative) slope, which corresponds to a lower demand for legal services. This is shown in Figure 9.2.

As long as ρ_i<1, (9.16) implies that the firm will operate where marginal damages exceed marginal abatement costs. The social welfare function is still (9.1), since we don't count legal expenses as a benefit or cost, they are just transfers among agents in this framework. If (9.3) holds true then

$$\pi_i(e_i^*) = \Delta_i D(E^*) \qquad (9.18).$$

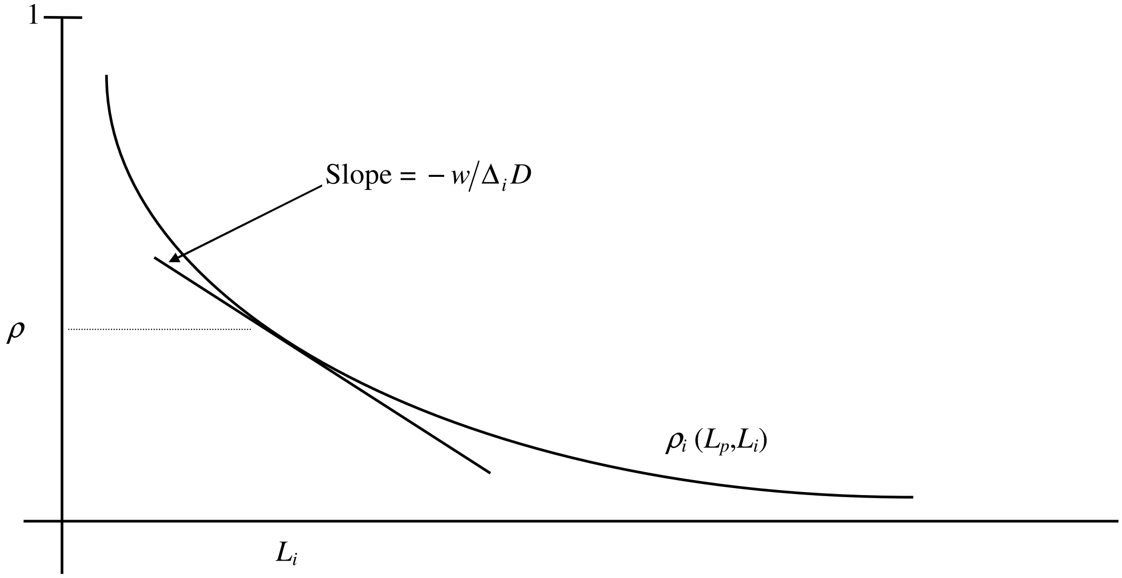

Figure 9.2: Contest Success Function for Defendant

What we want to know is whether firm n^* is actually the marginal firm, or whether it is still earning positive profits, in which case further entry would occur. The profits of firm n are given by (9.15). If we substitute in (9.18) we can rearrange this expression to

$$(1-\rho_n)\Delta_n D(E) - wL_n \qquad (9.19).$$

To evaluate the sign of (9.19) suppose that firm n is taken to court. It could settle with the plaintiff by offering to pay the maximum award the plaintiff could hope to achieve, which in this case is damages less court costs (wL_p). Hence the maximum fraction the defendant expects to pay is

$$\rho_n < \frac{\Delta_n D - wL_p}{\Delta_n D},$$

which rearranges to

$$(1-\rho_n)\Delta_n D - wL_p > 0 \qquad (9.20).$$

As long as the defendant expects to use about as much legal effort as the plaintiff ($L_n = L_p$) then (9.20) implies the expression in (9.19) is positive. Thus, at the point where social welfare is maximized the marginal firm is earning positive profits and this implies there will be continued entry. So not only are the firms each emitting too much, but there will be too many firms.

It is possible to fix the incentives for over-emitting on the part of individual firms, by allowing courts to charge punitive damages. However, as we saw in the previous section, it is very difficult to specify a formula for punitive damages that gets individual behaviour correct that does not result in excessive exit from the industry.

9.4 Victim Overexposure.

The next issue is related to the question of whether victims ought to be compensated for injuries *ex post*. In the Sandmo model (present in the last chapter), and in all the other models of externalities we've examined, no payments are made to victims in compensation for the damages they experience. A charge is placed on the polluter, but the damages themselves are incurred without compensation. But the tort law system assumes that the damage fee paid by an injuring party will be paid to the victim. This can cause an inefficient outcome if the victim exploits this situation and in the process over-exposes himself or herself to damages. The problem arises only when the victim, prior to the injury, exercises some control over the size of the injury, in expectation of some form of damage compensation being paid. It does not arise if the compensation can be set up as a "lump sum" amount, but it is hard to do this in a sensible way.

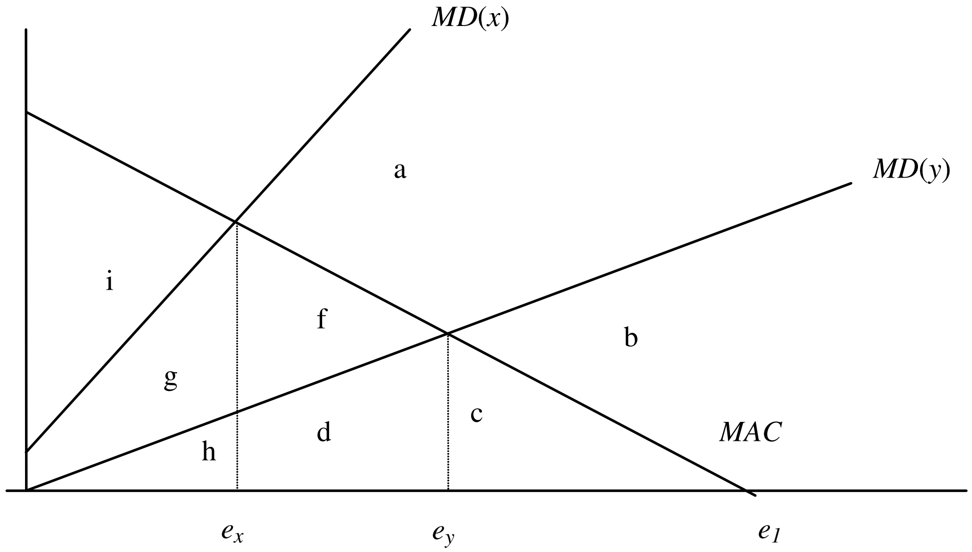

Figure 9.3 Victim Over-Exposure

To illustrate this problem, suppose a potential victim can build his house in one of two locations, x and y. x is very close to a smoky factory, while y is far away. Because of the environmental laws in that region, the victim has the right to full compensation for smoke damage incurred. We illustrate the choice to be made in the Figure 9.3.

The marginal damages associated with the locations x and y are as drawn. The MAC function for the smoky factory is also shown. The unregulated emissions level is e_1.

If the victim chooses location x, he can force the polluter to emit at e_x. Here, the polluter's liability is g+h, and the total abatement costs are c+d+f, for a total cost of c+d+f+g+h. The victim suffers damages g+h, but is paid compensation g+h, for a net cost of zero.

If the victim chooses location y, he can force the polluter to emit at e_y. The polluter's liability is h+d and abatement costs are c, for a total cost of c+d+h. The victim suffers damages h+d, but is paid h+d in compensation and so is no worse off.

The problem is that the victim is indifferent between x and y, since he expects full compensation payments for any damages. But the firm, which has to make the payments, is not indifferent: it prefers the victim to locate at y, at which it incurs costs which are less by the amount f+g. The potential for the victim to inflict an inefficient outcome on the polluter may not be that worrisome however. In this case it would pay the polluter to offer the victim some amount z, where $0 < z < f+g$, to induce the victim to locate at y. Since the victim is indifferent between x and y, the payment z could be arbitrarily small, so the firm can secure the preferred outcome at a low cost in this case. Since we are assuming that direct bargaining is possible, it seems reasonable that such a solution would be sought by the parties.

Now consider what the victim would do if no compensation payments were expected. The loss in each situation would be the damages incurred in equilibrium. For x these would be g+h, while for y they would be h+d. Which is worse? The first is, in effect, light damage up close, while the second is heavy damage far away. Clearly, x is preferred to y iff $g > d$. Again, the polluting firm could possibly arrange some sort of side payment z here to ensure that $g+z > d$, depending on the magnitudes involved.

To illustrate these results, it is worth drawing a parallel to the recent 'liability crisis' in the United States. Over the 20th century, US courts have extended doctrines of strict liability to cover new areas, such as the sale of commodities and the hiring of labour. Many such transactions now implicitly involve an insurance component, because one party or the other is potentially liable for a later damage claim. The trouble is, the proliferation of product and workplace liability has led to moral hazard problems, in which people who perceive themselves to be entitled to full compensation for damages take less precaution against mishap than they otherwise would. So, for instance, the threat of liability has forced many motel and hotel owners to remove diving boards from their swimming pools; transit fares in some US cities now include liability insurance costs which account for as much as 17 per cent of the ticket cost, new ladders in the US are up to 25 per cent more expensive due to the insurance premiums carried by the manufacturer, etc (see Viscusi 1991 for these examples). Related to this problem is the well-documented fact that safety regulations occasionally induce such extreme reductions in precautionary behaviour which more than offset the intent of the law. When child-proof caps were made mandatory on drug containers, hospitals subsequently reported *increases* in child poisoning rates, which was attributed to the careless storage of medicine containers induced by the fact that, since they were in hard-to-open bottles, parents expected their children to be safe even if they took less care. When seatbelts were made mandatory in the 1970's, incidents of speeding, dangerous driving, life-threatening collisions and pedestrians being struck all increased, which was again attributed to the fact that belted occupants took more risks in their driving, expecting the seatbelt to keep them safe in the event of collision (again, see Viscusi 1991 for these examples). Hence, the above model is not implausible in suggesting that victims may willingly increase their exposure to pollution hazards if they acquire an expectation that they will be compensated.

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Chapter 10: International Trade and Pollution

10.1 Pollution Havens: Empirical Evidence

The volume of global trade has been rapidly rising in recent decades. A new aspect to this is the increasing involvement of 3rd world countries in trade arrangements with developed countries, e.g. Mexico (and possibly Chile) in NAFTA. Also, developing countries are actively seeking foreign direct investment as a vehicle for domestic growth. This sometimes leads to the concern that companies engaged in pollution-intensive production will deliberately locate in poor countries in order to evade high pollution standards, then export goods to the developed countries (who retain stringent pollution standards) at a larger profit than would otherwise have been possible. This possibility is called the “Pollution haven hypothesis”

It is also closely related to the concept of “environmental dumping,” which is the idea that companies emit excess pollution by locating in a country with lax pollution standards, which reduces their cost of production, and this confers an ‘unfair’ advantage in trading relations. This possibility was a major concern expressed in Congressional debates over NAFTA. Such concerns have led to calls for ‘environmental tariffs’, which would be punitive levies on imports from ‘pollution havens’ to compensate domestic producers for the competitive disadvantage of operating under higher pollution standards, and to punish nations for trying to lure industries by relaxing emission standards.

Do countries try to obtain trade advantages this way? Thus it appears that the bulk of empirical evidence suggests they do not. There appears to be little relationship between the stringency of a country’s pollution policy and its trade flows or rate of foreign investment. However, the phenomena are hard to measure and more recent econometric evidence is divided on the question of a linkage between trade policy and environmental conditions.

10.1.1 Trade Flows and Pollution

An early series of studies looked at changes in the composition of traded goods over time, asking whether the share of ‘dirty’ production in a national economy was rising, and whether this change could be attributed to trade liberalization. ‘Dirty’ production includes capital- and resource-intensive production like iron and steelmaking, industrial chemical manufacturing, petroleum refineries, petroleum and coal production, etc. Some of this work was done at the World Bank and the working papers are available on-line at http://www.worldbank.org/nipr/work_paper/index.htm. For the most part these papers concluded that dirty production as a share of GDP was falling in developed countries and rising in undeveloped countries. This was the conclusion of Lucas et al. (1992), who surveyed evidence from 80 countries from 1960 to 1988. They point out that this finding is consistent with the pollution haven hypothesis. Low and Yeats (1992) found the share of dirty goods in exports (as opposed to in GDP) fell over the interval 1965-1988 among developed countries but rose among low income countries. Other studies reaching similar conclusions are discussed in Copeland and Taylor (2004).

However, as Copeland and Taylor point out, while this evidence is *consistent* with the pollution haven hypothesis, it is also consistent with predictions from models in which there are no pollution havens. A simple way to categorize the effects is as follows. Suppose there are two types of goods being produced: x, which is 'dirty' or pollution-intensive, and y which is 'clean'. The world price for each is denoted p_x^o, p_y^o respectively. The total value (or scale) of a country's output is

$$S = p_x^o x + p_y^o y \qquad (10.1).$$

Emissions e arise only from production of x, and emissions intensity is z, i.e. $e = zx$. The (value) share of dirty production is $\varphi_x = p_x^o x / S$. Hence pollution can be written

$$e = Sz\varphi_x / p_x^o \qquad (10.2).$$

Take the log of (10.2) and differentiate to get

$$\hat{e} = \hat{S} + \hat{z} + \hat{\varphi}_x \qquad (10.3)$$

where $\hat{e} = de/e$ (the percent change) etc. and we have assumed the price of x does not change. Equation (10.3) factorizes a change in emissions into three components:

(1) $\hat{S}$ is the *scale effect*, the percentage growth in total output. If everything else stays constant we expect that this is positive. If real output grows while emissions intensity and the share of dirty goods in production stays the same, emissions will grow.

(2) $\hat{z}$ is the *technique effect*, capturing the change in the emissions intensity of production. Again, if all else is constant, an increase in emissions intensity will increase emissions.

(3) $\hat{\varphi}_x$ is the *composition effect*, indicating the share of dirty goods in total production.

Whether increased trade flows cause total pollution to rise depends on how trade liberalization affects each of these three factors. In a simple MD-MAC model, if trade liberalization increases the rate of return to the emitting activity we expect the MAC curve to shift to the right, increasing pollution (either unregulated or optimally regulated) through a scale effect. If trade liberalization also increases real incomes, say by reducing consumer prices as well as by increasing the return to factors, we expect income to rise, increasing the demand for environmental quality and thereby shifting the MD curve to the left. This would, via an optimal policy mechanism, reduce z, the emissions intensity, causing the technique effect to work opposite to the scale effect.

The change in the composition effect will depend on the country's comparative advantage. In general we expect that wealthy countries have a comparative advantage in capital-intensive production and poor countries have a comparative advantage in labour-intensive production. Since the most pollution-intensive industries tend to be capital-intensive, the composition effect will, *ceteris paribus*, cause an increase in pollution in developed countries following trade liberalization, and a decrease in pollution in poor countries.

Hence there are three potentially offsetting effects. In their own empirical work, Copeland and Taylor (with Werner Antweiler, 2001) examined changes in urban SO_2 concentrations around the world and used macroeconomic data to estimate separate scale, technique and composition effects. They find that the coefficients have the expected signs, including a positive effect on pollution as the capital-intensity of the economy increases. However when expressed in elasticity form they add up to nearly zero:

$$\frac{\hat{e}}{\hat{S}}+\frac{\hat{e}}{\hat{z}}+\frac{\hat{e}}{\hat{\varphi}_x}=0.3-2.1+1.6=-0.2$$

Each term on the left shows the % change in concentrations resulting from a % change in a right-hand side variable in (10.3). The authors also estimate the elasticity of SO_2 levels with respect to a change in trade intensity ((Exports+Imports)/GDP). According to the pollution haven hypothesis, the elasticities should be higher in poor countries. But the data do not support this. There is little relationship between income and the pollution elasticity of trade openness, and what little relationship there is appears to be positive: trade liberalization tends to have a slight positive effect on pollution in developed countries (via the composition effect) and a slight negative effect in poor countries. This is consistent with a positive linkage between pollution and capital-intensive production.

It also suggests that the early studies focusing on the trends in pollution-intensive production may have missed the underlying dynamics. Since economic growth in general involves capital formation, the data may have merely shown that low-income countries were experiencing more rapid relative growth in their capital stocks than high-income countries. This could have happened even without any pollution haven mechanisms at work.

10.1.2 Foreign Direct Investment and Pollution

The question of whether or not industries migrate to avoid environmental regulation can only be resolved by looking at the data. Copeland and Taylor (2004) briefly review some of the work done by World Bank economists, and others. While some examples exist of pollution-related industrial flight, statistical evidence of systematic migration in search of lower environmental standards does not exist, despite many studies attempting to identify such effects.

Wheeler (2000) looks at three large developing countries (China, Brazil and Mexico) during intervals in which they experienced sharp increases in foreign direct investment. If these countries were using lax pollution standards to attract investment, there should be an accompanying increase in air pollution. But no such relationship exists:

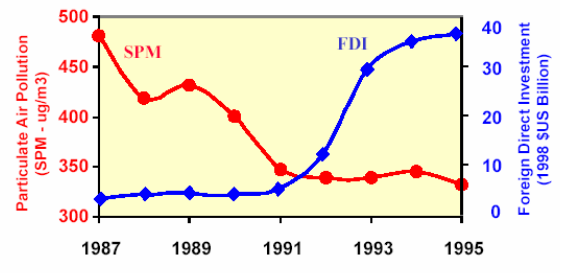
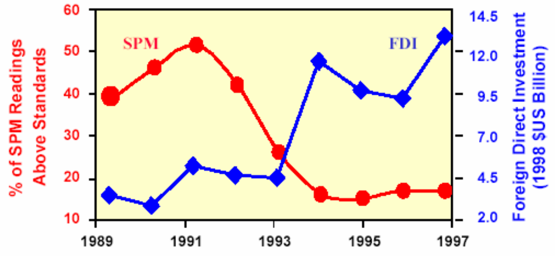
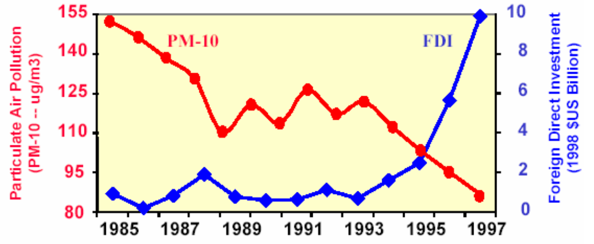
 Sources: SPM -- China Environmental Monitoring Center FDI -- World Development Indicators (World Bank)	CHINA (average of particulate levels across 50 cities)
 Sources: FDI -- World Development Indicators (World Bank) SPM Readings -- SEMARNAP (National Environment Ministry) at http://www.ine.gob.mx/dggia/cal_aire/libros/segu_info/mexico.html	MEXICO CITY particulate levels
 Sources: PM-10 -- CETESB (Sao Paulo State Environmental Agency) FDI -- SEADE (Sao Paulo State System for Data Analysis) World Development Indicators, World Bank	BRAZIL (particulate levels in cities of Sao Paulo State)

Figure 10.1 Findings of Wheeler (2001).

Evidence has been found that high income countries are specializing in cleaner goods and low income countries are specializing in relatively dirtier goods, but stringency of environmental regulation does not seem statistically linked with re-location of existing manufacturing plants. This was recently shown in a plant-level analysis for India conducted by economists at the World Bank.[13] They looked at the factors which determined location decisions for 418 new industrial investments in 14 states throughout India in 1994. After taking account of differing labour costs, power supply quality, population, literacy, etc, they found that variations in stringency of enforcement of environmental laws had no effect on the probability of locating in that region. Interestingly, higher government spending on environmental quality in a state has a strong *positive* effect on the location decision, which the authors suggested reflects better overall government administration in that area.

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[13] See Mani, M., Pargal, S., and Wheeler, D. (1996) "Does Environmental Regulation Matter? Determinants of the Location of New Manufacturing Plants in India in 1994." World Bank Discussion Paper November 1996, Available at http://www.nipr.org/work_paper/1718/index.htm.

In both these studies the lack of a role of environmental regulation is probably due to the fact that other business factors outweigh pollution control expenses. Compliance costs under even stringent environmental regulation are typically quite small (less than 3 per cent and often less than 1 per cent of revenues) so other cost factors (labour, energy, capital, taxes) will generally dominate a transnational firm's location decision.

However, the jury is still out on this issue too. A problem is that trade policy and income growth are jointly causal, so a country's openness to trade cannot be assumed to be strictly exogenous. Studies that have controlled for endogeneity of trade and pollution policy have sometimes found significant (though still small) relationships between pollution policy and industry location decisions. A recent survey and analysis is in Brunnermier and Levinson (2004).

10.2 Trade Liberalization and the Environment

10.2.1 Model Set-up

In order to explore the theory of trade and the environment, we'll set up a simple model based on Copeland and Taylor (2004). There are two goods, *x* and *y*. As before, *y* is 'clean', and is produced using labour L_y and capital K_y. *x* is 'dirty', and is also produced using labour and capital (L_x, K_x). We can distinguish between *potential* and *actual* output using the standard iso-emissions, iso-profit diagram as follows.

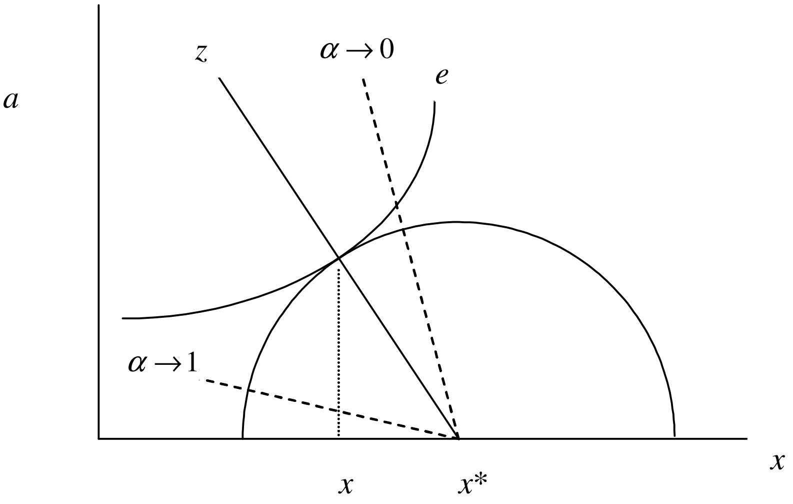

Figure 10.2 Actual output and potential output

In figure 10.2 the potential output is *x**, the unregulated level, and the locus of tangencies is the line *zx**. If the firm must constrain emissions to *e* then the optimal output level is *x*. Suppose we parameterize the relationship between actual and potential output using the equation:

$$x = e^{\alpha}(x^*)^{1-\alpha} = e^{\alpha}(F(K_x, L_x))^{1-\alpha} \tag{10.4}$$

where 0<α<1. If α is close to 0, then x stays close to x^* as e rises, which implies the locus of tangencies looks like the steeper of the 2 dashed lines in figure 10.1. If α is close to 1 then as e rises, x also rises and converges to x^*. This implies the tangency locus looks like the lower dashed line.

Since (10.4) is a Cobb-Douglas function, if emissions level *e* is attained in response to an emissions tax τ (remember the output-abatement pair will be the same is under a level standard) then the share of emission tax revenues in total value-added will equal α. This implies:

$$\alpha = \frac{\tau e}{p_x x} \Rightarrow r = \frac{p_x \alpha}{\tau} \tag{10.5}$$

where *r* is emissions intensity, i.e. the ratio of emissions *e* to output *x*. Equation (10.5) shows that emissions intensity *r* falls as τ goes up and rises as the selling price of *x* goes up.

The remainder of the production side of the economy can be specified and yields the usual result that outputs are functions of relative prices and factor endowments:

$$\begin{aligned} x &= x(p, \tau, K, L) \\ y &= y(p, \tau, K, L) \end{aligned} \tag{10.6}.$$

In (10.6) we have set the price of *y* as the numeraire so $p = p_x / p_y = p_x$. The total value of output in the economy is given by (10.1), which in a competitive setting corresponds to the outcome from maximizing the value of national income subject to a given level of emissions *e*. In other words the national income *G* is the level that maximizes the value of output subject to a technology constraint *T*(*K,L,e*):

$$G(p, K, L, e) = \max_{(x,y)}\{px + y \mid (x, y) \in T(K, L, e)\} \tag{10.7}.$$

This is a common way of setting up national economic models for use in applied trade theory, and it represents the GDP-formation process as if it were the profit function of a single large firm. As such, (10.7) inherits all the properties of neoclassical profit functions, including, by Hotelling's rule,

$$\tau = \frac{\partial G}{\partial e} \tag{10.8}.$$

This is simply a re-statement at the national level of the previously-derived result that in response to an emissions tax, firms operate where τ=*MAC*, and the *MAC* is the derivative of the profit function with respect to emissions. Hence (10.8) is the 'demand curve' for emissions in this economy.

The consumer side of the economy is handled the same way as before, using an expenditure function $I = m(p,e,u)$ which shows the amount of income I required to achieve utility u at prices p in the presence of emissions e. But it is convenient this time to invert the expenditure function to an indirect utility function:

$$I = m(p,e,u) \Leftrightarrow u = V(I,p,e).$$

We define marginal damages as the change in income required to hold utility constant given a small change in e, holding p constant. $dV = V_I dI + V_e de = 0$ gives us:

$$\frac{\partial I}{\partial e} = -\frac{V_e}{V_I} \qquad (10.9)$$

The right hand side looks like Roy's identity, which it is. (10.9) defines an ordinary *MD* curve, which in this context is like a 'supply' curve for emissions.

Finding the equilibrium in this economy involves assuming a functional form for V and imposing an income constraint. We assume there are N identical consumers and each one has an indirect utility function

$$V(I,p,e) = v(I/B(p)) - h(e). \qquad (10.10)$$

This imposes separability between emissions and goods consumption, which will make the remainder of the analysis easier. B is a function of prices, and can be thought of as a price index. The income constraint is

$$I = G(p,K,L,e)/N \qquad (10.11).$$

If we maximize (10.10) while substituting (10.11) in for income, taking p as fixed (at world prices) we get $V_I G_e / N + V_e = 0$, which implies (using 10.8)

$$\tau = N\left(-\frac{V_e}{V_I}\right) = N \cdot MD \qquad (10.12).$$

In other words, the optimal emissions tax should be set equal to the sum of marginal damages. Since there are no other taxes in this economy this is the expected solution.

10.2.2 Welfare Analysis

Since we are interested in the welfare effects of trade liberalization, we need to distinguish between total domestic supply of x, denoted X^s and per capita domestic demand, denoted x^d. Using (10.7) we know that total production is $X^s = G_p$, implying per capita domestic production is

$$x^s = G_p / N \qquad (10.13).$$

Domestic demand can be derived applying Roy's identity to (10.10):

$$x^d = -\frac{V_p}{V_I}.$$

It will be convenient to use the fact that $V_I = V'/B$, or $B = V'/V_I$. Since $V_p = V' \cdot (-IB'/B^2)$ this implies

$$x^d = \frac{IB'}{B} \qquad (10.14).$$

Now suppose trade opens up, and as a result the relative price of *x* changes. The welfare effect can be derived by differentiating *V*:

$$du = V'\left[\frac{BdI - IB'dp}{B^2}\right] + V_e de.$$

It will be convenient to divide both sides by V_I. Since $I = G/N$ we have the following:

$$\frac{du}{V_I} = \frac{V'}{V_I}\left[\frac{1}{B}\frac{G_p}{N}dp + \frac{1}{B}\frac{G_e}{N}de - \frac{1}{B^2}IB'dp\right] + \frac{V_e}{V_I}de.$$

Using $B = V'/V_I$ this rearranges to

$$\frac{du}{V_I} = \left(\frac{G_p}{N} - \frac{IB'}{B}\right)dp + \left(\frac{G_e}{N} + \frac{V_e}{V_I}\right)de,$$

and using (10.12—14) this gives us

$$\frac{du}{V_I} = (x^s - x^d)dp + \frac{1}{N}(\tau - N \cdot MD)de \qquad (10.15).$$

The left hand side shows the utility change as a fraction of the marginal utility of money, and can be interpreted as a shadow price. The welfare effect decomposes into two parts. The first is the classical gains from trade. If a country is a net importer, the term in the brackets is negative, and trade liberalization will reduce the import cost ($dp < 0$), so the product is positive. If the country is a net exporter, the term in the brackets is positive and trade liberalization will increase the world price, so again the welfare effect is positive.

The second term represents the effect from the emissions change. If an optimal policy is in place, i.e. (10.12), then the term in the brackets is zero and trade liberalization must improve welfare. If the emissions tax policy is not optimal, then the effect on welfare is ambiguous. If trade liberalization causes emissions to rise, but emissions are undertaxed, the combination is negative and offsets the gains from trade.

Note that in (10.15), if emissions are controlled by tradable permits, *de* = 0, and in this case the gains from trade would not be diminished even if there are too many permits sold, so the price is less than marginal damages. This is an interesting asymmetry between permits and taxes.

Also note that (10.15) shows that if optimal environmental policy is in place, then trade liberalization is welfare-improving. If environmental policy is not optimal, trade liberalization may reduce welfare. But in that case the solution is not to avoid trade liberalization, it is to improve environmental policy, so that the gains from trade may also be realized.

10.2.3 Environmental Effects of Trade Liberalization: The Pollution Haven versus Factor Endowment Hypothesis

The model outlined in the previous section describes an economy with two goods, a dirty one (*x*) and a clean one (*y*). Each country will have supply functions of the form (10.6), implying the existence of *relative* supply functions:

$$R(p,\tau,K,L)=\frac{x(p,\tau,K,L)}{y(p,\tau,K,L)} \qquad (10.16).$$

Of course we're just dividing *x* by *y*. The reason for doing so is that it allows for a more compressed presentation of the trading relationship. We will use (R^N, R^S) to denote, respectively, relative supply curves for the *north* (i.e. the rich, capital-intensive economy) and the *south* (i.e. the poor, labour intensive economy).

For each country there will also be a relative demand curve, denoted *D*, which for convenience we will assume is the same in each country.

Prior to trade, the north has a comparative advantage in production of *x*, so its relative supply curve sits below and to the right of that of the south. This implies a lower autarky relative price in the North p^N (see Figure 10.3). Each country produces the relative supply indicated by the intersection between demand *D* and their respective relative supply curve, so the north produces more and the domestic price is lower. When trade opens up between the economies, the price difference between the North and the South creates an impetus for trade, which flows until the price is equalized between regions.

This occurs at p^W where the world supply curve intersects the world demand curve, along the world relative supply curve. The world supply curve is determined by assuming the North and South face the same price.

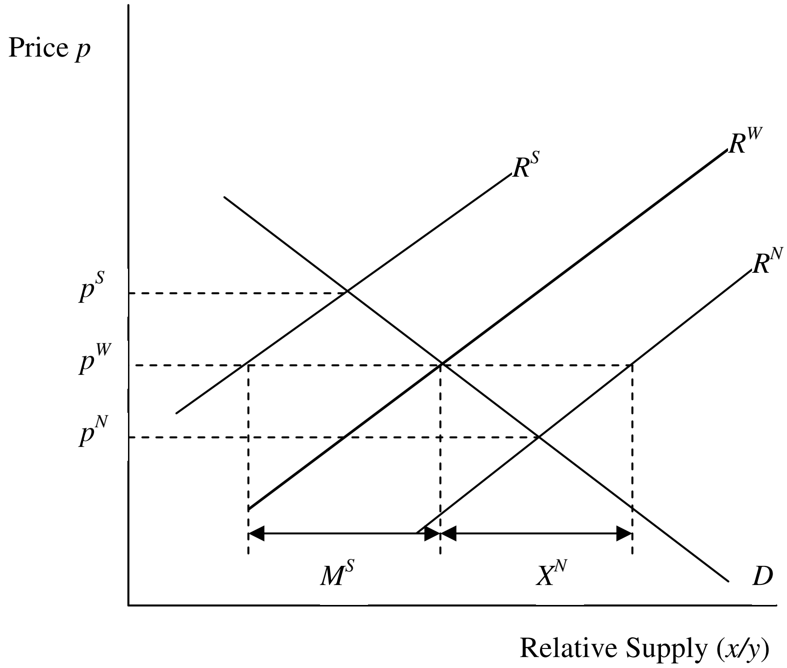

Figure 10.3 Opening trade between North and South.

For the North, trade increases the selling price of x/y from p^N to p^W, allowing production to increase to where p^W intersects the North's relative supply curve R^N. This implies that the North now exports the fraction X^N. Relative supply in the south falls to where R^S intersects the world demand curve, implying the South now imports the fraction M^S.

Since the relative supply of x has grown in the North and declined in the South, Figure 10.3 implies that trade will cause pollution to grow in the North and decline in the South, as a result of trade liberalization. However, this runs opposite to the pollution haven hypothesis, which conjectures that trade liberalization will cause pollution to increase in the South. With two opposite prediction from rival theories, it should be possible to use data to test which is more likely to be true. What we need is to identify how pollution changes in response to openness to trade, and see if it tends to go in different directions in rich-versus-poor countries, and if so where it tends to go up following trade liberalization. If the factor endowment hypothesis, as shown in Figure 10.2, is correct, then pollution should go up in rich countries and down in poor countries following trade liberalization.

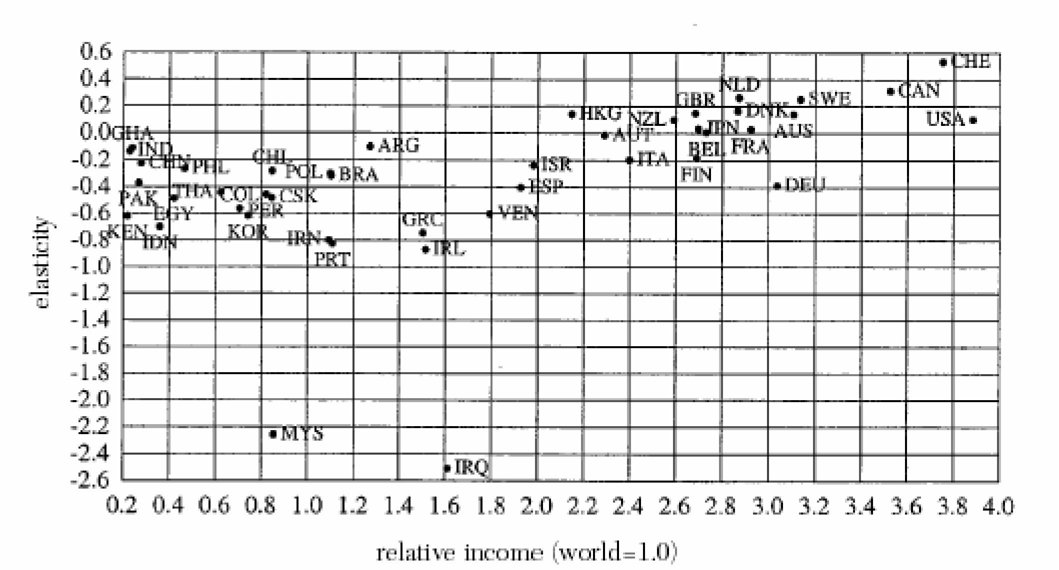

Figure 10.4. From Copeland and Taylor (2004): elasticity of emissions with respect to trade liberalization, versus relative income.

There is some support in the data for this. Figure 10.4 reproduces Figure 9 from Copeland and Taylor (2004). On the vertical axis is shown the elasticity

$$\frac{\%\Delta(SO_2)}{\%\Delta(trade)},$$

the percentage change in average urban SO_2 concentrations given a 1% increase in openness to trade (as measured by (exports+imports)/GDP). As you move into relatively higher-income countries, the elasticity goes from negative to positive. In wealth countries, trade liberalization is associated with increased SO_2 levels, and vice-versa for relatively poor countries. This is an area where more empirical work is needed, looking at other air contaminants, and looking at emissions as well as concentrations.

Chapter 10 References

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Chapter 11: Sustainability and the National Accounts

11.1 Introduction

The economic treatment of "sustainability" or sustainable development has several goals: defining the term, determining if it is possible to test whether an economy is sustainable using current data, and determining, theoretically, if an economy can be sustained if output depends on nonrenewable resources. We will mainly look at the first two topics, but comment briefly on the third as well.

The definition of sustainability emerges in the context of an economic model. Roughly speaking, sustainability means that future utility, which depends on produced goods as well as environmental services, is not diminished by current consumption. Since the total consumption stream is generated as a return on a total social capital stock, encompassing physical, human and natural capital, the theory of sustainable consumption is an application of capital theory. The definition and measurement of sustainability has been addressed many times in the economics literature (see, e.g., Solow 1991, Hartwick 1978). The empirical side of this literature concerns the development of national statistics that can indicate whether the economy is on a sustainable path. Hartwick (2000), Hamilton (2001) and Cairns (2001) are some recent contributions on this theme.

This chapter will review the basic foundations of the connection between environmental sustainability, productivity and the national capital stock. The intention is to establish an equality between currently-observable data and the discounted stream of potential future consumption. A method will then be outlined for constructing national measures to track sustainability. Some comments will be made on recent proposals for so-called "Genuine Progress Indicators," stressing that their lack of theoretical foundation makes their interpretation problematic.

For intuition, suppose a $1000 financial bond earns 5% annually. You could consume $50 each year forever without depleting your capital. If the value of the bond is W and the rate of return is r then maximum sustainable consumption (*MSC*) each year is rW. By saving a bit today, one can increase potential consumption in every subsequent year. Denote current consumption as C, an increase in wealth over the current period as $\dot{W}$, current income as Y and the interest rate as r. Then the budget constraint each period is

$$Y = rW = C + \dot{W} \qquad (11.1).$$

For the moment a suitable utility function is the discounted present value of future consumption:

$$U = \int_{t=0}^{\infty} C(s)e^{-rs}ds \qquad (11.2).$$

For now we can ignore the distinction between real and nominal consumption by assuming the price of C is fixed at 1.

In a steady state, when we have built our wealth up as much as we want to, we will have rW^* income each period, where the * denotes an optimal choice. Since we are no longer accumulating wealth, rW^* will equal the optimal steady-state consumption C^*. Then wealth is related to the discounted stream of future utility in a simple way:

$$\begin{aligned}
&\int_{t=0}^{\infty} C^* e^{-rs}ds = C^*\left(\tfrac{-1}{r}\right)\left(e^{-rs}\Big|_0^{\infty}\right) \\
&= \frac{C^*}{r} \\
&= W^*
\end{aligned}$$

In other words, when we are in the optimal steady-state, the budget constraint $rW^*=C^*$ implies that wealth equals (or is defined as) the discounted value of future consumption possibilities.

11.2 Net National Product

The term *Net National Product* denotes GNP minus depreciation expenses and ‘set-asides’. We will denote all forms of productive capital as K. If the rate of depreciation is δ, net investment is gross investment I minus depreciation δK and this gives us the actual change in the capital stock at time t:

$$\dot{K}(t) = I(t) - \delta K(t) \qquad (11.3).$$

Hicksian income is the level of consumption which the capital stock K can generate without being depleted. If the marginal product of capital is determined in a competitive market, it will equal the interest rate r. Then sustainable, or Hicksian, national income is rK. Income can either be consumed or devoted to net investment, so the national budget constraint is:

$$rK(t) = C(t) + \dot{K}(t) \qquad (11.4).$$

As before, we can start from equation (4) and show that at some initial time 0, the capital stock is a measure of the discounted present value of future consumption. In the previous section we saw that this was true when we were in an optimal steady state, but it turns out to be true whenever Net National Product is “correctly” measured using the Hicksian definition of national income, and is fully allocated between consumption and investment.

Rearrange (11.4) and multiply both sides by e^{-rt} to get

$$(\dot{K}(t) - rK(t))e^{-rt} = -C(t)e^{-rt} \tag{11.5}$$

Note that

$$\frac{d}{dt}K(t)e^{-rt} = e^{-rt}\dot{K}(t) - rK(t)e^{-rt} = (\dot{K}(t) - rK(t))e^{-rt}$$

hence (11.5) can be re-written:

$$\frac{d}{dt}K(t)e^{-rt} = -C(t)e^{-rt} \tag{11.6}$$

Now integrate both sides from time t=0 to infinity:

$$\int_{t=0}^{\infty} \frac{d}{ds}K(s)e^{-rs}ds = -\int_{t=0}^{\infty} C(s)e^{-rs}ds$$

$$K(s)e^{-r\infty} - K(s)e^{-r0} = -\int_{t=0}^{\infty} C(s)e^{-rs}ds$$

Thus

$$K(0) = \int_{t=0}^{\infty} C(s)e^{-rs}ds \tag{11.7}$$

At time zero, the value of a nation's capital stock equals the discounted present value of the stream of consumption it will generate. This result depends on (11.4), in which we defined national income in Hicksian terms, and (11.3), in which we defined net investment. This is why defining sustainability requires an economic model. The maximum sustainable income is Hicksian income.

By defining utility as eq. (11.2) we have treated consumption and welfare each period as if they were the same thing. It is preferable to work with utility functions rather than consumption directly, so we will re-derive some results in terms of optimal intertemporal utility-maximization, rather than consumption-maximization. We have also ignored the role of prices, but by introducing a utility function we are able to introduce a relative price for consumption and a shadow value of capital in a convenient way.

We will assume that the optimal planning problem is solved at time 0. We will also leave unspecified the production possibility frontier between consumption and investment, but assume that it is a convex set and the shadow price of capital is variable over time. Define the intertemporal social objective function

$$V(0) = \int_{t=0}^{\infty} e^{-rt} U(C(s))ds \qquad (11.8).$$

The intertemporal utility maximization problem at the start of time 0 is:

$$\max_{\{C(t)\}} \int_{t=0}^{\infty} e^{-rt} U(C(s))ds \qquad (11.9)$$

subject to $\dot{K}(t) = I(t) - \delta K(t)$
$(C(t),\ \dot{K}(t))$ feasible each period;
given $K(0),\ p(t)$.

The Hamiltonian equation for this problem is

$$H(t) = U(C(t)) + \lambda \dot{K}(t) \qquad (11.10)$$

where λ is the shadow value of capital. The 'shadow value of capital' is the value to the consumer of one more unit of capital, in terms of additional (present discounted) utility. At time t=0, the marginal value of capital in equation (11.8) is $V_K(0)$. More generally, the shadow price of capital at time t is $V_K(t)$. Also, equation (11.3) plus the national accounting identity (Y=C+I) implies $\dot{K}(t) = Y(t) - C(t)$. So we can re-write (11.10) as

$$H(t) = U(C(t)) + V_K(t)(Y(t) - C(t)).$$

Along the optimal path for (11.9), $H_C = 0$, which gives us[14]

$$U_C(t) = V_K(t) \qquad (11.11).$$

Finally, the Hamilton-Jacobi equation in dynamic optimization tells us that, along the optimal path,

$$rV = \max_{\{C\}}[U(C) + V_K \dot{K}]$$

where the time arguments have been dropped for convenience. When the optimal consumption level is substituted into the Hamilton-Jacobi equation, and we use (11.8) and the result in (11.11), we get

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[14] A similar derivation is in Hartwick (1993).

$$r\int_{t=0}^{\infty} e^{-rt}U(C^*(s))ds = rV^* = U(C^*(t)) + U_C(t)\dot{K}(t) \qquad (11.12).$$

The right-hand side term tells us the welfare value of the optimal current consumption-investment mix, where units of capital are valued in utility terms by multiplying them by the marginal utility of an extra unit of consumption. The left-hand side is r times the discounted value of all future consumption, which corresponds to the middle term.

How do we interpret (11.12)? Note that (11.8) defines the economy's 'true' wealth: in effect, the real wealth of a nation is its capacity to generate utility into the perpetual future. At time 0, true wealth is therefore $V(0)$. The left hand side of (11.12) is the interest on true national wealth, which corresponds to the meaning of 'Hicksian' income: the amount of consumption that leaves capital intact, where capital is valued with welfare-relevant weights. The right hand side of (11.12) is the utility-value of consumption plus net investment. This is the utility value of NNP.[15]

The curious thing about equation (11.12) is that it suggests that current data (namely Net National Product) can approximately reveal the economy's *permanently sustainable consumption level*. There are many assumptions being made to support this result, and some authors have criticized it as very unrealistic. For instance the relative cost of capital and consumption would change if we actually tried to exploit the above result by consuming all our Hicksian income, so the result is inherently over-stated.[16]

But at least (11.12) gets us started at thinking about how to measure and test for sustainability. However it is important to keep some related concepts separate.

- Cairns (2002) has pointed out that Hicksian income is not the same as sustainable income, it is a "**stationary equivalent**" to sustainable income. It tells us the constant amount we could consume forever given our current social capital stock. But lots of different income paths are "sustainable" in the sense that they yield non-decreasing future consumption possibilities, and the optimal consumption path may not be a permanently sustainable one.

- Early researchers on this topic were interested in the problem of nonrenewable resources: could an economy generate constant consumption in the future even while depleting a non-renewable resource stock? Back in 1974 Solow proved that it could, as long as certain conditions were met regarding the elasticity of substitution in production. John Hartwick later showed that an economy satisfying the Solow conditions could remain on a **constant consumption path** by investing all nonrenewable resource rents in renewable capital. This is called the "**Hartwick**

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[15] If the utility function is linear ($U=C$) and the consumption good is the numeraire (so the price of investment goods p equals U_C), equation (11.12) corresponds to equations (10) and (11) in Weitzman (1976).

[16] In addition to making this point, Dan Usher has criticized this whole line of research for its lack of a robust relationship to the methods used to compute actual NNP (see Usher 1992.)

> **rule**." Others have since shown that the optimal consumption path yields a constant consumption path under the Hartwick rule only if the social planner is maximizing a Rawlsian social welfare function. Otherwise the Hartwick rule is not a necessary condition for the optimal consumption path defined by (11.12).

11.3. Measuring Sustainability

Both equations (11.7) and (11.12) can, in principle, supply a method for measuring "sustainability." If we add to (11.12) a measure of the change in the value of non-marketed capital (e.g. resources and environmental quality) then a non-decreasing NNP implies a non-decreasing stream of future consumption possibilities. Using (11.7) we can also examine the "net savings" in a year, and argue that as long as the total value of the capital stock is increasing, future consumption possibilities are not being diminished.

If we over-estimate current investment, our published NNP, or total savings statistics, will over-state sustainable future consumption, and vice-versa. Many people worry that we are using up natural and environmental resources without properly accounting for them, which means that we are overstating investment (by understating depreciation). On the other hand, some people point out that we generally understate investments in human capital, because we don't account for current and future productivity gains arising from education and training.

While there has been little attention paid to the human capital issue, a great deal of attention has been paid to finding ways of including resource and environmental stocks in the national accounts. The aim is to get NNP closer to the right-hand side of equation (11.12). The National Round Table on the Environment and the Economy (NRTEE 2001) has produced a proposal for a measure of whether current consumption is depleting future consumption possibilities. The particular method they suggested is wrong, as will be critically reviewed below, and I will explain an alternative that more closely reflects the theoretical foundations outlined above.

In a recent paper, Weitzman and Lofgren (1997) examine a simple economy with a growing stock of productive labour and a capital stock that includes resources and the environment. They calculate (very roughly of course) that the ratio of sustainable consumption to current NNP is about 1.4; that is our NNP statistics, on net, understate the true sustainable consumption level by about 40 per cent.

11.3.1 Green Net National Product and Net Savings

In this section we introduce two modifications in preparation for developing an empirical example: differentiating among capital types and using a discrete time approximation.

Call financial wealth (measured in dollars) *W*. Physical capital (including land and marketed resources) is denoted *K*, its price is p_K and its value is denoted $V(K) = p_K K$. Non-marketed resources (including environmental quality) is denoted *N* and its value is $V(N) = p_N N$. Each one generates a net rate of return r_i ("net" implies here an adjustment for capital depreciation). We can invest in each type of capital, and thereby increase the level available for the future.

Assume that the price of consumption is the numeraire so the national Hicksian budget constraint can be written:

$$r_W W + r_K V(K) + r_N V(N) = C + \Delta W + \Delta V(K) + \Delta V(N) = MSC \quad (11.13).$$

MSC denotes maximum sustainable consumption. The first terms are the rates of return on the different capital stocks. The middle terms represent the disposition of income between consumption and net investment. The equality with *MSC* reminds us that we could perpetually consume our entire net returns to existing capital if we wanted to.

As stated above, if we want to measure "sustainability" there are two options. The so-called "green Net National Product" approach uses the middle form of the above equation. Ordinary Net National Product is defined as consumption plus net investment:

$$NNP = C + \Delta W + \Delta V(K)$$

If we add in the value of the change in non-marketed capital $\Delta V(K)$ we get "Green NNP" which reveals our true maximum sustainable consumption:

$$GNNP = C + \Delta W + \Delta V(K) + \Delta V(N) \quad (11.14).$$

Three important points are:

- If in one year there is no change in $V(N)$ (either because $\Delta N = 0$ or the change in p_N exactly offsets the change in N) then *GNNP* reduces to ordinary *NNP*.
- N only includes those forms of "natural" capital that generate returns in the form of consumption (or utility) for people.
- The expressions above use stock *values*, not *quantities*.

Using the *GNNP* criterion we would conclude that the economy is on a sustainable path as long as

$$\Delta GNNP \geq 0 \quad (11.15).$$

That is, as long as augmented *NNP* is not diminishing over time we are not reducing the maximum sustainable consumption level. It would make sense to measure *GNNP* in per-capita terms to ensure average *MSC* is not declining.

Another way of measuring sustainability uses equation (11.7), the equality between the value of the capital stock today and the value of the future consumption stream it can generate, discounted by the rate of return. Since maintaining future consumption possibilities is what we mean when discuss "sustainability" a suitable indicator of sustainable growth would be positive net savings:

$$\Delta W + \Delta V(K) + \Delta V(N) \geq 0 \qquad (11.16).$$

If this condition holds true then the future consumption stream is not diminished by current consumption. This again ought to be studied in per-capita terms. Recent criticism of the Green NNP approach suggests the Net Savings measure is preferable. In practice people who work on environmental accounting have focused on this measure (e.g. Hamilton 2001).

11.3.2 Environmental Valuation

We are concerned with measuring the value of, among other things, environmental quality. This is simply the state of land, air and water as it is affected by human activity, and over which people have preferences. The state of the environment generates a return in the form of utility for which people are willing to pay. If the state of the environment changes then this will affect the future consumption of environmental quality. Hence we can ask how the state of the environment has changed, and how these changes are valued. The valuation of changes in environmental quality is constrained by actual budgets, hence it is referred to as *Willingness To Pay* (WTP).

There are two practical tools for computing WTP measures for environmental amenities: *hedonic* and *contingent* valuation. These correspond, approximately, with two categories of value: *use* and *existence*. Hedonic valuation considers how the value of a marketed good changes as a result of a change in a nonmarketed, complementary local attribute. This type of valuation is appropriate for measuring changes in environmental quality for amenities that people regularly use or experience. For instance, if the air quality in a city or neighbourhood improves, this will make the area more attractive to live in and will raise the local property values. Property values can rise or fall for many reasons, including changes in crime rates, local economic conditions, and local environmental quality. Since for the purpose of an aggregate measure of net savings we are interested in the total impact of all these things on wealth, there is no need to separately identify the environmental influence. However we will need to be careful about how net savings measures are categorized, as will be discussed below.

Not all environmental attributes are related to local usage. People have preferences over some amenities merely because of their existence. Canadians have supported setting aside large amounts of wilderness even though very few ever plan to visit those areas. Similarly people have voiced interest in preserving endangered species even though few people would ever encounter or even recognize such plants or animals.

To measure *existence* values the preferred technique among economists is *contingent valuation* (CV). This is a survey-based methodology that elicits bids from respondents for how much they are willing to pay contingent on some change in the quality of the environment. CV surveys are very common in the US for applied cost-benefit analysis in public lands management, and are becoming more routine in Canadian situations as well. There has been much debate about the best way to construct a CV survey in order to avoid biases related to free-riding, protest bids, strategic responses, etc. The techniques developed over the past decade attempt to filter out such potential biases, and the relevant methods continue to be refined (and debated).[17]

A point to emphasize here is that the only aspects of the stock of environmental quality that need to be quantified in this way are those *not already counted* by the hedonic valuation of tangible capital assets. Pure existence values would be defined (albeit with difficulty) for such amenities as remote wilderness areas, endangered species counts and contamination of remote lands and waterways. Fortunately for the purpose of computing a net savings measure the quantities of these things changes little from one year to the next.

There have been some recent proposals to add in global-scale environmental changes. But it should be noted that they are both highly uncertain and largely exogenous. It is unlikely that Canadians have well-defined preferences over the concentration of atmospheric CO_2, and even if they did, Canadian emissions make very little difference to it. In any case CO_2 levels are not the issue, what is at issue is the effect (if any) of changes in such levels on the weather Canadians experience. This can not reliably be quantified, nor is it something that could meaningfully be valued. To the extent people have tried, Canada seems to be better off with higher CO_2 levels.

Similarly the ozone column depth over Canada is a rather intangible aspect of environmental quality and following the elimination of freon production under the Montreal Protocol it is not something we exercize control over anyway. Canadians do control their exposure to UV radiation through use of sunscreen, time indoors, limitation of southern travel, etc. The costs of these measures are already factored into asset values. Hence separate valuation is not needed for computing Net Savings.

11.3.3 Human Capital

This is difficult to define but a conventional measure among labour economists is average schooling. However there is too much heterogeneity in quality and relevance of schooling and it is confounded with local capital availability and other regional variables, so it is thought to be a poor measure. Mulligan and Sala-i-Martin (1995) proposed instead a labour income-based human capital (LIHK) measure that controls for heterogeneity of schooling, experience, health, capital availability, etc. The measure turns out to be easy to compute: it is the average (across all locations) of the local ratio of total labour income per capita divided by the labour income of a person with zero-years schooling. This latter item is not observed directly but can be computed using something called a Mincer regression. This involves identifying the labour market return to years of schooling then extrapolating back to zero years.

When multiplied by population the LIHK provides a measure of human capital that accounts for education, health status, heterogeneous skills, etc. However it is an index

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[17] The US Department of Agriculture has an on-line resource at http://www.ecosystemvaluation.org/dollar_based.htm which explains both hedonic valuation and contingent valuation methods.

rather than an amount that would fit into the Balance Sheet Accounts. The next section proposes a way to convert it to a monetized capital stock.

11.3.4 Canadian Net Savings 1993 to 1997

	Socio-Economic		Natural				
	Location	**Produced**	**Resources**	**Amenities**	**Human**	**Financial**	**TOTAL**
1993	21,629	45,653	-17,225	-104	-114,534	-22,211	-86,791
1994	27,869	65,632	13,126	-10	30,163	-8,199	128,580
1995	8,017	42,384	24,072	-193	19,289	7,274	100,843
1996	13,246	16,961	2,962	-10	97,734	24,179	155,071
1997	18,698	51,222	3,192	-92	8,036	10,550	91,607

Table 1 Sample National Net Savings (millions current Canadian $)

	Socio-Economic		Natural				
	Location	**Produced**	**Resources**	**Amenities**	**Human**	**Financial**	**TOTAL**
1993	2.9	6.2	-2.3	0.0	-15.5	-3.0	-11.8
1994	3.6	8.4	1.7	0.0	3.9	-1.0	16.4
1995	1.0	5.2	2.9	0.0	2.3	0.9	12.3
1996	1.6	2.0	0.3	0.0	11.5	2.9	18.3
1997	2.1	5.7	0.4	0.0	0.9	1.2	10.2

Table 2 Sample National Net Savings as a % of Current GDP

	Socio-Economic		Natural				
	Location	**Produced**	**Resources**	**Amenities**	**Human**	**Financial**	**TOTAL**
1993	751	1,585	-598	-4	-3,975	-771	-3,012
1994	956	2,252	450	0	1,035	-281	4,412
1995	272	1,439	817	-7	655	247	3,424
1996	445	570	99	0	3,283	812	5,209
1997	622	1,703	106	-3	267	351	3,046

Table 3 Sample National Net Savings Per Capita (Current $)

Currently available data support constructing a broadly-based Net Savings Indicator. Here I demonstrate an approach that aggregates changes in four categories:

- Socio-Economic Capital,
- Natural Capital,
- Human Capital and
- Financial Capital.

Table 11.1 gives an estimate of the level of Net Savings for Canada from 1993 to 1997. Table 11.2 shows the same information as a percentage of GDP. Table 11.3 shows Net Savings on a per capita basis in each category. The interpretation for sustainability is that as long as Per Capita Net Savings (the last column in Table 11.3) is positive, the future standard of living is enhanced by the current period's economic activity. As computed below, current economic activity on balance enhanced long-term sustainable consumption opportunities for Canadians in each year of the series except for 1993.

The following section explains how these tables were produced. Some of the steps involve an apparent valuation of a total stock. This is just a computational step, but the results are only expressed as changes in total value, for the reasons explained above.

Socio-Economic Capital is subdivided into Locational and Produced Capital. Locational capital is the value of land, and includes the full capitalized values of living or operating an enterprise at a location, since this determines what people are willing to pay to own the land. This will include hedonic valuation of environmental and economic attributes, as well as social characteristics such as crime rates, public services and proximity to social amenities. Produced capital includes buildings and equipment. Both measures are published in the National Balance Sheet Accounts (specific CANSIM series numbers are in Appendix 11.A).

Natural Capital includes Resources and Amenities. The Resources measure shown here is from the National Balance Sheet Accounts. It consists of all Non-Produced Assets except Land. At present the record on CANSIM is complete only up to 1995 so this category was assumed to grow (in levels) by two percent per year for the final two years.

The Amenities measure is defined as those environmental assets over which people have preferences primarily for their existence, even though they are not routinely encountered. The sample measure shown here is computed as follows. It is assumed that as of 1992 the total value of amenities to Canadians is \$1000 per capita. (The level does not matter since only deviations end up in the Net Savings figures.) It is assumed that the addition of a species to the list of those At Risk reduces the basic amenity value by \$1 per capita, or \$30 million nationally, so the per capita amenity value is (\$1000-R), where R is the number of species at risk. Data available from Environment Canada for the years prior to 2000 only include the total number of species. Since the list includes many different plants and animals, from ferns to mammals, and not all species are equally valued, it will be important to develop a list of the different types of species and their contingent values to Canadians. Added to the total value of amenities was the value of additions to the stock of land set aside for permanent wilderness, valued at \$1000 per square km, and the total area set aside as permanent grassland, valued at \$100 per square km. These are rough guesses of course, for illustrative purposes only.

The human capital measure uses an approximation to the LIHK measure described above. The average weekly earnings for all industrial workers was obtained from Statistics Canada. To get the average earnings for a worker with zero years of schooling I used the average weekly earnings of people on social assistance. Then the variable L is defined as the ratio of these two, and has a value of between 1.5 and 1.6 across the sample. This ratio L is a key step in the human capital measure, but it must be stressed that two shortcuts were taken here for convenience. First, it is necessary to get the average earnings of workers with zero years of schooling from a model such as a Mincer regression. Second, the proper measure is the average of the ratios across individual regions, not the ratio of the average earnings levels across all regions. Actual implementation of this procedure would be straightforward since the data are available, but for the purposes of this paper I use these approximations instead.

The ratio L is then multiplied by total population to yield an index I_{HK} of human capital. This is converted into an estimate of the value of human capital (K_H) using the following argument. Human capital is the stock which generates a return each period equal to total labour income. In a year with (nearly) full employment, if the stock of human capital generates a competitive rate of return it should be possible to infer its value. The competitive real rate of return on capital assets over the long run is about 7%. So if 7% of K_H is the total labour income in a year with low unemployment, we can divide labour income by 0.07 to get human capital for that year. 1997 was the year with the lowest unemployment in the sample. Dividing total (nominal) labour income for 1997 by 0.07 yielded an estimate of K_H. We cannot use the same procedure in other years because higher unemployment implies part of the human capital stock is 'idle' and not generating a return. But we can use the index I_{HK} to adjust the human capital stock measure. I_{HK} was calibrated to the 1997 human capital stock, and the calibration coefficient was then used to construct the human capital stock for the other sample years.

Financial capital is taken from Statistics Canada, and is defined as Canada's total international investment position. We are only interested in total foreign assets (or, if negative, liabilities). Domestic assets net out to zero: a bond for the holder is a liability for the borrower. The international position represents the net value of assets and liabilities between Canada and all other countries.

Note that all these measures are nominal rather than real (inflation adjusted). Since the results in Table 11.2 are reported as a fraction of GDP for that year, no adjustment for inflation is needed. For the other tables GDP deflators should be applied to the final estimates, though this was not done for this exercize.

Each of these stocks were aggregated over the period 1992 to 1997. The per capita national Net Savings (Table 11.3) is computed as the first difference of the per capita total social capital stock each year. The total national Net Savings (Table 11.1) is computed using the figures in Table 3 with each row multiplied by population.

Total National Net Savings Per Capita is graphed in Figure 11.1. There is wide variation in net savings across the sample years. In 1993, while the country was still emerging from the recession of 1991-92, Net Savings was negative. The value of the resource stock fell as did the value of the stocks of financial and human capital. The latter fell because the rate of return to education was diminished during the recession. However it rebounded rapidly in the mid-1990s as the labour market improved. The rise in the average wage rate indicates that the pre-existing skill set of the labour force became highly valuable, pushing the rate of growth of the value of human capital into double digits for the next three years. Investment in produced capital was strong across the sample years.

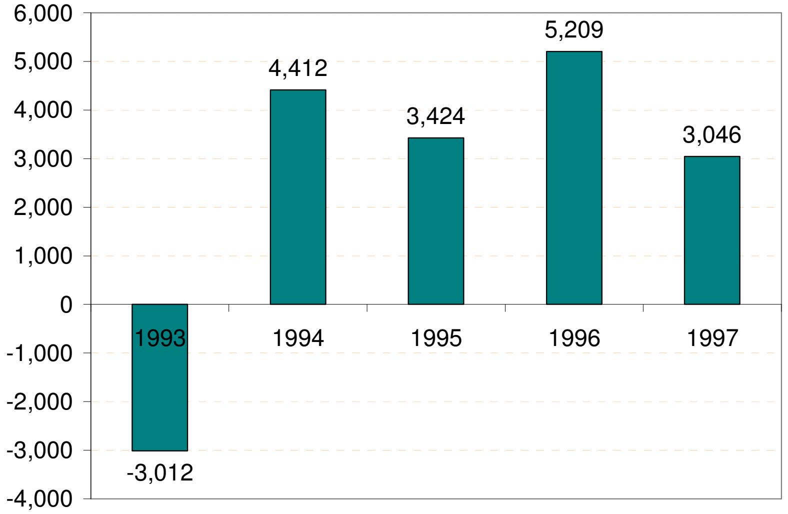

Figure 11.1: Nominal Net Savings Per Capita (Cdn $), 1993 to 1997.

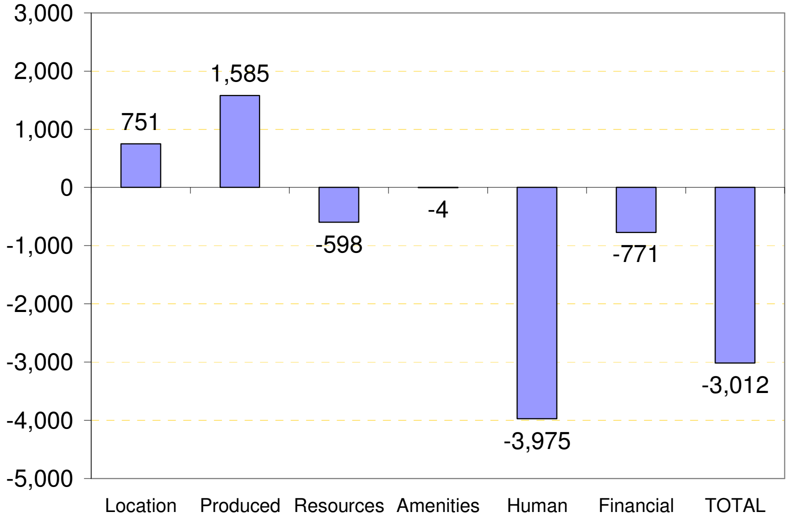

Figure 11.2: Net Savings (nominal Cdn $) in Different Capital Categories, 1993.

The capital categories for 1993 are graphed in Figure 11.2. Looking at Table 11.2 it is clear that the dominant categories are produced and human capital. While the numbers shown here are merely illustrative it is likely that this will be true of any net savings-based measure. The 1990s was a time of considerable investment in human capital and growth of real earnings based on acquisition of knowledge and skill. Labour and investment are the main categories of national income so the underlying "capital" stocks are very influential in determining current living standards and the overall sustainability of future consumption. The series shown here indicates that the resource stock generally gains value, reflecting additions to proven reserves as well as marginal valuation changes.

The amenity values are very small in comparison to other categories of value. This too is likely to be true of any net savings-based indicator. Note however that most aspects of environmental quality are capitalized into Location values, so the amenities measure here only refers to existence-based values. If we arbitrarily multiply the amenity values by 10, i.e. increase them by a full order of magnitude, they remain below 0.5 percent in each year of the sample. The shadow value of changes in amenities is constrained by peoples' willingness to pay. The research done by the federal government to allocate money for compensating landowners who lose assets under the new Species At Risk Act suggests amounts more than a few hundred million dollars are difficult to motivate. The measure used here arbitrarily pegs the average value of adding a species to the At Risk list at about $30 million. Changing this to $300 million would not make a difference in the scale of the above numbers.

11.4 Stock-Based Indicators

Some groups have recently proposed indicators of environmental sustainability based on measuring stocks of environmental quality and natural resources directly, without using prices. For instance, the National Round Table on the Environment and the Economy (2001) proposed such a method for Canada. These types of measures are sometimes referred to as "Genuine Progress Indicators."

People have long worried about scarcity and depletion of resource stocks. British Columbia convened its first Royal Commission into forest depletion (the Fulton Commission) in 1909. The UK convened its first Royal Commission on the subject in 1548! Appendix 11.B lists some further historical examples. If anything, people today have less reason to worry about resource scarcity than before.

The common mistake, especially in 20th century treatments of the "running out" problem, is a failure to distinguish between stock *size* and *scarcity*. We are "running out" of PCB-contaminated oil. But that is not a problem, because it (likely) has no value. Running out of zinc would be a problem, because it is valuable. So the key is not stock size, but its value at the margin.

The relevant term is *scarcity*. This refers to the balance between supply and demand, and it has a specific measure: the competitive market price. The price tells us how much of our other wealth (or labour time or other resources) we must give up to get one more unit of something. The question we need to ask is whether resources are becoming more or less scarce.

A focus on resource stock size would predispose an indicator to the view that we are getting worse off over time. Of course nonrenewable resource stocks are declining. The question is whether they are getting less scarce or not. Table 11.4 shows the % change in the real price (deflated by the US CPI) of key minerals from 1975 to 1997. A ton of copper at the end of the interval cost about 56% of what it cost at the start. The value of Mercury fell 70%. Even gold lost about 30% of its value.

All these resources became less scarce while the total *stocks* of all these resources fell. The reasons for the price decline include falling demand for some minerals, new source discoveries and technological improvements that reduced extraction and processing costs.

% Change in Real Cost of Minerals from 1975 to 1997

Copper	-44.2
Nickel	-38.6
Mercury	-70.8
Zinc	-44.5
Tin	-62.4
Platinum	-18.8
Aluminum	-25.7
Tungsten	-72.1
Gold	-31.0
Silver	-62.9

Table 11.4 Source: US Geological Survey http://minerals.usgs.gov/minerals/pub/metal-prices/; US Consumer Price Index from US Commerce Department.

The relevance here is that if the *value* of resources are falling, *sustainability requires that we deplete the stock of these resources and invest the money in alternate forms of capital that are appreciating over time*. Using stock values allows interpretation of an indicator in terms of sustainability. This applies to all forms of capital to be included: without a price-based measure of scarcity there is no way to distinguish those stocks for which sustainability calls for reduced quantities and those for which sustainability requires increased quantities.

Asset values, especially land, are already in the National Balance Sheet Accounts. It is important to recognize that property values capitalize many of the ecosystem services discussed. For instance, while property in Sydney, Nova Scotia, is less valuable on average than that of, say, Halifax because of general economic differences, within Sydney there is a drop in value based on proximity to the tar ponds. Within any city there are neighbourhoods that have dirtier air, are closer to the garbage dump, etc. Property values in these areas reflect the disutility of these things. In Mississauga the neighbourhoods that are under the flight paths in and out of Pearson airport are less valued due to the noise.

The point here is that many of the routine air and water quality measures discussed under “ecosystem services” are already evaluated in land and housing prices. Uninhabited areas may not have active markets to allow observation of land values, but then again these areas (e.g. high elevation sites in the Rockies) usually do not have air or water pollution problems. And the fact that they are uninhabited may mean that the land is not commercially valued by anyone.

It is not simply the case that “sustainability” requires pollution levels to go down. It requires that the total value of the social capital stock, broadly defined, goes up. Increasing pollution can be entirely consistent with enhanced sustainability if by drawing down the stock of environmental cleanliness we simultaneously generate income which is invested in other forms of capital of greater value at the margin.

A recent NRTEE document (2001) proposes to track the contribution of air quality to sustainability using an “exposure-weighted” measure. How would we interpret it if the exposure-weighted air pollution measure goes up? It could be taken to mean that people are worse off. But it could just as easily mean that people who prefer the amenities of the city—despite the air pollution—to the amenities of the countryside are making their way into cities, so more people are better off. Without a theoretical model of how peoples’ behaviour reveals their valuation of the local environment we have no reason to assume the first interpretation is correct.

11.5 Conclusions

Under reasonably general conditions the value of current capital is a proxy for the value of the discounted future consumption path. If “capital” is augmented to include natural assets the theory provides a basis for attaching a meaning to the term “sustainability.” The practical value of this literature is demonstrated by developing some sample estimates of net savings for Canada over the period 1993 to 1997. These (very preliminary) figures suggest that Canadian economic growth is sustainable in most years, in the sense that per capita net savings are positive. They also show that investment in labour and physical capital is such a dominant component of net savings that changes in environmental quality are unlikely on their own to change the sign of net savings.

Chapter 11 References

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Appendix 11.A

Data Sources (For Details See Text):

Variable:	Descriptions	Source:
Location:	Land from Balance Sheet Accounts	Cansim II V34963
Produced:	Produced Assets from BSA	Cansim II V34956
Population:	End of year estimate (mils)	Cansim II V1
Resources	BSA Non-produced assets less land. Post 1995 series extrapolated by 2% p.a.	Cansim II V34962 less V34963
Amenities	(1000-#End Spec) per capita+Major Prot@1000/km2+Perm Grass@100/km2	OECD Env Statistics
Avg Wage	Average weekly earnings, all employees, by industry	Cansim I L186863
Base Wage	Average weekly earnings, all employees, by industry, Social Assistance	Cansim II V1558828
Income	GDP-Income Based, Wages Salaries and Supplementary Labour Income	Cansim I D15654
Financial	Canada's Net International Investment Position, All Countries	Cansim I D65219
GDP	Expenditure-Based, Millions of Current Dollars	Cansim I D15689

Appendix 11.B

Is Concern About Resource Depletion A Recent Phenomenon?

The answer is NO, but many environmentalists try to claim that ours is the first generation to notice or care about the state of the Earth.

In January 2000 the “Y2K” moment passed without the expected calamity. But the turning of the calendar was an occasion for other putative calamities to be discussed. The Sierra Club magazine introduced a symposium on the state of the environment with these thoughts.

> It’s been a dismal thousand years, environmentally speaking. We cut down most of the earth's forests, drove most large carnivores to the brink of extinction, spread disruptive exotic species around the globe, manufactured poisons on a monumental scale, and set in motion a potentially catastrophic warming of the atmosphere. Now, with the blank slate of a new millennium before us, we have a chance to get it right.
> (*Sierra Magazine*, January 2000.)

Carl Pope, the Club's executive director, began his comments in the same article by noting how attitudes towards the environment are beginning to change, albeit late in the day.

> We are headed off an environmental cliff, but governments and corporations continue to operate on short time horizons—resisting popular desire to minimize technological risk, for example, or exposure to toxic chemicals. Indeed, they may lag those they nominally serve by as much as a generation. So the question I would like to pose is this: How can our collective behavior catch up with our individual concerns? How, in the next century, can we translate public attitudes into real environmental progress?

These comments encapsulate three common views about the state of the environment. First, there is the idea that things have been getting worse lately because of modern economic growth—implying that they were better in a golden age now ended. Second, there is the theme of impending disaster, unnoticed by oblivious decision-makers in government and industry. Finally, there is the idea that we grasp these things now, but we didn't before.

Here are some additional examples, all drawn from relatively recent publications:

> "The gap between what we need to do to reverse the degradation of the planet and what we are doing widens with each passing year. How do we cross the threshold of political change that will shrink this gap, reversing the trends of environmental degradation that are undermining the economy? Most environment ministers understand that we are headed for economic decline, but there is not yet enough political support to overcome the vested interests that oppose changes."
> Lester Brown and Jennifer Mitchell, *State of the World* 1998 (Worldwatch Institute p. 183).

> "The United States [is] approaching a turning point, leaving behind the false choices and short-sighted policies that for far too long guided American action, or more often, inaction. We were asked to choose between the economy and the environment, between jobs and the health of our communities. The goals of a prosperous economy and a clean environment are not mutually exclusive. We now recognize that economic growth demands environmental protection and that protecting the environment can create jobs. There are clear signs of America's renewed commitment to environmental sustainability.
> Al Gore, US Vice-President, in *Environment Strategy Europe* 1993, p. 11

> "Time is short for us to rectify the present unsustainable patterns of human development. We must eradicate poverty. We must achieve greater equality within and between nations. We must reconcile human activities and human numbers with the laws of nature. Human history has now reached a watershed where fundamental policy changes become unavoidable…There is no turning back from realizing that we are heading towards a crisis of uncontrollable dimensions unless we change course. The North, as well as the rich in the South, will have to change their unsustainable consumption and production patterns. A global partnership must start with a commitment by industrialized countries to reduce sharply the burden they impose on the carrying capacity of the earth's ecosystems."
> Gro Harlem Brundtland, Prime Minister of Norway
> and Chairman of the UN World Commission on Environment and Development,
> *Environment Strategy Europe* 1992, pp. 99-101.

> "Archaeological discoveries of recent decades suggest that even great civilizations, such as the Sumerians and the Mayans, met devastation at least in part by failing to live in harmony with

> the natural environment. We, too, have tempted fate for most of the past two hundred years, fuelled by breakthroughs in science and technology and the belief that natural limits to human well-being had been conquered. Climate change is a prime example of this. Today we know better, and have begun to transform our societies, albeit haltingly. So far, our scientific understanding continues to run ahead of our social and political response. With some honourable exceptions, our efforts to change course are too few and too little."
> UN Secretary-General Kofi Annan, "Towards a Sustainable Future",
> The American Museum of Natural History, New York, May 2002

We hear in these quotations a sort of 3-alarm fire: economic growth is ruining the environment, disaster is imminent, and only now are we waking up to the problem. In the Chapter 1 we looked at the first two alarms. Here I'd like to show that public concern for resources and the environment goes back a long way.

The Brundtland Report
The same apocalyptic themes seen in the quotations above were raised in the 1987 Report of the UN World Commission on Environment and Development, better known as the Brundtland Commission (after its chair, Gro Harlem Brundtland). The opening chapter, "A Threatened Future," describes how in the past societies wrestled with local resource and environmental challenges, but today the scale and severity of these challenges is increasing because of economic changes. "Economics and ecology bind us in every-tightening networks. Today, many regions face risks of irreversible damage to the human environment that threatens the basis for human progress" (p. 27.) A long litany of growing environmental stresses was said to pose an imminent danger: "Little time is available for corrective action. In some cases we may already be close to transgressing critical thresholds…Failures to manage the environment and to sustain development threaten to overwhelm all countries" (pp. 35, 37.)

And recognition of these concerns is presented as though it were a "new" feature of public attitudes. The Brundtland Commission quotes Charles Caccia, a former Canadian Member of Parliament (and Chair of the House of Commons Environment Committee): "We are just now beginning to realize that we must find an alternative to our ingrained behaviour of burdening future generations resulting from our misplaced belief that there is a choice between economy and the environment. That choice, in the long term, turns out to be an illusion with awesome consequences for humanity" (p. 38.)

Warnings in the 1970s
But long before 1987, people worried about the state of the Earth. In 1973 a famous book called *The Limits to Growth,* from a group called the Club of Rome, warned of imminent collapse due to heavy consumption of nonrenewable minerals and fossil fuels. A year earlier, in a book entitled *Population Resources Environment: Issues in Human Ecology*, Stanford scientists Paul and Anne Ehrlich warned: "Spaceship Earth is now filled to capacity or beyond and is in danger of running out of food. And yet the people traveling first class are, without thinking, demolishing the ship's already overstrained life-supporting systems" (p. 3). They went on to make some specific predictions about the coming 30 years. A now-famous chart on page 71 of their book predicted that by 2000 the world would have exhausted all supplies of natural gas, uranium, tungsten, copper, lead, zinc, tin, gold, silver and platinum, and would have less than 30 year's supply of crude oil left. In their concluding chapter they warned that the planet was "grossly overpopulated" and that "the limits of human capacity to produce food by conventional means have very nearly been reached…Attempts to increase food production further will tend to accelerate the deterioration of our environment, which in turn will eventually *reduce* the capacity of the Earth to produce food. It is not clear whether environmental decay has now gone so far as to be essentially irreversible; it is

possible the capacity of the planet to support human life has been permanently impaired" (pp. 441-442).

Ehrlich and Ehrlich also include a quotation from a valedictory address given at Mills College in 1969, poignantly expressing the pessimism of that age from a young woman's point of view: "The future is a cruel hoax…I am terribly saddened by the fact that the most humane thing for me to do is to have no children at all."

This, remember, was well over 30 years ago: and about 15 years before the Brundtland Report "discovered" the environmental problem. But even this was not the beginning of such concerns. In 1963 Harold Barnett and Chandler Morse published a landmark study called *Scarcity and Growth: The Economics of Natural Resource Availability* (Washington, Resources for the Future Press). They set out to evaluate then-prevalent ideas about the growing scarcity of natural resources and the limits these would impose on economic growth. Based on their analysis of available data on prices, methods and production trends, they came to reject the hypothesis of increasing scarcity, on the grounds that innovation had hitherto been sufficient to trigger discovery of new resources, replacements for scarce materials or new efficiencies. "Few components of the Earth's crust, including farm land, are so specific as to defy economic replacement, or so resistant to technological advance as to be incapable of eventually yielding extractive products at constant or declining cost" (p. 10.) Their conclusion is telling, but so is the fact that as early as 1963 concerns about the limits to growth were so widespread as to necessitate their book.

The Limits of the Earth, ca. 1953

Barnett and Morse provide a fascinating review of a series of books and papers published in the US in the 1940s and 1950s raising concerns that sound as if they were taken straight out of current environmental literature. Samuel Ordway's 1953 book *Resources and the American Dream* was written (they quote him saying) to present "A Theory of the Limit of Growth" motivated by the fear that "within foreseeable time increasing consumption of resources can produce scarcities serious enough to destroy our American Dream of an ever-higher level of living, and with it our present culture." Henry Fairfield Osborne, President of the New York Zoological Society, wrote in his 1953 book *Limits of the Earth*, "Now as we look, we can see the limits of the earth…If we are blind to this law, or delude ourselves into minimizing its power, of one thing we can be assured—the human race will enter into days of increasing trouble, conflict and darkness" (quoted in Barnett and Morse p. 27.) An earlier book by Osborne bore the title *Our Plundered Planet*. William Vogt's 1948 book *Road to Survival* asserted that strategies to prevent economic collapse were urgently needed, and "unless population control and conservation are included, other means are certain to fail."

In 1955 Dr. Allan Gregg of the Rockefeller Foundation's Medical Division proposed that the presence of humans on Earth was analogous to a terminal disease. "There is an alarming parallel between the growth of a cancer in the body of an organism and the growth of human populations in the earth's ecological community…Humanity should now face the question of an optimum population" (quoted in Barnett and Morse, p. 31.) In 1950 economist W.C. Mitchell warned: "The appalling wastes of natural resources that are going on seem due largely to the policy of handing over the nation's heritage to individuals to be exploited as they see fit…what is rational on the basis of this short-run private view may be exceedingly unwise on the basis of long-run public interest" (Barnett and Morse p. 48).

The expressions of concern go back still further. In the 1930s and 40s Presidents Roosevelt, Eisenhower and Truman all expressed alarm about rapid depletion of resources, and a series of commissions (such as the Kestenbaum Commission, the Paley Commission and the Hoover Commission) were formed to advise the government on appropriate policy responses. President Roosevelt himself had expressed particular concern about the extensive changes in land cover during the settling of the American west, warning that "the throwing out of balance of the resources of nature throws out of balance also the lives of men" (Barnett and Morse p. 20).

The Imperative Duty of 1912

But even these writings are late compared to the voluminous work of the Conservation Movement at the turn of the twentieth century. This was an influential group in the US, led in part by President Theodore Roosevelt and Chief Forester Gifford Pinchot. In his 1910 book *The Fight for Conservation* Pinchot warns:

> "The five indispensably essential materials in our civilization are wood, water, coal, iron and agricultural products…We have timber for less than thirty years at the present rate of cutting. The figures indicate that our demands upon the forest have increased twice as fast as our population. We have anthracite coal for but fifty years, and bituminous coal for less than 200. Our supplies of iron ore, mineral oil and natural gas are being rapidly depleted, and many of the great fields are already exhausted."

Three years later, William Temple Hornaday, Director of the New York Zoological Park, published an impassioned book *Our Vanishing Wildlife: Its Extermination and Preservation* to accompany the founding of the Permanent Wildlife Protection Fund, devoted to campaigning for protection and preservation of wildlife. The preface was written by Henry Fairfield Osborne, mentioned above. Here, in a passage dated December 1912, Osborne sounds the same urgent alarm he would raise in his own book 40 years later:

> "The preservation of animal and plant life, and of the general beauty of Nature, is one of the foremost duties of the men and women of today. It is an imperative duty, for it must be performed at once, for otherwise it will be too late…Air and water are polluted, rivers and streams serve as sewers and dumping grounds, forests are swept away and fishes are driven from the streams. Many birds are becoming extinct and certain mammals are on the verge of extermination. Vulgar advertisements hide the landscape and in all that disfigures the wonderful heritage of the beauty of Nature today, we Americans are in the lead."
> (Henry Fairfield Osborne, 1912, from the Preface to *Our Vanishing Wildlife: Its Extermination and Preservation* by William Temple Hornaday.)

The Conservation Movement, of which Hornaday's book was a part, is approximately dated from 1850 to 1920. It was influenced by the poetry of Henry David Thoreau, reaction against the intense deforestation that accompanied the settlement of the North American interior, and other intellectual currents, including the writings of Thomas Malthus earlier in the 19th century. Malthus, one of the better known catastrophists even today, warned in the 1820s that population growth must inevitably outstrip the availability of natural resources (especially agriculture); the same idea can be found in Adam Smith before him.

Concern about resource depletion was not confined to the US either. In 1865 the British economist Stanley Jevons published his book *The Coal Question*, warning that the UK was using up its coal too quickly and thereby losing the resource upon which all its industry was based. In Canada, meanwhile, the deforestation wrought by agricultural settlers was decried by Prime Minister Sir John A. MacDonald, who in 1871 said: "We are recklessly destroying the timber of Canada and there is scarcely the possibility of replacing it" (quoted in Elizabeth Brubaker, *Property Rights in The Defence of Nature* p. 142.) In June 1872 an article in the *Canadian Monthly* warned "We are wasting our forests, habitually, wickedly, insanely, and at a rate which must soon bankrupt us in all that element of wealth" (quoted by Brubaker, p. 142.) At the turn of the century the government of British Columbia was so concerned about the pace of deforestation that it convened the first Royal Commission (the Fulton Commission of 1905) into the state of the forests.

Our Protests Grow Larger

We could go back further in history, and were the documents available we would find in every age people warning about the depletion of resources and damage to the local environment. In 1844 Friedrich Engels described the Irk River near Manchester England as “a narrow, coal black, foul-smelling stream full of debris and refuse…from the depths of which bubbles of miasmatic gas constantly arise and give forth a stench unendurable even on the bridge forty or fifty feet above the surface of the stream.” (quoted in Brubaker, p. 128). The UK government passed its first Smoke Abatement Act in 1853, a largely ineffective response to heavy smoke loads in urban air. The Parliamentary Committee examining the issue heard from boaters on the Thames complaining of smoke so thick there were stretches of zero visibility on calm days (see J.F. Brenner, “Nuisance Law and the Industrial Revolution, *Journal of Legal Studies* 3(2) 1974, 403—33). The UK House of Lords convened a select committee into air pollution in 1862, and another one in 1878. The first inquiry found appalling destruction of woods, crops and pastures from the effects of burning sulphurous coal near St. Helen’s, while in Lancashire and Glamorganshire air pollution due to alkali, chlorine gas and other emissions was implicated in increased rates of respiratory disease and death in factory towns. Life expectancy in London in 1841 was 37 years, whereas in heavily-polluted Liverpool it was 26 and Manchester 24 (discussed in Brenner, pp. 415-18).

All over 16th century Europe the forests were disappearing. In 1548 the English government ordered an inquiry into the deteriorating state of its forests. Indeed resource scarcity was ubiquitous in Europe, and elsewhere, well before the 20th century, hence the need for gold, silver and other metals was a driving force for exploration. In 1492 an Italian journalist named Matarazzo wrote that “[There is] a great shortage of timber…people cut domestic trees…as these do not suffice people have now begun to cut even olive trees and entire olive groves have been destroyed” (quoted in Carlo Cippola, *Before the Industrial Revolution* p. 246.)

Our search doesn’t end there. A famous quote from an even earlier writer shows just how much today’s concerns about resources and the quality of the local environment were shared by others in ages past.

> “Everything has been visited, everything known, everything exploited. Now pleasant estates obliterate the famous wilderness areas of the past. Plowed fields have replaced forests, domesticated animals have dispersed wildlife…There are as many cities as, in former years, there were dwellings…Everywhere there are buildings, everywhere people, everywhere communities, everywhere life…We weigh upon the world; its resources hardly suffice to support us. As our needs grow larger, so do our protests, that already nature does not sustain us.”

The author? Tertullian, a prolific writer living in Carthage, circa 200 AD. (*Treatise on the Soul* Chapter XXX, http://www.ccel.org/fathers2/ANF-03/anf03-22.htm#P2881_991991).