Richard S.J. Tol

Environmental Economics

Lecture Notes, version 0.4 (Student's version)

October 13, 2024

Tol Tales Publishing

to Huib Jansen and David Pearce

Acknowledgements

I have taught environmental economics for many years, first at Hamburg, using *Natural Resource and Environmental Economics* by Roger Perman, Yu Ma, Michael Common, David J. Maddison and James McGilvray, and later at Sussex, using *Intermediate Environmental Economics* by Charles D. Kolstad. These two books have influenced what you find here and I have learned a lot from David and Charlie over the years.

I started writing this as a complement to the Kolstad textbook I was using at the time, first offering material that I thought was missing but gradually adding stuff that could do with an alternative explanation or more suitable or up-to-date examples. The decision to turn this into a proper textbook came much later. The reason is that the aforementioned books are aging while more recent books are less suitable. Most textbooks on environmental economics are aimed at undergraduate liberal arts students, who know very little economics. Indeed, environmental economics may be the only economics class they ever take. Other textbooks are aimed at master's and PhD level. In contrast, this book is for advanced undergraduate students of economics, students who have read principles, two terms of micro and macro, calculus, and introduction to econometrics.

George MacKerron helped in many ways, small and big. Sarah Jacobsen challenged me to look deeper into Malthus and the Romanticists. Michael Munger helped clarify what Robert Carlyle wrote, Marcel Severijnen pointed me to Tacitus. Paul Kelleher has a cameo in a footnote. Tatyana Deryugina and Frances Moore co-wrote the chapter on the Coase Theorem.

Contents

List of Figures

List of boxes

Chapter 1
Origins

In this chapter, I discuss the origins of environmental economics. This is intimately connected with the history of economics. My classification of periods in the history of economics is shown in Figure 1.1. Note that while the start of a new paradigm can be marked, elements of the previous paradigms continue. For instance, the *invisible hand* of the Classical period became the *First Fundamental Theorem of Welfare Theory*, which is as true now as when it was first posited in the Classical period, proved in the Neoclassical period, and qualified during the Modern Synthesis.

Conventionally, economics starts with the publication of the *Wealth of Nations* by Adam Smith. Earlier scholars wrote about aspects of the economy before that, but there was no coherent programme in research and education. *Classical Economics* made way for *Neo-classical Economics* with the *Marginalist Revolution* in the books by Jevons, Menger and Walras. The economics profession focused on individual people and single companies. That changed with Keynes' *General Theory*, which was about the macroeconomy and business cycles. Samuelson's *Foundations* sought to re-unite *Keynesian* macro- and *Neo-classical* micro-economics. In this period, economics became a mathematical science. This is the economics of caricatures, and what the uninitiated refer to as "neo-classical" economics. It came to an end with Dixit and Stiglitz' paper on monopolistic competition, which paved the way for increasing returns to scale and hence the *New Economics* of endogenous technological change, incomplete specialization and intrasectoral trade, and spatial agglomeration.

Most chronologies of economic dogma treat the *German Historical School* as a heterodox dead end, but I think it is better seen as a precursor of the *Credibility Revolution*. I date the latter at 1993, when econometric methods were refined to study *natural* experiments. The first *controlled* experiments in economics were published by Edward Chamberlin (1948), Heinz Sauermann and Reinhard Selten (1959) and Vernon Smith (1962), and these papers could be seen as the starting point of *Credible Economics*. The *Modern Synthesis* emphasized rigour over realism. The elegance of the mathematical proof was sometimes more important than the applicability of the theorem. In contrast, after the *Credibility Revolution*, economics has become a thoroughly empirical science. The statistical analysis is rigorous, but the results are driven by the data rather than mathematical convenience.

Gary Becker's 1955 PhD thesis is another landmark en route to the current orthodoxy in economics, which is not only empirical in nature but also easier to delineate by its methodological coherence rather than its thematic focus. Becker pushed economics beyond its original focus on consumers and producers in formal markets with observable prices. Economists now study every aspect of human behaviour, and increasingly turn to non-human behaviour and inanimate systems too. As Jacob Viner said, economics is what economists do.

There is irony here. The German Historical School argued for an economics discipline that is empirical and porous with fields of study, such as law and politics. The German Historical School lost the *Methodenstreit* with the Austrian School, who argued for economic theory and a narrow focus on markets. Although the German Historical School lost the battle, they won the war. The current generation of economists is much closer to Gustav von Schmoller than to Carl Menger.

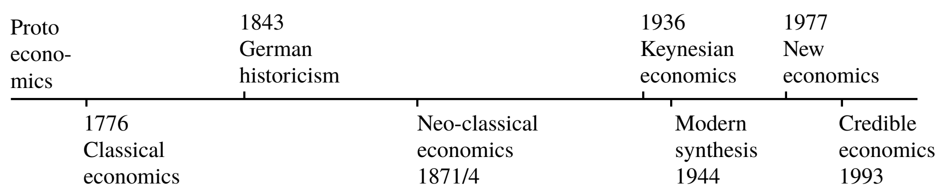


Fig. 1.1: The history of economic dogma

1776	Smith's *Wealth of Nations*
1843	Roscher's *Grundriss*
1871/4	Jevons' *Theory*, Menger's *Grundsätze*, Walras' *Eléments*
1936	Keynes' *General Theory*
1944	Samuelson's *Foundations*
1977	Dixit and Stiglitz' *Monopolistic competition*
1993	Card and Krueger's *Minimum wages*

1.1 Proto-economics

Trigger warning: Many of the quotes in this section are rather racist.

Economics conventionally starts with the publication of *The Wealth of Nations* in 1776 by Adam Smith.[1] Before that, however, many anticipated what later became elements of economics.

In those early days, agriculture was the dominant sector of the economy. Production was production of food, trade was trade in food, consumption was consumption of food. Cato (*de Agri Cultura*, c160 BCE), Varro (*Res Rustica*, 37 BCE), Columella (*De Re Rustica*, 41-68) and Palladius (*Opus Agriculturae*, c400) all wrote handbooks

[1] Smith (1723-1790) taught philosophy and law at the University of Glasgow.

on farm management.[2] These proto-economists, like all farmers and land-owners, were keenly aware of the importance of climate and geography.

In those days, teleology was common: Things were as they should be. Marcus Tullius Cicero[3] (44 BCE, On Duties, I 42 151) argues that

> of all the occupations by which gain is secured, none is better than agriculture, none more profitable, none more delightful, none more becoming to a free man

Cicero was writing about large landowners, not about farmhands or peasants. He argued that the landowning elite, which dominated Rome politically and economically, was morally superior. Those on top deserved to be on top. In the words of John Kenneth Galbraith[4]

> what is called sound economics is very often what mirrors the needs of the respectably affluent.

1.1.1 Environmental determinism

Ancient scholars did not just think that the natural environment was important. They thought it was predominant. For instance, Hippocrates[5] (400 BCE, On Airs, Waters, Places, 23) wrote

> The other races in Europe differ from one another, both as to stature and shape, owing to the changes of the seasons, which are very great and frequent, and because the heat is strong, the winters severe, and there are frequent rains, and again protracted droughts, and winds, from which many and diversified changes are induced. These changes are likely to have an effect upon generation in the coagulation of the semen, as this process cannot be the same in summer as in winter, nor in rainy as in dry weather; wherefore, I think, that the figures of Europeans differ more than those of Asiatics; and they differ very much from one another as to stature in the same city; for vitiations of the semen occur in its coagulation more frequently during frequent changes of the seasons, than where they are alike and equable. And the same may be said of their dispositions, for the wild, and unsociable, and the passionate occur in such a constitution; for frequent excitement of the mind induces wildness, and extinguishes sociableness and mildness of disposition, and therefore I think the inhabitants of Europe more courageous than those of Asia; for a climate which is always the same induces indolence, but a changeable climate, laborious exertions both of body and mind; and from rest and indolence cowardice is engendered, and from laborious exertions and pains, courage. On this account the inhabitants of Europe are than the Asiatics, and also owing to their institutions, because they are not governed by kings like the latter, for where men are governed by kings there they must be very cowardly, as I have stated before; for their souls are enslaved, and they will not willingly, or readily undergo dangers in order to promote the power of another; but those that are free undertake dangers on their own

---

[2] Indeed, the word "economics" comes from the Greek οἶκος and νομός, the knowledge to run a farm household.

[3] Cicero (106-43 BC) was a statesman, lawyer, and scholar.

[4] Galbraith (1908-2006) taught economics at Harvard University. His work was mostly qualitative and rather critical of stylized mathematical models.

[5] Ἱπποκράτης ὁ Κῷος (c460-c370 BC) was a physician, often regarded the father of medicine.

> account, and not for the sake of others; they court hazard and go out to meet it, for they themselves bear off the rewards of victory, and thus their institutions contribute not a little to their courage.

Hippocrates' prediction that Europeans can never have absolute monarchs is wrong in retrospect. Note that he argues that there are all sorts of things wrong with non-Greek Europeans and Asiatics—because of where they live—implying that the climate in Greece is responsible for the superiority of him and his countrymen.

Aristotle[6] (350 BCE, Politics, 7 VII) wrote

> Those who live in a cold climate and in Europe are full of spirit, but wanting in intelligence and skill; and therefore they retain comparative freedom, but have no political organization, and are incapable of ruling over others. Whereas the natives of Asia are intelligent and inventive, but they are wanting in spirit, and therefore they are always in a state of subjection and slavery. But the Hellenic race, which is situated between them, is likewise intermediate in character, being high-spirited and also intelligent. Hence it continues free, and is the best-governed of any nation, and, if it could be formed into one state, would be able to rule the world.

Aristotle predicted that Europeans could never rule over others. While he foresaw the empire of Alexander the Great,[7] he missed the empires founded by Romans, Franks, Arabs, Mongols, Spaniards, Portuguese, Dutch, Mughals, English, French, Sikhs, and Russians. Like Hippocrates, he argued that his own people were superior by virtue of their climate.

The ancient Greeks were not alone. In an important, early Chinese text, Guan Zhong[8] (780 BCE, Guanzi, XIV 39) writes

> What is water? It is the root of all things and the ancestral hall of all life. It is that from which beauty and ugliness, worthiness and unworthiness, stupidity and giftedness are produced.
>
> How do we know this to be so? Now the water of Qi is forceful, swift and twisting. Therefore its people are greedy, uncouth and warlike. The water of Chu is gentle, yielding, and pure. Therefore its people are lighthearted, resolute, and sure of themselves. The water of Yue is turbid, sluggish, and soaks the land. Therefore its people are stupid, disease ridden, and filthy. The water of Qin is thick like gruel and stagnant. It is obstructed, choked with silt, and wanders in confusion free of its banks. Therefore its people are greedy, violent, and deceptive, and they like to meddle in affairs. The water of Jin is bitter, harsh, and polluted. Therefore its people are flattering and deceitful, cunning and profit seeking. The water of Yan collects in low places and is weak. It sinks into the ground, is clogged, and wanders in confusion free of its banks. Therefore its people are stupid, idiotic, and given to divination. They treat disease lightly and die readily. The water of Song is light, strong, and pure. Therefore its people are simple and at ease with themselves, and they like things to be done in the correct way. For this reason, the sages' transformation in the world lay in understanding water.
>
> Now, when the water is unadulterated, people's hearts will be correct, they have no desire to be corrupt. When people's hearts are at easy, their conduct will never be depraved. For this reason, the sages' bringing good order to the world did not lie in preaching to every person or persuading every household, but in taking water as their central concern.

[6] Ἀριστοτέλης (384-322 BC) made early contributions to physics, mathematics, biology, political science, psychology, and economics, among others.

[7] Aristotle taught Prince Alexander from age 13 to 16.

[8] 管仲(c720-645 BC) was a philosopher and politician.

The idea that you are what river shore you dwell on, seems odd to us. But note that Guan Zhong argues that you should not appeal to people's innate goodness. Instead, a wise ruler improves water courses. He so justifies the elite in a hydraulic society, whose main role was to provide public goods in water management.

The idea of environmental determinism lingered. Ibn Khaldun[9] (1377, Muqaddimah 1 4)

> We have seen that Negroes are in general characterized by levity, excitability, and great emotionalism. They are found eager to dance whenever they hear a melody. They are everywhere described as stupid. The real reason for these (opinions) is that, as has been shown by philosophers in the proper place, joy and gladness are due to expansion and diffusion of the animal spirit. Sadness is due to the opposite, namely, contraction and concentration of the animal spirit. It has been shown that heat expands and rarefies air and vapors and increases their quantity. [...]
>
> Now, Negroes live in the hot zone (of the earth). Heat dominates their temperament and formation. Therefore, they have in their spirits an amount of heat corresponding to that in their bodies and that of the zone in which they live. In comparison with the spirits of the inhabitants of the fourth zone,[10] theirs are hotter and, consequently, more expanded. As a result, they are more quickly moved to joy and gladness, and they are merrier. Excitability is the direct consequence.
>
> In the same way, the inhabitants of coastal regions are somewhat similar to the inhabitants of the south. The air in which they live is very much hotter because of the reflection of the light and the rays of (the sun from) the surface of the sea. Therefore, their share in the qualities resulting from heat, that is, joy and levity, is larger than that of the (inhabitants of) cold and hilly or mountainous countries. To a degree, this may be observed in the inhabitants of the Jarid in the third zone. The heat is abundant in it and in the air there, since it lies south of the coastal plains and hills. Another example is furnished by the Egyptians. Egypt lies at about the same latitude as the Jarid. The Egyptians are dominated by joyfulness, levity, and disregard for the future. They store no provisions of food, neither for a month nor a year ahead, but purchase most of it (daily) in the market. Fez in the Maghrib, on the other hand, lies inland (and is) surrounded by cold hills. Its inhabitants can be observed to look sad and gloomy and to be too much concerned for the future. Although a man in Fez might have provisions of wheat stored, sufficient to last him for years, he always goes to the market early to buy his food for the day, because he is afraid to consume any of his hoarded food.
>
> If one pays attention to this sort of thing in the various zones and countries, the influence of the varying quality of the air upon the character (of the inhabitants) will become apparent. God is the Creator, the Knowing One. Al-Masudi undertook to investigate the reason for the levity, excitability, and emotionalism in Negroes, and attempted to explain it. However, he did no better than to report, on the authority of Galen and Ya'qub b. Ishaq al Kind!, that the reason is a weakness of their brains which results in a weakness of their intellect. This is an inconclusive and unproven statement. God guides whomever He wants to guide.

Like Hippocrates and Aristotle, Ibn Khaldun argued that his climate was the best. He adds Cicero's teleology. Arabs were superior because Allah had bestowed them with the optimal climate. The dominant position of Arabs was not by happenstance, but God's will.

[9] أبو زيد عبد الرحمن بن محمد بن خلدون الحضرمي (1332-1406) was a philosopher, social scientist and historian.

[10] Ibn Khaldun split the world into seven climate zones. The fourth zone, the middle one, had the optimal climate. Other zones were too hot or too cold. Ibn Khaldun lived in, where else, the optimal climate.

Ibn Khaldun's sentiment is reflected in the expression *God's own country*, which has been used to describe, amongst others, Kerala, Yorkshire, and Rhodesia. Robert Rankin[11] mockingly places the Garden of Eden in Brentford.

Montesquieu[12] (1748, The Spirit of Laws, 1 XIV) argues that the climate of France is best. He writes that

> [...] the temper of the mind and the passions of the heart are extremely different in different climates [...]
>
> People are therefore more vigorous in cold climates. [...] In cold countries they have very little sensibility for pleasure; in temperate countries they have more; in warm countries their sensibility is exquisite. [...]
>
> In northern climates, scarcely has the animal part of love a power of making itself felt. In temperate climates, love, attended by a thousand appendages, endeavours to please by things that have, at first, the appearance, though not the reality, of this passion. In warmer climates, it is liked for its own sake, it is the only cause of happiness, it is life itself.

In other words, only the French have the right mix of strength and purpose.

More than 200 years later, Ellsworth Huntington[13] (1915, Civilization and Climate) wrote

> Today a certain peculiar type of climate prevails wherever civilization is high. In the past, the same type seems to have prevailed wherever a great civilization arose.

Huntington's main innovation on earlier environmental determinists was that he argued that climate is not static. Instead, climate changes. Huntington argued that climate changes people:

> In tropical countries weakness of will is unfortunately a quality displayed not only by the natives, but by a large proportion of the northerner sojourners. If manifests itself in many ways. Four of these, namely, lack of industry, an irascible temper, drunkenness, and sexual indulgence are particularly prominent, and may be taken as typical.

At the same time, he argued that

> the effect of a diverse inheritance would last indefinitely

in a thought experiment about "Teutons" and "negroes" moving to an empty country much like Egypt.

It was only in 1922 that Lucien Febvre[14] started the intellectual pushback against environmental determinism. It is now an uncommon position in the social sciences. Indeed, the racist and self-serving reasoning of the early environmental determinists render it disreputable in the eyes of many of our contemporaries.

---

[11] Rankin (1949-), Magus to the Hermetic Order of the Golden Sprout, 12th Dan Master of Dimac, is a writer of far-fetched fiction, tall tales and old toot.

[12] Charles-Louis de Secondat, Baron de La Brède et de Montesquieu (1689-1755) was a judge, man of letters, and political philosopher.

[13] Huntington (1867-1947) taught geography at Yale University.

[14] Febvre (1878-1956) taught history at the University of Strassbourg.

That said, environmental determinism has not disappeared. Jared Diamond[15] is probably the most prominent of current environmental determinists. Diamond argues that poor countries are poor because of unfavourable geography. The orientation of the axes of continents determines how easily innovations can spread. The presence of domesticable species drives the emergence of agriculture. Geographical barriers create conditions for political competition and innovation.

Such determinism can also be found in parts of the environmental movement. The organizations *Extinction Rebellion* and the *Last Generation*, for instance, argue that environmental change leads to the extinction of humankind.

1.1.2 Early concerns about pollution

Early scholars wrote about the natural environment and its effect on society. Environmental pollution and resource degradation wer recognized too. Ancient Greece and Turkey, for instance, suffered from deforestation and soil erosion. Of his native Attica, Plato[16] (Critias, 360 BCE) wrote

> its mountains were high hills covered with soil, and the plains [...] were full of rich earth, and there was abundance of wood in the mountains.

but

> now losing the water which flows off the bare earth into the sea

That is, Plato understood the relationship between deforestation, soil erosion, and water run-off. Visitors to modern Greece may wonder how such a barren landscape could have supported such a rich civilisation. It did not. Greece was not barren then.

Rome and its empire suffered from lead poisoning in water and air, but they themselves were not aware of this—see Box 1.1. Air pollution was more easily detected. Seneca[17] Letters from a stoic, CIV, 61) wrote about

> the oppressive atmosphere of the city and that reek of smoking cookers which pour out, along with a cloud of ashes, all the poisonous fumes.

Environmental policy also goes way back. As the price of fuel wood rose in London, people switched to sea coal, bituminous coal mined on the northeast coast of England. Burning this made the air intolerable to breathe, and King Edward I of England banned the use of sea coal in lime kilns in 1273 and again in 1307. The ban was no success and later kings issued their own regulations. Nonetheless, smog continued to plague London. In December 1952, some 4,000 people were killed by air pollution and maybe 8,000 more in the following months. The Clean Air Act

[15] Diamond (1937-) is a physiologist, ornithologist and environmental historian, who teaches geography at the University of California, Los Angeles.

[16] Πλάτῶν (c425-c347 BC) was a philosopher. He founded the Academy in Athens.

[17] Lucius Annaeus Seneca the Younger (c4 BC-65 AD) was a philosopher, statesman, and dramatist.

of 1956 marks the beginning of the transition away from coal as the prime fuel for heating in the cities of the UK.

Condorcet[18] (Thoughts on the wheat trade, 1776) wrote of stubble burning that

> by corrupting the air, causes illnesses in neighboring homes.

This may be the first formulation of an externality, the unintended and uncompensated impact of an economic activity on a third party. Stubble burning is still a big problem, regularly causing major air pollution on the Indian subcontinent. Condorcet argued that externalities like these are the *only* legitimate legal restraint on property rights.

Box 1.1: Lead

Lead is a metal with several applications, from bullets to ballast, roofing to insulation, paint to mascara. Lead is poisonous when a large dose is inhaled or swallowed. This was known in ancient times. Not known then was that small doses are detrimental too. Particularly, chronic lead exposure hampers neurochemical development, leading to cognitive impairment and aggressive behaviour. The Romans used lead pipes to transport drinking water. It is not known how much this contributed to the demise of their empire.

After Roman times, lead had niche applications. Exposure was low. This changed when tetraethyl lead, $Pb(C_2H_5)_4$, was added to gasoline to improve fuel economy. Over time, this avoided a substantial amount of carbon dioxide emissions. Unleaded gasoline was introduced in the mid-1970s, not because regulators were concerned about lead, but because lead messes up the catalytic converters needed to reduce urban air pollution. This history implies that there is a "Generation Lead"—in the USA, people between 45 and 75 (in 2025)—who were exposed to high concentrations of lead in their formative years. Pundits have commented on their voting behaviour but causality is hard to establish.

Many old cars are exported to developing countries. Unleaded gasoline continues to be used there. Catalytic converters are easily removed. A meta-analysis finds that differential exposure to lead can explain one-fifth of the difference in learning outcomes between rich and poor countries.

1.2 Classical economics

1.2.1 Adam Smith on public goods

Adam Smith's 1776 book *An Inquiry into the Nature and Causes of the Wealth of Nations* is often seen as the starting point of economics as a separate discipline.

[18] Marie Jean Antoine Nicolas de Caritat, Marquis of Condorcet (1743-1794) was a philosopher and mathematician, remembered in economics for his work on voting.

Smith is seen as a proponent of laissez-faire, the idea that the government should not intervene much in the economy, particularly through the doctrine of the invisible hand, in which the market coordinates selfish interests to deliver the social good.[19] We now call this the First Fundamental Welfare Theorem. We recognize that it only holds under rather stringent conditions, and that Smith's social good is a Pareto optimum.

Smith (Wealth of Nations, 1776 V 1) did argue, though, that

> The third and last duty of the sovereign or commonwealth is that of erecting and maintaining those public institutions and those public works, which, though they may be in the highest degree advantageous to a great society, are, however, of such a nature that the profit could never repay the expense to any individual or small number of individuals, and which it therefore cannot be expected that any individual or small number of individuals should erect or maintain. [...] The performance of this duty requires, too, very different degrees of expense in the different periods of society.
>
> After the public institutions and public works necessary for the defence of the society, and for the administration of justice, both of which have already been mentioned, the other works and institutions of this kind are chiefly those for facilitating the commerce of the society [such as good roads, bridges, navigable canals, harbours], and those for promoting the instruction of the people.

Smith realized that the market underprovides public goods, and called for government intervention—Smith's sole deviation from *laissez faire*.[20]

Recall that, in the same year, Condorcet called for government intervention on externalities. The intellectual foundation for environmental economics was laid in 1776.

1.2.2 Malthus, Ricardo and Mill on resource limits

Thomas Robert Malthus[21] (1798, An Essay on the Principle of Population) wrote

> Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio.

Figure 1.2 illustrates this. The supply of food increases linearly or arithmetically. The number of people, and so the demand for food increases exponentially or geometrically. Exponential growth is faster than linear growth. We will therefore run out of food at some point in the future, the *Malthusian Catastrophe*.[22]

---

[19] You have one chance to make a first impression. Lay people typically think that Smith's views on economic policy are shared by all economists. This is peculiar, because Karl Marx was an eminent economist too. After World War II, many economists advocated some form of central planning, including Nobelists Tinbergen, Kantorovich, Koopmans and Klein.

[20] Smith argued that the government should *not encourage* cartel formation, but take no action otherwise.

[21] Malthus (1766-1834) was an English cleric and scholar. He was the first professor of economics.

[22] Thomas Carlyle, an historian, philosopher and mathematician, lived from 1795 to 1881. Carlyle (1839, Chartism) referred to Malthus' work as "[d]reary, stolid, dismal, without hope for this world

Malthus had a solution too: Abstinence.[23] At that time, you could not have babies without sex.

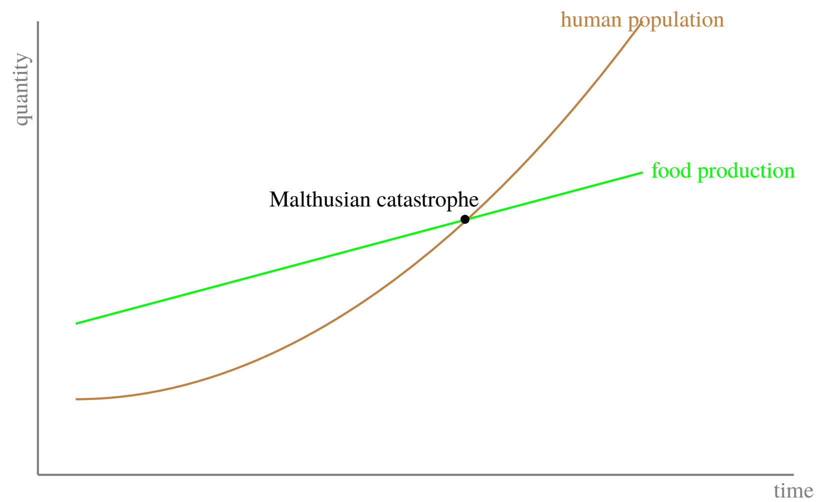


Fig. 1.2: Supply and demand for food over time

Malthus' argument that food production grows only linearly hinges on decreasing returns to scale in agriculture. If you double the number of farmhands, on a piece of land, you will increase but not double the harvest.

David Ricardo[24] refined the argument. He distinguished between the *internal margin* and the *external margin*. You can increase food production at the internal margin by working crop lands harder. As Malthus noted, this is subject to decreasing returns to scale. At the external margin, you can take virgin lands into crop production. Malthus ignored this. Ricardo did not. Ricardo argued, however, that the external margin would not get around the Malthusian Catastrophe because our ancestors cultivated the best lands first. Expansion on the external margin is thus subject to decreasing quality.

---

or the next". Carlyle (1849, The Negro Question) coined the term *the dismal science* in 1849, dismal in "find[ing] the secret of this Universe in 'supply and demand', and reducing the duty of human governors to that of letting men alone". Carlyle argued *for* slavery. Carlyle's suggestion was resisted by, among others, John Stuart Mill. Carlyle used the pejorative "dismal" to dismiss the arguments of economists against slavery. Dismal is an insult to be worn with pride.

[23] Charles Trevelyan (1807-1886), one of Malthus' star students, contributed greatly to the *Great Famine* in Ireland and made smaller contributions to a series of famines in India.

[24] Ricardo (1772-1823) was a banker and Member of Parliament of the Great Britain and Ireland. He is best known for his work on international trade.

John Stuart Mill[25] further refined the Malthusian argument, noting that the Malthusian Catastrophe can be postponed by input substitution. Fertilizers make up for a shortage of soil nutrients, irrigation for a shortfall of rain. However, like Malthus and Ricardo and indeed all Classical Economists, Mill was convinced that economic growth must come to a halt because of resource constraints.

1.2.3 Romanticism

The Classical economists were sons of the *Enlightenment*. A central part of the Enlightenment was that arguments should be based on observations rather than authority and that decisions should be rational. Economics at the time was typically called *political economy*, a reference to rational, scientifically informed government of markets.

Romanticism was a countermovement to the Enlightenment. It was concentrated in the arts, mostly literature (Brontë sisters, François-René de Chateaubriand, Johann Wolfgang von Goethe, Friedrich Schilling, Hendry David Thoreau, William Wordsworth) and to a lesser extent painting (e.g., Caspar David Friedrich) and music (e.g., Johann Sebastian Bach). Romanticists shared three traits. They drew on the older school of *Sentimentalism*, arguing that emotions are a valid basis for decisions—as opposed to the reason favoured by the Enlightenment. Romanticists also harked back to a simpler, better past, with comely maidens dancing at the crossroads. And they believed that nature was beautiful and to be enjoyed, rather than dangerous and to be subjugated. These conflicting portrayals of nature continue to today, from Bruno Latour's "how could I love nature? I'm from Burgundy" to Seamus Heaney's Death of a Naturalist.

Romanticism had three major offshoots: Communism, Nazism/Fascism, and Environmentalism.

Mao Zedong and Pol Pot took the harking for the—largely misremembered—past to the extreme, forcing city dwellers to move to the countryside and take up farming like their ancestors.[26] The longing for the past extended to the mighty and just leaders of yore, such as Arthur, the once and future King, and the fascists' desire for a strongman—although other Romanticists misremember a past of direct democracy.[27] In that mythical past, everyone was blond with blue eyes. The racial purity of *Blut und Boden* is a key part of Nazism. Early expressions of nationalism were a reaction to the radical equality of the Enlightenment.

[25] Mill (1806-1873) was a colonial administrator. Although his work was published under his name, Harriet Taylor (1807-1858) was a frequent co-author.

[26] In the Communist Manifesto, Marx and Engels wrote about the "idiocy of rural life".

[27] Direct democracy is probably more common among environmentalists than authoritarianism, even though people do not necessarily vote green in referendums.

Environmentalists tend to argue that things used to be better, and often believe in the myth of the noble savage,[28] who represents the lost morality of the olden days. There is a famous quote

> Only when the last tree has been cut down, the last fish been caught, and the last stream poisoned, will we realize we cannot eat money.

This is often presented as a Cree Indian proverb, exemplifying the wisdom and environmental stewardship of pre-modern people.[29] In fact, whenever *homo sapiens* introduced itself to a new ecosystem, it wreaked great havoc, including mass extinctions. Some environmentalists embrace Wicca or some such. Respect for nature is a common trait in neo-paganism. The belief in magic is as anti-Enlightenment as it gets.

Environmentalism shares its roots with odious ideologies, but few environmentalists would support them.[30] That said, environmentalists tend to be to the political left, although the watermelon epithet—green on the outside, red on the inside—is an exaggeration. Some environmentalists argue that democracy is not suited for solving the crisis in the environment, calling for "scientific" oversight of policies or political candidates to be vetted by "experts".[31] The term *eco-fascist* is used with abandon in some circles. Although there are environmentalists who do not tolerate dissent and pursue their green goals through violent means, this is a small minority.

In older literature, danger lurked in the deep dark wood, be it bears, wolves, gruffaloes, or cut-throats. Romanticists were the first to describe nature as something to enjoy rather than fear. This is a reflection of the times. Large predators had mostly disappeared from Western Europe, and you were never far from people. Nature had been tamed and could be enjoyed. People even started swimming in the sea—in Brighton. The oldest environmental organizations began as nature conservation.[32] Early naturalists argued that hiking is good for your physical and mental health[33] and emphasized that nature made you a morally better person.

Many people care about the environment but not about Romanticism. The *Eco-modernist* movement explicitly embraces the Enlightenment and combines it with concern for the environment. It takes positions that are often controversial to environmentalists, arguing for instance that nuclear power is a valid strategy to reduce carbon

---

[28] The noble savage was introduced into modern thought by Michel de Montaigne (1533-1592), a philosopher, in 1580. Earlier, in 98, Tacitus (56-120), a historian and politician, had described the Germans as noble savages.

[29] It is actually a modern quote from an Abenaki activist who left the reservation at age 7. The quote was popularized by Greenpeace.

[30] Many fascists love nature, Hitler prime amongst them, Communists less so. Guilt by association is a logical fallacy.

[31] The clergy in Iran has a similar position. Francis Bacon (1561-1622), a philosopher and statesman, put scientists in charge of his utopian Bensalem.

[32] The World Wide Fund for Nature was started to protect the African hunting grounds of European nobility and royalty from the incursion by black people after the end of colonialism. One of its founders was a member of the *Hitlerjugend*, the other of the *Afrikaner Broederbond*. WWF has never quite lost that attitude, see its scandals with indigenous rights and physical abuse.

[33] There is now much evidence to support this.

dioxide emissions and that intensive agriculture is better for nature than the organic sort. Environmental economists are probably more comfortable with ecomodernism while ecological economists tend to associate more with environmentalism.

1.2.4 Mill on amenity values

John Stuart Mill (1848, Principles of Political Economy) brought some Romantic elements into economics,[34] writing

> There is room in world, no doubt, for a great increase in population, supposing the arts of life to go on improving, and capital to increase. [...] The density of population necessary to obtain all of the advantages both of cooperation and of social intercourse [...] has been attained. A population may be too crowded, though all be amply supplied with food and raiment. [...] Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature.

and adding, for good measure,

> it is only in backward countries of the world that increased production is still an important object[ive]

That is, Mill argued against equating well-being with *material* well-being. This foreshadows Kuznets'[35] admonishment that Gross Domestic Product (GDP) is a measure of economic activity, not welfare. Mill noted the importance of social intercourse (which we would now rather call interaction) and emphasized the amenity value of nature. Harriett Taylor and John Stuart Mill were far ahead of their time.

Note that, while they believed that resource constraints would put a limit on economic growth, they argued that it would be better not to seek these planetary boundaries but rather constrain ourselves to be content with less.[36]

[34] Romanticists were fond of Malthus' work, but he was not a Romantic. Malthus was a numbers man, striving for a better future rather than pining for a misremembered past and, as most Classical economists, rather wary of a strong government.

[35] Simon Kuznets (1901-1985) taught economics at the University of Pennsylvania, Johns Hopkins University, and Harvard University. He won the 1971 Nobel Prize for his work on inequality. He invented the Gross Domestic Product.

[36] In microeconomics, agents are assumed to maximize utility subject to a budget constraint. In Buddhist economics, agents are assumed to minimize harm to the environment, subject to a survival constraint.

1.3 Neo-classical economics

The neo-classical revolution, led by William Stanley Jevons[37], Carl Menger[38] and Léon Walras[39], radically changed economics. The now common tools of partial and general equilibrium and marginal analysis go back to this period.

Jevons (1865, The Coal Question) worried that

> I must point out the painful fact that such a rate of growth will before long render our consumption of coal comparable with the total supply. In the increasing depth and difficulty of coal mining we shall meet that vague, but inevitable boundary that will stop our progress.

a Malthusian position with coal replacing food. However, by and large, the neo-classical revolutionaries were not really interested in issues of environment and resources. This is partly because analysis had moved to the margin, and partly a reflection of the time: Technological progress and industrialization were rapid, and land seemed boundless, with the push into the American west, the Siberian east, and the African interior.

Harold Hotelling[40] was one of the few other neo-classical economists to work on resource problems, developing the *Hotelling rule* that the price of an exhaustible resource should rise at the rate of interest. Earlier, but largely ignored until much later, Martin Faustmann[41] had developed a Hotelling rule for a renewable resource, forestry. Despite Hotelling's prominence, this work was largely ignored until the 1974 papers in the *Review of Economic Studies* by Robert Solow[42] and Dasgupta and Heal. Partha Dasgupta[43] and Geoffrey Heal[44] later gave this a book length treatment.

Although neo-classical economists paid little attention to the environment, they did lay the foundations for the economic analysis of environmental problems

---

[37] Jevons (1835-1882) taught economics at what is now the University of Manchester and at University College London. He was the first to graduate in economics.

[38] Menger (1840-1921) taught economics at the University of Vienna.

[39] Walras (1840-1905) taught economics at the University of Lausanne.

[40] Hotelling (1895-1973) taught at the University of North Carolina, Columbia University and Stanford University. He is one of the true greats of economics and statistics. Besides the Hotelling rule of resource depletion, he is responsible for Hotelling's law of minimum differentiation of products, for Hotelling's lemma that relates optimal production to marginal profits, for Hotelling's T^2 distribution which generalizes Student's t, for canonical correlation analysis, and for principal component analysis. He also helped prove the First and Second Fundamental Welfare Theorems, and trained Ken Arrow.

[41] Faustmann (1822-1876) was a German forester.

[42] Solow (1924-) taught economics at MIT. He won the 1987 Nobel Prize for his work on economic growth.

[43] Dasgupta (1942-) taught economics at the University of Cambridge. He is a student of Nobelist James Mirrlees and married to a daughter of Nobelist James Meade. He is best known for his work on bringing natural resources into economics.

[44] Heal (1944-) teaches corporate social responsibility at Columbia University. His research is in environmental and resource economics. He did his most influential work while at the University of Sussex.

and environmental policy. In 1906, Vilfredo Pareto[45] formulated *Pareto superiority*—situation A is better than situation B if at least one person is better off and no one is worse off—*Pareto improvement*—moving from B to A—and *Pareto optimality*—a situation is Pareto optimal if there are no Pareto improvements. Abba Lerner[46] leaned on this and Adam Smith's invisible hand to state the *First Fundamental Welfare Theorem*—the equilibrium in a perfectly competitive market is a Pareto optimum—and the *Second Fundamental Welfare Theorem*—any Pareto optimum can be reached in a perfectly competitive market with the appropriate redistribution of initial endowments. Lerner showed this graphically, the first mathematical proof is due to Hotelling.

Although much of neo-classical analysis was centred on perfectly competitive markets, these economists were not blind to the limitations of this assumption. They just did not know what to do about it. Alfred Marshall[47] was aware of open-access resources, he called them "free goods", but did not know how to fit them into economic theory.

Marshall also noted that markets were imperfect because of externalities—an externality is an unintended and uncompensated effect of an economic activity on a third party—and spillovers.[48] It was Pigou[49] who, in 1912, found the first solution to the problem that externalities and spillovers. pose to the efficiency of the market. Pigou (1928, Economics of Welfare (3rd edition), II.XI.11) wrote

> If the amount of investment in any industry was carried exactly to the point at which the value of the marginal social net product there is equal to the central value of marginal social net products, the national dividend, so far as that industry is concerned, would be maximised. Disregarding the possibility of multiple maximum positions, I propose, for convenience, to call the investment that would then be made in the industry the ideal investment and the output that would be obtained the ideal output.
>
> Under conditions of simple competition, if in any industry the value of the marginal social net product of investment is greater than the value of the marginal private net product, this implies that the output obtained is less than the ideal output: if the value of the marginal social net product is less than the value of the marginal private net product, this implies that the output obtained is greater than the ideal output.
>
> It follows that, under conditions of simple competition, for every industry in which the value of the marginal social net product is greater than that of the marginal private net product, there will be certain rates of bounty, the granting of which by the State would modify output

---

[45] Pareto (1848-1923) taught political economy at the University of Lausanne, succeeding Léon Walras. Besides his work in welfare economics, he worked on the distribution of income, proposing the Pareto distribution in the process. He also made important contributions to sociology.

[46] Lerner (1903-1982) taught at more than 30 universities. His contributions to economics are just as prolific although he is remembered in the Lerner Curve, a measure of market power.

[47] Marshall (1842-1924) taught economics at the University of Cambridge. His 1890 textbook Principles of Economics dominated university education for many years. Mary Paley, his wife, co-authored much of his work, but was never credited.

[48] Spillovers between firms within an industry are known as Marshall-Arrow-Romer spillovers, Arrow being Kenneth and Romer Paul. Spillovers between industries in one location are associated with Edward Glazer.

[49] Arthur Cecil Pigou (1877-1959) taught economics at the University of Cambridge. He was Marshall's student.

> in such a way as to make the value of the marginal social net product there more nearly equal to the value of the marginal social net product of resources in general, thus—provided that the funds for the bounty can be raised by a mere transfer that does not inflict any indirect injury on production—increasing the size of the national dividend and the sum of economic welfare; and there will be one rate of bounty, the granting of which would have the optimum effect in this respect.
>
> In like manner, for every industry in which the value of the marginal social net product is less than that of the marginal private net product, there will be certain rates of tax, the imposition of which by the State would increase the size of the national dividend and increase economic welfare; and one rate of tax, which would have the optimum effect in this respect.
>
> These conclusions, taken in conjunction with what has been said in the preceding paragraphs, create a presumption in favour of State bounties to industries in which conditions of decreasing supply price *simpliciter* are operating, and of State taxes upon industries in which conditions of increasing supply price from the standpoint of the community are operating.

Pigou argues for the State to intervene to internalize externalities, by imposing taxes on negative ones and subsidies ("bounties") on positive ones.[50]

Pigou's contribution was verbal. A formal treatment of externalities had to wait till Meade (1952, *Economic Journal*)[51] and Bator 1958, *Quarterly Journal of Economics*.[52]

1.4 Keynes and the modern synthesis

For all the methodological advances in economics, the Great Depression caught the discipline empty-handed. The policy, if you can call it that, of *laissez faire* had failed. Economics was micro, but the problems of the economy were macro. John Maynard Keynes[53] single-handedly created macroeconomics, focusing on the business cycle and countercyclical government policy. However, Keynes' focus was on the short-run as "in the long run, we are all dead". Neo-classical economics did not pay much attention to the environment because it focussed on the micro, Keynesian economics because it focussed on the short-run.

After World War II, the discipline of economics worked on the *Modern Synthesis*[54] of the recent Keynesian macroeconomics with the older neo-classical microe-

[50] Some students complain about the use of mathematics in undergraduate economics. Compare and contrast Pigou's definition of the Pigou tax to the one you find in any textbook, and the one below.

[51] James Meade (1907-1995) taught economics at the London School of Economics. He won the 1977 Nobel Prize for his work on international trade.

[52] Francis Bator (1925-2018) taught public policy at Harvard University.

[53] Keynes (1883-1946) taught economics at the University of Cambridge. He worked for the UK government in various roles, and was instrumental in building international institutions after World War I and World War II.

[54] In Kant's sense of the words, the Modern Synthesis is analytic. Synthetic economics had to wait for the Credibility Revolution of 1993.

conomics. One result was the growth models of Harrod[55] and Domar[56], of Solow, and of Ramsey[57], Cass[58] and Koopmans[59]. At the core of these models lies the Cobb-Douglas production function,[60] which has that economic output depends on three factors, labour, capital, and technology. Natural resources are not there. A one-sector growth model can be interpreted as a multi-sector dynamic general equilibrium model if markets are perfect, that is, if there are no public goods and no externalities.

Methodological progress was made. In 1952, *Resources for the Future* (RFF) was founded, the first think tank devoted to resource economics; environmental economics was added later. John Krutilla[61] discovered existence values—we derive utility from merely knowing that some animals are out there—and helped create the theory of resource conservation and cost-benefit analysis. His colleague Allen Kneese[62] was an architect of market instruments for environmental policy. In 1954, Scott Gordon[63] developed the theory of exploitation of common pool resources. In the same year, Paul Samuelson[64] formulated the conditions for providing public goods. Mancur Olson[65] coined the term free-rider in 1965. Francis Bator[66] laid the foundation for the modern understanding of externalities in 1958. Ronald Coase[67]

---

[55] Roy Harrod (1900-1978) taught economics at the University of Oxford.

[56] Evsey Domar (1914-1997) taught economics at the Massachusetts Institute of Technology.

[57] Frank Ramsey (1903-1927) taught mathematics at the University of Cambridge. He made noted contributions to mathematics, economics, and philosophy.

[58] David Cass (1937-2008) taught economics at the University of Pennsylvania.

[59] Tjalling Koopmans (1910-1985) taught economics at the University of Chicago and Yale University. He led the Cowles Foundation. He won the 1975 Nobel Prize for his work on linear programming. His work on autocorrelation is seminal, and he made an important contribution to quantum chemistry.

[60] The Cobb-Douglas function was invented by Philip Wicksteed (1844-1927), who taught economics at the University of London. Charles Cobb (1875-1949), who lectured at Amherst College, and Paul Douglas (1892-1976), who taught at the University of Chicago, popularized the function named after them through their empirical work.

[61] Krutilla (1922-2003) was an independent scholar, associated with RFF.

[62] Kneese (1930-2001) was an economist at RFF.

[63] Gordon (1924-2019) taught economics at Carleton University, Indiana University, and Queen's University.

[64] Samuelson (1915-2009) taught economics at the Massachusetts Institute of Technology. He was awarded the 1970 Nobel Prize. Samuelson is a key architect of the Modern Synthesis, that merged neo-classical microeconomics with Keynesian macroeconomics. Samuelson contributed greatly to the mathematization of economics. His textbooks led the market for decades.

[65] Olson (1932-1998) taught economics at the University of Maryland.

[66] Bator (1925-2018) taught economics at Harvard University.

[67] Coase (1910-2013) taught economics at the University of Chicago. He won the 1991 Nobel Prize for this work on transaction costs and property rights, which helped to explain why firms exist.

published his "theorem" in 1960. In 1966, Thomas Crocker[68] suggested tradable pollution permits,[69] an idea picked up by John Dales[70] two years later.[71]

Neo-classical and Keynesian economics largely ignored nature and the environment. As shown above, this changed during the Modern Synthesis, but environmental and resources economics was not yet recognizable as a separate field of economics.

1.5 Environmental economics

Things changed in 1970s. As before, economics changed not because of internal pressures but because society changed. After World War II, economic growth was rapid. People could afford cars, and ended up in traffic jams. Those cars emitted gases and particles into the atmosphere. Electricity demand grew rapidly with the use of appliances, and coal-fired power plants added to the pollution of the air. New products were invented, new chemicals developed. What seemed like brilliant inventions at first—fertilizers, pesticides, coolants —turned out to be harmful later—causing eutrophication[72], cancer, and the hole in the ozone layer. The waste of the rapid industrialization was dumped. Rachel Carson[73] published *Silent Spring* in 1962, a book that noted that pesticides weaken egg shells, harming bird reproduction; she predicted a future without birdsong. In 1969, the Cuyahoga River was so polluted it caught fire. In 1972, the Club of Rome published its report on the *Limits to Growth*, a Malthusian tract that predicted society's collapse because of resource constraints well before the average reader of these lecture notes was born. (Hint: It did not happen.) In the same year, the crew of Apollo 17 took the first photo with Earth in full view. Although people had known *intellectually* that our planet is a globe, this was the first *sensory* perception that the Earth is round and finite and we're all in this together. The first oil crisis struck in 1973, the second in 1978.

After all that, no one could plausibly deny that

- natural resources are scarce;
- environmental externalities are substantial; and
- environmental services are valuable.

Environmental economics was born out of that realization. It aims to bring the tools of economic analysis—developed earlier by Krutilla, Kneese, Gordon, Samuelson,

---

[68] Crocker (c1945-) was a PhD student at the University of Wisconsin at the time. He taught economics at the University of Wyoming, working with Ralph d'Arge to lay the foundations of environmental economics.

[69] Crocker, Thomas D. 1966. "The Structure of Atmospheric Pollution Control Systems." In *The Economics of Air Pollution*, edited by H. Wolozin, 61-86. New York: W. W. Norton.

[70] Dales (1920-2007) taught economics at the University of Toronto.

[71] John Harkness Dales 1968. *Pollution, property and prices : an essay in policy-making and economics*. Toronto: University of Toronto Press.

[72] hypoxia in American English

[73] Carson (1907-1964) was a nature writer.

Olson, Bator, Coase, Crocker and Dales as sketched above—to bear on environmental problems and environmental policy.

Kenneth E. Boulding[74] reportedly said

> anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist.

Boulding was a prominent economist, author of a well-read textbook and president of the American Economic Association. He set out his Malthusian views in a 1966 lecture The Economics of the Coming Spaceship Earth, in which he emphasized that the economy operates on a finite planet.[75]

Nicholas Georgescu-Roegen[76] (1971, The Entropy Law and the Economic Process) wrote

> economics gives no signs of acknowledging the role of natural resources in the economic process . . . the product of the economic process is waste, waste is an inevitable result of that process and ceteris paribus increases in greater proportion than the intensity of economic activity

Georgescu-Roegen argued that economies are bound by nature (like Boulding), and that models of the economy too should reflect the laws of nature. He pioneered the coupling of models of the natural world with models of the economy.

Environmental economics took a different route, however. The *Limits to Growth* report had drawn fiery criticism from economists like Graciela Chichilnisky[77] and William Nordhaus[78]. In 1980, Julian Simon[79] challenged Paul Ehrlich[80] to a wager. Ehrlich predicted that resource scarcity would drive up the prices of copper, chromium, nickel, tin, and tungsten between 1980 and 1990. Simon predicted a price fall as new discoveries would increase supply and improved technology would reduce demand. Simon won.

A common interpretation of the Simon-Ehrlich wager is that human ingenuity is the ultimate resource. We are so clever that we can overcome any challenge that nature might throw at us. This has been true until now. Whether it will be true in the future remains to be seen.

---

[74] Boulding (1910-1993) taught economics at the University of Wisconsin and other universities.

[75] His spaceship metaphor is meant to convey a closed system with scarce resources. Other people saw it as a piece of engineering under autocratic control.

[76] Georgescu-Roegen (1906-1994) taught economics at Vanderbilt University.

[77] Chichilnisky (1946-) teaches economics at Columbia University.

[78] Nordhaus (1941-) teaches economics at Yale University. He won the 2018 Nobel Prize for his work on the economics of climate change.

[79] Simon (1932-1998) taught business at the University of Illinois at Urbana-Champaign and the University of Maryland.

[80] Ehrlich (1932-) taught biology at Stanford University and is a prominent member of the Club of Rome. He predicted, in 1970, that “sometime in the next fifteen years, the end will come. And by ’the end’ I mean an utter breakdown of the capacity of the planet to support humanity.” My favourite prophet of doom is David Bowie who, in 1972, predicted that “we’ve got five years” as “Earth is really dying”.

Another interpretation is that Simon represents the Enlightenment and Ehrlich Romanticism, the former advocating for the development of new technologies to solve environmental problems, the latter arguing for a return to the old ways to prevent environmental problems.

Environmental economics has adopted the position that the tools of economic analysis—first developed during the Enlightenment but extended to the environment by Bator, Baumol, Gordon, Knees, Krutilla, Samuelson—can be used to analyze environmental problems and that these problems can be solved by changing incentives at the margin.

Ecological economics, on the other hand, takes the position that the tools of economics are inadequate and that environmental problems require a Utopian overhaul of society. These Romantic roots are best visible among the degrowth movement, who call for economic shrink to solve environmental problems and other social ills, and argue that life is better when all are poor.

I am an environmental economist, and these lecture notes are for a course in environmental economics.

Further reading

Spencer Banzhaf's *Pricing the priceless* is a book about the history of environmental economics.

Chapter 2
Social choice

2.1 Alternative views on ethics

Social science is about three questions: *what if*; *so what*; and *what to do*.[81] Here is an example of the three questions. What if: What would happen to eutrophication if fertilizer is taxed based on its nitrogen content? So what: Do the costs of restricting nitrogen application to farmers and consumers matter more than the impacts of eutrophication on nature and recreation? What to do: Is it better to tax fertilizer or to forbid certain applications?

The first question, what if, is a positive one. It requires an as-accurate-as-possible, as-objective-as-feasible description of the relevant parts of the world as it is, as well as predictions of how the world would be should some things change. The third question, what to do, is normative. You cannot rank options without a clear idea of what is better and worse. The second question is a mix of normative and positive—the measurement of costs and benefits is positive, but the decisions what and who to include and exclude are normative.

The idea of what is better and worse is key to answering normative questions. Normative questions are rife in public policy advice and evaluation, including all aspects of environmental policy. Indeed, the aim of public policy in general and environmental policy in particular is to make things better. You cannot do that without an understanding of better.

Environmental economics, when informing public policy, has a more profound normative problem than other branches of applied public economics. The economic analysis of education, health care or labour markets is invariably confronted with making trade-offs between people. In environmental economics, we often make

[81] Natural science is only about *what if* questions. The incomplete education of natural scientists leads to endless confusion and discussion when they leave the ivory tower to partake in policy debates where *so what* and *what to do* questions are prominent. They even created a new paradigm for this called *post-normal science*, where *normal* is a reference to Thomas Kuhn (1922-1998), a philosopher of science, and *post* means *not* rather than *after*. Post-normal science is a half-baked reinvention of the social sciences.

trade-offs between people too, but we also make trade-offs between humans and non-humans.

It is therefore important to discuss what we mean by better and worse. Economics is by and large based on utilitarian ethics. Alternative views are rarely discussed. Yet, utilitarianism is a minority view among moral philosophers.

I discuss three major strands in moral philosophy, viz. *naturalist ethics* and two strands of humanist ethics, *libertarianism* and *utilitarianism*. I particularly focus on utilitarianism, because economics is based on that. There are other, less relevant strands of ethics, but these are not discussed here.

2.2 Universality

Immanuel Kant[82] is one of the most important philosophers in history. Although he died more than two centuries ago, young philosophers still study his work, only to discover what a singularly obscure writer he was. Among other innovations, Kant introduced the *moral agent* and the *Universal Law* or *Categorical Imperative*.

A moral agent is the unit of analysis in ethics. Rights and duties can be bestowed on moral agents and on moral agents only. Only the pain and pleasure of moral agents count in the felicific calculus.

Kant's universal law holds that, if a rule applies to one moral agent, it applies to all moral agents. For instance, assume that you and I are both moral agents. If I argue that you cannot chop off my arm, then I cannot chop off your arm either.[83]

2.3 Naturalism

Naturalist moral philosophy is centred on the question *who* is a moral agent. This is perhaps best illustrated with a review of political rights.

It used to be that only the views and interests of rich white male Protestants mattered.[84] Rich white male Protestants argued that only they mattered because only they were worthy and capable. And because they were in power,it was irrelevant that others might have disagreed.

---

[82] Kant (1724-1804) taught anthropology at the University of Köningsberg, now Kaliningrad, maybe one day Královec, the city where he was born and died. Besides his work on ethics, he is best known for his contributions to epistemology, aesthetics, and political science. He was also an early advocate of racism.

[83] If you want to wind up a philosopher, say that the Universal Law is the same as the Golden Rule—the Christian "do unto others as you would have them do unto you", a sentiment found in most other religions too. The difference between the Categorical Imperative and the Golden Rule is subtle.

[84] This story is placed in Northwestern Europe and North America

Then along came Jeremy Bentham,[85] a rich white male Protestant, who wrote that government should strive for the greatest good for the greatest number. This was a radical proposition.[86] Poor lives matter.[87] The government should serve not just the elite, but the less fortunate too. Bentham argued in favour of people who were not like him.[88]

This intervention set off a cascade. If you cannot argue that someone else is worthy only if she is just like you, then you need a different criterion to delineate moral agents from other entities.

Catholics were emancipated first.[89] You cannot maintain that someone is less worthy because he reads a different translation of the same book. The poor followed. Women were next. The notion that women are too hysterical to own property or vote was shown to be a self-serving lie that men liked (like?) to tell each other. Skin colour was last. A physiological adaptation to the limited sunlight of Northern Europe and a shift away from a diet heavy in red meat—a light skin promotes the creation of vitamin D, at the expense of sunburn and a higher risk of skin cancer—has nothing to do with other human capabilities.

However, if as a rich white male Protestant you cannot argue that only rich white male Protestants matter, then as a human you cannot argue that only humans matter. It is a self-serving argument.

Some people argue that the right delineation is a sense of self. If you put a parakeet in front of a mirror, it will sing to its mirror image—and will continue to do so even if the mirror does not answer back. A parakeet does not have a concept of self and no concept of other. A moral rule that constrains the self in how it treats others is therefore meaningless to a parakeet. That said, other primates, dolphins, and elephants do recognize themselves in the mirror. These animals also have an understanding of cause and consequence and seem to have a sense of right and wrong. Some human rights would therefore also apply to other higher animals. In 2015, a judge in Argentina ruled that, since Sandra had broken no laws, it was illegal to hold her captive. That is an unremarkable verdict—until you note that Sandra is an orangutan.

Utilitarianism is not about rights and duties. It is about minimizing pain and maximising pleasure. If that is the ethical starting point, then what sets a moral agent apart is not her ability to self-identify, but rather her ability to experience pain and pleasure. Cats may not recognize themselves in the mirror—there are countless

---

[85] Bentham (1747-1832) was an independent scholar.

[86] When he lived, only some 3% of English men had the vote. In the year he died, voting rights were extended to some 16%.

[87] Bentham went much further. Although not fond of Catholics, non-whites, women or homosexuals, he argued that they had rights too and may even be allowed to vote—note that his support for gay rights was published long after his death. He also argued, while still alive, for animal rights.

[88] Bentham lived to see the Catholic Emancipation of 1829. The movie *Enola Holmes* is set against the Reform Bill, which extended the vote to the richest 60% of men in 1884, more than half a century after Bentham's death and mummification.

[89] A Catholic still cannot be King or Queen of the United Kingdom.

videos on YouTube that prove this point[90]—but cats sure are able to experience pain and pleasure. Many people oppose the torture of animals as they oppose the torture of humans, and many countries have laws against cruelty to animals. That is, we recognize, to a certain extent, animals as moral agents.

The human ability to experience pain and pleasure derives from our central nervous system, with nerves throughout the body and a brain to coordinate it all. Worms do not have a central nervous system. If you chop a human in two, you have two halves of a dead human. If you chop a worm in two, you have two viable worms. But if you cannot argue that someone is unworthy because they have a different skin tone—a physical characteristic—then you cannot argue that something is unworthy because it lacks a central nervous system. Octopuses have nine brains, a big one in the body plus smaller ones in each tentacle. Octopuses are smart and have complex personalities. They are like us in some ways, and unlike us in others—but who are we to deny them our rights just because they are different? Extending human rights to all animals may seem extreme to people who grew up in a society influenced by Christianity or Islam, but it is a common position in Hinduism. Vegetarians oppose killing animals for food, vegans all animal-derived products. Jains go further, respecting insects as well.

Trees too signal distress in a way that is alien to humans but clearly recognizable nonetheless. Fruitarians extend the well-accepted rule against cannibalism to all living beings.

The cascade does not stop there. The occasional media flurry on the discovery of life on Mars or, more recently, Venus is rooted in our inability to distinguish organic material from dead material. At the macroscopic scale, it is easy to tell a bear from a tree from a rock. At the microscopic scale, such distinctions are blurred. Viruses, for instance, are somewhere between alive and not. Deep ecologists like Aldo Leopold[91] and Arne Naess[92] argue that non-living entities indeed have a right to integrity of body just like humans do. Certain religions recognize abiotic entities, such as rivers or mountains, as spiritual beings worthy of respect and protection. The Whanganui River in New Zealand is a legal person. Kant's Categorical Imperative has that, much as I may not poison a human, I may not poison this river either.

2.4 Libertarianism

Libertarianism is one of the schools of humanist moral philosophy. It grants rights and duties to humans only, although some of the reasoning can readily be extended to other species. Libertarianism judges situations by how they arose. Libertarianism is *procedural* justice. It is *deontological*.

---

90 Here is an exception.

91 Leopold (1887-1948) was the first professor of wildlife management, teaching at the University of Wisconsin. He is one of the early thinkers of deep ecology. and developed the *land ethic*, which holds that humans are not conquerors but rather citizens of nature.

92 Naess (1912-2009) taught philosophy at the University of Oslo.

As the name suggests, libertarianism is about individual rights and liberties. John Locke[93] argued property is *just* if it is acquired through labour. That is, if someone goes into the forest, cuts down the trees and starts cultivating the land, then that land is theirs. When Locke wrote this, King James VII and II was trying to establish an absolute monarchy in England and Scotland, including the notion that all land belongs to the crown. Locke disagreed. This thinking is reflected in the US Homestead Act of 1862, and it reflects Germanic traditions of property law. It was also used to argue that hunter-gatherers do not own their lands *as they did not improve it*[94] and can therefore be removed.

Locke's idea of just property is impractical. Robert Nozick[95] added that property is just if obtained through free consent. Just property, acquired through labour, remains just after a voluntary exchange. Aristotle would agree.

Libertarianism is thus only concerned with *procedural* justice. What matters is how you get there, not where you end up. An unequal distribution of resources is of no concern to a libertarian provided that the rich got rich by moral means.

The role of the state is rather limited in libertarianism. The government should guard against unjust holdings, such as theft. The government should also guard against negative externalities, which are involuntary impositions on the liberties and properties of others. That is all.

Libertarians argue that taxation is wrong. It is, after all, an involuntary transfer of property. Governments can therefore not redistribute resources from the rich to the poor. Income inequality should be alleviated by charity. The government may provide public goods, but contributions to that should be strictly voluntary.

Classical economists would have agreed with libertarians on many points.

2.5 Utilitarianism

Utilitarianism is the polar opposite of libertarianism. Utilitarianism is *consequential* justice. What matters is where you end up, not how you got there. Utilitarianism is *teleological*.

At the individual level, utilitarianism is about pain and pleasure. At the social level, utilitarianism is about the greatest good for the greatest number. In narrow definitions of utilitarianism, this means the sum total of the utility of people.

---

[93] Locke (1632-1704) was a philosopher and physician. He is noted for his work on the theory of mind and the social contract. His work on liberalism and republicanism is reflected in the US Declaration of Independence.

[94] Actually, hunter-gatherers do manage the landscape, just not in a way that an agriculturalist would recognize.

[95] Nozick (1938-2002) taught philosophy at Harvard University. He also worked on the theory of knowledge.

In broad definitions of utilitarianism, the greatest good for the greatest number means some aggregate of the utility of people and perhaps animals.[96] The *Pigou-Dalton Principle*[97] is the dividing line between narrow and broad utilitarianism. According to the Pigou-Dalton Principle, social welfare should improve if income is transferred from rich to poor (without making the formerly rich poorer than the formerly poor). Narrow utilitarianism neither satisfies nor violates this principle. Broad utilitarianism either violates or, more typically, satisfies Pigou-Dalton.

According to utilitarians, the government should deliver the greatest good for the greatest number. It does not matter how. An autocratic government that brings material welfare to its citizens is better, according to utilitarians, than a democratic government of a poorer country.

The Pareto optimum is sometimes mistaken for a true optimum, but it is only the best we can do given an initial allocation of endowments. The Second Welfare Theorem has that there are many Pareto optima, each corresponding to a different initial allocation. Utilitarianism allows us to choose between these optima.

Broad interpretations of utilitarianism can be captured with a Bergson-Samuelson-Atkinson welfare function

$$W = W(U_1, U_2, \dots, U_n) = \frac{1}{1-\gamma} \sum_{i=1}^{n} U_i^{1-\gamma} \tag{2.1}$$

where W denotes social welfare and U_i the utility of individual $i = 1, 2, \dots, n$. The right-hand side is due to Anthony Atkinson,[98] the middle part was independently suggested by Abram Bergson[99] and Paul Samuelson.[100] The parameter γ is relative inequity aversion.

At the margin, individuals i and j contribute to social welfare as follows

$$\frac{\frac{\partial W}{\partial U_i}}{\frac{\partial W}{\partial U_j}} = \left(\frac{U_j}{U_i}\right)^{\gamma} \tag{2.2}$$

If $\gamma = 0$, the social planner is inequity neutral. $W = \sum_{i=1}^{n} U_i$. It does not matter whether the utility of i or j goes up, because the ratio of their marginal contributions to welfare is always equal to one.

---

96 Some philosophers argue that broad utilitarianism is not utilitarianism at all, but I have yet to see a cogent argument why not.

97 Pigou is Alfred Cecil Pigou, also known for the Pigou tax. Hugh Dalton (1887-1962) taught economics at the University of London, where he worked on income inequality. He later become a Member of Parliament and Chancellor of the Exchequer.

98 Atkinson (1944-2017) taught economics at the University of Oxford and the London School of Economics. He worked on inequality and poverty.

99 Bergson (1914-2003) taught economics at Columbia University and Harvard University. He worked on social welfare theory and the calculation of national output in Soviet economies.

100 Samuelson (1915-2009) taught economics at the Massachusetts Institute of Technology. He won the 1970 Nobel Prize. He made many contributions, including the *modern synthesis*, the merger of Keynesian and neoclassical traditions. Through his work, his students, and his textbooks, Samuelson was responsible for the increased use of mathematics in economic analysis.

For $\gamma > 0$, the social planner is inequity averse. The social welfare function satisfies the Pigou-Dalton Principle. If i is happier than j, $U_i > U_j$, then $\left(\frac{U_j}{U_i}\right)^\gamma < 1$. That is, a utility gain for happy i is less important than a utility gain for miserable j.

There is another way to see the same thing:

$$W = \begin{cases} \min_i U_i & \text{if } \gamma \uparrow \inf \text{ (Rawls)} \\ \prod_i U_i & \text{if } \gamma = 1 \text{ (Bernoulli-Nash)} \\ \sum_i U_i & \text{if } \gamma = 0 \text{ (Bentham)} \\ \max_i U_i & \text{if } \gamma \downarrow -\inf \text{ (Nietzsche)} \end{cases} \tag{2.3}$$

As γ grows, more and more emphasis is placed on the plight of the worst-off in society.

Note that, for completeness, Equation (2.3) also includes the case $\gamma < 0$. The Pigou-Dalton Principle is violated. Social welfare increases when income is transferred from poor to rich. Few people would consider this to be desirable.[101]

2.6 The Impossibility Theorem

In his 1951 PhD thesis, Kenneth Arrow[102] published his *Impossibility Theorem*. It shows that a welfare function cannot be an aggregate of individual preferences. That does not mean that you should not use social welfare functions. It does mean that you should be aware of their limitations.

More specifically, the Impossibility Theorem is about a society with two or more people and three or more goods.[103] Suppose that all agents in this society have a clearly defined preference order. Arrow showed that there cannot be social preference order that is non-dictatorial, universal, independent of irrelevant alternatives, and unanimous.

These are all desirable properties. Non-dictatorship means that no agent can dictate his preferences to any other agent. Universality (or unrestricted domain) means that the social preference order applies to every conceivable outcome. Independence of irrelevant alternatives means that the ranking of two options does not change if a third option is added or removed; if A is better than B then A is better than B

---

[101] In an upbeat moment, Nietzsche wrote that the best we can hope for is if all humanity would work to make a single man fleetingly happy.

[102] Arrow (1921-2017) taught economics at Stanford University. He shared the 1972 Nobel Prize with John Hicks. Arrow's contributions to economics are many, but two stand out. His early work on social welfare theory demonstrated that a social planner cannot solve all problems. His later work with Gerard Debreu on general equilibrium theory showed that markets cannot be complete. The market cannot solve all problems either.

[103] It also works with two or more goods and three or more people. A society can be as small as a group of students sharing a flat.

regardless of whether C is there too. Unanimity means that if all prefer an option then so should society.[104]

In other words, any aggregate of individual preference orders has undesirable properties. As there is a one-to-one correspondence between preference orders and utility functions, any social welfare function that aggregates individual utility functions, is flawed too.

2.7 Critiques of utilitarianism

Utilitarianism is unpopular outside economics. Besides the alternative schools of moral philosophy, I highlight the work of two criticasters.

John Rawls[105] is seen as one of the key ethicists of the 20th century. Rawls thought and wrote about what a just society would look like. He argued that a just society would be one that everyone in that society would agree on, if they were free to decide, rational, and impartial. For impartiality, Rawls introduced his *veil of ignorance*: You can be impartial only if you do not know what position you hold in society, if you do not know how skilled or talented you are, and if you do not know your attitudes towards risk, inequality and such things.

On that basis, Rawls argued that a just society would be as free as possible. Anyone should be who they like to be and do what they want to do, as long as it does not infringe on other people's liberties. For instance, if you do not whether you would be a man or woman, gay or straight, black or white, able-bodied or not, then you would self-interestedly argue against any form of discrimination. Rawls emphasized process; he is a libertarian in this sense.

Rawls also argued that a just society would minimize differences in outcomes. Incomes should only deviate if that income difference makes everyone better off, and if that income difference is attached to position. For example, doctors and firefighters have to be on standby for 24/7, so it stands to reason that they are compensated for their sacrifice lest no one wants to take that job. Doctors are trained for a longer period than nurses so it is reasonable to compensate them for that—but not for the fact they were born into a different class or have a greater aptitude for academic study. Rawls' just society is nothing like ours.

As shown in Equation (2.3, a Rawlsian income distribution can be captured in a social welfare function. Other aspects of Rawlsian justice, such as maximum freedom, cannot. Rawls' view of justice mixes procedural and consequential elements.

---

104 The original version of the Impossibility Theorem did not have unanimity. Instead, it had monotonicity and non-imposition. Monotonicity means that if some agent begins to like an option more, then society should not begin to like it less. Non-imposition has that society should not prefer things that no-one in society prefers.

105 Rawls (1921-2002) taught philosophy at Harvard University. His work focused on justice and democracy.

Amartya Sen[106] notes other problems. A utilitarian would applaud the government of Singapore which is fairly authoritarian but has made its people rich. The governments of South Korea and Taiwan were similarly down on freedom but up on economic growth, and were removed by the people. Not everyone agrees that material wealth is all that matters. Sen noted a deeper problem. An aggregate of individual utilities, cannot reflect properties of society, such as democratic freedoms: A Bergson-Samuelson function has that $W = W(U_1, U_2, \dots, U_n)$. That is, $W \neq W(U_1, U_2, \dots, U_n, F)$, where F stands for freedom. Nor is it easy to add freedom as an attribute to a utility function: Freedom is not consumed or produced in any conventional meaning of those words, and it is property of society rather than an individual. I may be free to speak, but it is not freedom of speech unless you are allowed to speak too. Freedom is not a public good either; freedom is a right.

Sen, like Rawls, thus deviates from utilitarianism in emphasizing the *process* by which decisions are reached. Like Rawls, Sen also underlined the importance of an equal distribution. In some of his earlier work, Sen sought to extend the social welfare function with measures of the distribution of outcomes, but his approach was less elegant than Atkinson's. Later, Sen argued that what really matters is an equal distribution of opportunities. He refers to these as capabilities, which include not just health and education but also the freedoms and opportunities to make the most of these endowments. Sen's capabilities approach is at odds with utilitarianism as it is no longer about outcomes at all.

Sen also highlighted altruism. At first sight, altruism is compatible with utilitarianism. If person i cares about person j, $U_i = U(C_i, U_j)$. That is, besides her own consumption C_i, utility is a function of the other person's happiness (or perhaps perceived happiness or consumption). There are two problems with this. First, the construction of the aggregate demand curve assumes that individual demand curves are independent of each other. The vertical aggregation of demand curves allows for the kind of altruism that affects our well-being but not our behaviour. You can work your way around this (not in an undergraduate class though) but then a different problem emerges. A social welfare function is supposed to be the foundation on which to give policy advice. A social welfare function that includes altruism has a fundamental inequity build-in. If your utility depends on your well-being and the well-being of the people you care about, then a social welfare function that reflects your utility double-counts the utility of those you care about. That would not be a problem if care were equally distributed. If not, such a social welfare function is biased towards popular people and biased against unpopular ones, biased towards people with large families and biased against people with small families. That cannot be right.

Sen further wrote about agency. People behave differently in different roles. You are different around your family than when you are with friends or colleagues. This is first and foremost a positive problem, an issue with describing and predicting what economic agents do. It is hard to construct a utility function and budget constraints, that together manifest themselves in first-order conditions that solve differently de-

---

[106] Sen (1933-) taught economics at a number of universities in India, the UK and the USA. He won the Nobel Prize in 1988. He is best known for his work on social welfare and on famine.

pending on who else is in the room.[107] But this also affects the social evaluation of individual behaviour, which is after all what a welfare function is about. A middle-aged man chatting up a young woman in a bar is met with pity, a middle-aged male professor chatting up a female student after class stands accused of harassment and abuse of power. A businessman giving preferential treatment to an old friend is giving away his own money, whereas a politician would give away public funds. Different roles come with different expectations and responsibilities, so that a transaction can be legitimate and welfare-improving in one circumstance but not in another.

Utilitarianism is therefore an ethical system with many drawbacks. Applications of social welfare functions should always be treated with caution and inspected for flaws.

Further reading

In *How economics can save the world*, the philosopher Erik Angner discusses the role of economics and economists in public policy. The first few chapters of Timothy Taylors' *Unexpected Economics* lays out some of the ethical dilemmas in public policy.

Exercises

2.1 Post a summary of this chapter on TikTok with #envecon
2.2 Rawls' Difference Principle asserts it is only just to have an unequal distribution of wealth if all are better off in that situation, relative to an equal distribution. However, the total level of wealth attainable might depend on its distribution, for instance, because incentives stimulate technological progress. Discuss the implications.
2.3 Nozick's libertarian ethics have been enthusiastically adopted by those who believe in a limited role for government. What should a night watch government do about unjust holdings? About common and open-access resources? About externalities and public goods?
2.4 If animals or plants have rights, such rights can only be protected by imposing constraints on human behaviour. What rights should be given to whales and primates? What constraints should be imposed on humans to protect these rights?

[107] Hard, but not impossible.

Chapter 3
Sustainability

3.1 Introduction

Sustainability is a core concept in environmental policy. Since it was popularized in 1987 by the Brundtland Commission almost every government, every company, every university, and every other organization strives to be sustainable.

Sustainability is sometimes interpreted as a property of the social welfare function, but more commonly as a constraint we should impose on any decision we make.

3.2 Roots

John Stuart Mill[108] (1848, Principles of Political Economy) wrote

> If the earth must lose that great portion of its pleasantness which it owes to things that the unlimited increases of wealth and population would extirpate from it, for the mere purpose of enabling it to support a larger, but not a happier or better population, I sincerely hope, for the sake of posterity, that they will be content to be stationary long before necessity compels them to it.

Like his fellow Classical economists, Mill believed that economic growth must come to a halt as resources are finite. In the above passage, he argues that economic expansion should stop before economic output reaches its maximum because there is "pleasantness" apart from material wealth. He further argues that we should do this not for our own sake but for those who come after. Mill thus captured the essence of sustainability.

[108] Mill (1806-1873) worked for the British East India Company and was a Member of Parliament. He wrote about a wide range of economic, social, and political issues and is often considered to be the most influential English-speaking philosopher of the 19th century. Late in life, he said that most of his work was co-written with Harriet Taylor Mill (1807-1858).

Gro Harlem Brundtland[109] and colleagues (1987, Our Common Future) give the following definition

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

This is intuitively appealing. We should grow but without hurting our children. We should leave the planet as we would have liked to find it. The appeal of the Brundtland report led to a rapid and widespread support of sustainability. Every country and every organization wants to develop sustainably. Sustainability is the shared end goal, sustainabilizability the intermediate target.[110]

The Brundtland definition is vague. What are *needs*? Food and water are beyond dispute, but I sometimes have a desperate urge to watch a silly show on TV. What is the *ability* to meet needs? Are we content if our descendants could have met their needs but did not? And what does *compromising* that ability mean? If their ability is reduced by 10% is it compromised, or is the threshold at 90%?

Brundtland's vagueness is her strength. The direction of travel is clear—do not leave the planet in a worse state than you found it, or perhaps leave the planet as you would have liked to find it—but there is no precise prescription, which allows people from different convictions to subscribe to sustainable development—and that is exactly what has happened: Everyone wants to be sustainable.

Academics, however, do not like vagueness. There have therefore been many attempts to give a precise definition of sustainability. I review these below, in three major groups. However, as Billy Bragg noted,

> The temptation
> To take the precious things we have apart
> To see how they work
> Must be resisted for they never fit together again.

Precise definitions break the consensus on sustainability because no one can quite agree on what it really means. Trying to put substance to the slogan reveals that sustainability is a rallying cry. Rallying cries are important because they motivate people, in this particular case to do the right thing. Intellectualizing a rallying cry strips it of its power.

Academics have not been able to resist the temptation, and there are now many precise definitions of sustainability. I review the key ones below.

---

[109] Harlem Brundtland (1939-) was a physician, Prime Minister of Norway, and Director-General of the World Health Organization.

[110] The aim is to be sustainable. To that end, we need to sustainabilize society. The ability to sustainabilize is known as sustainabilizability.

3.3 Weak sustainability

Jack Pezzey[111] argued that sustainability means that *utility* should not fall. We want to sustain human happiness.

Utility is an elusive concept, though. John M. Hartwick[112] therefore argued that sustainability means that *consumption* should not fall. In 1977, he formulated the Hartwick Rule: A constant level of consumption can be maintained perpetually from an environmental endowment if all the scarcity rents (net price, profit) from resource extraction are invested in other capital. That is, we should keep the principal intact, live off the service flow alone. Sacrificing a piece of natural capital is fine as long as the proceeds are invested in human-made capital that delivers services that are just as good or better.

Robert M. Solow[113] argued that, with finite resources of essential inputs, non-declining consumption is indeed constant. Herman E. Daly[114] argued for a steady-state economy, in which population and human-made capital are constant.

The Hartwick Rule appears sensible—do not run down your capital stock—and precise. But the Hartwick Rule does not specify whose consumption should be kept constant, however. Is it the average consumer's? The median? Everyone's? Nor does it say at what time-scale should consumption be constant? Every day, every year, every decade, every century? And it does not define the bundle of consumption. Does it include everything or just core elements? Material goods only or intangibles too? Is it the same bundle over time? Is it correct to assume that future generations will value the same things as we do? Is it right to impose our preferences on them?

In order to overcome the last problem, Talbot Page[115] and Robert Solow suggested that *production possibilities* should not fall. This avoids the problem of defining consumption for now and forever. As an analysis of sustainability is done by current scholars, assumptions about future consumption necessarily reflect current preferences. A focus on production is less paternalistic. Problems of time scale and representation remain, however.

A key aspect of all these definitions is that *substitution* is allowed. The Hartwick Rule explicitly says that it is fine to run down natural resources as long as the revenue is used to build up physical capital. According to these *weak* definitions of sustainability, what matters is that human welfare will not fall. A walk in the forest

---

[111] Pezzey (c1956-) has been a civil servant, researcher, consultant, and lecturer in the UK, the USA, and Australia.

[112] Hartwick (1944-) taught economics at Queen's University, Kingston, Ontario.

[113] Solow (1924-2023) taught economics at MIT. He won the 1961 John Bates Clark Medal for his work on the distribution of income and the 1987 Nobel Memorial Prize for his research on economic growth.

[114] Economists are famous for arguing "on the hand ... but on the other hand ...", so much as so that an exasperated President Truman called for a one-armed economist. ”Here I am", Daly would shout whenever someone made that joke at a conference. He had lost an arm to polio. Daly (1938-2022) taught economics at the University of Maryland at College Park and later worked at the World Bank.

[115] Page taught economics at Brown University.

can be replaced with a walk in virtual reality. The virtual walk is probably better, as you can edit out the mud and add bluebells all year round.

3.4 Strong sustainability

The defining feature of weak sustainability is that human-made capital can substitute for natural capital. Advocates of strong sustainability disagree. Some go as far as arguing that sustainability means that each *natural capital stock* should be maintained.

This has far-reaching implications. Fossil fuels can no longer be used, or fossil water. Trees can only be cut for lumber if new trees are planted. Building materials would be scarce, as mining for sand and limestone comes to an end.

If all natural capital stocks were to stay at their current levels, human activity would be severely curtailed. A new road takes up space, necessarily taking away space from something else. Building a new house thus means taking down an old one. If strong sustainability is defined at the local level, the old house needs to be in the same county.

In practice, therefore, some substitution must be allowed. But at what spatial scale? If a forest has to make way for a new road in England, should new trees be planted in England or is it fine to plant new trees in Hungary? To what extent do new trees substitute for old trees, which provide a much richer habitat for birds, plants, and insects?

What natural capital stocks should be maintained? Ecosystems, species, or genes? The polar bear is a subspecies of the brown bear. Not much genetic diversity would be lost if the polar bear goes extinct. We should be more concerned about the tree lobster than about the polar bear if we want to keep the largest possible gene pool. Or maybe we do want to preserve every individual species from extinction, whether caused by humans or evolutionary dynamics. And what should we do with viruses and pests? Should we let malaria roam freely? Was Carter wrong to try and end the Guinea Worm? Would we not rather be without the Covid-19 virus?

These views reflect natural moral philosophy, although it is more usually referred to as *deep ecology*,[116] which emphasizes the inherent worth of all living beings, human or not.

The desire to maintain natural capital stocks reflects a static view of the natural environment. Things should stay as they are or return to how they used to be. An alternative view on strong sustainability argues that, instead, *services from natural capital stocks* should not decline. What matters is that there are enough photosynthesizing plants to make sufficient oxygen; it does not really matter what species these plants are. What matters is that there are coastal forests to break storms and provide shelter and sustenance for fish larvae; it matters less whether there are more mangrove palms than buttonwoods.

---

[116] The term was coined by Arne Naess. See footnote 92.

A focus on nature's services begs the question, a service to whom or what? Most plants can live without animals but no animal can live without plants. And at what spatial or temporal scale should services be maintained?

A third group of definitions of strong sustainability centres on *ecosystem stability and resilience*. This does not solve the fundamental problem of lack of specificity, because stability has to be defined in terms of either stocks or services.

The key feature of strong sustainability is that it imposes stronger constraints on human behaviour than does weak sustainability. Weak sustainability argues that all is fine as long as humans are fine. This is a utilitarian, humanist perspective. Strong sustainability wants other species to be fine too, even if it comes at the expense of humans. This is a naturalist perspective.

Box 3.1: Degrowth

Adherents of weak sustainability argue that human welfare should be maintained or grown. Proponents of strong sustainability argue that human growth should not come at the expense of nature and the environment. Related to this, some people call for *degrowth*. Degrowth is an unnecessary neologism, as there was already a perfectly good word in English. Degrowth means (economic) shrink.

The starting point of the advocates for degrowth is that pollution and resource degradation are so large that only a reduction in economic activity can restore nature and the environment to an acceptable quality. Some, Patricia MacCormack for example, go a step further: Earth would be better off without humans.

One objection to this position is that the relationship between growth and the environment is more complicated than assumed. Economic growth is associated with the reduction of sulphur and other pollutants. We return to these issues in the chapter on the environmental Kuznets curve.

Another objection is that degrowth is a political non-starter. It is true that some politicians have tanked their country's economy—but none did so deliberately and those that did are very unpopular and often see their tenure cut short. Champions of degrowth soften their message by calling for a different kind of growth, that emphasizes immaterial aspects of well-being over material things. We return to the measurement of growth in the chapter on environmental accounting.

Many people in the richer parts of the world indeed do not need or want more stuff. There are also many people who are materially deprived, unable to afford adequate shelter, clothing, and food. Supporters of degrowth think this problem can be solved through redistribution. There is majority support for progressive taxation, development aid and charity, but not for a material reduction in living standards in support of egalitarianism.

In short, degrowth is the hobby horse of a few well-to-do idealists. It is not a serious policy proposal.

3.5 A social construct

The academic quest for a more precise definition of sustainable development than Brundtland's has thus led to a variety of definitions that are not particularly precise either. There is a third group of definitions: Sustainability is what we decide it to be.

This is a truism. Sustainability is not some property of the real world, such as the speed of light, that we try to uncover. It is not God's command that we can read in the Bible or the Quran. Sustainability is an abstract human desire, a social construct. But the people who argue this have a deeper motive. Brundtland'secommendation that development should be sustainable was so popular that it crowded out other objectives of government. Advocates of other worthy goals can either resist the new kid on the block, or seek to co-opt the item newly at the top of the agenda. People who argue that sustainability is a social construct also argue that it matters how society construes sustainability, a libertarian focus on procedure over outcome, and typically advocate deliberative, participatory democracy.

Sustainable development was initially about environmental quality, but this was quickly replaced by the three pillars of sustainable development: Environmental quality, distributional justice, and economic efficiency. These are worthy goal, but the environment is no longer the sole focus.

The United Nations now has no fewer than 17 *sustainable development goals*: a half one about economic growth, one about participatory democracy, three about the environment, and eleven and a half about development.[117] Sustainable development is now more about development than about the environment.

Box 3.2: Sustainable Development Goals

1. End poverty in all its forms everywhere
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3. Ensure healthy lives and promote well-being for all at all ages
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5. Achieve gender equality and empower all women and girls
6. Ensure availability and sustainable management of water and sanitation for all
7. Ensure access to affordable, reliable, sustainable and modern energy for all
8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
10. Reduce inequality with and among countries

[117] Sustainable development goal #12 says that production and consumption should be sustainable. This is a tautology. The goal of sustainability is to be sustainable.

11 Make cities and human settlements inclusive, safe, resilient and sustainable
12 Ensure sustainable consumption and production patterns
13 Take urgent action to combat climate change and its impacts
14 Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and biodiversity loss
16 Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17 Strengthen the means of implementation and revitalize the global partnership for sustainable development

Blurring concepts and re-purposing slogans is excellent politics but poor policy. Putting its three pillars under one heading masks the real trade-offs in sustainable development. Agriculture puts a lot of pressure on the environment. Cleaner forms of food production with less pesticides and fertilizers are more expensive. Greater environmental quality implies lower economic growth. Novel protein food are excellent but expensive substitutes for meat. Food is a necessary good. Poorer people spend a larger share of their income on food. Greater environmental quality implies a more unequal income distribution. Lumping everything under sustainable development hides these trade-offs. Vague words that appeal to every constituency make great politics. Ignoring the negative consequences of interventions is poor policy.

Jan Tinbergen[118] showed that if you have N policy problems, you need N policy instruments. This is the Tinbergen Rule. It is a corollary of Joseph-Louis LaGrange's work on constrained optimization. A simple example illustrates this. If you have two cars, you need two steering wheels. You can imagine a single car with two steering wheels, but negotiating a bend in the road requires a lot of coordination between the two drivers. Two cars that share a single steering wheel do fine as long as they go straight. Turning a corner is rather tricky, unless the road is very wide. Killing two birds with one stone is so remarkable we made it into a proverb. Tinbergen says you really need two stones—although his brother Luuk would probably tell you not to kill birds.[119]

Returning to the example of food production, there are three objectives. A reduction in environmental pollution requires a change in farm practices. Economic efficiency demands that you do so at the lowest possible cost. As shown below, that

[118] Tinbergen (1903-1994) taught economics at Erasmus University Rotterdam, was the founding director of economic statistics division of the Central Bureau of Statistics and later the founding director of the Central Planning Bureau of the Netherlands. He won the 1969 Nobel Memorial Prize for building and estimating the first ever macroeconomic model.

[119] Jan's brother Niko (1907-1988) won the Nobel Prize for Physiology for his work on social insects. They agreed that their brother Luuk (1915-1955), who studied birds, was the clever one.

is best done through a tax on emissions. Distributional justice dictates that part of the tax revenue be used to raise the income of the poorest. Giving three problems the same name falsely suggests there is only one problem, and that one intervention is enough to solve it.

Further reading

Jason Hickel's *Less is more—How degrowth will save the world* and Kate Raworth's *Doughnut economics—How to think like a 21st century economist* are popular but unbalanced. *Blueprint for a green economy* by Edward B. Barbier, Anil Markandya, and David W. Pearce is much better. It is the first in a series of seven. The latest, *A new blueprint*, by Barbier and Markandya, updates both data and thinking about sustainability.

Exercises

3.1 Post a summary of this chapter on TikTok with #envecon
3.2 How does weak sustainability relate to utilitarianism?
3.3 How does strong sustainability relate to naturalism?
3.4 How would a libertarian define sustainability?

Chapter 4
Externalities and public goods

4.1 Market efficiency

Let's recap the definition of *efficiency*, also known as *Pareto optimality*. Situation A is *Pareto superior* to situation B if no one is worse off and at least one person is better off in A than in B. We call A a *Pareto improvement* on B. A situation is Pareto optimal, or efficient, if no Pareto improvement is possible.

Aristotle noted that a voluntary exchange is mutually beneficial—in current jargon, Pareto improving. If the bargain were detrimental to either party, why would they agree to it? If we assume that economic agents are rational and all exchanges voluntary, the market improves welfare in Pareto's sense of that word—every market exchange is Pareto improving. If we assume that agents are insatiable and trade is costless, then they will continue trading until no Pareto improving deal can be struck. If we further assume that agents are perfectly informed about all offers on the market (and can accept these as trade is costless), then they will strike the best deals. This is the *First Welfare Theorem*, the Classical notion that the equilibrium of a free market is a Pareto optimum.[120]

A Pareto optimum is conditional on the initial distribution of endowments. If we rearrange the starting point, a perfect market would still be efficient, but the equilibrium reached would be a different one. This is the *Second Welfare Theorem*.[121] In order to choose between Pareto optima, we would need a social welfare function that reflects our collective preferences for the level and distribution of consumption.[122]

Let us now make this more precise.

---

120 Adam Smith argued this verbally, Abba Lerner showed it graphically, Harold Hotelling analytically for a static economy, and Kenneth Arrow and Gerard Debreu for a dynamic economy.

121 There is no Third Welfare Theorem, although the Coase Theorem may qualify.

122 Arrow's Impossibility Theorem, another contender for the title Third Welfare Theorem, shows that is hard if not impossible to construct a social welfare function.

4.1.1 Exchange economy

Consider an economy with two agents, A and B, two goods, X and Y, and two inputs, L and K.

Utility U depends on consumption: $U^A = U(X^A, Y^A)$ and $U^B = U(X^B, Y^B)$ where the superscripts denote *whose* utility and whose consumption. Both goods are made with both inputs: $X = X(L^X, K^X)$ and $Y = Y(L^Y, K^Y)$. Subscripts denote first partial derivatives: $U^A_X := \frac{\partial U^A}{\partial X^A}$ is the marginal utility of agent A consuming good X and $MP^Y_L := \frac{\partial Y}{\partial L_X}$ is the marginal output MP of good X in input L.

Consumption efficiency requires that the ratio of marginal utilities, called the *marginal rate of substitution*, be equal for both agents:

$$\frac{U^A_X}{U^A_Y} = \frac{U^B_X}{U^B_Y} \tag{4.1}$$

Suppose that this is not the case. For instance, let the ratio be 5-to-1 for A and 1-to-5 for B. Then, A should give one unit of Y to B in exchange for one unit of X. A would lose one util and gain five, a profitable exchange. Similarly, B would lose one util and gain five. This deal is Pareto improving, so the original situation was neither optimal nor in equilibrium. Only when the marginal rates of substitution are equal is it impossible to strike a mutually advantageous bargain.

Production efficiency requires that the ratio of marginal production, called the *marginal rate of transformation*, be equal for both producers:

$$\frac{MP^X_L}{MP^X_K} = \frac{MP^Y_L}{MP^Y_K} \tag{4.2}$$

If this is not the case, then it would be possible to shift L from the production of X to the production of Y and K from Y to X (or vice versa) and make more of both X and Y.

Allocative efficiency—also called cross-efficiency, x-efficiency or product-mix efficiency—requires that the marginal rate of substitution equals the marginal rate of transformation:

$$\left(\frac{U^A_X}{U^A_Y} =\right) \frac{U^B_X}{U^B_Y} = \frac{MP^Y_K}{MP^X_K} \left(= \frac{MP^Y_L}{MP^X_L}\right) \tag{4.3}$$

At the margin, the relative gain should equal the marginal cost. To see why, suppose that the ratios on the left-hand-side is 5-to-1 and the ratios on the right-hand-side 1-to-5. That is, an additional unit of X is worth 5 utils while an additional unit of Y is worth 1 util. An additional unit of K or L makes one additional unit of Y and five additional units of X. If we shift 1 unit each of K and L from making Y to making X, we lose 1 Y at the cost of 1 util but win 5 X at a gain of 25 utils.

Together, consumption efficiency, production efficiency, and allocative efficiency make efficiency. Production and allocative efficiency are a precondition for optimality, whether Pareto optimality or some other kind. This is because production and allocative *in*efficiency means that the pie is smaller than it can be. Regardless of your stance on the distribution of income, the total should always be as large as possible. (Recall that we have yet to introduce environmental concerns.)

Optimality relates to consumption efficiency—we seek the greatest good for the greatest number of consumers. If we want to maximize some social welfare function $W = W(U^A, U^B)$ then the first-order conditions require that

$$\frac{W_{U^A}}{W_{U^B}} = \frac{U_X^A}{U_X^B} = \left(\frac{U_Y^A}{U_Y^B} = \frac{U_Y^A}{U_X^B}\frac{MP_K^Y}{MP_K^X}\right) \tag{4.4}$$

As the ratio of marginal utilities of the two agents now needs to be a particular number, we have introduced a new constraint on our economy. A new constraint can only be met if we also introduce a new instrument. A new requirement needs a new degree of freedom. That new instrument could be a transfer of initial endowments from one agent to the other.

4.1.2 Market economy

Let us now introduce prices. *Consumption efficiency* requires that the ratio of marginal utilities is equal to the price ratio:

$$\frac{U_X^A}{U_Y^A} = \frac{P_X^A}{P_Y^A} = \frac{P_X}{P_Y} = \frac{P_X^B}{P_Y^B} = \frac{U_X^B}{U_Y^B} \tag{4.5}$$

where the step in the middle assumes that both agents face the same relative prices—a sign of a well-developed market. If the price ratio is not equal to the marginal rate of substitution, an agent could readily improve her utility. Let the price ratio be 5-to-1 and the utility ratio 1-to-5. The agent could then sell one X, a utility loss of 1, and use the money to buy 5 Y, a utility gain of 25.

Production efficiency requires that the ratio of marginal productivities equals the input price ratio:

$$\frac{MP_L^X}{MP_K^X} = \frac{P_L^X}{P_K^X} = \frac{P_L}{P_K} = \frac{P_L^Y}{P_K^Y} = \frac{MP_L^Y}{MP_K^Y} \tag{4.6}$$

If not, a producer would buy less of one input and spend the savings on buying more of the other, raising production.

A rational producer sets marginal revenue equal to marginal cost. For input L in product X this is $P_X = MP_L^X P_L$. This implies that

$$\frac{P_X}{P_Y} = \frac{MP_L^X}{MP_L^Y}\frac{P_L}{P_L} = \frac{MP_L^X}{MP_L^Y} \tag{4.7}$$

This is the condition for *allocative efficiency*.

We have thus established that a market equilibrium is efficient.

There are a number of conditions, though. Agents need to be rational and perfectly informed. Rational agents maximise utility or profit. Without rationality, nothing of the above holds—if agents act against their self-interest, voluntary actions no longer improve their welfare. Agents also need perfect information about prices—otherwise they would not be able to seek out the best deals. Trade needs to be costless—if not, good deals cannot be closed. Markets need to be perfectly competitive—otherwise markups break the equality of marginal costs and revenues. From an environmental perspective, the key condition is that markets are complete. Every transaction has a market. In other words, there are no externalities, and no public goods.

We now turn to these two conditions, considering externalities first.

4.2 Externalities

An *externality* is the unintended and uncompensated effect of an economic activity on a third party.

Intent: We burn coal to make electricity, not to emit carbon dioxide and soot. We hold bees to make honey, not to pollinate flowers. The externality is incidental to the economic activity

Compensation: If pollination is remunerated or emissions taxed, the market failure is less pronounced; or may disappear altogether if the price is right. More importantly, externalities affect the utility of other agents. If compensated, this welfare effect disappears, at least in part.

Third party: The victim of pollution or the beneficiary of pollination does not engage in an economic transaction with the polluter or pollinator. Again, if compensation occurs, the victim or beneficiary becomes part of the transaction and is no longer a third party.

You can call a negative externality an external effect, an external cost, or an external diseconomy. These words all mean the same thing. An externality may be beneficial or adverse. It may come about by consumption or production and may affect consumption or production. If properly taxed, the externality is said to be *internalised*.[123] The history of the concept is discussed in Box 4.1.

Box 4.1: Externalities defined

An externality is the unintended and uncompensated effect of an economic activity on a third party.

[123] An externality on one-self is called an *internality*, which can be loosely defined as doing something stupid but being unable to stop yourself. The "third party" in the definition of an externality sets it apart from an internality. Internalities are extensively discussed in courses on behavioural economics.

Historical accounts

Alfred Marshall was the first to describe external economies, in the 1st edition (1890) of his textbook Principles of Economics, referring to "all matters of Trade-knowledge", including both market intelligence and technical know-how. We would now refer to this as economies of agglomeration.

His student and successor, Arthur Pigou,[a] in his 1920 book Economics of Welfare, notes that external effects make the market inefficient, proposing the Pigou tax to remedy that. Pigou refers back to Marshall's agglomeration economies[b] and writes about what we now call principal/agent problems. He also refers to what we now call externalities. He notes the positive effects of outdoor lighting on neighbours, the impact of afforestation on the local climate, and the injury caused by smoke from chimneys.

Jacob Viner (1931 ZNatOek) distinguished between *pecuniary* and *technological* external effects. The latter are the same as Marshall's. Pecuniary externalities occur when the actions of one company affect another company "through the market". An increase in supply by the first company would lower prices for both companies. Pecuniary externalities do not pose an efficiency problem.

Tibor Scitovsky (1954 JPE) distinguishes four types of technological externalities, from consumer to consumer, from producer to consumer, from consumer to producer, and from producer to producer. The example he gives for consumption externalities on consumption is, in fact, altruism or empathy: I take pleasure from you enjoying your ice cream. He dismisses the other types of externalities as unimportant or, for production externalities on consumption, because they are trivially solved by government intervention. Scitovsky extends Viner's pecuniary externalities to investment.

James Meade (1952 EJ) published the first formal analysis of externalities, but in a way that is not readily recognizable today. He distinguishes two types of externalities, both positive, and both related to production only. He refers to the first type as "unpaid factors", giving the example of the bee-keeper's bees pollinating nearby apple blossom.[c] The second type, "creation of atmosphere", is Marshall's knowledge spillovers.

Francis Bator (1958 QJE) put externalities in the form that is now commonly found in textbooks. A Pareto optimum requires that the marginal rate of substitution equals the output price ratio, the marginal rate of transformation the input price ratio, and the ratio of marginal productivities the output price ratio. Bator splits marginal social benefits and costs into its private and external parts. In an unregulated market, a consumer would only pay the marginal private benefits, disregarding the externality. A producer would only consider its marginal private costs, ignore the externality. The market would thus use price ratios that are not Pareto optimal. In Bator's words

"'Price equal to MC' is saved, but wrong." This immediately justifies a Pigou tax to correct the market price.
After this clear exposition, Bator then muddies the water by distinguishing three types of externalities. The first he calls "ownership" externalities, which cover the free services of positive externalities and the uncompensated damages of negative externalities. He also considers "technical" externalities, where prices and marginal costs are misaligned because of indivisibility or returns to scale. And he writes about "public good" externalities, where prices are wrong because consumption is non-rival or non-excludable. These latter two are market imperfections but perhaps best kept separate from externalities proper.

Contemporary accounts

In the 3rd edition of *Microeconomic Analysis*, Hal Varian defines a consumption externality as a direct effect of the action of one consumer on the utility of another; and a production externality as a direct effect on the production set. In their *Lectures on Public Economics*, Tony Atkinson and Joe Stiglitz clarify that "direct" means "not through the price system". Varian omits both intent and compensation.
In the 17th edition of *Economics*, Paul Samuelson and Bill Nordhaus write that "[e]xternalities occur when firms or people impose costs and benefits on others outside the marketplace." Intent is omitted, lack of compensation is implicit.
In version 1 of The Economy, CORE uses the following definition: "A positive (negative) external effect is a positive effect of a production, consumption, or other economic decision on another person or people that is not specified as a benefit (liability) in a contract." Intent is missing, lack of compensation implicit.
The definition in *Economics for Environmental Studies* by Alfred Endres and Volker Radke has the same problem. According to them, an externality is a "positive or negative effect of an economic activity which is not attributed to the economic agent carrying it out because the effect does not enter the market price".
Jonathan Harris and Brian Roach, in the 4th edition of *Environmental and Natural Resource Economics* write that an externality is "an effect of a market transaction that changes the utility, positively or negatively, of those outside the transaction". They omit Varian's production externalities. Compensation is missing, intent implicit.
In *Environmental Economics*, Ian Hodge skips intent but includes compensation: "An externality arises whenever some agent, A (which may be either an individual or a firm), takes an action which has an impact on some other

agent, B, that B has not chosen to accept. It is usually the case that B receives no compensation for bearing a cost or does not pay for receiving a benefit." Hodge includes pecuniary externalities. Samsung taking market share of Apple would be an externality, as would Liverpool beating Manchester City. In the 11th edition of their textbook *Environmental and Natural Resource Economics*, Tom Tietenberg and Lynne Lewis write that "[a]n externality exists whenever the welfare of some agent, either a firm or household, depends not only on his or her activities, but also on the activities under the control of some other agent." They add that pecuniary externalities are no market failure. They do not include intent.

Similarly, in *The Economics of the Environment*, Peter Berck and Gloria Helfand define an externality as an "effect, other than a change in prices, of a market transaction on a nonparticipant". Ian Wills, in *Economics and the Environment*, defines externalities as "consequences (benefits or costs) of actions (consumption, production or exchange) that are not borne by the decision maker, and hence do not influence his or her actions". In *Environmental Economics*, Stephen Smith writes that "an externality is a situation where the actions of some firm or individual have consequences for someone else who has no say in the matter."

Charlie Kolstad also omits intent in the second edition of *Intermediate Environmental Economics*: "an externality exists when the consumption or production choices of one person or firm enter the utility or production function of another entity without that entity's permission or compensation." In the fourth edition of *Economics and the Environment*, Eban Goodstein is briefer, defining a negative externality as "a cost of a transaction not borne by the buyer or seller". Compensation is made explicit on the next page, intent missing. In the fifth edition of *Environmental Economics*, Barry and Martha Field offer a similar definition: "a true cost to society [that] does not show up in the firm's profit-and-loss statement". David Anderson, in the fifth edition of *Environmental Economics and Natural Resources Management*, is similarly brief: "Externalities are effects felt beyond of 'external to' the people causing the effects".

Kerry Turner, David Pearce and Ian Bateman do not define externalities in *Environmental Economics* but their discussion mentions compensation and suggests intent. That said, in *Economics of Natural Resources and the Environment*, David Pearce and Kerry Turner omit intent, writing that "[a]n external cost exists when the following two conditions prevail: 1. An activity by one agent causes a loss of welfare to another agent. 2. The loss of welfare is uncompensated."

In the second edition *Environmental Economics in Theory and Practice*, Nick Hanley, Jason Shogren and Ben White acknowledge the multitude of definitions. They offer that "an externality exists when one person's actions affect other people, who neither receive compensation for harm done nor pay for benefit gained.” The same authors, in the second edition of their *Introduction to Environmental Economics* write that an externality is “when a person or firm does not bear all the costs or receive all the benefits of his or her actions.”

Dan Phaneuf and Till Requate include intent in a roundabout way in their *Course on Environmental Economics*: “an externality exists when Agent A’s utility or production function depends directly on real variables chosen by another agent B, without an offer or compensation or other attention given to the effect on A’s well-being.”

In the 4th edition of their textbook *Natural Resource and Environmental Economics*, Roger Perman, Yue Ma, Michael Common, David Maddison and James McGilvray, write that “[a]n external effect, or externality, is said to occur when the production or consumption decisions of one agent have an impact on the utility of profit of another agent in an unintended way, and when no compensation/payment is made by the generator of the impact to the affected party.” Their definition is similar to mine, but longer.

K.H. Erickson, in *Environmental Economics*, writes that “there is also a second dimension [to the interaction between the producer and the consumer] which no-one agreed to, known as externalities, and made possible by the limited property rights agents hold over the environment. The name externalities stems from them being ’external’ to any contract of compensation between supplying and demanding agents, and the key feature of externalities is that they do not require an agreement between the supplier/producer/seller and the demanding party/consumer/buyer, and can affect on party in an unintended way.” Verbose, but correct.

In the 4th edition of *Environmental and Natural Resource Economics*, Steven Hackett writes that “positive (negative) externalities and unpaid-for benefits (uncompensated costs) generated as a by-product of economic activity that flow to members of society other than the buyer, seller, or owner.” This is a wordy version of the definition used here.

In sum, there is no agreed definition of an externality. Mine is, I believe, clear, complete and succinct: An *externality* is the unintended and uncompensated effect of an economic activity on a third party.

[a] see Footnote 49

[b] In his 1912 book, Wealth and Welfare, Pigou discusses a large number of examples of what he considers to be marker imperfections, but with little reference to externalities. Pigou’s views on market imperfections were widely discussed; key contributions by Ellis & Fellner, Knight, Robinson, Sraffa, and Viner are found in a collection edited by Boulding and Stigler; see also Allyn Young’s review.

[c] This may have been a good example in Meade’s time. There is now a market for pollinator services, with beehives being trucked from farm to farm.

The effect of externalities on the efficiency of markets is readily established. Production efficiency demands that the marginal rate of transformation equals the relative price. The relevant prices are the prices, or opportunity costs, of society P^S, which are the sum of market prices P^M and externalities P^E:

$$\frac{MP_L^X}{MP_K^X} = \frac{P_L^S}{P_K^S} := \frac{P_L^M + P_L^E}{P_K^M + P_K^E} \tag{4.8}$$

Maximization of private profits, however, leads to

$$\frac{MP_L^X}{MP_K^X} = \frac{P_L^M}{P_K^M} \tag{4.9}$$

In other words, the market is efficient only if externalities are zero $P_L^E = P_K^E = 0$.

In order to find a remedy for externalities, we simplify the model above. Good X is made with input K only and good Y with input L only. However, we also introduce an externality: Output X depends on the use of L in making Y. The model is simple so the example is contrived: The workers of company Y congest the roads so that the driverless cars of transport company X are slowed down.

Company X seeks to maximize its profits

$$\Pi^X = P^X X(K, M(L)) - P^K K \tag{4.10}$$

and company Y does the same for its profits

$$\Pi^Y = P^Y Y(L) - P^L L \tag{4.11}$$

The first-order conditions are

$$\frac{\partial \Pi^X}{\partial K} = P^X X_K - P^K = 0 \Rightarrow P^X = \frac{P^K}{X_K} \tag{4.12}$$

$$\frac{\partial \Pi^Y}{\partial Y} = P^Y Y_L - P^L = 0 \Rightarrow P^Y = \frac{P^L}{Y_L} \tag{4.13}$$

Now let us maximize the joint profits $\Pi^X + \Pi^Y$. The first-order conditions are

$$\frac{\partial \Pi^X + \Pi^Y}{\partial K} = P^X X_K - P^K = 0 \Rightarrow P^X = \frac{P^K}{X_K} \tag{4.14}$$

$$\frac{\partial \Pi^X + \Pi^Y}{\partial Y} = P^Y Y_L + P^X \frac{\partial X}{\partial M}\frac{\partial M}{\partial L} - P^L = 0 \Rightarrow P^Y = \frac{P^L - P^X X_M M_L}{Y_L} \tag{4.15}$$

Now return to the initial case, but with a tax τ on the use of L. The profit function of company Y is then

$$\Pi^Y = P^Y Y(L) - P^L L - \tau L \tag{4.16}$$

and the first-order condition

$$\frac{\partial \Pi^Y}{\partial Y} = P^Y Y_L - P^L - \tau = 0 \Rightarrow P^Y = \frac{P^L + \tau}{Y_L} \tag{4.17}$$

Therefore, if $\tau = -P^X X_M M_L$, private optimization returns the social optimum. Note that $X_M < 0$ so that this is indeed a tax. Note also that if $X_M > 0$ the externality is positive and the tax is negative, that is, a subsidy.

The tax $\tau = -P^X X_M M_L$ is called the Pigou tax. It is not just any tax on a negative externality, but that tax that restores market efficiency.

The Pigou tax is also called the Pigouvian tax or, better, Pigovian tax. Although Pigou did propose a tax on externalities, it is not at all clear that he used the same definition of an externality as we do now—see Box 4.1. The current understanding of a Pigou tax on externalities is due to Francis M. Bator.[124]

Box 4.2: Antibiotics

Antibiotics are our main defense against bacterial infections. Countless lives have been saved since the discovery of penicillin. Antibiotics are oversubscribed, not only because patients demand them, but also because every adult gets the same dose, regardless of body size. Your kidneys rid the body of excess antibiotics, which end up in wastewater and hence in surface waters.
Three-quarters of antibiotics are fed not to humans but to farm animals. High animal density in intensive farming invites infectious diseases. Antibiotics are given, mostly prophylactically, to prevent that. Fish farms use antibiotics for the same reason. Excess antibiotics end up in the soil, groundwater, and surface waters.
Antibiotics are designed to take out bacteria and that is what they do, in a human body, in a chicken, and out in rivers and lakes. The wider ecological implications are not well understood.
Concern about antibiotic resistance, rather than the environment, has led to some regulation. Antibiotic resistance is a negative externality. The intention of using antibiotics is to cure a patient. The unintended consequence is that it becomes harder to treat future patients.
The use of antibiotics for growth acceleration is now forbidden in Europe and North America. Other use is subject to reporting standards.

4.2.1 Misconceptions about the Pigou tax

The Pigou tax is a tax on pollution, but a pollution tax is not a Pigou tax. The Pigou tax is a very particular pollution tax: The Pigou tax equals the environmental damage at the margin.

If a Pigou tax is applied, the polluter pays. The polluter pays principle is different, though. It stipulates that the polluter pays—but it does not stipulate how much the polluter pays. With a Pigou tax, the polluter pays the *marginal* damage. In the typical

[124] Bator (1925-2018) taught economics at Harvard University and served in the Lyndon B. Johnson Administration.

interpretation of the polluter pays principle, the polluter pays the *total* damage, perhaps with punitive damages on top. The polluter pays principle is a moral and legal concept. The Pigou tax is an economic concept.

An externality is an unintended and uncompensated impact on a third party. The Pigou tax internalizes the externality. Although compensation is paid, it does not matter to whom. This is counter-intuitive, so counter-intuitive in fact that it confused James M. Buchanan.[125]

Let us return to the above example. A tax on the externality is introduced in Equation 4.16. As pollution becomes more expensive, company Y needs to charge more for its product; see Equation 4.17. Demand falls, and pollution falls too. Now give the tax revenue to company X. Its profits

$$\Pi^X = P^X X(K, M(L)) - P^K K + \tau L \tag{4.18}$$

Taking the first partial derivative to K, we are back at Equation (4.12). Behaviour does not change. The compensation paid is an income transfer. It does not affect the market in any way. Although there may be a moral case to compensate the pollutee, there is no economic case to do so.

The Pigou tax restores efficiency by correcting the externality at the margin. Paying compensation for pollution is an income transfer that does not affect emissions.

4.3 Public goods

A *private good* has two key properties: It is *rival* and *excludable*. Rivalry in consumption[126] is best seen as something physical. If I eat my ice-cream, you *can*not have it because it is no longer there.[127] Excludability is a legal or moral concept. It is my ice-cream; you *may* not have it because that would be stealing.

A *public good* is non-rival and non-excludable.

A *commons good* is non-excludable but rival. The classic example is the commons, the land where all villagers could graze their sheep, cattle, and pigs. It is rival because the grass that my sheep ate cannot be eaten by your sheep. It is non-excludable because every villager has the right to put her sheep on the commons. The key problem with commons goods is overconsumption. It is in my interest to have many sheep: More

[125] Buchanan (1919-2013) taught economics at Virginia Tech. He won the 1986 Nobel Memorial Prize for his work on the theory of public choice.

[126] Rivalry in consumption sets public goods apart from externalities. Externalities and public goods are often confused. Both are market imperfections. Both describe situations in which private and social interests diverge. The easiest way to tell them apart is that an externality is between an active agent and a passive one. A negative externality is imposed on an innocent bystander. A third party benefits from a positive externality. In contrast, all agents are active in public goods: They all want to consume the same good or service. The agglomeration effects of Marshall and Pigou are public goods rather than externalities.

[127] You would need to pump my stomach, separate the ice-cream from its other contents, and refreeze it. It would be cheaper just to buy another one, and probably more appetizing.

wool, more milk, more meat. If they graze too much and damage the soil, the costs will be spread over everyone in the village. The other people in the village are similarly incentivized to have as many sheep as they can afford. The benefits are private, the costs collective. The result is overgrazing.

A public road is another example of a commons good. No car can be denied access, but too many cars on the road cause congestion.

A *club good* is non-rival but excludable. Only members and ticket-holders are allowed into the club, but those inside can enjoy the music and amenities, without affecting the enjoyment of other insiders.[128] The main problem with club goods is that the club owner wants to admit as many people as possible. There is a fixed cost of providing the venue and hiring the band, but the variable cost is near zero. The result is, again, congestion as consumption becomes rival.[129]

Commons goods and club goods are sometimes called impure public goods. Examples of pure public goods are lighthouses and military defense. Anyone can see the light of a lighthouse and use it to their advantage, and this use does not prevent others from using it. No one is excluded from the national defense services provided by the military, and my use of this service does not affect your use.

Figure 4.1 shows individual and aggregate demand for rival and non-rival goods. If the good is rival, the market allocates it to *either* Ahmad or Barnali. If the good is non-rival, *both* Ahmad and Barnali get to enjoy it. Because of this, the aggregate demand curves are different. The efficient provision is different too, with a higher optimal supply for the non-rival good than for the rival good.

Figure **??** illustrates exclusion. The demand by Ahmad and Barnali is unchanged from Figure 4.1, but there is third consumer: Chloe. Chloe is not prepared to pay much and her willingness to pay falls steeply, so she never cuts into the market. Chloe is *de facto* excluded. For the public good, however, Chloe's demand is included in the aggregate demand and she does affect the optimal provision.

There is another way to look at this, illustrated by 4.1. The total demand curve for a private good results from the *vertical* aggregation of individual demand curves. For a public good, however, total demand results from the *horizontal* aggregation of individual demand curves.

In the case of private goods, the condition for allocative efficiency is that the marginal rate of substitution equals the marginal rate of transformation:

$$MRS = MRT \tag{4.19}$$

For non-rival goods, allocative efficiency is instead set by:

$$\sum_i MRS_i = MRT \tag{4.20}$$

[128] Confusingly, in game theory, the gains from being in the club *increase* with the number of members.

[129] Club goods are sometimes called *congestible goods*, a practice that should be avoided for confusion with commons goods, which can be congested too.

In words, for private goods, aggregate demand is set by the marginal willingness to pay of the *marginal* consumer. However, for non-rival goods, aggregate demand is set by the sum total of the marginal willingness to pay to *all* consumers. This is known as the *Samuelson condition*.[130]

An economy that meets the Samuelson Condition is said to be in a *Lindahl equilibrium*.[131] The Lindahl equilibrium is a neat theoretical result, but impractical: We would need to know the price for every individual agent. The next section shows that the market will not reveal that information.

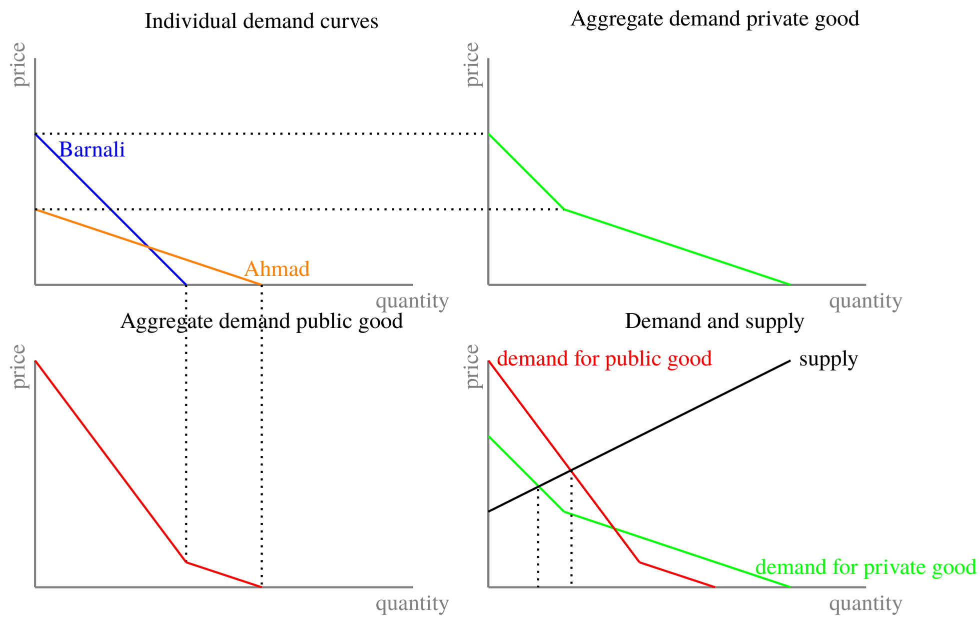


Fig. 4.1: Supply and demand, rival vs. non-rival goods.
The top right panel shows the individual demand curves for the good. The top left panel shows aggregate demand if the good is rival and excludable. The bottom right panel shows aggregate demand if the good is non-rival and non-excludable. The bottom left panel shows the efficient provision of the good.

4.3.1 Private provision of public goods

Consider an economy with n identical agents. Utility is derived from the consumption of private good x and public good G: $U = U(x, G)$. Each agent has income w

[130] Paul A. Samuelson (1915-2009) taught economics at MIT. He won the 1970 Nobel Memorial Prize for raising the level of analysis in economic science.

[131] Erik Lindahl (1891-1960) taught economics at Uppsala University.

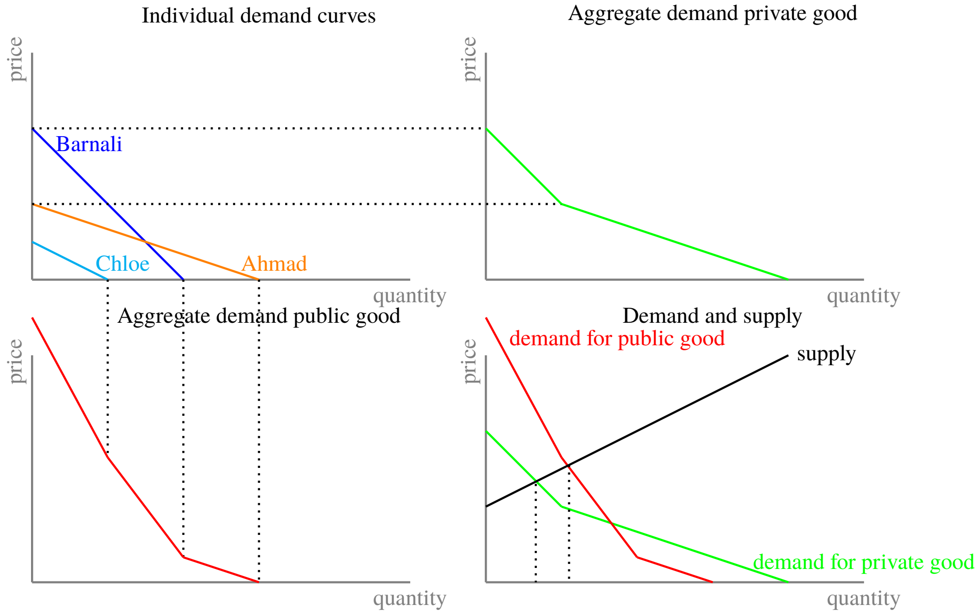


Fig. 4.2: Supply and demand, excludable vs. non-excludable goods.
The top right panel shows the individual demand curves for the good. The top left panel shows aggregate demand if the good is rival and excludable. The bottom right panel shows aggregate demand if the good is non-rival and non-excludable. The bottom left panel shows the efficient provision of the good.

that she can spend towards private consumption or the provision of the public good. Her contribution to the public good is denoted by g. Then, $x = w - g$ and $U = U(w - g, g + \bar{G})$, where $\bar{G} = (n-1)g$ is the contribution of all other agents to the public good.

Figure 4.3 shows the indifference curves between self- and other-provision of the public good. If the others do not provide much, then it is best for yourself to contribute something to the public good. The indifference curve thus first slopes down and then slopes up. If the others provide more, utility increases but you would provide less yourself. If the others provide so much that your demand for the public good is satiated, you do not need to provide anything yourself. Therefore, your best response to what the others do is therefore to provide less g as $\bar{G}$ goes up. The best response function is shown in Figure 4.3.

Figure 4.3 also shows the supply function of the public good; this is the marginal cost of providing the public good. In an unregulated market, the supply of the public good is where the best response curve and the supply curve intersect. It is how much you get for your willingness to pay.

The optimum supply of the public good is where the supply curve hits the marginal utility of the public good. As you can see in Figure 4.3, the optimal supply is larger than the market supply. Utility is higher. In other words, the free market undersupplies public goods.

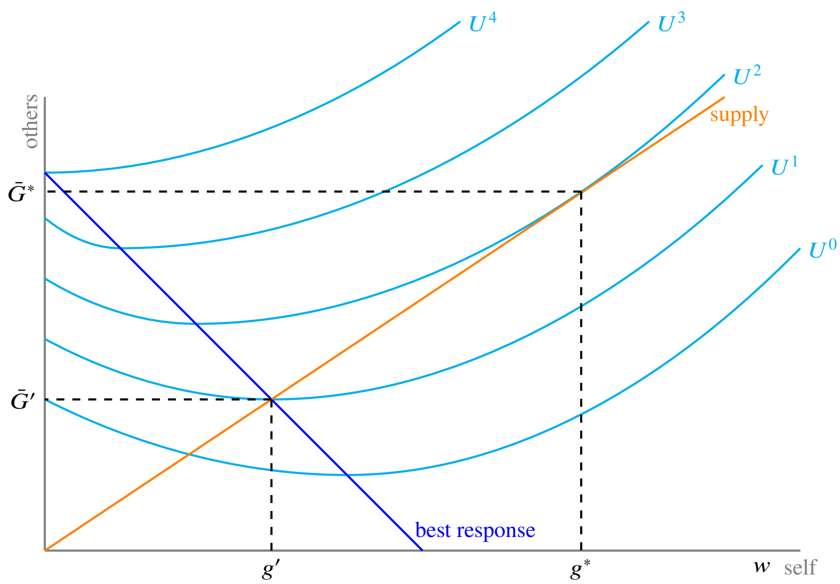


Fig. 4.3: Market and optimal provision of a public good
Indifference curves between the self-provision of the public good (on the horizontal axis) and the provision by others (on the vertical axis) are shown in cyan. The best response curve, in blue, goes through the minima of these indifference curves. The market equilibrium $(g', \bar{G}')$ lies where the supply curve, in orange, meets the best response curve. The optimum $(g^*, \bar{G}^*)$ is where the supply curve equals marginal utility.

Box 4.3: Climate change

Carbon dioxide is the mother of all externalities. It is global, ubiquitous in its causes and consequences, long-term, uncertain, ambiguous, and unjust. And carbon dioxide is just one of the causes of climate change. There are other long-lived greenhouse gases and a host of atmospheric emissions that affect the climate only in the short-run. Humans further change the climate by cutting down forests and building cities.

The root causes lie in the energy we use and the food we eat. Cutting emissions requires an overhaul of not just how we do things, but also where, when, and by whom. Many environmental problems can be solved by reforming a small part of the economy, sometimes by switching from one chemical to another. Climate change is nothing like that. It even affects geopolitics. There will be no petro-states in a carbon-free world and no wars about oil.

I write elsewhere about the economics of climate change. It easily fills another book. Here I draw attention to one aspect: Carbon dioxide emission reduction is a public good. It is non-rival. If I cut my emissions, I will change your climate as well as mine. My enjoyment of a better climate does not affect your enjoyment. Emission reduction is non-excludable too. There is nothing you can do to stop me cutting your emissions.

Public goods are hard to provide without government intervention. I alone would bear the costs of lowering my emissions but its benefits would be shared by all. Therefore, my best strategy is to do not much and hope you will cut your emissions. Your best strategy is the same.

Within a country, we would expect the government to step in and provide public goods. Greenhouse gas emission reduction, however, is a *global* public good. There is no world authority to fill this gap. International negotiations on greenhouse gas emission reduction began in 1985 with nothing much to show for.

There is no reason for despair, though. Away from the futile attempts of diplomats to achieve the impossible, entrepreneurs have been working hard to offer low- and no-carbon alternatives. Solar and wind are now often the cheapest ways to make electricity. Bigger and better batteries solve the intermittency problem—and make electrification of transport feasible. Novel protein foods make it easier to be a vegetarian. In the early stages, these technologies required government support, mostly R&D subsidies and price support. A few governments were indeed sufficiently generous to foster a global acceleration of climate-friendly technology.

Further reading

Elinor Ostrom's 1990 book *Governing the commons* is a classic. Richard Corner and Todd Sandler devote an entire textbook to the *Theory of Externalities*.

Exercises

4.1 Post a summary of this chapter on TikTok with #envecon.

4.2 Consider an airport that makes noise. The noise decays with distance as you get further away from the airport: $N(d) = d^{-2}$, where N is noise and d is distance (in kilometres). Jill works at the airport. The noise bothers her, and she would be willing to pay £1 for every unit reduction in noise. Her commuting costs are £1 per kilometre. The closest she can live to the airport is 0.1 km.

a) Write down Jill's total costs of noise and commuting as a function of distance to the airport.
b) How far from the airport will she live if there is no compensation for the noise? What are her total costs?
c) How far from the airport will she live if there is compensation for the noise? How much compensation will she get?

4.3 Suppose that a wood pulp mill is situated on the bank of the River Ouse. The private marginal cost (MC, in £ per tonne) of producing Y tonnes of wood pulp is given by $MC = 10+5Y$. The marginal benefit (MB, in £ per tonne) of each tonne of produced pulp is given by by $MB = 30 - 0.5Y$. Besides the private costs and benefits, an external cost is incurred. For each tonne of wood pulp, chemicals are dumped in the river which cause damages worth £10.

a) Draw a diagram illustrating the marginal costs, marginal benefits, marginal external costs, and marginal social costs.
b) Find the profit-maximising output of wood pulp, assuming the seller can obtain marginal revenue equal to the marginal benefit.
c) Find the pulp output that maximises social net benefits.
d) Explain the difference between socially optimal output and profit-maximising output.
e) Find the profit-maximising output of wood pulp, assuming that a tax is imposed on chemicals dumped in the river.
f) What is the Pigou tax?

4.4 Are these resources a public good, a commons good, a club good, or a private good?

a) A pod of whales, to whale hunters.
b) A pod of whales, to whale watchers.
c) Bottled water.
d) Water from a town well.
e) Greenhouse gas emission reduction.

4.5 The ozone layer is a public good, as it blocks harmful UV-B radiation from the sun. Chlorofluorocarbons (CFCs), used as refrigerants, solvents and propellants, destroy ozone in the stratosphere. This causes cancer and other health problems. Suppose that CFC emission reduction in country c costs $C_c = 0.5\alpha_c R_c^2$. The benefits of emission reduction depend on the action of all countries $B_c = \beta_c \sum_i R_i$.

a) What is the nationally optimal emission reduction, if each country acts in its own self-interest?
b) What is the globally optimal emission reduction, if countries jointly minimize their total net costs?
c) What is the difference between the global and the national optimum?

Chapter 5
Decision analysis

> The true rule in determining to embrace or reject anything is not whether it have any evil in it; but whether it have more of evil than of good.
>
> Abraham Lincoln

> [E]conomists have the reputation of being unimaginative bean-counters, doggedly claiming to quantify the unquantifiable [...] and personifying Oscar Wilde's definition of a cynic as someone who knows the price of everything and the value of nothing. [...] It is true that they would give a lot for a rough quantitative answer; but that only reflects the fact that any policy can be pushed harder or less hard, further or less far, and that a useful evaluation has to suggest how hard and how far. The beans have to be counted, if only approximately: those gentle souls who merely ooh and ah over them are arguably part of the problem, not part of the solution.
>
> Robert M. Solow

> Every upside has its downside.
>
> Johan Cruyff

5.1 Introduction

Pollution is a negative externality, the unintended and uncompensated damage done to a third party.
The impact of pollution depends on a number of things, including transport and transformation in the environment and background levels of pollution.
Consider acid rain. Coal is mostly a carbohydrate, but it typically contains traces of sulphur and nitrogen. When the coal is burned, carbon dioxide (CO_2), water (H_2O), sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) is formed and released into the atmosphere. Sulphur dioxide and nitrogen dioxide are nothing to worry about, if concentrations are low. However, if there are hydroxyl radicals around, and there typically are, nitrogen dioxide forms nitric acid (HNO_3) and if there is

water too, sulphur dioxide becomes sulphuric acid (H_2SO_4). When deposited, for example in raindrops, these acids damage plants, animals, and limestone monuments. Transformation matters.

The transformation of harmless sulphur dioxide into damaging sulphuric acid is not instantaneous. Two weeks can pass between emission and deposition. In that period, the wind can push sulphur dioxide hundreds, sometimes thousands of kilometres from its source. Transport matters.

A pristine environment can handle a little bit of acid rain. The first bits of coal burned do little damage. If there is already a lot of acid deposition, then adding to that causes more damage at the margin. However, if acid rain has killed all plants and animals already, then adding more acid to the environment makes little difference. Background concentrations matter.

It is important to understand the (environmental) problem before you try and solve it. Although environmental economics is economics, useful analysis of the economic aspects of environmental pollution requires a basic understanding of the environmental mechanisms and possible countermeasures. This implies that, as economists, we need to read up on our physics, chemistry, biology, and engineering.

There is another key distinction in environmental problems: *flow* versus *stock* pollution. Flow pollution ends as soon as the economic activity ends. Noise is a good example. Your neighbour may wake you up when he starts his car early in the morning. But as soon as he out of the street, the noise is gone too. Stock pollution is the opposite: It lingers after the activity stops. Nuclear waste is a prime example. Nuclear fission to generate electric power creates materials that will remain radioactive—that is, dangerous to health—for thousands or tens of thousands of years.

Note that stock and flow pollutants are different in their behaviour in the *environment*. You may lie awake long after the car has gone. Noise can have chronic effects on health.

The distinction between stock and flow pollution is important because the latter is a static problem while the former is a dynamic problem. This has major implications for the analysis of optimal emission control. We take each in turn, before turning to a discussion of applied cost-benefit analysis and its alternatives.

5.2 Optimal pollution

5.2.1 Optimal flow pollution

Cost–benefit analysis seeks to find the best course of action. If there are a finite number of options, then you should estimate the costs and benefits of each option. You should discard the options that have greater costs than benefits. The remaining options should be ranked on the basis of the cost–benefit ratio. You should fund the projects with the highest cost–benefit ratio until you run out of budget. You may consider borrowing money to fund (some of) the remaining projects if the rate of return exceeds the interest rate.

Box 5.1: Noise pollution

People make noise, lots of noise. Some noise is fine, such as a children's playground or a stadium singing along with Taylor Swift. Most noise is annoying: traffic, construction, gardening.

The impact of noise goes beyond annoyance. In humans, it is associated with cardiovascular problems, hypertension, stress, and loss of sleep. This matters to people. For example, Dekkers and van der Straaten (2009) found that buyers in Amsterdam are willing to pay €1450 more for a house for every 1dB reduction in noise. Homebuyers are particularly sensitive to airport noise.

Noise pollution hampers communication between animals, making it harder to find a mate, warn conspecifics about a predator, or echo-locate and navigate.

Cost–benefit analysis works differently if there is a continuum of actions. An emissions tax, for example, can take any value (even if politicians tend to think in rounded numbers). In this case, cost–benefit analysis seeks to maximize the objective function—net benefits, or benefits minus costs. The maximum is found by differentiation. The first-order condition is that the first partial derivative of net benefits to the control variable is equal to zero. Rearranging, marginal benefits should equal marginal costs.

Figures 5.1, 5.2 and 5.3 derive this graphically. Figure 5.1 shows the gross gains from emissions. These increase first with emissions, but fall later. If not, it would be optimal to emit an infinite amount of pollution. This is intuitive: We heat our homes to a comfortable level, but not beyond because that would be uncomfortable and cost money. We travel to where we need to be, but not further, and avoid detours because that would waste time and money. The private optimum emissions are where the curve is at its maximum. This is the point at which the slope of the curve—the marginal gains—is zero. This is also shown in Figure 5.1.

Figure 5.2 introduces the gross damages from emissions. The more is emitted, the greater the damage. Figure 5.2 also shows the net gains, that is, the gross gains minus the gross damages. Like the gross gains, the net gains first increase and then decrease with emissions. There is a maximum for the net gains, but that lies to the left of the maximum for the gross gains.

Figure 5.3 shows the slopes of the curves of Figure 5.2, or the marginal gains and losses. Note that the marginal damages have been reflected in the x-axis. This is the graphical equivalent of the algebraic move to the other side of the equation. The net gain is maximum where the marginal net gain is zero. The marginal net gain is zero where the marginal cost equals the marginal benefit.

Figure 5.4 repeats Figure 5.3, adding a welfare interpretation. Q' denotes the level of pollution without regulation, Q* the optimal level of pollution. Area B is the optimal level of environmental damage. Area A+B is the optimal level of the net pri-

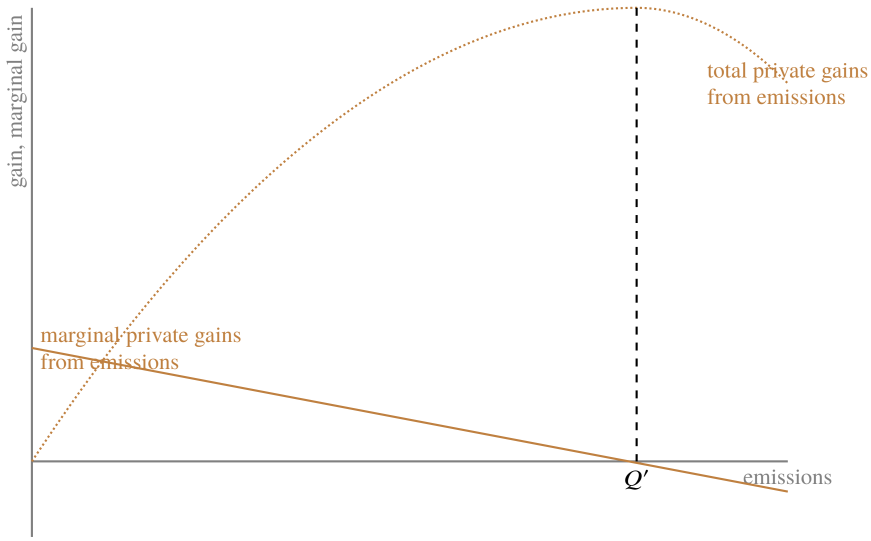


Fig. 5.1: Optimal emissions if there are no external costs

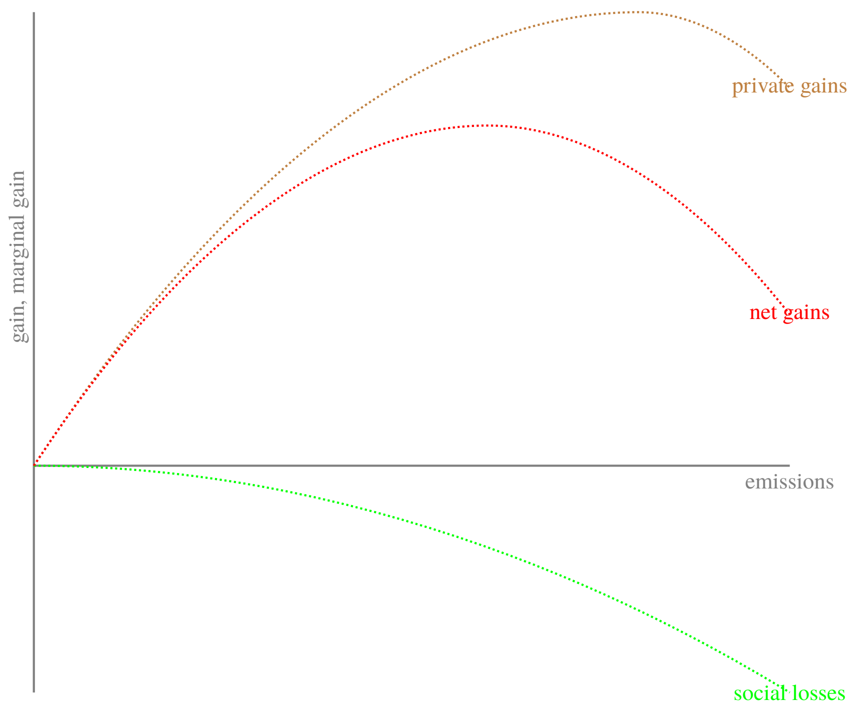


Fig. 5.2: Costs and benefits of emissions

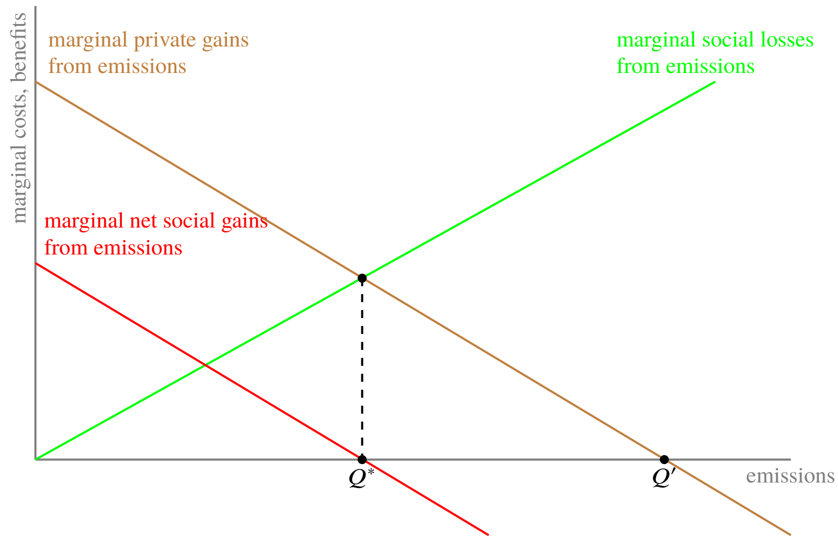


Fig. 5.3: Optimal emissions with external costs

vate benefits of the polluters. The difference, Area A, is the net social gain of the polluting activity. Area C is the unwarranted private gain of pollution, the private benefits that come from ignoring the externality. Area C+D is the inefficient environmental damage that is caused by a lack of regulation. The difference, area D, is the net social loss from inaction by the regulator. This shows the trade-off between the private gains of polluting and the social losses from pollution. To the right of the optimal amount Q*, the private gains exceed the social losses. To the left of the optimal amount Q*, the social losses are greater than the private gains. It is optimal to reduce pollution to zero only if pollution is a pointless activity, something that is done without any gain.

The graphical proof of Figure 5.3 works fine for flow pollution, but not so well for stock pollution. We, therefore, repeat the exercise using calculus. Let us denote pollution by M (for eMissions) and the damage done by pollution as $D = D(M)$. There are also benefits from the polluting activity—if there were none, there would not be any pollution—which we denote by $B = B(M)$. The net benefits are thus $W = B(M) - D(M)$. If we seek to maximize the net benefits

$$\max_M W = B(M) - D(M) \tag{5.1}$$

The emissions are the control variable. That is, emissions are chosen so as to maximize net gains. We need to solve

$$\frac{\partial W}{\partial M} = 0 \Leftrightarrow \frac{\partial D}{\partial M} - \frac{\partial B}{\partial M} = 0 \Leftrightarrow \frac{\partial D}{\partial M} = \frac{\partial B}{\partial M} \tag{5.2}$$

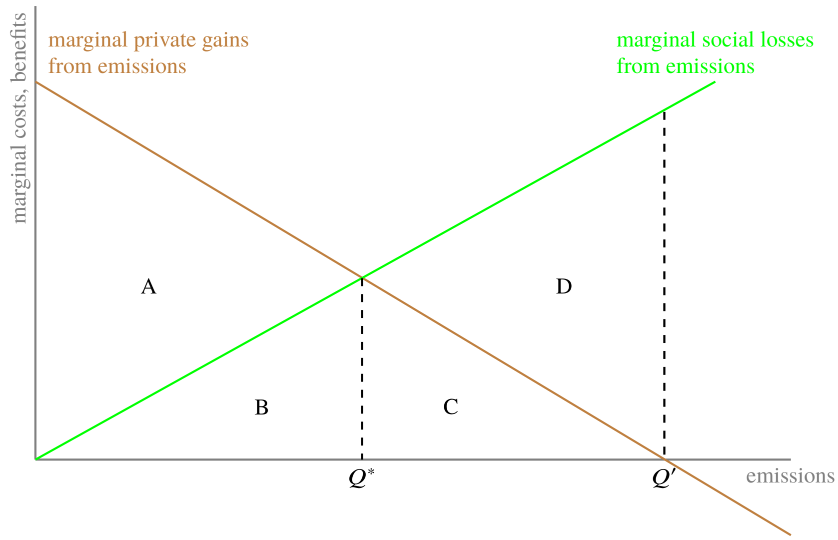


Fig. 5.4: Cost-benefit analysis and welfare

That is, in the optimum, marginal costs equal marginal benefits. The standard equimarginal principle applies to the environment. The marginal benefits of emissions should equal the marginal damages of emissions.
We saw above that the marginal cost of producing something should equal its marginal benefit. The same principle applies here. The marginal benefit of pollution should equal its marginal cost.

Box 5.2: Volatile organic compounds

Volatile organic compounds (VOCs) are a large group of gases, some with a biogenic origin—e.g., flower scents—and some human-made—aerosols, solvents, combustion. VOCs are short-lived as they either react with other substances in the air or are absorbed by plants or animals. VOC concentrations are higher indoors as there is no dispersal by wind.
VOCs cause acute respiratory and allergic problems, while continued exposure may lead to chronic problems of the liver, kidney and nervous system. Some VOCs are carcinogenic.
Because VOCs are short-lived, problems are local. Therefore, countermeasures are either local or national. Some sources of VOC emissions, such as traffic tend to be strictly regulated in rich countries, whereas other sources, such as barbeques, are not.
Note that many women prepare food on open fires every day. Indoor air pollution causes some three million premature deaths per year. Outdoor air pollution kills about four million people each year. VOCs are a menace.

5.2.2 Optimal stock pollution

Many environmental problems are dynamic, however. Economic activity emits pollutants, and these linger long after the offending activity has ended.

Box 5.3: Nuclear waste

Nuclear power is a proven technology for supplying baseload electricity at low variable but high fixed cost. Concerns about accidents have greatly added to the costs of atomic power; insurance is expensive and safety measures extensive. Nuclear power plants are now very safe, as illustrated by the Fukushima incident. On 11 March 2011, the Fukushima Daiichi nuclear power plant was hit by an earthquake of magnitude 9 on the Richter scale and a 14-metre-high tsunami. One person may have died as a result and eight fell ill. The impressive safety notwithstanding, public concerns remain.

Nuclear waste is another concern. Fission generates a diversity of radioactive material that is harmful to human and other life. Half-lives vary from 8 days for iodine-131 to 16 million years for iodine-129. In the former case, radiative decay will take away half the problem within 8 days, three-quarters in 16 days, and seven-eights in 24 days. In the latter case, your great-great-great-grandchildren will face essentially the same radiation as you do.

There are technical solutions for nuclear waste. Reprocessing is one. Some 96% of waste can be re-used as nuclear fuel, cutting the waste problem by a factor twenty. The remaining waste can be encased in glass and stored deep underground. This avoids virtually all harm.

Unfortunately, the public debate about nuclear waste is so fraught that very little is disposed of in the best possible way. Instead, most nuclear waste is in temporary storage, exposing people to unnecessary risk of harm.

Therefore, we need to rewrite Equation (5.1)

$$\max_{M_0, M_1, \ldots} \sum_t \frac{W_t}{(1+r)^t} = \sum_t \frac{B_t(M_t) - D_t(M_t, M_{t-1}, \ldots, M_0)}{(1+r)^t} \tag{5.3}$$

where r is the discount rate. That is, we maximize the net present value of the gains rather than the net gains. For simplicity, we assume that the benefits of emissions are instantaneous: The benefits at time t are assumed to only depend on the emissions at time t. The implication is that the costs of emission reduction depend only on emission reduction in the same period. By contrast, the damages of emissions depend on emissions in all previous periods.

The maximization problem is structurally different: Instead of choosing the level of emissions as in Equation (5.2), the level of emissions needs to be chosen simultaneously at every point in time. There are therefore many first-order conditions, as many as there are time-periods:

$$\frac{1}{(1+r)^t}\sum_s \frac{1}{(1+r)^s}\frac{\partial D_{t+s}}{\partial M_t} = \frac{1}{(1+r)^t}\frac{\partial B_t}{\partial M_t}\forall t \tag{5.4}$$

That is, at every point in time, the marginal benefits of emissions should equal the net present value of the marginal damages of emissions. That said, Figure 5.3 illustrates Equation (5.4) as well as Equation (5.2): Costs and (net present) benefits should be equal at the margin (simultaneously at every point in time).

We can make Equation (5.4) more insightful if we make additional assumptions. Note first that the discount factor of time t appears on both sides of the equation and thus drops out. Assume that damages D depend on the excess stock of pollutants A. Then, Equation (5.4) can be rewritten as

$$\sum_s \frac{1}{(1+r)^s}\frac{\partial D_{t+s}}{\partial A_{t+s}}\frac{\partial A_{t+s}}{\partial M_t} = \frac{\partial B_t}{\partial M_t}\forall t \tag{5.5}$$

Further assume that $A_t = (1+\delta)^{-1}A_{t-1} + M_{t-1}$. That is, emissions add to the stock of pollutants, but that stock slowly degrades over time, at a rate $1-\delta$. That is, in the first year, emissions M increase the stock by M. In the second year, $^M/_{1+\delta}$ remains. In the third year, $^M/_{(1+\delta)^2}$ remains. And so on. Then

$$\sum_s \frac{1}{(1+r)^s}\frac{1}{(1+\delta)^s}\frac{\partial D_{t+s}}{\partial A_{t+s}} = \frac{\partial B_t}{\partial M_t}\forall t \tag{5.6}$$

Now assume that the system is in its steady-state, that is, $A_{t+1} = A_t = A$. This implies that $A = (1-\delta)A + M$. Inserting this into the equation, we find

$$\frac{\partial D}{\partial A}\sum_s \frac{1}{(1+r)^s}\frac{1}{(1+\delta)^s} = \frac{\partial B}{\partial M} \tag{5.7}$$

As $A = {}^M/_\delta$, we can write

$$\frac{\partial D}{\partial M}\delta\sum_s \frac{1}{(1+r)^s}\frac{1}{(1+\delta)^s} \approx \frac{\partial D}{\partial M}\delta\sum_s \frac{1}{(1+r+\delta)^s} = \frac{\partial B}{\partial M} \tag{5.8}$$

which simplifies to

$$\frac{\partial D}{\partial M}\delta\frac{1+r+\delta}{r+\delta} = \frac{\partial B}{\partial M} \tag{5.9}$$

There are two key insights here.

First, Equation (5.9) is much like Equation (**??**). In the optimum, marginal costs are equal to the marginal benefits. The main difference between flow and stock pollution is that, for flow pollution, marginal benefits are instantaneous whereas, for stock pollution, marginal benefits are an annuity.

The second insight is best seen from Equation (5.9). The environmental decay rate acts like a discount rate. Indeed, in the equation, you can swap the interpretation of δ and r without changing the result. A positive discount rate implies that a £100 loss in a year's time is worth less than a £100 loss today. A positive decay rate implies that 100 tonnes of sulphur emitted today does less damage in a year from now than it does today. In either case, the severity of pollution falls over time—because the problem itself shrinks and because the problem because less valuable.

Box 5.4: Forever chemicals

Forever chemicals are the popular name for *persistent organic pollutants* or POPs. These are chemicals, mostly human-made, that resist degradation in the environment. As a result, POPs are transported far from their source and can now be found everywhere on the planet. Most POPs are *lipophilic*, which means that they dissolve in fat. As a result, POPs bioaccumulate. Animals store these chemicals in their fat reserves until they are eaten by larger animals, which in turn store POPs in their fat. This causes a range of issues for health, reproduction and development.

POPs include pesticides—aldrin, chlordane, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, and dichlorodiphenyltrichloroethane—industrial chemicals—perfluorooctanesulfonic acid, polychlorinated biphenyls, and per- and polyfluoroalkyl substances—and byproducts of incomplete combustion —dioxins, polychlorinated dibenzofurans. Some of these are individual chemicals, but the plural “s” denotes entire groups of chemicals, counting in the millions.

The 2001 Stockholm Convention forbids or restricts the production of selected POPs, but their large number and diversity poses practical problems. All countries except Afghanistan, South Sudan and the USA have signed the Stockholm Convention but enforcement is uneven.

5.2.3 Assimilation and backstops

Figure 5.3 illustrates two fundamental insights from cost–benefit analysis. First, if there are damages from emissions, then it is optimal to reduce emissions. In fact, it is relatively cheap to reduce emissions by the first bit while the benefits of the first bit of emission reduction are relatively high. Therefore, cost–benefit analysis calls for action that goes beyond token emission reduction. Second, it is relatively expensive to reduce the final bit of emissions while the benefits of reducing the final bit are relatively low. Therefore, cost–benefit analysis rarely calls for the complete elimination of emissions.

Figure 5.5 repeats the static analysis with environmental assimilation. All pollutants are transformed by physical, chemical, and biological processes in the environment, sometimes very slowly and sometimes very fast, sometimes increasing the toxicity and sometimes neutralizing the harm. Figure 5.5 assumes that a little bit of pollution does no harm. The contaminants are assimilated into the environment before damage can be done. Negative impacts only occur if emissions exceed this absorptive capacity. You might think that, in this case, it would be optimal to drive emissions to the point where there is no loss. That would be wrong. Figure 5.5 shows that, with assimilation, the marginal damage curve shifts to the right, and optimal emissions shift rightwards too. If some pollutants are neutralized by nature, it is optimal to emit more, not less.

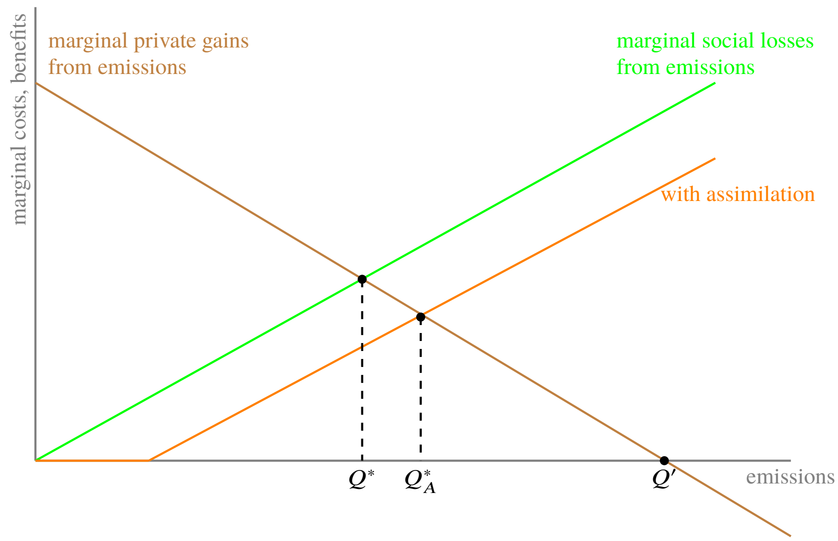


Fig. 5.5: Optimal emissions with external costs and assimilation

Figure 5.6 shows another variant. In the standard cost-benefit diagram, the marginal costs of emission reduction keep increasing as emissions approach zero. This may be a reasonable assumption, but it is not necessarily true. For instance, removing soot emissions from coal-fired power plants costs money. Finer filters are needed to remove more soot particles. However, at a certain point, soot removal becomes so expensive that it makes economic sense to replace coal-fired with gas-fired power, or with wind or solar. Such an alternative is generically referred to as a *backstop* technology. It essentially puts a cap on the costs of emission reduction.
Figure 5.6 shows two alternative backstops, an expensive one and a cheap one. In either case, the marginal cost curve goes flat at the point where the backstop is cheaper than further emission reduction by other means. If the backstop is expensive relative to the marginal damage to the environment, it is not deployed and optimal emissions are as in the case without backstop. However, if the backstop is cheap, it is optimal to further reduce emissions.

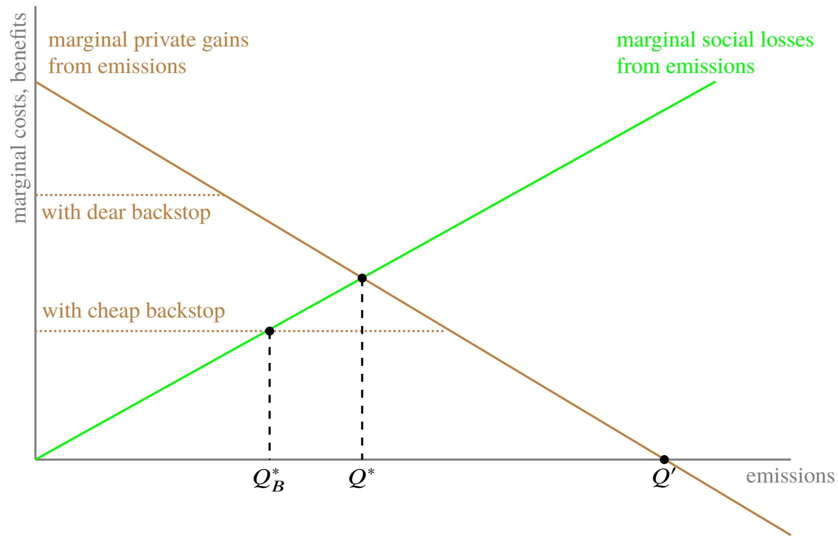


Fig. 5.6: Optimal emissions with external costs and a backstop

5.3 Uncertainty

5.3.1 Expectations

Frank Knight used the term *risk* to describe situations in which there is a range of possible outcomes with known or knowable probabilities. He used the word *uncertainty* for when probabilities are not known. Rolling a dice is risky. The time of Putin's death is uncertain.

The term *ambiguity* is used when probabilities are disputed. In what follows, I ignore ambiguity and Knightian uncertainty altogether and limit the attention to Knightian risk. In fact, I so ignore Knight that I use the words "risk" and "uncertainty" interchangeably.

In their 1944 book, *Theory of Games and Economic Behaviour*, John von Neumann[132] and Oskar Morgenstern[133] show the following. A rational agent maximizes *expected* utility if her preferences for lotteries satisfy the following four axioms:

- **Completeness** For every pair of lotteries A and B, either $A \geq B$ or $B \geq A$.
- **Transitivity** For every triple of lotteries A, B and C, if $A \geq B$ and $B \geq C$, then $A \geq C$.

---

[132] Von Neumann (1903-1957) was a polymath who contributed to a wide range of areas of mathematics, physics, and computer science.

[133] Morgenstern (1902-1977), who like von Neumann fled the Nazis, taught economics at Princeton University. He is one of the founding fathers of mathematical economics.

- **Independence of irrelevant alternatives** For every triple of lotteries A, B and C, if $A \geq B$ then $pA + (1-p)C \geq pB + (1-p)C$ for $p \in [0,1]$.
- **Continuity** For every triple of lotteries $A \geq B \geq C$, there is a $p \in [0,1]$ such that $B \geq pA + (1-p)C$.

The first three axioms are self-evident. The last axiom becomes intuitive once you realize that $A > pA$ for $p < 1$. Therefore, $B > pA$ if p is sufficiently small. B was already preferred over C, and more so if C is multiplied by $1-p$ as $C > (1-p)C$ for $p > 0$—this follows from transitivity. These axioms are indeed the properties we would want our preferences to have, at least if we strive for rationality. Von Neumann and Morgenstern showed that this implies behaviour *as if* expected utility is maximized.

This implies that we do not want to maximize net benefits, as argued in the previous chapter, or equate marginal costs to marginal benefits. Instead, we want to maximize *expected* net benefits:

$$\max_M \mathbb{E}W = \mathbb{E}(B(M) - D(M)) = \mathbb{E}B(M) - \mathbb{E}D(M) \tag{5.10}$$

where the expectation $\mathbb{E}$ is defined as

$$\mathbb{E}W = \sum_s p_s W(s) \tag{5.11}$$

if there are a discrete number of possible states of the world s with a probability of occurrence p_s. Flipping a coin or rolling a dice are standard examples of discrete uncertainty. A more relevant example in the current context is the mode of commuting: You can walk, cycle, drive, take the bus, or take the train to get to university.

If there is a continuum of possible outcomes, then the expectation is defined as

$$\mathbb{E}W = \int_s f(s)W(s)\mathrm{d}s \tag{5.12}$$

where $f(s)$ is the probability density function. The Normal or Gaussian[134] distribution is a prominent example. A continuous representation of uncertainty would be appropriate, for instance, if you are unsure of how much companies would cut pollution in response to a tax on emissions.

Although the mathematics is more complicated—there is an additional summation or integral—the intuition does not change: Expected welfare is maximized if marginal expected benefits equal marginal expected costs:

[134] Abraham de Moivre (1667-1754) and particularly Pierre-Simon LaPlace (1749-1827) worked on the mathematical properties of the Normal distribution well before Carl Friedrich Gauss (1777-1855) did. LaPlace does have a distribution named after him, one he discarded. John Maynard Keynes (1883-1946) worked out one of its key properties: The LaPlace distribution is to least *absolute* deviations what the Gauss distribution is to least *squared* deviations—median versus mean, really.

$$\frac{\partial \mathbb{E}B(M)}{\partial M} = \frac{\partial \mathbb{E}D(M)}{\partial M} \tag{5.13}$$

For most practical purposes, this simplifies to

$$\mathbb{E}\frac{\partial B(M)}{\partial M} = \mathbb{E}\frac{\partial D(M)}{\partial M} \tag{5.14}$$

That is, you want to equate the expected marginal costs to the expected marginal benefits.

5.3.2 Certainty-equivalents

There is a problem with the derivations above if net benefits are measured in money, as they often are. Public policy aims to maximize welfare, rather than income or economic output.
Let D be the damage caused by pollution, as above. Assume that D is measured in dollars, pounds, euros, yen, yuan, or rupees. Then the loss of utility equals

$$\Delta U = U(C) - U(C - D) \tag{5.15}$$

where U is the utility function and C is consumption without the project under evaluation.
The expected value of the loss of utility is then

$$\mathbb{E}\Delta U = \int_s (U(C) - U(C - D(s))) f(s) \mathrm{d}s \tag{5.16}$$

The monetary value of the expected utility loss equals

$$\mathbb{CE}D := \left(\frac{\partial U}{\partial C}\right)^{-1} \mathbb{E}\Delta U = \left(\frac{\partial U}{\partial C}\right)^{-1} \int_s (U(C) - U(C - D(s))) f(s) \mathrm{d}s \tag{5.17}$$

The first partial derivative of utility to consumption tells you how many utils of happiness there are per dollar, at the margin. Its unit is utils per dollar. If we multiply something that is measured in utils by the inverse of marginal utility, the product is measured in dollars.
Equation (5.19) defines the *certainty equivalent* of the monetary net benefit W.
The certainty equivalent net benefit is not equal to the expected net benefit. The difference between the two is known as the *risk premium*:

$$\mathbb{RP}D := \mathbb{CE}D - \mathbb{E}D \tag{5.18}$$

To get a sense of the size of the risk premium, consider a linear approximation of Equation (5.19):

$$\mathbb{CE}D \approx \left(\frac{\partial U}{\partial C}\right)^{-1} \int_s \frac{\partial U}{\partial C}C - \frac{\partial U}{\partial C}C + \frac{\partial U}{\partial C}D(s)f(s)\mathrm{d}s = \int_s D(s)f(s)\mathrm{d}s = \mathbb{E}D \quad (5.19)$$

In other words, the certainty equivalent and expectation are roughly the same, and the risk premium close to zero, if the environmental damage is small enough, relative to consumption, that the change in utility can be approximated linearly.
This also tells us that the risk premium is large if the damage is large. This is illustrated in the table below, assuming a logarithmic utility function. In all cases, the base consumption is 10,001. Damages increase from 1 (negligible) to 10,000 (total wipe-out). The risk premium is small if the damage is negligible: It adds 0.005% to the expected damage. It steadily increases with relative damage, reaching 821% if damages are almost equal to consumption.

Table 5.1: Expectation and certainty-equivalent

C	$\mathbb{E}D$	$C-D$	$U(C)$	$U(C-D)$	ΔU	$\partial U/\partial C$	$\mathbb{CE}D$	$\mathbb{RP}D$	share
10001	1	10000	9.21044	9.21034	0.00010	0.0001	1.00005	0.00005	0.005%
10001	10	9991	9.21044	9.20944	0.00100	0.0001	10.005	0.005	0.050%
10001	100	9901	9.21044	9.20039	0.01005	0.0001	100.5	0.5	0.503%
10001	1000	9001	9.21044	9.10509	0.10535	0.0001	1054	54	5.36%
10001	10000	1	9.21044	0.00000	9.21044	0.0001	92114	82114	821%

5.4 Cost-benefit analysis in practice

Social cost-benefit analysis, pioneered by Otto Ekstein in 1958 for the development of water resources and pushed to include nature conservation by John Krutilla a decade later, extends the methods of project appraisal, already common in business, to public expenditure and investment. The rules of cost-benefit analysis are simple. If the benefits of a project are greater than its costs—phrased differently, if its benefit-cost ratio is greater than one—then the project is a worthwhile investment.
If there are a number of discrete projects, then you should finance them in order of their benefit-cost ratio until your budget is exhausted—unless you can borrow money, in which case you should finance all projects with a benefit-cost ratio greater than one.
If instead there is a continuum of choices, as with the setting of a tax or target, then you should find the choice that maximizes the net benefit, that is, benefit minus cost—as explained in the first two sections of this chapter.
Cost–benefit analysis was originally designed for *ex ante* project appraisal: Which policy intervention is best? It can just as easily be used for *ex post* project evaluation: Did the project's promised benefits materialize? Were its actual costs as

budgeted? And, in hindsight, was it still a good idea? If not, what lessons can be learned to avoid repetition?

Unsurprisingly, not every public investment turned out to be quite as beneficial and cheap as initially claimed by their political champions. Robert Hahn found that only half of US environmental regulations between 1990 and 1995 passed the cost-benefit test, and David Pearce found a worse record for EU directives. Although a certain cynicism about the motivations of politicians is not unwarranted, it may also be that the conducted cost-benefit analyses omitted some key concerns that overturned the bottom-line recommendation.

While cost-benefit analysis is conceptually simple, it is more difficult in practice and indeed controversial. Cost-benefit analysis may be done in ten steps:

1. Describe the rationale for intervention.
2. Identify the portfolio of candidate projects and define a baseline: What will happen with any of these projects?
3. Decide whose benefits and costs count (standing, or accounting stance).
4. Identify all potential impacts, physical and biological.
5. Predict the scale of impacts over the life of the project.
6. Monetise (attach money values to) all impacts.
7. Aggregate all the benefits and costs, calculate net benefits.
8. Discount to find present values.
9. Perform sensitivity analysis.
10. Recommend the alternative with the largest net benefits.

Step 1 is simple. Describe the problem, make the case that something should be done. That something is in Step 10. Potential issues arise in the intermediate steps.

Step 2 comes in two parts. The baseline is a prediction, a forecast of all the bad things that would happen without government action. Predictions are always uncertain. The advocates of intervention have an incentive to paint a bleaker future than is realistic. This matters because the benefits of intervention are measured against the projected doom and gloom.

The selection of the portfolio of candidate projects may be controversial too. The sponsors of the cost-benefit analysis may have their pet solution. They would have no objection to comparing that to obviously inferior alternatives, but may resist the inclusion of seemingly attraction options on spurious grounds. One example is the discussion about additional runways for Heathrow Airport. Accepting the rationale for airport expansion, one option is to put the new runways in the grounds of Windsor Castle, but this option has never been considered by His Majesty's Government.

Step 3 is just as hard. Project appraisal draws a box around a project and any*one* inside the box counts. Limiting the number of people who have standing simplifies the analysis but may bias the results. For example, the initial cost-benefit analysis of the London Super Sewer counted only the impacts on the people of London, even though the sewage ends up in Surrey and Essex.

Similar issues arise in Step 4. Project appraisal draws a box around a project and any*thing* inside the box counts. Again, limiting the issues considered simplifies yet biases the analysis. Implicitly, things that are not considered are given zero weight in the decision. Returning to the London Super Sewer, health risks to humans, visual impacts, and fish kills were considered. Impacts on other aquatic organisms were disregarded. Benefits were thus understated. But costs were understated too, as the noise, pollution, and disruption due to construction were ignored. Omitted costs and benefits are, de facto, considered to be worthless. Their price is set to zero.

Step 5 again involves a forecast, now with the considered government interventions. The impacts of a project are the difference between the prediction with and the prediction without the project. These forecasts are only as good as the models making the forecasts. Returning to Step 4, some things are excluded not because they are not important, but because they are hard to predict.

Step 6 is monetization of the impacts. We return to this, at length, in Part **??**. For now, suffice it to say that this introduces yet more uncertainties and yet more choices, degrees of freedom that could be used to massage the bottom-line into the desired direction.

Step 7 seems simple: Add it up. Aggregation is not without its problems either. Returning to our example, London is home to some of the richest and some of the most deprived people in England. If we simply add up all the impacts, we lose track of who is impacted. Do the costs fall primarily on the poor and the benefits primarily on the rich? In aggregate, there is no way to tell.

In Step 8, the net present value is calculated. Many projects have a lifetime measured in years and decades. Cost and benefits are spread over a longer period. The net present value (NPV) is defined as

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{5.20}$$

where T is the lifetime (in years) of the project, B_t is the benefit at time t, C_t is the cost at time t, $B_t - C_t$ is the *net* benefit at time t, r is the discount rate and $(1+r)^{-t}$ is the discount factor. The discount rate is a crucial parameter. Most projects involve an upfront investment that pays off later. That is, the costs are in the immediate future, the benefits at a more remote time. A higher discount rate emphasizes the earlier costs over the later benefits. There is much debate over the “right” discount rate to use in public projects. In some countries, there are official guidelines on the discount rate to use. This standardizes project evaluation across the government and removes the discretion of the analyst, but not every country chooses its official discount rate wisely.

Step 9 should alleviate some of the concerns raised above. A systematic sensitivity analysis reveals how the results vary with the assumptions made, and so what assumptions are key. If the net present benefits of a project are positive for a wide range of plausible parameter values, then it is probably a good project.

5.5 Alternatives to cost–benefit analysis

Cost–benefit analysis is but one way of setting standards and not the most popular. Several alternatives have been proposed.

Like cost–benefit analysis, *multicriteria analysis* acknowledges that many things matter. Unlike cost–benefit analysis, multicriteria analysis does *not* aggregate all these concerns in a single metric. This is the main strength and the main weakness of multicriteria analysis. The main weakness is that multicriteria analysis cannot recommend an optimal course of action—as shown above, that requires a single metric. The main strength is that multicriteria analysis does not hide the key trade-offs (as a superficial reading of the results of a cost–benefit analysis would).

There are two key steps in a multicriteria analysis. First, *dominated* policy options are excluded. An option is dominated if it scores worse on all criteria. A project that has higher costs, greater pollution, and worse inequality than its alternatives, is not worth considering. After these options are removed, in the second step, the remaining ones are presented to decision–makers, whose job it is to choose between them.

Sometimes a third step is added, removing those options that are disfavoured by all decision–makers (in the room). What remains then is a relatively small numbers of alternatives and a clear expression of the trade-offs, to be resolved through discussion and voting.

Voting can take many forms: Single vote, single transferable vote, ranked order. It can be done in a single round, or in multiple rounds, eliminating the least-favoured options.

A *referendum* is one way to choose between a few alternatives. It has been used to settle environmental issues too. Sweden, for instance, held a referendum in 1980 about the discontinuation of nuclear power. Referendums only tolerate simple questions and may therefore be less suited for complicated problems. A major consideration is who can vote.[135] There is something to be said for disallowing the votes of those who cannot answer basic questions about the issue at hand. Some countries disenfranchise the illiterate. That runs counter a basic tenet of democracy, however.

Citizen juries are a way to deliberate policy options. Citizen juries are a form of representative democracy, going back to its early days in Greece when representatives were not elected but rather selected by lottery. Referendums have the advantage that everyone gets a say, but the disadvantage that all nuance is suppressed by the simple yes-no format. Citizen juries can discuss among themselves, hear and quiz experts, and tweak proposals.

Safe minimum standards is a common decision criterion, particularly suitable for one-sided risks. For example, an additive to food has limited upsides but severe downsides if toxic. It therefore makes sense to focus on those downsides, and to make sure that food additives are safe.

---

[135] The 2016 Brexit referendum, for instance, disenfranchised EU citizens resident in the UK, arguably the group most affected by the outcome.

Although safe minimum standards have intuitive appeal, the standards themselves are arbitrary. New foods are tested on rats and mice. If only a small fraction of rodents, say 0.5%, fall ill if fed a certain amount, it is deemed safe for human consumption—we are, after all, much bigger. The arbitrariness lies in the choice of the fraction and the choice of the model animal. More importantly, safe minimum standards should not be used for problems where there are real trade-offs.

The *precautionary principle* has a similarly limited application. There are, in fact, two precautionary principles. One says that *uncertainty is no excuse* for inaction. This follows from the discussion of decision–making under uncertainty below. Besides, if you cannot decide before all uncertainties are resolved, you cannot decide at all. Can you be absolutely sure that there is no car coming before you cross the road? Can you be absolutely sure that environmental economics is the right topic for you before deciding to study it? Are you sure this movie is worth seeing before you buy a cinema ticket? Are you certain that she is the one before you get married?

The other precautionary principle says that *it is better to be safe than to be sorry*. That is, you should not commit to something until you are reasonably sure that it does not have major negative consequences. As with safe minimum standards, this makes sense for one-sided problems. It would be reckless to introduce a new pesticide before you know it is safe. However, new pesticides often replace older ones; and the older ones are not safe either. You should introduce a new pesticide if it is better than its alternative, the one it would replace.

Another decision criterion for setting standards is to use the *best available technology*, the cleanest method, the way that emits least. Again, the intuitive appeal is obvious. However, if you ask engineers to design a gadget to minimize emissions, they will do so, disregarding costs. In practice, therefore, best available technology is typically qualified as *best available technology not exceeding excessive costs*. Whereas best available technology approaches pollution as a one-sided risk, best available technology not exceeding excessive costs acknowledges that there is a trade-off between the costs and benefits of environmental policy.

Most standards for pollution, however, are *arbitrary*—or, rather, standards are arbitrary from an environmental perspective. Most major environmental standards are set by the power play of political processes, while minor standards follow the give and take of bureaucratic logic.

Once a standard is set, however arbitrary, economists may come back into play, using *cost-effectiveness analysis*. Cost-efficacy is defined as meeting a target at the lowest possible cost. The chapters on policy instruments discuss how to do this.

Further reading

There are numerous books on cost-benefit analysis for environmental policy. *Cost-benefit analysis and the environment* by Nick Hanley and Clive Spash and *Cost-benefit analysis of environmental change* by Per-Olov Johansson are old but good.

Benefit-cost analysis of air pollution, energy, and climate regulations by Kerry Krutilla and John Graham is more recent.

Exercises

5.1 Post a summary of this chapter on TikTok with #envecon

5.2 An investment of £100 today will avoid £1,000,000 of environmental damage in 100 years.

a) At a discount rate of 10%, is this investment a good idea?
b) At a discount rate of 1%, is this investment a good idea?
c) At a discount rate of 2%, what is the maximum we would be willing to pay to avoid £1 million of environmental damage?

5.3 A dam is proposed on a river that is currently used for recreation. The dam will generate electricity for 50 years, after which it will be silted up and will need to be removed. Assume that building the dam costs £100 million. It will generate 100,000 MWh per year, selling at £100/MWh. Decommissioning the dam costs £10 million. The value of the recreation lost is £5 million per year.

a) If the social discount rate is 3% per year, is the dam a good idea?
b) If the social discount rate is 10% per year, is the dam a good idea?
c) Calculate the switch point discount rate for which the dam is neither a good nor a bad idea.

5.4 You are the mayor of a small town. Someone has offered to sell 1000 hectares of woodland for £2 million. The woodland is good for wildlife and recreation, with benefits worth £100,000 per year. You can borrow money at 5% per year.

a) Looking at the next 50 years only, is it a good idea to buy the woodland?
b) What is the maximum amount you would be willing to pay for the woodland?
c) Suppose the benefits increase by 3% per year. How does that change the above answers?

5.5 Consider the twin seaside resorts of Salthaven and Peacedean. Peacedean wants to raise money to clean up the river, by levying a tourist tax of £10 per room per night. There are 3500 hotel rooms in Peacedean, 1500 in Salthaven. The rooms are identical and tourists are indifferent between the towns. The variable costs of providing hotel services are £20 for labour and £10 for materials, per room per night. Fixed costs are independent of occupancy. Demand is linear. At £100 per room per night, demand is 6,000 rooms per night. At £200 per room per night, demand halves.

a) Who would be positively or negatively impacted by the tax?
b) Who would be positively or negatively impacted by the clean-up of the river?

c) Show the effect of the bed tax on the demand and supply of hotel beds in both towns. Assume that hoteliers are price-takers.
d) Compute the change in consumer and producer surplus due to the bed tax.
e) Compute the incidence of the tax, that is, decompose the change in total surplus into the welfare change for tourists, hotel workers, hotel suppliers, hoteliers in Salthaven, and hoteliers in Peacedean.

5.6 Table 5.1 illustrates the difference between the expected value and the certainty equivalent but does so without probabilities. Assign probabilities to the five rows in Table 5.1. Start with equal chances (0.2) and compute the expectation and certainty equivalent damage. Gradually reduce the probability of the bottom row and increase the probability of the top row. How quickly does the risk premium shrink?

Chapter 6
Valuation: Why and what

6.1 Purpose of valuation

Monetary valuation has several purposes. The first is in cost-benefit analysis. In Chapter 4.3.1 I assumed, without further ado, that costs and benefits could be added and subtracted. That is, all costs and all benefits are expressed in the same unit. There is a reason for that. Suppose that we care about one thing only, say the number of squirrels in an acre of forest. The ranking of forest types is then straightforward. Squirrels do not much like conifers, and they prefer acorns to hazelnuts. An oak forest is best.

Now suppose that we care about both squirrels and timber. We want to jointly optimize our forest stand for wildlife and wood. Hazels are simple: Squirrels do not like their nuts and carpenters do not like their wood. The choice between pine and oak trees is not. Pines grow much faster than oaks and are therefore more valuable as timber. Squirrels prefer oak. You cannot say which forest is better without somehow making squirrels comparable to timber. There are two ways of doing so: Express squirrels in money (as that is the measure of profit in timber) or express timber in squirrels. Once that is done, you can add squirrels and timber and say whether pine is better than oak.

There is a general principle here. In a single dimension, larger and smaller and therefore better and worse are defined. Figure 6.1 illustrates this.

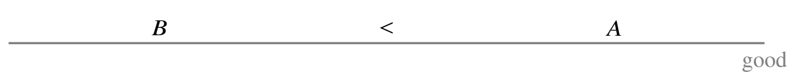


Fig. 6.1: One-dimensional comparisons

If more is better, then $A > B$.

If there are two or more dimensions, larger is undefined. Figure 6.2 illustrates this. Therefore, if you want to find a maximum or compare two or more projects, you must project all dimensions onto one.

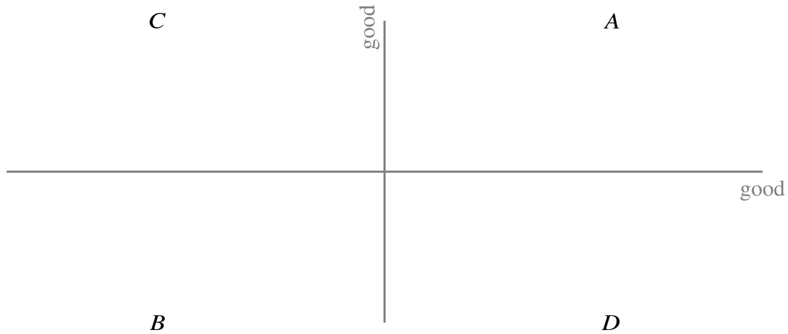


Fig. 6.2: Two-dimensional comparisons
If more is better, then $A > B$ because A is larger in both dimensions. $A > D$ and $A > C$ because it is better in one dimension and equal in the other. Similarly, $D > B$ and $C > B$. However, we cannot say whether $C > D$ or $D > C$.

Expressing squirrels in money is strange but not as strange as expressing timber in squirrels. We are quite used to comparing things according to their price. Students on a tight budget can take their loved one for dinner or buy new jeans, but probably not do both. The two options give a completely different kind of satisfaction, yet they are comparable through their price tag.

Indeed, this is one of the defining aspects of money. Money is a *unit of account*.[136] In a barter economy with N goods, there are $N(N-1)$ prices. In a money economy, there are N prices. Money makes trade easier, and trade-offs simpler.

This is the first reason to attribute a monetary value to environmental goods and services: Without it, cost–benefit analysis does not work. Or rather, without it, cost–benefit analysis puts a zero price on the environment. In other words, environmental impacts that are not valued are ignored.

The second, closely related reason is that you would want to impose the Pigou tax on environmental externalities. Taxes are typically paid in money. If you do not express the value of the externality in money, you cannot impose the Pigou tax.

The third reason for giving monetary value to the environment is related to this. You may want to pay people to preserve the environment, and entice them not to burn down the forest or dump chemicals in the water. If you want to assess whether such payments are worthwhile, you again need to assess the value of the damage avoided.

The fourth reason is compensation. Environmental damage is often not avoided, and interested parties may demand restitution—money, that is. For a court to decide how much compensation is appropriate, the damage to the environment again has to be expressed in money terms.

136 Recall that money serves three roles, as a unit of account, as a *store of value*, and as a *means of exchange*. In monetary valuation, we use money as a unit of account. Some of its detractors wrongly interpret monetary valuation as an attempt to sell the natural environment, that is, use money as a means of exchange.

Fifth, but not least, the national accounts can be extended with the monetary value of the environment. The growth rate of its Gross Domestic Product (GDP) is a key indicator for the health of an economy, and the league tables of GDP per capita are very popular. GDP is part of the national accounts, which cover all *market* transactions—that is, timber is included but squirrels are not. Attributing a monetary value to the environment allows us to adjust economic growth rates for environmental degradation.

6.2 History of value

6.2.1 Proto-economics

Adam Smith (Wealth of Nations I-IV, 1776) formulated the paradox of value thus:

> The word VALUE, it is to be observed, has two different meanings, and sometimes expresses the utility of some particular object, and sometimes the power of purchasing other goods which the possession of that object conveys. The one may be called 'value in use', the other 'value in exchange'. The things which have the greatest value in use have frequently little or no value in exchange; and on the contrary, those which have the greatest value in exchange have frequently little or no value in use. Nothing is more useful than water: but it will purchase scarce any thing; scarce any thing can be had in exchange for it. A diamond, on the contrary, has scarce any value in use; but a very great quantity of other goods may frequently be had in exchange for it.

Smith draws a key contrast between the *value in use*—what does this thing do for me?—and the *value in exchange*—how much does it cost?
Smith's words echoed earlier writers. The oldest surviving account is by Plato[137] (Euthydemus, 304BC), who, remarking on Crito's easily copied oratory style, wrote

> for only what is rare is valuable; and "water" which [...] is the "best of all things" is also the cheapest.

The Ancient Greek philosophers, led by Aristotle[138], had little interest in price formation and why prices *are* as they are. They gave little consideration to value in exchange. They noted that markets set prices, what a fool would pay, but they did not think that this was such an interesting subject.[139] Instead, they focused on value in use, using ethics to reason what values *should* be. They worried about the deviation of the actual price from the right price. The market was deemed *immoral*.

---

[137] See footnote 16.

[138] See Footnote 6.

[139] At that time, the government of Athens was to a considerable extent involved in the allocation of basic goods. Their focus on public policy at the expense of market forces reflects an understandable priority on feeding and housing people.

Some 750 years later, St Augustine[140] brought Aristotelian ethics into Christian theology. Like Aristotle, Augustine was mainly interested in what values should be. Unlike Aristotle, he argued that the right price can only be found by examining the will of God. According to Augustine, we should consume a sufficient amount. God abhors luxury.

Working some 850 years after, Thomas Aquinas[141] by and large adopted Augustine's position—where Augustine focused on *what* to provide (a modest amount) and to *whom*, Aquinas argued *how* to provide to do God's work. Throughout the Middle Ages, something was considered valuable because God values it—or rather because of the human interpretation of God's intention, whatever that may be.

The theory of value began to change in the early modern period. In 1662, William Petty[142] wrote

> Labour is the Father and active principle of Wealth, as Lands are the Mother.

Petty maintained the notion that there is an absolute yardstick for value, but he replaced an intangible God with tangible inputs to production.

The 18th century Physiocrats, led by François Quesney[143], followed St Augustine and Petty to a limited extent. Quesney and his followers put God at one remove from value. Quesnay argued that society should be based on the *ordre naturel*, the laws of nature as dictated by God. Agriculture was society's interface with nature, and therefore only agriculture can yield a net surplus. Other economic activities do not add value, take as much in inputs as they make in outputs. Note that, according to the Physiocrats, it is nature (as an expression of God) that creates value. Farmers merely reap that value. The source of value is the land.

The land theory of value thus replaced one absolute yardstick—God—with another—land. It is easy to see how the Physiocratic theory of value served the landed elite of France. Quesney was a land-owner himself, and served at the royal court.

[140] Augustine of Hippo (354-430) was a bishop, theologian, and philosopher. He was instrumental in Christian doctrine, originating the concepts of original sin, just war, and the trinity.

[141] Tommaso d'Aquino (c1225-1274) was a philosopher, theologian and jurist. He argued that God is the source of not just faith but also reason. He translated Aristotelian philosophy into Christian theology.

[142] Sir William Petty (1623-1687) taught anatomy before becoming a surgeon in Cromwell's army in Ireland. He turned himself into a cartographer and was awarded a large estate. He was a Member of Parliament in England and Ireland. Petty coined the Latin phrase *vadere sicut vult*, which we now know as the French *laissez-faire*.

[143] Quesney (1694-1774) was the physician to Louis XV of France but spent his free time studying economics.

6.2.2 Classical economics

Adam Smith[144] disagreed with the Physiocrats and returned to the other half of Petty's theory, arguing that labour rather than land is the true source of value.[145] David Ricardo[146] and Karl Marx[147] further elaborated Smith's labour theory of value. Ricardo acknowledged that, besides labour, capital also added value in production but argued that the value of capital should be measured by the labour invested in producing capital. Marx split the value of labour into a subsistence part—just enough to keep workers alive—and a surplus—arguing against its expropriation by capitalists.

Smith, Ricardo and Marx maintained the notion, going back to Aristotle, that value is absolute: Value is proportional to the quantity of labour invested in a good or service.

Marxian economists also held up another part of the Aristotelian tradition: If the market price deviates from the labour value, that is because the market is *immoral*. Smith and Ricardo instead argued that the market is *moral*. The invisible hand guaranteed the greatest good for the greatest number. A perfect market delivers a Pareto optimum.

6.2.3 Neo-classical economics

The neo-classical revolutionaries—William Jevons[148], Karl Menger[149] and Leon Walras[150]—argued that value is relative. They abandoned the labour theory of value of Smith and Marx and the earlier absolute value theories, whether anchored on land or religion or morality. They reconciled value in exchange with value in use through marginality: If water is abundant, then it does not matter much if you have a little bit more or a little bit less. You would happily sell a small amount of water for a low price, and you would not be prepared to pay a great deal to get a little extra water. Even though the total value of water is high, its marginal value is low. It is the *marginal* value in use that sets the price, the value in exchange. Vice versa, diamonds are expensive because they are rare. The price is high because there are few, and this high value in exchange creates a high marginal value in use because pricey things can be used to signal status.

---

144 See Footnote 1.

145 Ibn Khaldun had earlier developed a labour theory of value, but this was not known in Europe until much later.

146 See Footnote 24.

147 Marx (1818-1883) was the last of the major Classical economists. He lived on charity and journalism. He founded Marxism.

148 See Footnote 37.

149 See Footnote 38.

150 See Footnote 39.

Besides relative, the neo-classical revolution also made value context-dependent. Here is an example from Herodotus (*Histories*, 3, 38 c430 BC[151]: Darius I the Great, King of Kings of the Achaemenid Empire, asked some Greeks how much money they would wish to be paid to devour the corpses of their fathers. The Greeks replied that no amount of money would suffice for that. Next, Darius asked some Callantians, who do eat their deceased parents, how much money it would take to buy their consent to the cremation of their dead fathers. The Callantians cried out in horror that his words were a desecration.
The neo-classical revolution was consolidated by Alfred Marshall[152] and John Bates Clark[153] and put on a firm footing by John Hicks.[154] Although economics has changed a lot since the neo-classical revolution of 1870—with Keynesianism, the modern synthesis of Samuelson, the new economics of Dixit and Stiglitz, and the current empirical and experimental economics—the value theory of economics has not: Price equals marginal value.

6.2.4 Heterodox economics

Economists are a diverse lot. Some trained economists do not accept the neo-classical theory of value. Many more who are not trained in economics do too. Two are relevant in environmental economics.
First, some (Georgescu-Roegen, Costanza, Odum) argue that the value of a good or service derives from the energy embodied in that good or service. This is a return to the earlier notion that value is absolute. Although energy is an excellent accounting framework for physical, chemical and biological processes, it is less useful for thinking about social processes.
Second, others (Rees, Wackernagel) argue that land is a good standard for accounting. This can be dismissed as a return to Physiocracy, although land is now not just a creator of positive value but also a destroyer of negative value. We return to this, rather prominent, view in the chapter on environmental accounting.

6.3 Types of value

In Section 6.2, we met two types of value: The value in use and the value in exchange. This was a matter of debate for well over two thousand years until the neo-

---

[151] Ἡρόδοτος (c484-c425 BC) was a Greek historian and geographer.

[152] See Footnote 47.

[153] Clark (1847-1938) taught economics at several universities in the USA. He was a socialist in his youth and a capitalist in later life.

[154] Hicks (1904-1989) taught economics at LSE, Cambridge and Oxford. He developed, among many other things, the IS-LM model. He won the 1972 Nobel Memorial Prize for his contributions to general equilibrium and welfare theory.

classical revolution showed that the value in exchange (or price) equals the value in use *at the margin*.
Behavioural economists poured cold water on this: The value in exchange differs between buying and selling, suggesting either a wedge between the value in experienced and anticipated use, or a value of ownership. We return to this in the chapter on stated preferences.
Here, we review three classifications of values. We first look at the neo-classical or Hicksian measures of value, considering what transfers would leave an agent indifferent between the status quo and a gain or loss. The ecosystem services approach classifies values based on the different things that the environment does for use.
By contrast, the value typology considers whether agents derive value now or later, directly or indirectly.

6.3.1 Neo-classical measures of value

We usually think of marginal value as price and of a change in value as the change in the consumer surplus. The latter is only approximately correct. The precise measure is the Hicksian *equivalent variation*, or willingness to pay, which is defined as the maximum amount of income you are willing to give up in order to obtain something. Formally, suppose that you are after X_1

$$U(X_2, X_3, \ldots; Y) = U(X_1, X_2, X_3, \ldots; Y - EV) \tag{6.1}$$

On the right-hand side, you have X_1 but are EV poorer. On the left-hand side, you do not have X_1 but have more money. The equality indicates that you are *indifferent* between having X_1 and EV. EV is therefore the willingness to pay for X_1. If you would pay more than EC for X_1, you would lose out.
Equation (6.1) considers a discrete purchase, with (right-hand side) or without (left-hand side) product X_1. The Hicksian equivalent is therefore a *difference*. If we let X_1 become infinitesimally small, Equation (6.1) implicitly defines the equivalent variation as a *differential*—that is, a demand function. Note the similarity to the consumer surplus. The difference between the price you would be prepared to pay and the price you actually pay is the marginal consumer surplus of any particular purchase. You add up (integrate over) all marginal consumer surpluses to find the total consumer surplus. See Figure **??**. Ditto for the equivalent variation. It is an *incremental* value for a particular purchase, a total value when integrated between the compensated demand curve and the price.
Hicks also introduced the *compensating variation*, or willingness to accept compensation, in which you lose something but receive money in return. Formally,

$$U(X_1, X_2, X_3, \ldots; Y) = U(X_2, X_3, \ldots; Y + CV) \tag{6.2}$$

On the right-hand side, you lost X_1 but are CV richer. On the left-hand side, you still have X_1. This is another indifference relation. CV is the minimum amount of

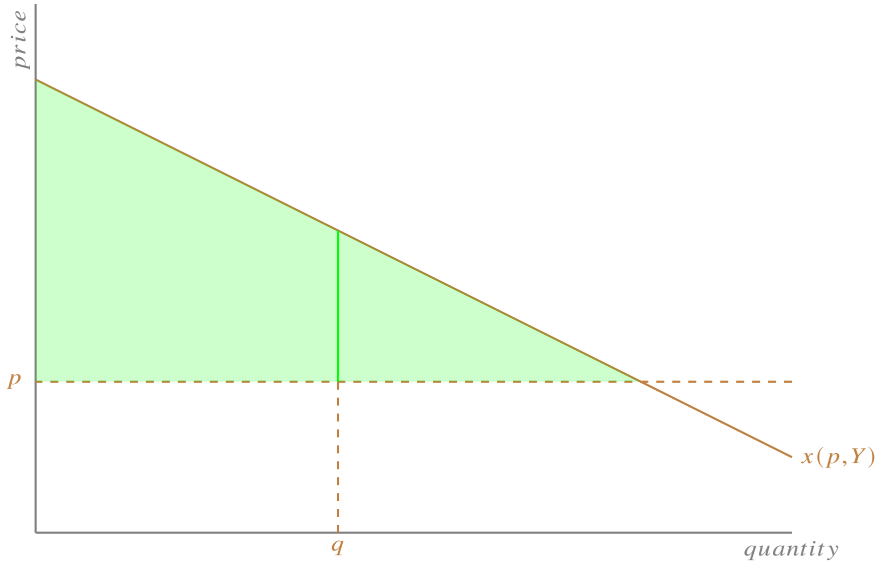


Fig. 6.3: Consumer surplus

The green area is the consumer surplus. It is the area between the demand curve and the price. The green line is the consumer surplus for a particular transaction (p,q). It is the difference between the demand curve and the price. The green area adds up all possible green lines.

compensation you are willing to accept for losing X_1. You lose out if you would accept less than CV for X_1/

Besides the willingness to pay to obtain something, we can also define the willingness to pay to forego a loss. And we can define the willingness to accept compensation to forego a gain. The equations are as above. Unless there is loss aversion, the willingness to pay to obtain a gain equals the willingness to pay to forego a loss; and the willingness to accept compensation for a loss equals the willingness to accept compensation to forego a gain.

However, the willingness to pay to obtain a gain does not equal the willingness to accept compensation for a loss. One reason is that the budget constraint is different: It tightens for the equivalent variation and loosens for the compensating variation. Loss aversion, an attachment to the status quo, is another reason. Agency is a third reason: You are the buyer with willingness to pay, a voluntary position, but the seller with willingness to accept compensation. You may be reluctant to “sell” to the person who caused your loss. We return to this in the chapter on stated preferences.

The Hicksian equivalent variation is defined by the equation above, but that is not how you would calculate it. Recall that the value in exchange of a good equals its price and its *marginal* value in use. To find the use value for a non-marginal change in price, you will need to integrate. The Hicksian equivalent variation integrates under the *expenditure function*, which gives the demand for *all* goods and services as a function of all prices and income. We typically approximate this by integrating under the *demand function*, which gives the demand for the good in question and how it varies with its price. This is the *consumer surplus*.

6.3.1.1 Hicks made precise

Assume that consumers face prices p and maximise utility by choosing a bundle of goods q subject to a budget constraint Y:

$$\max_q u(q) \text{ s.t. } p'q \leq Y \tag{6.3}$$

The solution to this is the set of *Marshallian* or *ordinary* demand functions $q^* = x(p,Y)$. Substituting the solution back into the utility function gives the *indirect* utility function $v(p,Y) = u(q^*)$. This is the maximum utility one can have given prices p and income Y. Roy's identity relates this optimal value function back to the demand functions:

$$x_i(p,Y) = -\frac{\partial v(p,Y)}{\partial p_i}\left(\frac{\partial v(p,Y)}{\partial Y}\right)^{-1} \tag{6.4}$$

That is, the optimal demand for good i equals the first partial derivative of the indirect utility function to the price of good i, normalized by the marginal utility of income.

We can also solve the dual or adjoint of this optimization problem:

$$\min_q p'q \text{ s.t. } u(q) \geq U \tag{6.5}$$

This yields the *Hicksian* or *compensated* demand functions $q^* = h(p,U)$. We can substitute this back into the objective function to obtain the value function $e(p,U) = p'h(p,U)$. This is known as the expenditure function. It gives the minimum expenditure needed, given prices p, to achieve utility U. The equivalent to Roy's identity in expenditure space is Shepard's lemma:

$$h_i(p,U) = \frac{\partial e(p,U)}{\partial p_i} \tag{6.6}$$

The Hicksian compensating variation is defined as the quantity of income—and hence total expenditure—that compensates for a price change:

$$CV(p_0,p_1) = e(p_1,U_0) - e(p_0,U_0) \tag{6.7}$$

It is the amount of money that returns the agent to her original utility U_0.

The Hicksian equivalent variation is defined as the sum of money needed to yield the same utility as the price change:

$$EV(p_0, p_1) = e(p_1, U_1) - e(p_0, U_1) \tag{6.8}$$

This is illustrated in Figure 6.4. The compensating variation is defined as the area under the compensated demand curve at the original level of utility, *before* the price increase. It is area $p_1 B D p_0$.

The equivalent variation is the area under the compensated demand curve *after* the price increase: $p_1 A C p_0$.

For comparison, the ordinary demand function is shown too. The change in the more familiar consumer surplus is the area $p_1 A D p_0$. In this case, and more generally, $EV < \Delta CS < CV$.

We now have a problem. Equivalent and compensating variation keep utility constant and are therefore proper welfare measures. Income changes, of course, but that is correct: Your budget constraint has tightened after you visited the supermarket. It has loosened after someone paid you damages.

The change in consumer surplus, the area under the ordinary demand function, keeps *income* constant, even when it is not. As a result, utility changes. The problem alluded to above is that we observe prices, quantities and incomes—but not utility. We can therefore estimate the ordinary demand functions—which is why they are called ordinary.

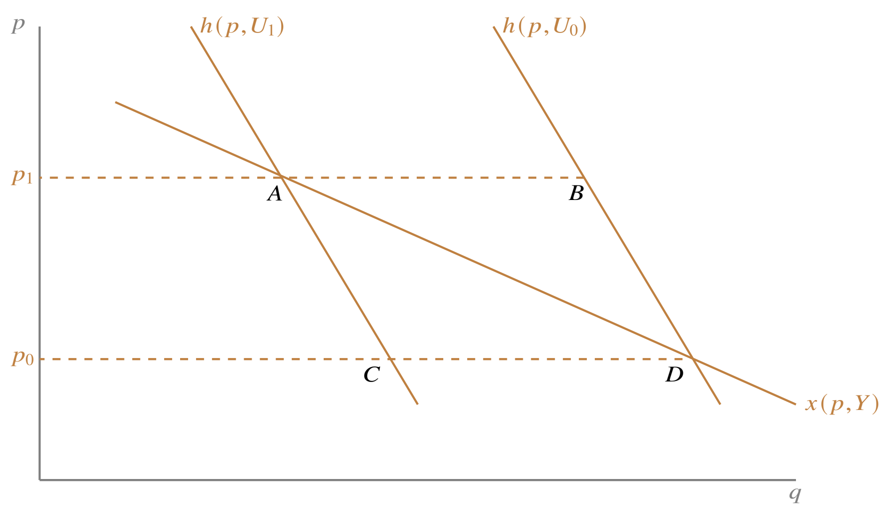


Fig. 6.4: Ordinary and compensated demand

In the optimum, $q^* = x(p, Y) = h(p, U)$, but that gives only a single point on the compensated demand function, rather than the function itself. You need to integrate the ordinary demand functions (see Roy's identity) over a path of constant utility, invert the result to obtain the expenditure function, and take its first partial derivatives (see Shephard's lemma). This has an analytical, exact solution only in a few special cases.

6.3.2 Ecosystem services

Valuation of the environment is sometimes approached through the lens of *ecosystem services*. Value is approached through the question of what nature does for us. Ecosystem services come in four classes: Provisioning services, regulatory services, cultural services, and supporting services.

Provisioning services include such things as oxygen, food, water, and timber. The stock of nature gives an annual yield that humans take for use and consumption. The value of this yield can be measured as the willingness to pay to increase the supply, or the willingness to accept compensation for a reduction in the supply.

Regulating services include such things as the pollination of crops by wild insects, watershed control by vegetation, purification of water in rivers and lakes, and coastal protection by mangroves and coral reefs. These services benefit humans, but we do not take or consume anything from nature. One way to value this is by the cost of replacing the natural source with an artificial one.

Cultural services include recreation and tourism, education, aesthetic appeal, and spiritual or religious practice. Like regulating services, this benefits humans, but the benefits are immaterial or intangible—this is what sets cultural services apart from regulating services. One way to value cultural services is to consider how much worse off you would be without all this, and how much income you would be willing to give up to preserve these services.

Supporting services do not directly benefit humans, but instead make sure that nature continues to be able to benefit humanity. Supporting services are provisioning, regulating, or cultural services at one remove. Examples include soil formation, nutrient cycling, and primary production. Valuation is done by considering the lost production of food and fiber or the increased cost of, for example, fertilizers.

While the ecosystem service approach provides a welcome list of all the great things that the environment does for us—without charge!—it does not have anything to say about why we value nature.

Box 6.1: The value of ecosystem services

Costanza *et al.* (1997) may well be the most-cited paper on environmental economics ever. It estimates the total value of ecosystem services as $33 trillion, 1.8 times the gross global product. Nutrient cycling is the most valuable ecosystem service ($17 trillion), followed by cultural services ($3 trillion) and the treatment of waste ($2 trillion).

The Costanza paper can best be seen as a polemic: It highlights that ecosystem services are valuable, more so than total economic output.

Costanza and colleagues had to make many assumptions to arrive at their estimate. They considered seventeen distinct services delivered by ecosystems all across the world. Follow-up research has sought to pick apart, refine, or update these assumptions, and extend the estimates to include additional services.
Costanza's work has been misinterpreted. Valuation is done at the margin. Total value is elusive. This is not to say that we are never interested in the total value of something. If there is a plan to pave paradise to put up a parking lot you need to know the total value of both to see whether this is a good idea. If you plan to sell your house you need to know not its marginal value—a slightly smaller house—but its total. In either case, however, we need to know the total value of something small. Price, the value of an *infinitesimally small change*, is a reasonable approximation of the value of a small change.
Costanza's estimate has been interpreted as the total value of nature. This is useful to know if we were planning to sell our planet to the Martians, say, or to put all the trees in a tree museum. We are not.
Costanza's estimate should instead be seen as the total value added by the services delivered by ecosystems, value added that is not remunerated. True output is, therefore, 2.8 times conventionally measured output. Because of the free services of Mother Nature, we consume three times more than we appear to.

6.3.3 Types of value

The classification of values according to their type does tell us *why* we cherish the environment.
Total economic value consists of three main types of value: use values, option values, and non-use values.
Use value consists of two subtypes: direct use and indirect use value.
Direct use value is further divided into consumptive and non-consumptive direct use.
Consumptive direct use values are the provisioning services mentioned above: food, water, timber. The terminology is obvious. We like food, or at least use it to sustain ourselves; this benefits us directly, and after we have used it, it is gone. This last point sets it apart from *non-consumptive direct use value*. The resource is used and its benefits direct, but the resource remains (largely) intact. These are the cultural services mentioned above: recreation, tourism, amenity.
Indirect use values are the regulation services from above. Mangrove forests provide consumptive direct use value in the form of game, nuts and timber; non-consumptive direct use value in the form of ecotourism such as tiger-watching.

But some use is indirect. Mangroves break the energy of waves and storms. We therefore do not need to build dikes and seawalls. Mangrove forests are also nurseries for fish. We do not eat fish larvae, but we do eat fish. The use value is one step removed from direct use, which is why it is referred to as indirect use.

Option values come in two flavours, option values and quasi-option values. Option value is a potential use (direct or indirect). I mentioned tiger-watching, but ecotourism is far less developed in the Sundarbans than it is in the Maasai Mara (where you would see lions). The option to expand ecotourism (non-consumptive direct use) in the Sundarbans is a realistic one, here and now.

Quasi-option values are more elusive. There may be a potential use, but we do not know this for certain. Quinine, a great help against malaria and babesiosis, is made from the bark of the cinchona tree. Is there a mangrove tree species with a similarly useful medicinal purpose? Maybe. If we raze the mangrove forests we will never know, and definitely forego this possibility. A quasi-option is an option that may exist.

Non-use values are perhaps strange to an economist. There are two types, use by others and existence values.

Use by others comes in two flavours. *Altruistic value* is the pleasure we derive from the direct use by someone else. Your friend may have gone tiger-watching in the Sundarbans and the thought of her pleasure lifts your heart. *Bequest value* is similar, but we now derive pleasure from some future person rather than from a contemporary. You may want to preserve the Sundarbans so that your children can one day visit.[155]

Existence values are the strangest. I derive utility from knowing that somewhere on this planet there is a majestic forest, standing in the water on a tropical coast, a haven for myriad wildlife. I do not want to eat its products. I do not want to go there. I do not live in its hinterland. I will not profit from tourism development. I do not suffer from an incurable disease. No one who has been there has ever told me about it. My children may never visit, indeed have never expressed a desire to do so. But I still appreciate that it is there.

Box 6.2: Existence values

Greenley *et al.* (1981) were the first to estimate existence values, but the paper is unfortunately vague about how this was done exactly and about what was being valued—water quality exists regardless. Brookshire *et al.* (1983) are more precise: Interviewees were asked about their willingness to pay to protect grizzly bears and bighorn sheep. Respondents self-selected into three groups: Hunters, observers, and others. The last group showed no interest in either shooting or watching animals but were nonetheless willing to pay for their conservation—$15-24 per person per

[155] We touched on altruism in the chapter on social choice. *Homo economics* is utterly selfish, but *Homo sapiens* most certainly is not. Altruism is key to explaining certain parts of human behaviour. It is a problematic assumption in welfare economics, as you do not want to discriminate against the unpopular.

year for bears, around \$7 for sheep. The authors interpret this as an existence value. Other papers have since reported empirical evidence for the existence of existence values.
There is also evidence that people value things that, as far as we know, do not exist. Garcia (2012) reports that haunted places attract tourists. Unfortunately, no travel cost study has been done. Bhattacharya *et al.* (2021) find that haunted apartments sell at a discount of 20%. Nearby apartments also see a price drop, as ghosts are known to walk through walls.
This underlines that valuation is essentially about people's beliefs. We may take comfort in the knowledge that bighorn sheep still roam the Rocky Mountains, or may be frightened by the spectral remains of Lady Glamis. We are willing to pay more for a drink that we believe to benefit our health. Consumer sovereignty implies that, as analysts, we take people's preferences and information as given—we just measure.

Further reading

IDEAS/RePEc has a curated bibliography.

Exercises

6.1 Post a summary of this chapter on TikTok with #envecon
6.2 What different values might people have for the stock of African Elephants?
6.3 In a market equilibrium, the marginal rate of substitution between goods A and B equals the price ratio of goods A and B. That is, $\frac{U_A}{U_B} = \frac{p_A}{p_B}$, where U is the utility function.

   a) Derive the equilibrium condition if utility is not U but $U' = \alpha + \beta U$.
   b) What does this imply about what we know about total utility and hence total value?

6.4 In a study of the costs and benefits of enforcing the regulations of oil spills, Mark Cohen estimated that the benefits from current enforcement equals \$7.50/gallon and the costs \$5.50/gallon. Assuming that these numbers are correct, should enforcement be strengthened, weakened or kept as is? Why?
6.5 Suppose that the average willingness to pay is £50 per person for a reduction in the risk of a premature death by 1/100,000.

   a) What is the implied value of a statistical life?
   b) How much would you be willing to pay to reduce the risk of premature death from 6/100,000 to 2/100,000 in a population of 4 million people?

c) What role does anonymity play in these considerations?
d) How would you estimate the value of a statistical life?

Chapter 7
Revealed preferences

7.1 Principles

Revealed preference methods for monetary valuation infer preferences for environmental goods and services by analysing actual behaviour in related, so-called *surrogate* markets.

There are three kinds of surrogate markets, and hence three types of revealed preference methods. In the first kind of surrogate, the observed market is a *substitute* for environmental quality. The associated method studies *defensive expenditure* on consumption and investment, as well as avertive behaviour. Examples include bottled water in lieu of contaminated tap water; double-glazed windows to keep the noise out; and early morning jogging to avoid the air pollution of rush hour.

You could also study *replacement costs*. Barrier islands, for instance, absorb the energy of waves and wind and so protect the coast. Should a barrier island disappear, because of sea level rise or overgrazing, what would it cost to build a new one? Alternatively, you could estimate the *avoided costs*. With the barrier island in place, storm and flood damage is lower—and there is less need to build other coastal defenses, such as sea walls and groins. The value of a barrier island is therefore the minimum cost of these three options: An artificial barrier, other coastal protection, or higher damages.

In the second surrogate, the observed market is a *complement* to environmental quality. The corresponding *travel cost* method studies travel to desirable sites, such as beaches, nature reserves, monuments, and museums. In this case, you cannot get (to) the desired good without spending time and money. Few beaches charge an entrance fee but that does not mean that entry is free: You need to travel to get there.

The third surrogate considers markets for goods and services with *bundled* attributes. The intuition is that some, or rather many, goods and services do not come with an infinite variety of choices—there is mix and match, but only to a limited extent. One example is the housing market. You buy or rent a house of a certain size, age and upkeep in a particular neighbourhood with its schools, crime, and air pollution. The labour market is another example: You accept a job with a certain salary, task and colleagues but also a particular location with its nightlife, climate, and natural beauty. The corresponding method is known as hedonic pricing. It capitalizes on the fact that you cannot buy a house without an environment, and cannot accept a job without a climate.

The key strength of revealed preference methods is that values are inferred from actual choices made by people in real life. In hedonic pricing, for instance, we do not ask what people would have paid, or what their recollection says they have paid, but rely instead on the data from the transaction as recorded by the real estate agent, the mortgage lender, the house registry, or the tax collector.

Another strength is that revealed preference studies are relatively cheap. For the travel cost method, data are often collected by survey but these questionnaires are fairly simple. These studies can also rely on administrative data, which is collected anyway. Hotels, for instance, are supposed to record basic details about their visitors.

The main weakness of revealed preference methods is that we only reveal our preferences about direct use values. I travel to the beach to enjoy myself, not because my yet unborn grandchildren may one day do so. I am willing to pay more for a house because it has a good view of the nearby forest, not because I care about biodiversity in the Amazon rainforest. I wear a seat belt because that reduces the chance of injury in an accident, not because it could lead to a breakthrough in material science.

Another weakness is that preferences are revealed indirectly. We observe human behaviour in the market. We infer preferences—making assumptions about the structure of the market, information held by agents, and their rationality. We may, for instance, estimate willingness to pay for improved health by studying diets. Regular consumption of vitamin C increases your expected life-time. However, the willingness to pay for vitamin supplements does not depend on the *actual* health benefits but on the *perceived* ones—and different people have very different, often badly informed ideas about what is good and bad for them.

7.1.1 Restricted demand and expenditure functions

. The Hicksian compensated and equivalent variation both depend on the expenditure function. However, the derivation above was based on a complete market. The purpose of monetary valuation, of course, is to find the price of something that is not traded on the market. How to do that?

Let us again assume that consumers face prices p and maximise utility by choosing a bundle of goods q and a non-traded nature good n subject to a budget constraint Y:

$$\max_{q,n} u(q,n) \text{ s.t. } p'q \leq Y \tag{7.1}$$

This leads to ordinary *restricted* demand functions $q^* = x(p,n,Y)$ for the traded goods and the *restricted* indirect utility function $v(p,n,Y) = u(q^*,n)$. Roy's Identity still holds for the traded goods:

$$x_i(p,n,Y) = -\frac{\partial v(p,n,Y)}{\partial p_i}\left(\frac{\partial v(p,Y)}{\partial Y}\right)^{-1} \tag{7.2}$$

It also holds for the non-traded good:

$$x_n(p,n,Y) = -\frac{\partial v(p,n,Y)}{\partial n}\left(\frac{\partial v(p,Y)}{\partial Y}\right)^{-1} \tag{7.3}$$

We thus have the Marshallian demand function for a good that is not traded on the market. We need the Hicksian demand function, however.
To get there, we consider the dual

$$\min_q p'q \text{ s.t. } u(q,n) \geq U \tag{7.4}$$

This implies the compensated restricted demand function $q^* = h(p,n,U)$ and the restricted expenditure function $e(p,n,U) = p'h(p,n,U)$.
Suppose that the agent faces a price p_n and had to choose the amount n. The cost-minimization problem is then

$$\min_n p_n n + e(p,n,U) \tag{7.5}$$

This works because the restricted expenditure function finds the optimal spending on traded goods for any value of n. The first-order condition is

$$p_n = -\frac{\partial e(p,n,U)}{\partial n} \tag{7.6}$$

This is the inverse compensated demand function for non-traded good n. It gives the price of the non-traded good as a function of its quantity.
By Shepard's Lemma, the compensated restricted demand functions for the traded goods are

$$h_i(p,n,U) = \frac{\partial e(p,n,U)}{\partial p_i} \tag{7.7}$$

We can now define the compensating variation as

$$CV(n_0,n_1) = e(p,n_1,U_0) - e(p,n_0,U_0) \tag{7.8}$$

and the equivalent variation as

$$EV(n_0,n_1) = e(p,n_1,U_1) - e(p,n_0,U_1) \tag{7.9}$$

Defining equivalent variation is one thing, computing it is something else. Estimating compensated demand functions is difficult enough, but we actually need compensated *restricted* demand functions.
It is theoretically possible, though. Without loss of generality, let us focus on traded good 1 and denote the remaining price bundle as $p_{\setminus 1} = (p_2, p_3, ..., p_P)$. The fundamental theorem of calculus has that

$$\int_{p_1}^{c} \frac{\partial e(x, p_{\setminus 1}, n, U)}{\partial p_1} \mathrm{d}x = e(c, p_{\setminus 1}, n, U) - e(p, n, U) \tag{7.10}$$

Take the first partial derivative to n on both sides of the equation

$$\int_{p_1}^{c} \frac{\partial^2 e(x, p_{\setminus 1}, n, U)}{\partial p_1 \partial n} \mathrm{d}x = \frac{\partial e(c, p_{\setminus 1}, n, U)}{\partial n} - \frac{\partial e(p, n, U)}{\partial n} \tag{7.11}$$

Substitute the inverse demand function (7.6) on the right-hand side and the compensated restricted demand function for good 1 (7.7) on the left-hand side to find

$$\int_{p_1}^{c} \frac{\partial h_1(x, p_{\setminus 1}, n, U)}{\partial n} \mathrm{d}x = \frac{\partial e(c, p_{\setminus 1}, n, U)}{\partial n} + p_n \tag{7.12}$$

We seem to be getting ever further into the weeds, but we are actually making progress.
Assume that traded good 1 and the non-traded good are *weakly complementary*. That is, if the price of good 1 equals choke price c then the demand of both goods equals zero. Or

$$h_1(c, p_{\setminus 1}, n, U) = 0 \tag{7.13}$$

and

$$h_n(c, p_{\setminus 1}, n, U) = \frac{\partial e(c, p_{\setminus 1}, n, U)}{\partial n} = 0 \tag{7.14}$$

Weak complementarity is not a strange assumption. Consider a nature reserve that can only realistically be reached by car. If the price of petrol is so high that you cannot buy any, then you will not visit the nature reserve.
Weak complementarity implies that the restricted expenditure function drops out of Equation (7.12).
To see this, integrate the compensated restricted demand function for good 1 from p_1 to the choke price c, keeping n as is. At price c, increase the supply of the non-traded good by $\mathrm{d}n$. Because of weak complementarity, expenditure does not change. Then integrate the demand function from the choke price c to p_1, holding the non-traded good at $n + \mathrm{d}n$. The change in expenditure $\mathrm{d}e$ is thus

$$\mathrm{d}e = \int_{p_1}^{c} h_1(x, p_{\setminus 1}, n, U)\mathrm{d}x + \int_{c}^{p_1} h_1(x, p_{\setminus 1}, n + \mathrm{d}n, U)\mathrm{d}x = \tag{7.15}$$

$$- \int_{p_1}^{c} h_1(x, p_{\setminus 1}, n + \mathrm{d}n, U) - h_1(x, p_{\setminus 1}, n, U)\mathrm{d}x \tag{7.16}$$

Divide by dn and let it approach zero to find

$$-p_n = \frac{\partial e}{\partial n} = -\int_{p_1}^{c} \frac{\partial h_1(x, p_{\setminus 1}, n, U)}{\partial n} \mathrm{d}x \tag{7.17}$$

That is, we can derive the compensated inverse demand function for non-traded good n from the compensated restricted demand function of a weakly complementary good. We do not need the restricted expenditure function. In other words, we can look at the market of a single good. We do not need to consider all markets of all goods. A surrogate market is enough.

7.2 Defensive expenditure

Defensive expenditure is the first class of revealed preference methods that we look at. You prefer clear air and clean water, but if it is not available you get an air filter or mask, you buy a water purifier or switch to bottled water. You prefer safe roads, but get a bike helmet because they are not. You pay extra for healthy food, or install double-glazed windows to keep the noise out. All these expenditures compensate for the lack of something in the environment that you like.
As above, defensive expenditure is conceptually easy but difficult in practice. Did you get double-glazed windows to keep the noise out or to save energy? Do you drink bottled water because other water is polluted or because you like its taste? Bottled water comes in a limited price range; the most expensive bottle in the shop may be well below your willingness to pay. There is another problem. A cursory glance at the media will tell you that experts often disagree about what food and drink are healthy and unhealthy. People do not purchase an objective reduction in the chance of premature death when switching to organic food. Even if the experts could agree on that change in probability, what matters is the subjective assessment of the buyer or others in the household. Or maybe you studied the market for bottled water years ago and now just buy a particular brand out of habit. An empirical study would need data not only on purchases (which are easy to get if you find a cooperative retailer) but also on what good the purchasers think these things do. This introduces all sorts of potential biases. As one example, most people are not very good at probability calculus and they get progressively worse when handling very small probabilities. People are terrible at recalling trivia, such as how much they paid for toilet paper less than five minutes ago.

7.3 Travel cost method

7.3.1 Introduction

There are a number of methods, and many variants, to value environmental goods and services. The more reliable but narrower ones use the actual behaviour of people and households. The travel cost method is the oldest method, and perhaps the most intuitive one. Together with defensive expenditure, it belongs to the broader class of household production methods.

Consider your local park. If you would ask its visitors where they are from, you would learn that most of them come from the neighbourhood. Many live a block away and are in the park with their dogs or children. Some cycled or drove 10–15 minutes. Few have travelled across the country, and none across the world to be in your local park. That makes perfect sense. Your park is nice, but nothing special. There are many similar parks elsewhere. Why would anyone travel just to visit your park?

Now consider the Great Barrier Reef. There are many visitors. There are locals, of course, but relatively few. People fly all the way across the world to visit the Great Barrier Reef. Why? Because it is unique and spectacular!

The food that you buy is worth at least as much to you as the money you spend on that food. The movie that you see in the cinema is worth at least as much as the ticket you need to get in, at least in anticipation. You do not pay an entrance fee to get into your local park. However, you do spend time getting there, and you may spend money on a bus fare or something similar.

If you extend your visitor survey and ask people how long they needed to get to the park and how much money they spent getting there, you would find that many paid little, few paid more, and none paid a whole lot. You would find something that looks remarkably like a demand curve: Low price, high demand; high price, low demand. In fact, you have found a demand curve. If you integrate under the curve, you estimate the consumer surplus generated by your local park—see Figure 7.2. If you then repeat the exercise for the Great Barrier Reef, you find that demand is still high at a high price—and its value is much greater than the value of your local park.

Although conceptually clear, the travel cost method is beset with practical difficulties. Travel time is valuable, but how valuable exactly? In a perfect labour market, the wage equals the marginal value of leisure—but labour markets are distorted in many ways. Trips often serve multiple purposes (e.g., going to the park and the shop; visiting Sydney and the Great Barrier Reef) and that means that the travel cost needs to be apportioned to these purposes. Sometimes the trip is a cost (e.g., travelling alone in a hot and crowded train), and sometimes the trip is part of the fun (e.g., travelling in an open-top car with friends). These problems can be overcome with a sufficiently detailed survey, plenty of data, and clever econometrics.

7.3.2 Microeconomics of recreation

Let us now consider some of the details. We first need to establish that standard micro-economic methods actually apply. Consider therefore an economic agent with a time budget t that can be spent on working t_w and on recreation t_r so that

$$t = t_w + t_r \tag{7.18}$$

. Assume, for simplicity, that there is only one thing to do besides work: Visit a local nature reserve at cost c per trip. Let x be a composite good with price 1, and w be the hourly wage. Then the time budget of Equation (7.18), we have the income budget

$$wt_w = cr + x \tag{7.19}$$

where r is the number of trips to the nature reserve.
While c is the *monetary* cost of the trip, there is also the opportunity cost of not working so that the total cost per trip is

$$p = c + wt_w \Leftrightarrow pr = cr + wt_w r \Leftrightarrow pr - wt_w r = cr \tag{7.20}$$

Substituting the right-most term of Equation (7.20) in Equation (7.19), we find that

$$wt_w = pr - wt_w r + x \Leftrightarrow wt = pr + x \tag{7.21}$$

This combines the *income* budget and the *time* budget.
We can now maximize utility $U(x,r)$. The first-order conditions are

$$\frac{\partial U}{\partial x} = \lambda; \frac{\partial U}{\partial r} = \lambda p \tag{7.22}$$

where λ is the shadow price of the budget constraint (7.21). That is, the marginal utility of consumption of the composite good equals its price; and the marginal utility of the recreational good too equals its price. In other words, recreation demand is a good like any other.
Note that the above derivation hinges on Equation (7.20), which essentially says that time is money. If you are prepared to make that assumption, standard microeconomics applies to the demand for recreation.

7.3.3 Zonal travel costs

> Let concentric circles be defined around each park so that the cost of travel to the park from all points in one of these zones is approximately constant. The persons entering the park in a year, or a suitably chosen sample of them, are to be listed according to the zone from which they come. The fact that they come means that the[] service of the park is at least worth the cost, and this cost can probably be estimated with fair accuracy. If we assume that the benefits are the same no matter what the distance, we have, for those living

> near the park, a consumers' surplus[156] consisting of the difference in transportation costs. The comparison of the cost of coming from a zone with the number of people who do come from it, together with a count of the population of the zone, enables us to plot one point for each zone on a demand curve for the service of the park. By a judicious process of fitting it should be possible to get a good enough approximation to this demand curve to provide, through integration, a measure of the consumers' surplus resulting from the availability of the park. It is _this consumers' surplus (calculated by the above process with deduction for the cost of operating the park) which measures the benefits to the public in the particular year. This, of course, might be capitalized to give a capital value for the park, or the annual measure of benefit might be compared directly with the estimated annual benefits of the hypothesis that the park area was used for some alternate purpose.

Thus, in a 1947 letter from Harold Hotelling[157] to Newton Drury, the director of the National Park Service, was born the zonal travel cost method—and indeed monetary valuation of goods and services that are not traded on markets. The first application was published by Marion Clawson[158] in 1959.
Figure 7.1 illustrates Hotelling's concentric circles. This is conceptually nice, but not particularly realistic. People do not travel as the crow flies, but along roads, bus routes, and rail lines.
Table 7.1 further illustrates the zonal travel cost method. There are five zones around the park of interest. Visitor numbers vary between 11,250 per year from zone 3 and 48,000 per year from zone 2. Zone 2 is closer by and has a larger population. Zone 4 has a larger population still but is further away, bringing only 45,000 visitors per year. Table 7.1 also shows the visitor rate r_i, the number of visitors per head. It falls steadily with travel cost c_i,[159] which is £10 per visit for people from zone 1 and £30 for people from zone 5. Regressing the visitor rate on the travel cost, we find that $r_i = 10.5 - 0.3c_i$.
We use this regression result to predict what would happen if the cost of visiting the park would increase by £5 per visit, say because the entrance fee is raised. Table 7.1 shows the results. The visitor rate is now $r_i' = 10.5 - 0.3(c_i + 5)$. In other words, it is 1.5 (per thousand) lower than it was. The new number of visitors then follows by multiplying the predicted visitor rate by the (unchanged) number of people per zone.
Table 7.2 takes it a step further, increasing the entrance fee by £5 at a time until no one wants to visit the park anymore. Figure 7.2 shows the same information again, but graphically, as well as the total consumer surplus, by integrating under the demand function.

---

[156] Hotelling refers to the *consumers' surplus*. This is what we would now call the *consumer surplus*. Hotelling's outdated parlance is more accurate. The surplus of a single consumer is the difference between her maximum willingness to pay and the price she actually paid. The consumer surplus is the integral under the aggregate demand curve and over the price, or the sum total of individual surpluses of all consumers. The current singular in consumer surplus refers to the representative consumer, a unitary representation of all consumers.

[157] See Footnote 40.

[158] Clawson (1905-1998) worked for the U.S. government as an agricultural economist before joining Resources for the Future as a researcher.

[159] The regularity in Table 7.1 can only be found in textbooks. Real data are quite a bit messier.

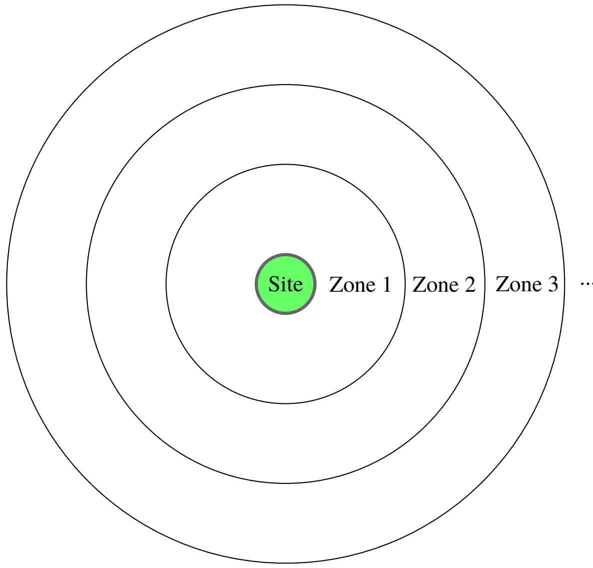


Fig. 7.1: Site and travel zones

Zone i	Observed visits v_i	Population n_i	Observed rate r_i	Travel cost c_i	Total cost $c_i + \alpha$	Predicted rate r'_i	Predicted visits $r'_i n_i$
1	15,000	2,000,000	7.5/1000	£10	£15	6.0/1000	12,000
2	48,000	8,000,000	6.0/1000	£15	£20	4.5/1000	36,000
3	11,250	2,500,000	4.5/1000	£20	£25	3.0/1000	7,500
4	45,000	15,000,000	3.0/1000	£25	£30	1.5/1000	22,500
5	34,000	22,660,000	1.5/1000	£30	£35	0.0/1000	0

Table 7.1: The travel cost method illustrated

Fee	α	£0	£5	£10	£15	£20	£25
Visitors	$\sum_i r'_i n_i$	153,250	78,000	36,750	18,000	3,000	0

Table 7.2: Total visitor numbers for various entrance fees

The definition of zones is a key step in the zonal cost model—you assume that, within a zone, travel costs are the same for all. That is a tall assumption, but visitor records may only record part of the address. However, if the study relies not on the administrative records of the study site, but collects primary data instead, then there is no reason not to ask for the exact location. In that case, every visitor has her own zone. This is known at the *individual travel cost* method. The analysis proceeds as above, but you can then of course also add other characteristics, such as age and gender.
There are several drawbacks to both the zonal and the individual travel cost model. The key drawback is that it finds the demand curve for a single site. However, the demand for any park, or whatever we are trying to value, depends on its substitutes.

Fig. 7.2: Visitor numbers as a function of the entrance fee

The value of a park falls if there are more or better parks nearby. Because we focus on a single park, we cannot study the effect of site quality on monetary value. Because the method is limited to a single site, multi-purpose trips are assumed away—you may stop by the shop on your way back from the park. With primary data collection for the individual travel cost method, questions can be asked about the quality of the trip and the opportunity cost of time. This is not possible for the zonal travel cost method. There, all trips are assumed to be the same, only differing in duration and cost. The opportunity cost of time is typically set equal to the average hourly wage.

As with all revealed preference methods, the travel cost method estimates only the value of direct use.

7.3.4 Random utility models

The *random utility model* includes competition between recreation sites and so their relative qualities.

The model works as follows. We observe that individual i chooses to visit site s out of all sites $1, 2, \ldots, S$. This implies that the utility i derives from visiting s is greater than from visiting any other site, or $U_{is} > U_{ij} \forall j \neq s$.

Now assume that tastes vary and consist of a systematic part V and a random part ε—that is why this is known as the random utility model—so that $V_{is} + \varepsilon_{is} > V_{ij} + \varepsilon_{ig} \forall j \neq s$.

The systematic part can now be made a function of observable characteristics, say travel costs and site quality: $V_{is} = \alpha c_{is} + \beta q_s$.
If we assume that ε follows a Gumbel distribution, then the probability of choosing site s equals

$$P(j = s) = \frac{V_{is}}{\sum_j V_{ij}} \tag{7.23}$$

This is the *predicted* probability. It lies between 0 and 1. The model, known as a conditional logit model,[160] is fitted by choosing α and β so that the predicted probability is as close to one as possible for the sites that are actually visited, and as close to zero as possible for the sites that were not. This is done by the method of maximum likelihood rather than the more familiar method of least squares.[161] See the Library of Statistical Techniques for guidance on how to do this.
Multiplying the predicted probability of visiting a site by the number of potential visitors, we have the predicted number of visits. More importantly, we also have the change in the predicted number of visits if travel costs change, or site qualities. Furthermore, we can predict what would happen if a site is closed or a new one, with particular qualities, is added. That allows us to compute the change in consumer surplus.
There are a few drawbacks to the random utility model. First, it predicts which *fraction* of total visits goes to each site. It does not predict how many visits there will be in total. This needs to be modelled separately. Second, the random utility model assumes *independence of irrelevant alternatives*. If you prefer to visit the Warner Bros. Studio over the Tower of London, then you would rather see Harry Potter regardless of whether Madame Tussaud is open or not. This is a reasonable assumption in many cases—but it could be that closing Madame Tussaud would mean longer queues at Hogwarts but not at the Tower.
The third, perhaps main drawback is that you need to specify the choice set: What sites are included in the study? This is a trivial decision when studying the relative attractiveness of tourist spots on Easter Island. There are only two handfuls, and the island is far away from anywhere. The example above, however, is about three popular sites in London. There are many more, and Oxford and Brighton are

---

[160] The *logit model* is used to predict a single, discrete choice: Did you vote leave or remain? Did you buy a mobile phone or not? Because it is a single choice, there can be no attributes of the choice. Logit models do include characteristics of the subjects making the choice. There are two generalizations of the logit model to choosing between multiple but discrete choices: Did you vote Tory, Labour or LibDem? Did you buy an iPhone, Samsung or Xiaomi? The first generalization is the *multinomial logit* model, which allows for measurably different subjects to make different choices but does not include attributes of the choice itself. The other generalization is the *conditional logit* model, which assumes that everyone is the same but does include measurable differences between the choices made. As we are interested in how environmental quality affects destination choice, the conditional logit model applies to the travel cost method. If you want to include both choice attributes and subject characteristics, then you should use a *mixed logit* model or, if you insist, a multinomial probit.

[161] Daniel McFadden (1937-) taught economics at the University of California at Berkeley. He was awarded the 2000 Nobel Prize in Economics for laying the foundations of discrete choice modelling, of which the random utility model is one example.

a day trip away. Any study faces the trade-off between including all the relevant competing sites without casting the net so wide that data collection and analysis[162] becomes unwieldy, if only because a larger choice set demands a larger number of visitors: In order to have adequate statistical power, your sample needs to include a fair number of visitors to each site. And there is a snowball effect. If “sites in London” includes a day-trip to Oxford, should you then not include Cambridge as well? Oxford is a day-trip from Birmingham too. Choices have to made and may well affect the results of the study.

7.4 Hedonic pricing

The third class of revealed preference methods analyzes household consumption. Hedonic pricing is the best-known example. A house that sits in a beautiful environment is worth more than the exact same house that sits in an ugly environment. The price difference is an indication of the value of environmental beauty.
Like the travel cost method, hedonic pricing is conceptually straightforward but difficult in practice. Builders are not stupid. They put the prettiest houses in the prettiest environments, and more ordinary houses elsewhere. Indeed, England’s first public parks were financed by building villas nearby. Expensive houses attract more well-to-do homeowners, who tend to be better educated and socially more attractive as neighbours. Such neighbourhoods tend to have better schools and other facilities.
Lancastrian demand[163] is the underlying principle of hedonic pricing. In the standard model of consumer demand, goods are infinitely divisible and unidimensional. If true, you can buy the exact amounts of what you need in whatever combination you desire. More often, goods come in discrete quantities—go try and buy 472 grams of pasta—and in bundles of attributes. This is true for houses: You do not buy the living room separately from the bathroom, and it comes with a garden and a distance to the bus stop. You cannot mix and match at will. You can mix pasta with what you think is the right amount of tomatoes, cheese, and oregano. You cannot do that with a house.
Therefore, a hedonic house price regression has to control for all or most of the things that explain the price of a house, besides the environmental issue of interest. This is less of a challenge than it sounds. Real estate agents are a key source of the necessary data. Advertisements include detailed descriptions of the house for sale—age, number of rooms, parking, garden—and the neighbourhood—schools, public transport, shopping—all the things that an experienced realtor thinks are relevant. Depending on the jurisdiction, other aspects may be disclosed too—energy rating, flood risk. The main disadvantage of real estate data is

[162] I write above that this model is estimated using maximum likelihood. That sounds easy but is in fact rather difficult with large data sets.

[163] Kelvin Lancaster (1924-1999) taught economics at Columbia University. He is best-known for his work on the theory of the second-best.

that typically the *asking* price is recorded. The land registry records the *sale* price but a more rudimentary description of the property. The location of the house can then be used to look up neighbourhood characteristics—average income, crime rates, ethnic make-up—and environmental quality—distance to parks and lakes, air pollution.

A key assumption is that the housing market works well, that buyers and sellers are rational and well-informed. As selling or buying a house is a major decision and both parties have expert advisors, this is not an outlandish assumption. One implication is that the characteristics of buyers and sellers are irrelevant, as they are cancelled out by alternative buyers and sellers. This is perhaps best understood with an example. We live near an excellent primary school. We paid a premium on our house for that. Our house did not lose value when the kids moved to secondary school. Even though primary school is no longer relevant to us, it is still important for potential buyers. The characteristics of the sellers are irrelevant. The same is true for the buyers. We would not accept a lower bid for our house from a childless couple than from a couple with children in primary school.

There is a major complication. The hedonic pricing method is most often applied to the housing market. Less often, it is applied to the labour market. Workers demand compensation for living in a less attractive place, are willing to accept a lower wage in a better place. However, wages do not just compensate for the attractiveness of the environment—wages also reflect the cost of living, of which house prices are a major component. House prices in turn reflect wages. That is, you really need to simultaneously estimate the hedonic house price and the hedonic wage equation.

Box 7.1: Mercury

Mercury is the first planet from the Sun, a Roman god, and a chemical element with the symbol Hg and atomic number 80. It is also known as quicksilver, which is why Farrokh Bulsara adopted this stage name. Mercury is the only metal that is liquid at room temperature. It is used in thermometers, fluorescent lamps, and many other devices. Mercury is highly toxic, both on its own and in organometallic compounds such as methylmercury $[CH_3Hg]^+$.

There are natural sources of mercury, including volcanoes, rock weathering, forest fires, and evaporation of ocean water. Mercury is also released by the burning of fossil fuels, household waste, and medical waste. Coal-fired power plants are a particularly important source.

Mercury's toxicity persists when it reacts with other elements. It bioaccumulates as methylmercury. It nestles in the various tissues of the body and is so transferred from prey to predator. Mercury concentrations increase with trophic level. Humans rarely eat the top predators of the sky and land, but we do eat the fish at the top of the aquatic food chain.

Mercury exposure in humans can lead to kidney, gastrointestinal, and cardiovascular disorders. Methylmercury can cross the blood-brain barrier and so cause neurological problems. It can also move through the placenta and affect developing brains. Low-level mercury exposure is associated with learning disabilities. Greater exposure can lead to reproductive problems. Some authorities in areas with high levels of mercury issue warnings about the consumption of fish. This is one route, perhaps the main one, through which the general public is warned about the dangers of mercury exposure. These so-called Fish Consumption Advisory notices have been shown to negatively affect house prices.

Further reading

Measuring the demand for environmental quality, edited by John B. Braden and Charles D. Kolstad, is old (1991) but good. IDEAS/RePEc has curated bibliographies on travel costs and hedonic pricing.

Exercises

7.1 Post a summary of this chapter on TikTok with #envecon

7.2 Novosibersk is a planned city. The Ministry of Housing built many identical houses at approximately the same distance of the city centre. The rental market has since been liberated. There is a chemical plant on one side of town. Air pollution therefore varies across town. Rents also vary. Both are shown in the table.

Pollution (μg/m3)	Rent (₽/month)
30	497
50	492
70	485
90	475
120	455
150	430
200	375
250	305
300	219

Plot the relationship between pollution levels and rents. On a separate graph, plot the relationship between pollution levels and the marginal valuation of pollution implicit in this relationship.

7.3 You have been commissioned to estimate the demand curve for admission to EuroLand, an amusement park near Athens. To do this, you spend a day surveying visitors to the park. You divided the area around the park into 10 zones, with the distance from the park roughly constant within a zone. You ask each interviewee where they're from. Combining that information with annual visitor numbers, you impute the visitor numbers by zone. These are the results:

Zone	Distance	Population	Visitors
1	10	5,000	500
2	20	10,000	900
3	30	25,000	2,000
4	40	10,000	700
5	50	100,000	6,000
6	60	500,000	25,000
7	70	200,000	8,000
8	80	50,000	1,500
9	90	100,000	2,000
10	100	100,000	1,000

Admission to EuroLand is €150 per person. Transportation costs, including time, are some €0.5 per person per kilometre. Calculate the demand curve for visits to EuroLand, showing visits as a function of the entry price. How many fewer visitors would you expect there to be if the admission fees is raised to €200? What is the change in consumer surplus?

7.4 Besides hedonic pricing (exercise 1) and travel costs (exercise 2), there is a third method to use revealed preferences to estimate the monetary value of economic goods and services: Defensive expenditures.

a) What is the key difference between defensive expenditures and travel costs?
b) What is the key difference between defensive expenditures and hedonic pricing?
c) What is the key difference between travel costs and hedonic pricing?

Chapter 8
Stated preferences

8.1 Introduction

The main drawback of revealed preference methods is that they can be applied to direct use values only. There are other values too. I care about whales. Nothing in my behaviour over the last 20 years will tell you that I do. I went whale-watching once, but the animals did not show and I will not go again. I do not contribute to Greenpeace, an NGO that protects marine mammals, because I disagree with their position on climate and energy. You could follow me around for years and inspect all my bank statements, but you would not uncover my love for whales. The only way to find out is to ask me directly.

Similarly, people do not visit the beach because they think this will help protect the coast for their children to enjoy. People do not pay more for a house because their friends would like the view from the bedroom. People do not accept a lower wage in an area because it has great potential for ecotourism. Whenever you travel somewhere or buy something, it is primarily if not exclusively because you want to enjoy its use. If you need to estimate the non-use value of an environmental good or service, you have to ask people.

This is exactly what stated preference methods do: People are interviewed about their willingness to pay to protect the environment. As you can ask people anything, these methods can be applied to any type of value:

- How much are you willing to pay to eat whale meat? (consumptive direct use)
- How much are you willing to pay to watch whales swim in the ocean? (non-consumptive direct use)
- Fish feed on zooplankton, which feed on phytoplankton, which feed on whale poo. How much are you willing to pay to protect whales so as to further commercial fisheries? (indirect use)
- How much are you willing to pay to protect whales so as to grow marine ecotourism in Scotland? (option value)
- How much are you willing to pay to protect whales so that we may learn something useful about their communication using sonar? (quasi-option value)

- How much are you willing to pay to protect whales so that your friends can enjoy them? (altruistic value)
- How much are you willing to pay to protect whales so that your children will enjoy them? (bequest value)
- How much are you willing to pay to protect whales so that they can exist without being bothered by people like you? (existence value)

Stated preference methods come in two major types, *contingent valuation* and *contingent choice*, discussed in turn below. Many of the design issues are the same between the two types but are only discussed for contingent valuation, the older of the two methods. Although widely applicable, both methods are subject to a range of biases, discussed at the end of the chapter. Contingent valuation may be more problematic than contingent choice.

8.2 Contingent valuation

8.2.1 Design

A contingent valuation study consists of the following steps:

8.1 You start with background research on the issues.
8.2 You then decide on the survey mode (face-to-face, mail, telephone, internet ...) and the strategy for sampling the target population.
8.3 Survey design comes next. This is discussed further below.
8.4 Pre-test the survey. Discuss it in a focus group, and interview respondents as to what went through their heads when they answered the questions.
8.5 Re-design the survey. You may need to pre-test again.
8.6 Hire and train interviewers (if applicable)
8.7 Deploy a pilot survey with real people.[164]
8.8 Re-design the survey again.
8.9 Deploy the main survey.
8.10 Data entry and quality control.
8.11 Econometric analysis
8.12 Test for validity, reliability, and other possible biases.
8.13 Aggregate the results to the overall willingness to pay.
8.14 Write the report, present the results.
8.15 Evaluate the study, draw lessons for future applications.

The first step seems trivial, but it is important to understand what you are trying to value, to understand how other people understand this, and how people might respond to your attempt at valuation. Recall that, almost always, you know more about the object of valuation than the respondents to your survey.

[164] The pre-test was probably done with students and colleagues, who are real people too, but rather unrepresentative of the target population.

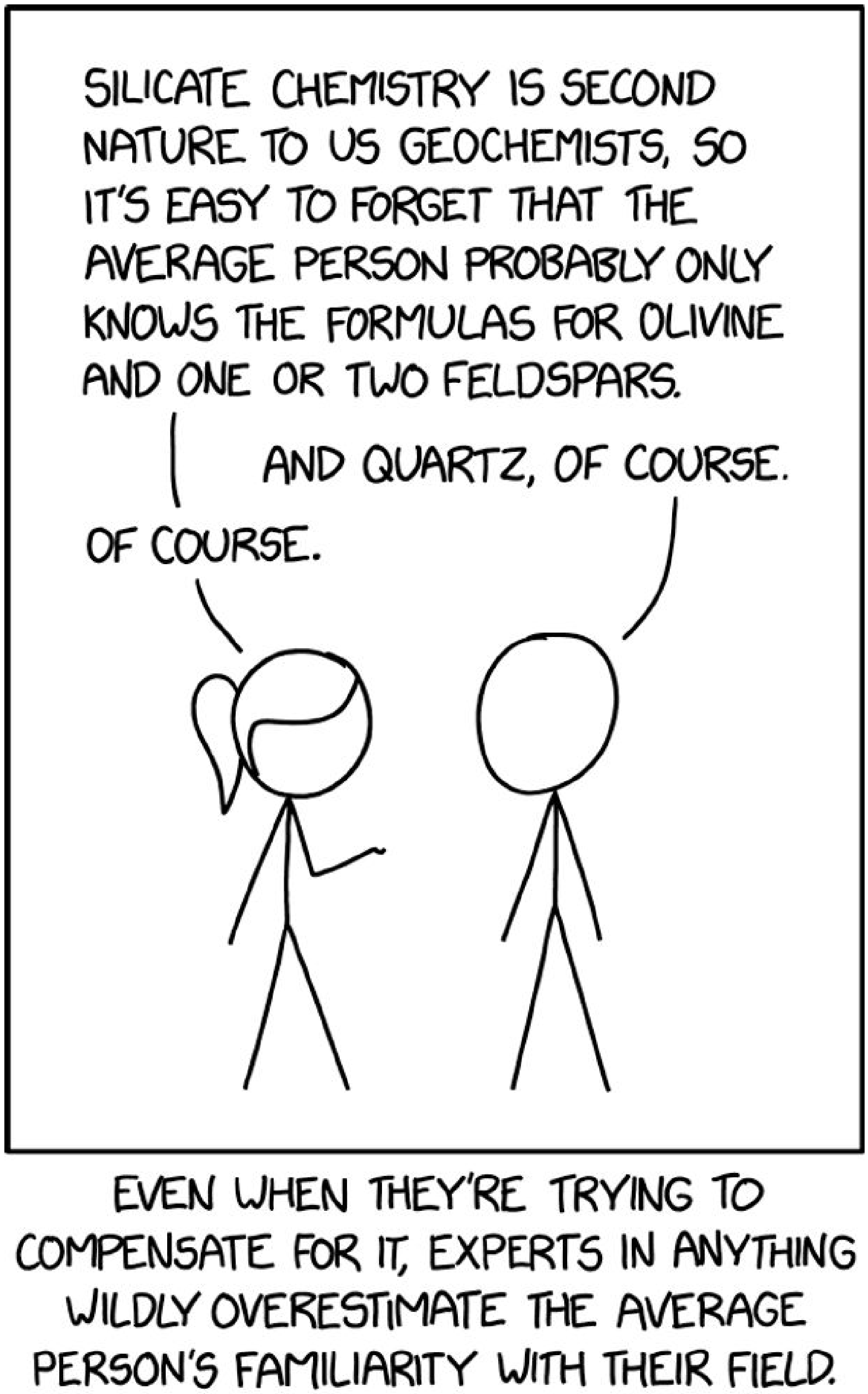


Fig. 8.1: Experts see things differently

This goes hand-in-hand with the need to test and re-design. By the time you are ready to first implement your survey, you have thought about it so much that your view of the survey is completely at odds with anyone who sees it for the first time—see Figure **??** —and views it as a chore they want to get through as quickly as possible.

The second step is key too: Internet studies are cheap but oversample younger, better-educated respondents. Respondents are less likely to rush through face-to-face interviews, but the cost is considerable. Telephone interviews will oversample those who still have a landline, who are at home during working hours, and who do not mind the intrusion. Mail surveys are readily ignored.

Surveys usually consist of the following elements:

8.1 Explore the respondent's knowledge and views. What is the state of the good or service being valued? Is the respondent satisfied with the current state of affairs?
8.2 Explore the respondent's attitudes. Does the respondent care deeply about the environment in general? And about the good or service being valued?
8.3 Describe the current situation and an alternative situation in which the environment is either better or worse.
8.4 Elicit the monetary value. How much is the respondent willing to pay to secure a better environment? Describe how said payment is made.
8.5 Explore why the respondent gave the answer she did. Is this a protest vote? Is it an attempt to influence the government? Did she try and please the interviewer?
8.6 Ask for the demographics (age, education, income, gender, race, family size). This comes at the end, because some respondents are put off by these questions.

The descriptions of the scenarios are key. The text on the current situation needs to be concise yet complete, accurate yet appealing, informative but not leading. The proposed situation needs to be credible and the difference with the current situation should be precise. After all, the elicited willingness to pay is for the difference between the current and proposed situation.

It is no good asking people for a small intervention that would prevent the extinction of whales—that is not credible. It is no good asking people for an increase in whale numbers—there are many species of whale, and an increase in number can be one or one million. Instead, you could ask respondents for their willingness to pay to increase the population of humpback whales by 5%.

The elicitation method matters too. There are several. You could ask people an open question: How much are you willing to pay? This is rather vague. As the valuation question is unfamiliar—in most of your purchases, you are offered a product at a fixed price; only in auctions are you expected to bid—responses may be strange. You could give people a choice. Are you willing to pay \$50? This *dichotomous choice* is a more familiar question, but you would need a bigger sample (and, of course, vary the \$50 between respondents). You could ask a follow-up question. If not, are you willing to pay \$25? If so, are you also willing to pay \$75? *Trichotomous choice* is more informative but more demanding for the respondents and the econometrician analyzing the results. You could follow-up your follow-up in *tessa-*

chotomous choice or add yet another layer and test your ability to count in Greek. There is a trade-off with sample size. Dichotomous choice does not yield much information per respondent: Only an upper or lower bound to their willingness to pay. Trichotomous choice gives an upper and lower bound for at least part of your sample. That is more information per respondent, so a smaller sample size would yield the same information in total.

You can also show respondents a payment card, that is, a menu of increasing prices—$25, $50, $75—from which they can choose. This is more demanding for the interviewees, but more informative for the surveyor.

Note that the prices cited above are silly. Is $50 $50 per person or $50 per household? Is this a one-time payment, a monthly one, or annual? Is that dollar Australian, Canadian, or Zimbabwean? If you do not specify this, respondents will make assumptions that you will not be able to recover.

The payment vehicle is important too. Is the financial contribution a donation to a charity, a surcharge on an entrance fee, a levy on a utility bill, or an increase in income tax? Different parts of the population will respond differently, regardless of their actual willingness to pay. People may dislike entrance fees as these imply gates and fences. Cyclists may like the idea of a parking fee for cars. Pensioners would support wage taxes as they are exempt anyway, while Republicans object to any tax increase. Issues like these would be part of the background research and the pre-tests.

Box 8.1: Light pollution

Humans do not like the dark. We started to control fire 1 perhaps 2 million years ago, but open fires are inefficient for lighting up a cave: 0.002 lumen per watt. The vegetable oil lamps of the Babylonians were much better (0.06 lumen/watt), but pale in comparison to tallow candles (0.1 lumen/watt), electric filament lamps (2.6 lumen/watt), compact fluorescent bulbs (68 lumen/watt), and LEDs (110 lumen/watt). As light is so cheap, we no longer light up a small corner of a cave. We light up the sky. Indeed, night lights, as measured by satellites, are now routinely used as a proxy for economic output and income.

This has negative implications for diurnal animals. Light disturbs sleep and so health. There are ecological effects too. Nocturnal animals that prefer the dark are at a disadvantage. The net effects of the change in species composition vary from ecosystem to ecosystem.

Light pollution upsets astronomers. A majority of Europeans can no longer see the Milky Way. Simpson and Gleeson Hanna (2009) use contingent valuation to estimate the willingness to pay of students of the Rochester Institute of Technology for less light pollution. The results are statistically and economically significant: Willingness to pay is between 1 and 2% of income.

8.2.2 Possible biases

8.2.2.1 Validity

There are various criteria by which to evaluate an empirical measurement—to assess its *validity*—in this case an estimate of the willingness to pay to protect or improve the environment.

Face validity is the first criterion, and perhaps the vaguest. Does the study make sense? Some obviously do not. There is little point in applying contingent valuation to something for which there is plenty of revealed preference data. If you want to know how much more people are willing to pay for green electricity or organically grown carrots, use market data. It does not make sense either to try and put a value on the prevention of all species loss. While this may be desirable—or perhaps not, I would be glad to see the end of the Guinea Worm—it cannot be achieved. Beyond the patently ridiculous, face validity is difficult to falsify.

Another criterion is *construct validity*. Does the study value what it intends to value? For instance, one study estimated the willingness to pay to underground a road near Stonehenge, so as to improve the view from the monument. This has been interpreted as the value of Stonehenge. It is not. Another study estimated the willingness to pay to protect fairy mounds, which mark the landscape of Ireland. This has been reported as the value of fairies. Jokes aside, the survey needs to be designed so that the respondents indeed value what the analyst hopes to value. There may be divergence because of careless wording in the survey, or because the human mind habitually interprets and contextualizes any information it receives.[165]

This is related to a third criterion, *content validity*: The willingness to pay expressed by the respondents may be for only a small part of what the analyst had in mind or, more commonly, for something larger. For example, the questions in a contingent valuation study may be about the preservation of humpback whales, but the answers could be about humpback whales near Newfoundland (a subset) or about all baleen whales (a superset).

Criterion validity is a call for accuracy. This is obviously desirable but hard to prove. Therefore, criterion validity is often interpreted as using best practice. Empirical measurements that used an outdated method are not worth much, particularly if the older method has known flaws. It is sometimes hard, however, to distinguish between "best practice" and "latest fad". Criterion validity can be tested by using different methods to value the same good or service. For instance, travel cost studies use interviews and are therefore readily combined with contingent valuation studies.

Convergent and *divergent validity* are one way to operationalize accuracy. Convergent validity asks whether the monetary value of similar goods and services correlates with the value of the good or service being studied. Is the value of this

[165] You may have noticed that people rarely answer the question you asked. Instead, if at all, they answer the question they think you asked, should have asked, or were too shy to ask. Indeed, taking people literally is a symptom of autism.

lake similar to the value of nearby lakes? Divergent validity is its complement. Unrelated goods and services should not correlate. A willingness to pay for entry into a nature reserve could be interpreted as a desire to protect nature, but it may also be seen as a wish to be away from people who cannot afford the entrance fee.
Compatibility with theory is a third way to operationalize accuracy. Own-price elasticities are typically negative, income elasticities positive. Preferences are transitive and monotone. If a study finds the opposite, it has some explaining to do.
The main problem with accuracy is that we do not know the "true" value. It is therefore impossible to assert that the measured value is right or wrong. Instead, we can look at *test-retest reliability*: Repeated valuation of the same or similar good or service in the same or similar context using the same or similar method should lead to roughly the same result.

8.2.2.2 Biases

A key problem with stated preferences is that they are *stated*, rather than revealed. This is known as the *hypothetical bias*. Respondents are asked what they would do, rather than are observed what they do do. Respondents spend fictional money on an imaginary solution to a fabricated problem. Some therefore dismiss contingent valuation studies as "ask a hypothetical question, get a hypothetical answer".
That may be a bit harsh. There are various ways to reduce hypothetical bias. It is important to give respondents time to think, because the questions asked are typically not just hypothetical but also unfamiliar—recall that contingent valuation methods are typically applied to goods and services that are not routinely traded on markets. Such time can be created by describing the scenario at the start of the questionnaire and asking the willingness to pay question at the end. Surveys can also be administered by mail, leaving respondents time to ponder.
Another option is to remind respondents that a serious answer is expected with a so-called cheap talk script. Here is an example:

> Studies have shown that people answering surveys such as this often say that they are willing to pay more than they would if the situation was real and this amount of money actually had to be handed over.
>
> What our 'yes' vote really means is that we are basically good people, and that we would like to see good things happen!
>
> But when the situation is real, and we would actually have to spend our money, we think in a different way. We basically still would like to see good things happen, but when we are faced with the possibility of having to spend money, we think about our options: If I spend money on this, that's money I don't have to spend on other things.
>
> So while answering this next question please think as if the situation we described were real and you would actually have to pay the amount of money stated.

Protest bids are another common problem in contingent valuation studies. Respondents can object to all sorts of things, including the payment vehicle, the proposed policy, and the very fact of monetary valuation. Protest bids manifest themselves as a zero willingness to pay. In order to distinguish protest bids from genuine zeroes, follow-up questions are in order. Typically, an open question will do—“why zero?”—to let respondents explain their bid.

Non-response bias would happen if the people who respond to the survey are not representative for the population. Young people are less likely to have a landline, old people to have internet. Busy people and foreigners avoid surveys if they can. These problems can be overcome by the appropriate weighting of the responses. It is more problematic if people opt out of the survey because of a characteristic that is not observed or, worse, because they have a strong opinion on the core theme of the survey. Unfortunately, the analyst cannot know this, because non-respondents are typically unknown.[166]

Respondents who notice that they are being asked for a hypothetical rather than an actual contribution, may *strategically bias* their response. They may care deeply for the environment. They may realize that they are not being asked to pay, but that their answer will be averaged with 1,000 other people, and suspect that the government will pay based on that average. If so, their rational response is to exaggerate their willingness to pay. Others may, less effectively, understate their willingness to pay for the opposite reason.

If willingness to pay is asked in an open question, strategic bias can only be found through the statistical detection of outliers. Only egregious exaggeration will be noticed. Elicitation methods, such as the payment ladder and dichotomous choice, on the one hand, limit the scale of strategic bias of any one respondent but, on the other hand, make it impossible to detect.

Dichotomous and trichotomous choice suffer from *starting-point* bias. The prompt may affect the respondents’ willingness to pay, as they think they have just been quoted a reasonable price. Splitting the sample into different starting-points helps, and is necessary anyway to obtain a demand curve. The range of starting-points may still exclude some legitimate bids, though.

Payment ladders have a similar problem, called *anchoring bias*. Some respondents may have no strong preference for the valued good or service, instead rely on a heuristic that they use for shopping, such as “always pick the middle price, not too high, not too low”. It can also be that the introductory text of the survey or the description of the scenario prompts the respondent to think about certain numbers. Again, sample splits help.

Information bias is an intractable problem. You cannot ask questions out of the blue. Every survey needs an introduction about the issues at hand. A contingent value study cannot do with a description of the scenario. This inevitably either tells the respondents something they did not know or reminds them of things they did. The very act of observing preferences may thus affect said preferences, a Heisenberg type of problem. A well-designed survey avoids *leading* questions or otherwise steering respondents in a particular direction—but information has to be provided, and preferably in a way that engages the audience.

Prominence bias is related to information bias. The very fact of being interviewed may lead the respondents to think that the issue at hand is more important than

[166] Most survey companies have a panel of respondents to multiple surveys, but they rarely share data across surveys.

they thought. *Yea-saying* is similar. Some respondents tend to want to please their audience. If an interviewer asks about my willingness to pay to protect whales, that much be because she thinks it is important, so I would do better to agree. Other people are, of course, *nay-sayers*.

Yea-saying and nay-saying may be more pronounced for certain interviewers—compare and contrast your response to a physically attractive interviewer and one with bad breath. *Interviewer bias* is relevant only for face-to-face and telephone interviews. It can be very important. A friend of the author administered a survey on the mathematical skills of ethnic minorities; she felt sorry for some of them, and helped them with their answers. An infamous example comes from testing for HIV, a survey that involved blood sampling. (You can imagine some issues with non-response here.) One interviewer did not want to ask people for their blood, and submit blood samples from a cow instead. Another interviewer submitted his own blood. (This was discovered because all his respondents appeared to be HIV-positive.)

The final, perhaps most serious bias goes by various names: *part-whole bias*, *embedding* or *temporal embedding*, *scope insensitivity*, *sequence effects*, and the *adding-up problem*. The most prominent example comes out of the Exxon Valdez litigation. The Exxon Valdez was an oil tanker that ran aground in the Prince William Sound, Alaska, on 24 March 1989, causing large damage to local wildlife. Compensation was demanded but the defendants hired prominent economists to cast doubt on the validity of the damage estimates. In one such study, respondents were asked for their willingness to pay to cover up oil ponds, saving migratory ducks. One-third of the sample was asked about saving 30,000 ducks, one-third about 300,000 ducks, and one-third about 3,000,000 ducks. The average response was statistically indistinguishable for the three subsamples. That is, the payment *per duck* varied by a factor 100.

Similar observations are made when people are asked to pay per month or per year: Responses do not seem to differ. Ditto for smaller and larger areas, whole and subpopulations. And sometimes this is not just observed between subsamples of the respondents, but for individual respondents too.

One interpretation is that contingent valuation is invalid. Observed preferences are not monotone, a clear violation of economic theory. People should be willing to pay more for a larger quantity. A milder interpretation is that the data are so noisy that no firm conclusions can be drawn.

There are two other interpretations. The first and most popular one is that people get a “warm glow” from contributing to a good cause. They prefer not to think about all the misery in the world, but do contribute to charity. They may work with a rough annual budget, say \$500, and a rule of thumb that they contribute \$50 to the first 10 requests for a donation. If the willingness to pay question is interpreted as such a donation, the answer is independent of the size of the good or service being valued. As long as it is seen as a good cause, the monetary amount will be the same.

The second alternative interpretation is that people cannot count, or cannot be bothered to. People may count ducks as 1, 2, 6, many; 30,000 and 3,000,000 ducks then both are many ducks and thus worth the same in the respondent's eye.
This ties in with a recent development in economic theory—just noticeable differences—and an older one—satisficing. The standard assumption of rationality and full information implies that we can and do know the difference between 30,000 and 30,001 ducks. I am not very good at counting ducks because they rarely sit still and it does not really matter to me. People make decisions based on what they know; and what they know depends on what they care about. I know Uncle Pier scored in the 40th minute against Ipswich Town but I am less up to speed with the size of the duck population in Alkmaar. The answers given in a survey are coloured by a lack of interest.
These two alternatives resurrect contingent valuation as a valid method, but the implication is that respondents do not answer the questions asked, but rather respond to something much vaguer.

Box 8.2: Value without rizz

Contingent valuation is limited to charismatic megafauna. People enthusiastically contribute to the conservation of elephants, tigers, and orangutans; dung beetles, not so much—a few Maya the Bee fans apart (but most are impecunious).
Dung beetles are nonetheless valuable. Stanbrook-Buyer *et al.* (2024) show that dung beetles accelerate cow pat decomposition from 4 to 11 gram per day. This is important because cattle avoid eating grass near manure. Furthermore, such grass matures faster and is therefore less palatable. Dung beetles thus allow for a 48% increase in cow density. Stanbrook-Buyer reckons this is worth some $1 million per year in Florida. This is small—Florida's gross product is around $1 trillion—but Florida is not the centre of dairy and beef farming.
More importantly, while CVM may not be the right tool for estimating the value of uncharismatic microfauna, that does not mean that dung beetles and similar critters are without value to humans.

8.3 Contingent choice

The contingent choice method seeks to overcome some of the shortcomings of the contingent valuation method, particularly the biases introduced by its unfamiliarity. No one has ever asked you how much you are willing to pay for a box of cornflakes. It is indeed a very strange question to ask. If you feel like eating cornflakes for breakfast, you go to the supermarket where you are confronted with a range of choices: Boxes of different colours and sizes, a variety of flavours, options with-

out gluten or sugar, organic and fair-trade cornflakes, and different prices. You pick from that menu.
The contingent choice method does essentially the same, albeit in a hypothetical fashion: Respondents are asked to choose from a menu, options with a better or worse quality of the environment, and higher and lower payment. And just like in the supermarket, there is always the option to walk away empty-handed. Contingent choice thus takes away some of the unfamiliarity bias in contingent valuation.
The overall design of a contingent choice study is the same as above. The key difference lies in the core questions about willingness to pay. Instead of a payment ladder or an open question, you present the interviewee with a number of choice cards. A choice card typically shows the alternative options in columns and their attributes in rows, like this:

Which option do you prefer?

	option 1	option 2	option 3
attribute A	high	middle	low
attribute B	low	high	middle
attribute C	middle	low	high
your choice			
none of the above			

A worked example would be something like this:

Which option do you prefer?

	option 1	option 2	option 3
Average number of sewage spills to rivers and seas, per day	825	425	25
Average number of sewage spills into homes, per day	1	100	10
Sewerage bill, per household per year	£450	£475	£600
your choice			
none of the above			

There are trade-offs in survey design. Many choice cards with fine-grained distinctions would yield a lot of information but test the patience of the respondent. A few choices with course-grained differences would be easy on the interviewees but not reveal much about their preferences. More attributes would be more informative but may test the cognitive skills of the people taking the survey.
There are design issues too. Attributes should have visual parity, lest the eye focuses on one at the expense of the others. There should be a trade-off on all choice cards—less pollution, higher cost—or perhaps on all but one to test whether the respondents are actually paying attention. The description of attributes and their levels should be precise, clear, intuitive, and concise. All of this is easier said than done. Careful design and pre-testing are key.

The analysis of the data proceeds as with the random utility model for travel. The appropriate statistical model is the conditional logit.[167]

Further reading

IDEAS/RePEc has curated bibliographies on contingent valuation and contingent choice.

Exercises

8.1 Post a summary of this chapter on TikTok with #envecon
8.2 The payment vehicle is a key design element of any stated preference survey. Discuss appropriate ways to pay for:
   a) maintenance of a nature reserve
   b) a new nature reserve
   c) a walking path across a farm
   d) rhinoceros conservation
   e) reduced sewage spills
8.3 Which of the biases in contingent valuation do you think is the largest?

[167] See Footnote 160.

Chapter 9
Criteria for policy instruments

The next chapters discuss a large variety of things a regulator can do to improve the quality of the environment. This requires a systematic comparison. I do so based on the following criteria:

- Cost-effectiveness
- Administrative costs
- Environmental effectiveness
- Long-run effects
- Flexibility
- Equity

Before discussing these criteria in turn, it is important to note that the design of environmental regulation should reflect the environmental problem at hand. Above, we looked at the differences between a flow pollutant and a stock pollutant. That is important for target-setting. It is also important for instrument choice. Policies to reduce stock pollutants need to last a long time and so need to be robust to changes in public mood and political will. This is less important for flow pollutants.

The environmental medium is key too. Air pollutants get blown around by the wind and may cross borders between jurisdictions. Water pollutants move too but in one direction only (downstream). Soil pollutants stay in place. Soil pollution can therefore be contained, either with a soil clean-up or a fence around the polluted area. This does not work for water and air pollutants.

Point sources of pollution should be approached differently than diffuse sources. There are 443 nuclear power plants in the world, using a handful of designs, and operated by two handfuls of companies. Numbers are, of course, much smaller in each jurisdiction: Only 8 plants and 2 companies in the UK. Regulation of nuclear waste is technically difficult but easy to organize: Just talk to EdF. There are about 1.5 billion cars on the planet, 33 million in the UK. Coordinating so many different users is a challenge.

Some environmental problems have a large impact in a small place, other problems have a small impact in many places. Dioxins are an example of the former. Dioxins form if municipal waste is burned at a low temperature. Dioxins cause cancer but

do not travel far. This can be solved by moving incineration away from residential areas and grazing land. This does not help against sulphur which can travel hundreds, sometimes thousands of kilometres in the air.
Finally, it matters whether the environmental problem is local, regional, national, continental, or global. Authorities at different levels have different powers. A tax on emissions cannot be imposed by the United Nations and most cities lack that power too. Countries have border controls but counties do not.
The nature of the environmental problem thus matters for its regulation. You need to understand a problem before you can hope to solve it.

9.1 Cost-effectiveness

Let us consider a social planner, who seeks to reduce emissions at a minimum cost to society:

$$B = \sum_n B_n = \sum_n \beta_n R_n^2 \tag{9.1}$$

where B are the total costs of emission reduction, B_n are the costs of company n, R_n are the emission reduction efforts of company n, and β_n are parameters, the unit cost of emission reduction. Let R denote the desired total emission reduction effort. Then, the least-cost solution to the emission reduction programme follows from

$$\min_{R_n} \sum_n B_n \text{ s.t. } \sum R_n \geq R \tag{9.2}$$

Form the Lagrangian

$$\mathcal{L} = \sum_n \beta_n R_n^2 - \lambda(\sum_n R_n - R) \tag{9.3}$$

and take the first partial derivative to the policy instruments (i.e., the emission reduction effort) to derive the first-order conditions for optimality:

$$\frac{\partial \mathcal{L}}{\partial R_n} = 2\beta_n R_n - \lambda = 0 \forall n \Rightarrow \frac{\partial C_n}{\partial R_n} = \lambda \forall n \tag{9.4}$$

That is, least-cost emission reduction requires that all emitters face the same abatement cost at the margin. Because there is a shared constraint R, the shadow price of the constraint λ is set at the societal level and is thus the same for all emitters.
The least-cost solution to meet a target is known as the *cost-effective* solution.
Cost-efficacy is an optimum. A solution cannot be more cost-effective than another solution; it is either cost-effective or it is not. Some people use the words “more cost-effective" as an “erudite" alternative to the word “cheaper", but in fact they demonstrate their lack of understanding of the meaning of the concept cost-efficacy. Other people, particularly native speakers of French and German, use the word “cost-efficiency" as a synonym for cost-efficacy. In fact, cost-efficiency is the dual of productive efficiency, and if you do not understand what that means,

then you should not use the word cost-efficiency.[168] Recall that besides productive efficiency, we also care about allocative and consumptive efficiency, which are included in cost-efficacy if applied at the macro-scale.

9.2 Administrative costs

The above assessment of cost-effectiveness only considers the costs of emission reduction. However, there are other costs too, particularly the costs of monitoring and enforcing environmental regulation. These administrative costs can be substantial and can differ greatly between policy interventions.

A Pigou tax is an excise, a tax on consumption that is proportional to some physical characteristic of the product. Excises are not cheap to implement, but they have been already. Retail companies routinely collect excises on behalf of the tax authorities. It is therefore cheap to raise existing excises to reflect damage to the environment or to introduce new excises on products that are sold through outlets that already sell other excised products. This is a matter of changing some parameters in existing computer code.

Similarly, most consumer products and production equipment are already subject to a wide range of regulations for performance and safety; and many are regularly checked while in use. Changing such regulations for environmental purposes requires a change in current practice, but can be done without setting up a new bureaucracy. Such interventions thus have a low administrative cost.

Other interventions are more expensive. A system of tradable permits, for instance, demands that every polluter monitors emissions with a legally prescribed level of precision and accuracy. A market for permits needs a trading floor and brokers. The regulator must compare the number of permits held to the amount of pollutants emitted, and prosecute non-compliance. All this requires equipment and labour, and so imposes costs.

Environmental permits that are not traded still require monitoring and enforcement. Eutrophication policy is one example. Farmers in some countries are now required to account for the manure produced by their animals, and for the way this is disposed of. Some nature conservation schemes reward farmers for the number of birds nesting in their fields—which requires counting nests. This adds to the costs of environmental regulation.

Administrative costs should be kept to a minimum. This can be difficult. Some administrative costs fall on polluters, who thus have an incentive to protest excessive regulations. Other administrative costs fall on the regulator. Regulators like additional bureaucracy as it increases their budget and so their importance in the civil service and their chance of promotion.

---

[168] Reminder: In the primal formulation, a company maximizes output subject to a constraint on production costs. In the dual formulation, a company minimizes costs subject to an output constraint.

Administrative costs can be a decisive factor in environmental policy. For instance, road fuels are taxed in many countries. Such taxes are cheap to impose. A fuel tax makes sense from a climate perspective: The carbon dioxide emitted is proportional to the fuel burned. Air pollutants, however, rather depend on driving behaviour, and the location and timing of the trip. Congestion depends on the time and location of travel. Taxes to reduce congestion and air pollution would require a detailed account of where, when and how you drive. Collecting such data used to be prohibitive—nowadays the concerns are about privacy rather than feasibility—so actual policies are simple if not crude. Urban air pollution is combated by imposing technical standards on all cars, including on cars that never come near a city. Congestion is combated by banning certain vehicles at certain times.

Box 9.1: Eutrophication

Eutrophication may strike Greek speakers as a peculiar problem: ευτροφος means well-fed. Eutrophication is caused by *excessive* amounts of nutrients, such as phosphates and nitrates. This leads to the growth of phytoplankton and algae and, consequently, the depletion of dissolved oxygen—which is why the Americans call this hypoxia, from the Greek υπο (under) and οξύ (acid, the first component of our oxygen). The lack of oxygen leads to the death of fish and shellfish. This has ramifications for biodiversity, fisheries, recreation—clear waters turn into green soup—and health—many algae are toxic to humans and other animals, while excess nitrate in drinking water turns babies blue.

There are multiple sources of the phosphates and nitrates that cause eutrophication. Detergents used to contain phosphates; phasing out started in the 1970s. Human and animal waste is another source. The former requires tertiary treatment of wastewater, which is far from universal in rich countries; the latter is rarely treated at all. Artificial fertilizers are another source. Risk-averse farmers often oversupply these, and the excess nutrients end up in ground- and surface water. Finally, there is atmospheric deposition: nitrous oxide is formed when fossil fuels combust.

Eutrophication is a hard problem to solve. Removing phosphates from detergents was relatively easy: There are substitute chemicals. Companies started advertising environmentally-friendly washing power well before the dirtier products were banned. There are technical solutions for the other sources as well, but roll-out is slowed because long-lived capital needs to be replaced or substantial new investment is required. Wastewater treatment plants are gradually upgraded to include nutrient removal, and sewerage systems to reduce spillage. Intensive animal farms now have waste management plans to reduce nutrient run-off, which requires storage, treatment, and limitations on dispersal.

Most of these measures are direct regulation but some market forces are also at play. Precision agriculture reduces the overapplication of fertilizers and may be profitable. Renewable energy gradually replaces fossil fuels, stimulated by a mix of regulatory standards, carbon prices, subsidies, and relative price changes.

9.3 Environmental effectiveness

The impact on the environment is an obvious criterion against which to evaluate environmental policy. Or it should be. Policies, including environmental policies, are typically supported by a broad coalition with a wide range of motives. Policies as enacted are often very different from policies as initially conceived. Various parties spin policies to put themselves in the best possible light. Because of these reasons, policies are not always what they seem, and environmental policies do not necessarily have the advertised impact on the environment.

On top of that, people and companies may respond differently to a policy intervention than the regulator had envisaged, The environment may not improve as much as planned, or even deteriorate. Or regulations may not be monitored and enforced and have little effect as a result.

All this is rather abstract. Let us look at a few examples. Road space rationing based on license plate parity is one. This was first tried in Athens in 1982. The Δακτύλιος programme only allows cars with even registration numbers to drive into the inner city on even dates, while cars with odd numbers are allowed in on odd dates. In a wider area, these restrictions apply only at times of high air pollution or congestion. Similar restrictions have been imposed in Santiago de Chile, México City, Manila, São Paolo, Bogotá, La Paz, San José, Quito, and all of Honduras. As there are just as many even-numbered as odd-numbered cars, this would cut the number of cars on the road by two. However, wealthier households now own two cars while poorer households resort to daily switching the number plates on their one car.

As another example, water companies in the United Kingdom are allowed to release untreated wastewater only in rare circumstances, such as heavy rainfall, blockage, or equipment failure. However, following years of underinvestment and asset sweating at the water companies combined with austerity affecting monitoring and enforcement at the water and environment regulators, raw sewage is now routinely dumped in the surface waters in and around Great Britain. The *force majeure* exception, rightly included in the legislation, provides a loophole that is used on a regular basis. In both examples, the effect of the regulation is not as intended.

9.4 Long-run effects

Environmental policy should improve the quality of the environment. It should do so in the short run as well as in the long run. In the discussion below, it will become clear that both environmental taxes and subsidies reduce emissions in the short run—but that taxes reduce emissions in the long run too whereas subsidies increase emissions above where they would have been. Policy instrument choice should take this into account.

9.5 Flexibility

Circumstances change all the time. We may discover new impacts on the environment from substances that were previously thought harmless—indeed, the environmental movement arguably started with the discovery of the impact of pesticides on bird reproductive success. We may develop new chemical compounds with new environmental effects. We may find new ways of reducing emissions, or new alternatives to polluting activities. Good environmental policy is therefore flexible: As new information arises, both targets and instruments need to adjust to the new situation.

Introducing new regulations always takes time. There are procedures to be followed, stakeholders to consult, impact assessments to be commissioned. However, different regulations adapt differently. Regulation that relies on detailed, technical prescriptions resists innovation. This is the case, for instance, in agriculture. It takes a long time to approve new pesticides, also if these new pesticides would replace old ones that are worse for farmers and the environment. If, instead, emissions are taxed, then new, low-emission technologies can be slotted into the production process without delay.

9.6 Equity

Environmental policy comes at a cost. Emissions that used to be free and unlimited are no longer free if taxed, unlimited if capped, unregulated if regulated. It is not just the total cost that matters. Section 9.1 above shows how to minimize the total cost. The *distribution* of the costs matters too.

Agriculture, energy, and transport are the economic sectors that pose the greatest burden on the environment. These sectors produce goods and services that are necessary. Poorer people tend to spend a larger share of their income on food and fuel than richer people. This implies that environmental regulation tends to be regressive as it increases the prices or restricts the availability of necessities. This is an argument to keep the *total* costs of environmental regulation low.

Some policy instruments have better implications for distributional justice than others. Direct regulation and taxation both raise costs and prices, but taxes bring government revenue that can be used to offset the negative impacts by raising incomes. Capital subsidies promote green investment but require co-financing and therefore disproportionally favour wealthier households. These things matter and should be assessed in policy instrument choice.
Although environmental policy tends to place a heavier burden on poorer people, and poorly designed environmental policy more so, environmental problems also tend to particularly affect the least well-off in society. Cleaning up the environment therefore primarily benefits the poor. The chapter on environmental justice discusses this in greater detail.

Further reading

Policy Instruments for Environmental and Natural Resource Management by Thomas Sterner and Jessica Coria is an excellent book.

Exercises

9.1 Post a summary of this chapter on TikTok with #envecon
9.2 Suppose that the costs of emission reduction of company n equal $B_n = e^{R_n/\beta_n}$. What is the cheapest way to meet the social target $\sum_n R_n \geq R$?
9.3 Suppose the costs of emissions reduction equal $B_n = \beta_n R_n^2$. Find the non-envy solution $B_n = C$. How does this compare to the cost-effective solution?

Chapter 10
Direct regulation

10.1 Introduction

Direct regulation, also known as command-and-control is by far the most common form of environmental regulation. Environmental policy came of age in the 1970s and 1980s. At the time, the environment in Europe and North America was dirty. Air, soil, and water were contaminated with toxic substances, often originating from a few large sources of pollution. In those days, environmental regulators were often natural scientists and lawyers by training—they still are—and they did what came naturally to them: Proscribe pollution or, if infeasible, prescribe alternatives. Direct regulation was very effective. The environment is much cleaner now than it was 40 years ago, at least in rich countries. The young people who pioneered environmental regulation rose in the ranks of the bureaucracy and, looking back at their past successes, hired people who too saw the power of direct regulation. Although the nature of environmental pollution has fundamentally changed—instead of a few large polluters we now have many small polluters; in lieu of obvious and acute harm to people, we now have subtle and chronic problems—environmental policy still to a large extent relies on instruments that worked well in an earlier era.

10.2 Types of direct regulation

Direct regulation tells polluters either what not to do or how to do it. Direct regulation can affect

- inputs into production and consumption—e.g., cars have to meet a minimum standard for fuel efficiency
- technology used in production and consumption—e.g., you are not allowed to drive a car without a catalytic converter
- outputs of production and consumption, including

  - volume measures on production and consumption—e.g., a cap on the total number of cows and pigs, or on the number of new houses
  - products characteristics—e.g., you cannot sell toys for toddlers with carcinogenic paint
  - waste arising from production and consumption—e.g., there is a maximum amount of sulfur dioxide that may be emitted by power plants

- timing of production and consumption—e.g., airplanes cannot take-off before 6 am or land after 11 pm at some airports
- location of production and consumption—national parks have strict limits on the economic activities within their borders
- prohibition of production and consumption—e.g., it is forbidden to make, sell, buy or own chlorofluorocarbons

10.3 Assessment

Equation (9.4) has that, in a cost-effective solution, the marginal costs of emission reduction are the same for all polluters:

$$\frac{\partial C_n}{\partial R_n} = 2\beta_n R_n = \lambda \forall n \Rightarrow R_n = \frac{\lambda}{2\beta_n} \tag{10.1}$$

A regulator can achieve this only if she knows β_n—the marginal costs of every polluter—and if she is allowed to discriminate between polluters based on their marginal costs.

Marginal abatement costs are rarely observed, but progress is being made on its measurement. Essentially, you need to estimate a production function that includes either the pollutant or the abatement technology, and use this to assess the total and marginal costs of emission reduction. This is doable if the right data are available, although even then you should not expect highly accurate estimates of the costs at the margin. However, direct regulation is often very specific and data may not be available. Returning to the examples above, data on the fuel efficiency of cars or the sulfur emissions of power plants are easy to get. Data on the chemicals in paint are not—or rather, data that are useful to a chemist can be had, data that are useful to an economist are much harder to find.

Even if the regulator would know the marginal abatement costs of every polluter, she may not be able to use that information. Discrimination is only allowed on simple, easily observable criteria, such as firm size, and then typically only in a few broad categories. A regulation that treats every firm differently is never going to happen. Direct regulation is, for legal and pragmatic reasons, one-size-fits-all.

There are conditions under which one size indeed fits all. If there are few large polluters, then it can be that the same regulation has a similar impact on these companies. One example is power generation. Economies of scale in thermal power dictate that there are a few, large generators of electricity. Nuclear power has a single

supplier in most countries. The power grid is a *natural* monopoly. In these circumstances, direct regulation may be appropriate: One size fits a few.
Direct regulation can also be close to cost-effective if there are many small but similar polluters. As they are all almost the same, one size nearly fits all. The fishing industry is an example. Because of the cut-throat competition in an open-access resource, fishing technologies are homogenous across companies. A regulation on, say, the mesh size of fishing nets would affect all fisherfolk similarly.
You need to be careful here. There are only two types of internal combustion engines: The Diesel engine (burning diesel) and the Otto engine (burning petrol or gasoline, depending on where you are from), both named after their inventors. It would be tempting to think that direct regulation of internal combustion engines would be cost-effective. This is not the case, because different people use the same technology very differently. For example, the requirement to have a catalytic converter fitted increases the price of every car by roughly the same (modest) amount. However, that catalytic converter avoids a lot of pollution in a car used by a sales representative but only a little in a car used to go to church once a week. One size fits all if both technology *and its use* are homogeneous.
Direct regulation is therefore an appropriate form of government intervention for some environmental problems, but it is less suited for other issues.

Box 10.1: The closing of the hole in the ozone layer

Fifteen to 35 kilometres above your head, the atmosphere is “rich” in ozone—for every million molecules, some ten are ozone, O_3. This so-called ozone layer is important because it keeps out ultraviolet radiation, particularly UV-B with a wavelength of 280 to 315 nanometres. UV-B radiation causes blindness and cancer and perhaps genetic damage too.
Chlorofluorocarbons (CFCs) were invented in 1928 as an alternative to the acutely toxic refrigerants used before. CFCs are brilliant. They have a wide range of applications beyond refrigeration. They are inert, do not react with anything. That means that you do not need to change the cooling liquid in your fridge, that fire extinguishers stay good for a very long time, and that you do not need to worry about the best-before date on deodorant and hairspray. It also means that you can freely vent CFCs into the atmosphere. Unfortunately, CFCs are not as inert as people thought. In the presence of UV-B radiation, CFCs react catalytically with ozone—one CFC molecule can destroy 100,000 ozone molecules.
When first discovered, the consequent thinning of the ozone layer was dismissed as a measurement error. It was real, though. This thinning was particularly pronounced over the South Pole. This was dubbed the “hole in the ozone layer".
This is one of the success stories of direct regulation. In 1987, the Montreal Protocol stipulated that CFCs should eventually be banned in a few countries. Later amendments brought in new countries and moved the ban forward in time. Direct regulation was successful because there was a

technical substitute for CFCs: Hydrochlorofluorcarbons (HFCs) are almost as good and only slightly more expensive. CFCs are now banned in most countries: You cannot make, sell, buy, or use them. The hole in the ozone layer is gradually closing.

10.4 Voluntary agreements

Direct regulation only works well if the regulator has intimate knowledge of the sector to be regulated. This is rarely the case. Realizing their relative ignorance, regulators try to co-opt the regulated. That is, governments and industry negotiate over emission targets and how to meet them. The results of these negotiations are then laid down in a voluntary agreement.

Note that this is a euphemism. Typically, the government threatens direct regulation or some other intervention if an agreement is not reached voluntarily.

Voluntary agreements go beyond the normal consultation that, at least in democracies, precedes new legislation or regulation. Governments do this to gauge popular support for or opposition to the planned intervention, and to discover potential problems that civil servants and their consultants did not think of—governments also do this because there is a statutory obligation to consult. However, a consultation is not a negotiation. Regulations are imposed whether the regulated agrees or not.

Voluntary agreements make use of the information in industry, and can therefore achieve the same improvement in environmental quality at a lower cost. Industry may of course use the negotiations to argue for less stringent regulation. Figure 10.1 shows that this can be beneficial nonetheless because there are two opposite movements. On the one hand, regulation is less stringent; this is bad for the environment but good for producers and consumers. On the other hand, regulation is cheaper, which is good for producers and consumers without harming the environment. Figure 10.1 shows that less stringent regulation at a lower cost can be beneficial.

Figure 10.2 shows the decisions and their pay-offs. In the first stage, the regulator decides whether or not to start negotiating a voluntary agreement. If not, the decision passes to the legislature, which may or may not impose new regulations. If a voluntary agreement is offered, the polluter may or may not accept it. If an agreement is reached, abatement is A_V as in Figure 10.1. If no agreement is reached, the decision reverts to the legislature. If we assume that it acts with probability p, the expected pay-offs are fully known. The polluter pays $C'_M A_M$ with mandatory regulation and $C'_V A_V$, so it should accept the agreement if $C'_V A_V < pC'_M A_M$. That is, if there little chance of mandatory regulation, there is no reason to agree to voluntarily reduce emissions. Without the stick of mandatory regulation, the carrot of voluntary abatement is not attractive.

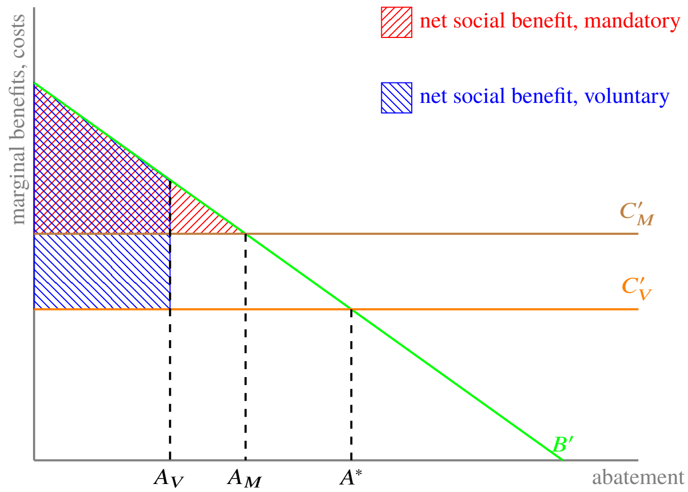


Fig. 10.1: Mandatory regulation and voluntary agreement
Marginal benefits of pollution abatement B' are shown in green, marginal costs in brown for mandatory regulation C'_M and in orange for voluntary agreement C'_V. Three levels of abatement are shown: Optimal abatement under perfect information $A*$, mandatory regulation A_M, and voluntary agreement A_V. The net social benefit of mandatory regulation equals the red area, of voluntary agreement the blue area.

The regulator should offer a voluntary agreement if $NSB_V(A_V) > pNSB_M(A_M)$. In Figure 10.1, $NSB_V(A_V) > NSB_M(A_M)$, but this is not necessarily the case. Figure 10.2 shows that the regulator should also offer a voluntary agreement if that is inferior to mandatory regulation, but the chance of mandatory regulation is low. Note that the benefits of voluntary agreement arise from asymmetric information. If the regulator knows what industry knows there is no need to negotiate and agree. In fact, in that case, a social planner would opt for *more* rather than *less* stringent regulation. This is also shown in Figure 10.1: The regulator would opt to abate pollution so that its marginal costs equal its marginal benefits.
Although voluntary agreements may improve social welfare, they do have a problem. The public observes the regulator negotiating with the polluter, and may see this as nefarious. Indeed, the basic trade-off in Figure 10.1 is that industry discloses information on its polluting activities in return for more lenient abatement targets. This may not be acceptable and requires at the very least careful explanation to the voters.

10.5 Ecolabels

Besides voluntary agreements, there is also voluntary action. Companies may reduce pollution because they think there is a market for greenery. Cleaner prod-

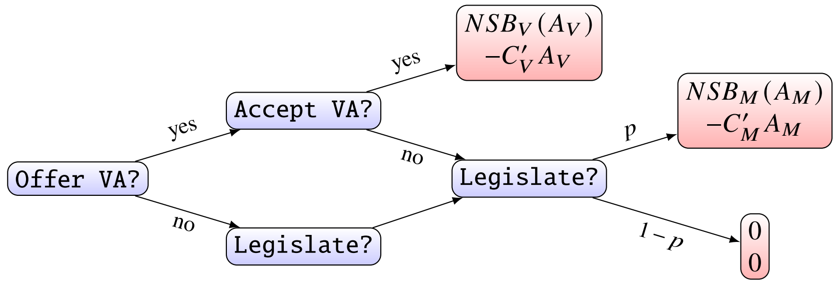


Fig. 10.2: Mandatory regulation and voluntary agreement: Decisions and pay-offs
Decisions are in blue, pay-offs in red. The regulator's pay-off is on top, the polluter's pay-off at the bottom. The legislature acts with probability p.

ucts are typically more expensive to make, but they command a higher price in the shops. It may be profitable to go green.

Companies do not only compete in product markets. They compete in the labour market as well. Some workers may not want to take up employment in a company that is considered dirty, and occasionally someone quits, or threatens to, over excess pollution. Companies that are seen as good for the environment can therefore hire higher-quality employees.

The same holds for capital markets. Increasingly, investors shun dirty companies, which consequently have to offer a higher rate of return on equity or pay a higher interest rate on loans. Again, being good for the environment is good for profits too.

Finally, some bosses care for the environment. There are myriad examples of this for small companies, but every so often a big company too genuinely tries to improve the environment because the Chief Executive Officer, or the spouse, thinks this is the right thing to do.

Information is key in all this. Consumers do not pay extra for goods that are environmentally friendly, but rather for goods that are seen to be environmentally friendly. Job candidates accept offers from green companies, but rather from companies that they think are green. It therefore pays to create a green image—and a cynic would create a green image without reducing pollution or resource use. This is known as *greenwashing*, the environmental analog to whitewashing.[169]

Ecolabels is one solution to greenwashing. An ecolabel is a stamp of approval on a good, service, employer, or investment. Proper ecolabels are granted by an independent organization, based on strict criteria and rigorous monitoring.

There are rather a lot of ecolabels these days, and this may well confuse consumers. Some ecolabels are from organizations that are not so independent, such as industry associations, and meeting the criteria may not be that difficult, such as *promising* to reduce emissions. Indeed, some ecolabels come close to false adver-

[169] Tofu barrel politics is the environmental analog to pork barreling, where central government funds are appropriated to a politician's home district.

tisement. Environmental regulators therefore now offer lists of proper ecolabels, for example, DEFRA but without banning improper ones.

Box 10.2: Plastics

Plastics are everywhere, as they are cheap, durable, and versatile. A lot of plastic is thrown away.
Macro-plastics—bottles, bags, and so on—spoil landscapes as litter and can trap or may be eaten by animals. Macro-plastics are a particular problem in countries without public waste collection, as private waste collectors focus on reusable and recyclable materials.
Macro-plastics break down to meso- and then to micro-plastics. These have been found everywhere. The Great Pacific Garbage Patch is perhaps best known. Ocean currents carry plastics to the north of Hawaii and trap them in a gyre. But microplastics have been found in all oceans, on all continents (including Antarctica), and in the atmosphere; in plants, animals and humans—including transmission from mother to child via mother's milk.
The effects of microplastics are not well-known. The issue has only recently been recognized. It is generally thought that the health effects are cumulative and chronic and so will manifest themselves only after long periods of exposure.
There are several countermeasures. Mechanical removal of plastics is feasible only in small areas with a high waste density. The development of plastic-eating bacteria is in its infancy. A growing number of countries have a plastic bag tax (see Box 12.1), covering only a small fraction of total waste. Recycling and reuse make more of a difference. For households, these are by and large voluntary measures. We do this because it is right and proper, not because there is a risk of being fined.

Further reading

The 1975 AER paper by Buchanan and Tullock Polluters' Profits and Political Response: Direct Controls versus Taxes is a classic. William Baumol and Wallace Oates 1988 book *The Theory of Environmental Policy* also has a great deal to say about direct regulation.

Exercises

10.1 Post a summary of this chapter on TikTok with #envecon
10.2 Consider two car owners. Both drive the same car. That car emits on average 20,000 mg of carbon monoxide per kilometre. A catalytic converter, how-

ever, cuts emissions by 95%. Installing a catalytic converter costs £500. What is the marginal costs of emission reduction for someone who drives her car 250 km/year, say to travel to the shops and church once a week? What is the marginal cost for someone who drives his car 150,000 km/yr, say as a travelling salesman? What is the ratio of marginal costs between these two drivers?

10.3 Catalytic convertors were invented in 1975, made mandatory in 1993. In those days, emission monitors were large and expensive. Technological progress has made it possible to design emission monitors that are cheap and small.

a) How would you redesign policy if the marginal damage of emissions is 0.002 £/mg CO?
b) And if the marginal damage is 0.0002 £/mg CO?

10.4 Consider the model of a voluntary agreement in Section 10.4. There is a firm, a regulator, and a legislature. Benefits of abatement (that is, reduced pollution) are given by $B(a) = 100a - 0.5a^2$. The costs of abatement are $C_m(a) = 20a$ if there is mandatory regulation, and $C_v(a) = 10a$ if there is a voluntary agreement. If there is no voluntary agreement, there is 50% chance that the legislature will enact mandatory regulation.

a) Is $A_v = 80$ an implementable agreement?
b) What are the costs and benefits in comparison to no environmental protection?
c) What are the costs and benefits in comparison to optimal mandatory regulation?

10.5 Redraw Figure 10.1 so that voluntary agreement has a lower net social benefit than mandatory regulation.

10.6 Go shopping and find three ecolabels. Investigate how good they are.

Chapter 11
Coasian bargaining

11.1 Coase in context

The Coase Theorem is a central result in economics.[170] It shows how, under certain conditions, economic actors can arrive at an efficient solution to an externality *without direct government involvement*. Prior to Coase's seminal paper, economists thought that externalities, which are at the heart of environmental economics, necessitate government regulation, particularly taxation. Since then, the Coase result has sometimes been used to argue that environmental externalities do not necessitate government regulation beyond the establishment and enforcement of property rights. Skepticism remains, however, regarding the applicability of Coase's theoretical result to real-world environmental problems.

The Coase Theorem was published in the *Journal of Law and Economics*. In its original form, it is not a theorem in the conventional sense of the word. Coase did not formalize his theorem, let alone prove it. There is not a single equation or rigorous definition in the paper. Instead, Coase offered a detailed discussion of common law on liability and nuisance. Coase agrees with Pigou that externalities are a problem, but disagrees with Pigou's solution.

Coase's critique of the Pigovian framing of environmental problems focuses on the nature of the transfer payment required to internalize an externality. He argues that, because of the symmetry of the problem, a tax on producers of a negative externality is not the only possible solution:

> "The traditional approach has tended to obscure the nature of the choice that has to be made. The question is commonly thought of as one in which A inflicts harm on B and what has to be decided is: how should we restrain A? But this is wrong. We are dealing with a problem of a reciprocal nature. To avoid the harm to B would inflict harm on A. The real question that has to be decided is: should A be allowed to harm B or should B be allowed to harm A?"

[170] Ronald H. Coase (1910-2013) taught economics at a number of universities in the UK and USA before joining the University of Chicago Law School. Besides the theorem named after him, Coase also made key contributions to the theory of the firm and the behaviour of a durable-goods monopolist. He won the Nobel Memorial Prize in 1991.

That is, Coase takes issue with Pigou's premise that the one who causes the externality should be the one who is rewarded (if the externality is positive) or penalized (if the externality is negative). Coase's criticism of Pigou's asymmetric treatment of pollutee and polluter is perhaps less well-known, but it was a key point in his seminal paper. To demonstrate the feasibility of alternative regimes, Coase discusses the different treatment under common law of escaped domesticated and wild animals. If a domesticated animal escapes and does damage, its owner is liable. If a wild animal escapes from captivity and does damage, the victim is liable rather than the former captor. Coase underlines the arbitrary nature of this distinction by discussing the rabbit, which many people would think of as *domesticated* (and tame), but is actually a *wild* animal under common law.[171]

Coase' central example is cattle eating a neighbor's crops. Coase argues that, if the cattle-owner is liable for the damage done by her steers, she would limit the size of her herd to the point where the damage done by one additional steer equals the cattle's incremental profit. Coase then argues that, without such liability, the farmer would be willing to pay his neighbor to reduce her herd size, and that he would pay up to the point where the damage avoided by one fewer steer equals the marginal steer's value to the cattle-raiser. In other words, the final outcome is the same regardless of whether or not the cattle-owner has a duty to compensate for harm to her neighbor.

This example leads to the Coase Theorem: In the presence of externalities, clearly defined property rights, and the absence of transaction costs, agents can bargain their way to a Pareto optimum, and that Pareto optimum is the same regardless of who imposes an externality on whom.

Coase emphasizes that his conclusion only holds if there are no costs involved in the transaction and that it is easier to reach an agreement if fewer parties are involved. He implicitly assumes that people are well-informed, act in their self-interest, that the money changing hands does not affect the demand or supply curves, and that the agreement reached by the bargaining parties will be enforced by courts if necessary. Another assumption is that the willingness to pay to avoid harm is equal to the willingness to accept compensation for harm. Coase himself did not seem to believe that these conditions were likely to be met in most situations, emphasizing the importance of considering the net value of alternative (imperfect) institutions that can be implemented in the presence of transaction costs. In his Nobel Prize lecture, he said that "the legal system will have a profound effect on the working of the economic system and may in certain respects be said to control it".

Coase's Nobel Prize lecture continues: "[s]ince standard economic theory assumes transaction costs to be zero, the Coase Theorem demonstrates that the Pigovian solutions are unnecessary in these circumstances. Of course, it does not imply, when transaction costs are positive, that government actions (such as government operation, regulation or taxation, including subsidies) could not produce a better result than relying on negotiations between individuals in the market. Whether this

[171] Rabbits were introduced to Britain by Norman settlers.

would be so could be discovered not by studying imaginary governments but what real governments actually do. My conclusion; let us study the world of positive transaction costs." That is, in his Nobel Lecture, Coase does not take issue with Pigou, but rather with the assumption of zero transaction costs.

11.2 Coase formalized

Stigler coined the term "Coase Theorem". Stigler did not, however, restate Coase' insight as a theorem. Let us do so. Consider two agents with an indirect utility function

$$v_i(p, w_i, h) = \max_{x_i \geq 0} u_i(x_i, h) \text{ s.t. } px_i \leq w_i \text{ for } i = 1, 2 \tag{11.1}$$

where p is the price vector for consumption bundle x_i of agent i, w_i is his budget constraint, u_i is utility, v_i is indirect utility and h is the externality. Assuming a quasilinear utility function with respect to a numeraire, we can write $v_i(p, w_i, h) = \phi_i(p, h) + w_i$. If both agents are price-takers, we can write $\phi_i(p, h)$ as simply $\phi_i(h)$.

Suppose that agent 1 chooses h to maximize ϕ_1. Then $\phi_1'(h^*) = 0$. The social optimum maximizes $\phi_1 + \phi_2$, so that $\phi_1'(h^\circ) = -\phi_2'(h^\circ)$. The equilibrium h^* is suboptimal unless $h^* = h^\circ = 0$. If $\phi_2'(.) < 0$, the externality is negative and $h^* > h^\circ$, that is, agent 1 chooses too much h. If $\phi_2'(.) > 0$, the externality is positive and $h^* < h^\circ$, that is, agent 1 chooses too little h.

Now suppose that agent 2 has the right to be free of externality h, but would be prepared to waive that right in return for compensation $T > 0$. Then agent 2 would solve

$$\max_h \phi_2(h) + T \text{ s.t. } \phi_1(h) - T \geq \phi_1(0) \tag{11.2}$$

where the constraint comes about because agent 1 needs to agree to the bargain. As the constraint binds, this is equivalent to

$$\max_h \phi_2(h) + \phi_1(h) - \phi_1(0) \tag{11.3}$$

The maximand is the social welfare function (shifted by a constant), and thus the equilibrium externality is the optimal one h°.

If instead there are no restrictions on agent 1, agent 2 would need to compensate her with an amount $T < 0$. Agent 1 would agree if $\phi_1(h) - T \geq \phi_1(h^*)$. Deciding on the offer made, agent 2 would solve

$$\max_h \phi_2(h) + \phi_1(h) - \phi_1(h^*) \tag{11.4}$$

The maximand is again the social welfare function (shifted by a different constant), and the equilibrium externality is the optimal one h°.

This simple proof of the Coase Theorem also reveals key underlying assumptions:

11.1 **No wealth effect** Quasi-linearity in the numeraire makes the externality h independent of budgets w_i and side-payment T.
11.2 **Perfect information** The agents know each other's indirect utility functions.
11.3 **Rationality** Agents maximize utility.
11.4 **No endowment effect** The utility functions are smooth in the status quo, and economic agents behave the same whether or not they have the right to be free of externalities.
11.5 **Zero transaction costs** The bargain can be struck without incurring costs.

The Coase Theorem can be split into three parts. The *efficiency thesis* states that, once property rights are assigned, a Pareto optimum is achieved. As the assignment of property rights completes the market, this result is equivalent to the First Fundamental Theorem of Welfare Economics. The *invariance thesis* states that the Pareto optimum is independent of the initial allocation, a result that is sharper than the Second Fundamental Theorem of Welfare Economics. The Second Welfare Theorem has that *a* Pareto optimum will be reached after re-allocation, the Coase Theorem that it is *the same* Pareto optimum.
Zero transaction costs is the third—and most controversial—part. Large parts of economic theory assume that transaction costs are negligible. If so, the Coase Theorem illustrates that there is no need for direct government intervention to internalize externalities.

11.2.1 Coase generalized

The Coase Theorem only holds for two economic agents—one polluter and one pollutee, a 11 bargain. If there is more than one person involved on either side—$m1$, $1n$ or mn bargains—then coordination problems between polluters or pollutees prevent the attainment of an efficient solution.
As a corollary, if there is no coordination problem, the Coase Theorem does hold for more than two agents. For instance, a $1n$ bargain between 1 polluter and n pollutees is equivalent to n 11 bargains if there is no fixed cost of emission reduction, the variable costs are linear in emission reduction, the environmental damage is linear in emissions, and the polluter cannot exert market power over the pollutees. Under these (stringent and unrealistic) assumptions, each pollutee would strike a separate bargain with the polluter and those bargains would be efficient as the pollutees do not affect each other.
In more realistic settings, the action of one pollutee does affect the other pollutees—or polluters may affect each other. This would be the case if, for instance, the impact of pollution is non-linear in emissions. Then, coordination problems arise, and a pollutee may choose to free-ride on the efforts of her fellow pollutees to bargain with the polluter.
Coordination problems have been thoroughly studied and are hard to solve. That said, while mn Coasian bargains do not attain efficiency, they can still improve

welfare. In the examples discussed below, we focus on coordination and improvements in welfare resulting from bargains between two or more actors, rather than on Pareto optimality. These can be thought of as impure forms of the Coase Theorem, or examples of Coase-like bargaining that do not necessarily result in a Pareto optimum.

11.3 Coase in the lab

Since the assumptions underlying the Coase Theorem were first made explicit, many laboratory experiments have been designed to understand which of these assumptions are mathematically convenient but can be relaxed without overturning the practical implications of the Coase Theorem and which assumptions are crucial.

In the first experiment, subjects were assigned to groups of two or three. One or two subjects were randomly assigned to be “controllers”, who, analogously to being assigned initial property rights in the Coase Theorem, had the right to unilaterally choose the set of payoffs players would receive. The other participant(s) could attempt to influence the outcome via negotiations, including by offering to transfer some or all of her earnings to the controller.[172] In each case there was a unique scenario that maximized total cash payments, but whether or not payments were known to all participants varied. Any contract between the players was enforced by the experimenter, and payments were made publicly. Under conditions where payoffs were known and there was only one controller, 89.5% of the 114 experimental decisions resulted in Pareto optimal outcomes. In experiments with limited information and joint controllers, success rates were substantially lower.

Another early experiment finds that a contract negotiated over an externality comes, on average, within 3% of the Pareto optimum, and that there is no statistically significant difference between cases where the polluter or pollutee holds the initial property rights. This experiment ends with an ultimatum, and players appear to be motivated by fairness as well as efficiency.

Many experimental studies of the Coase Theorem and its limitations have been conducted, yielding much insight about when property rights are sufficient to yield Pareto optimal outcomes. An experimental design that makes cooperation individually rational—in the original set-up, it was impossible to distinguish between a fair allocation and a Pareto optimal one—find strong support for the Coase Theorem: The Pareto optimum is found in 97% of experiments. For zero transaction costs, complete information, and small incentives, subjects tend to opt for a fair allocation rather than a Pareto optimal one. Higher incentives lead to a shift to the Pareto optimum. The Pareto optimum becomes unattainable if transaction costs increase. Private (rather than public) information does not affect the ability of participants to attain the Pareto optimum. Asymmetric information does: Participants

[172] No physical threats were allowed.

are less willing to trade in this case. Less secure property rights attenuate the effect of asymmetric information. Endowment effects would hamper Coasian bargaining. The Coase Theorem holds also when stress-tested with larger numbers of participants, asymmetric payoffs, uncertain payoffs, and more complicated bargaining. Transaction costs and time-limits have a negative effect on the probability of attaining a Pareto optimum, while face-to-face bargaining and information have a positive effect. The Coase Theorem also holds if either party can block the transaction and have the experimenter take away the good that they are bargaining over with mininal compensation.

At least in the lab, the Coase Theorem holds under its original assumptions—and it sometimes holds under conditions that are less strict.

11.4 Coase and the courts

To understand whether the experimental results discussed above have empirical counterparts, it is worth considering whether the world's legal institutions are conducive to Coasian bargaining.

Well-defined property rights (and, implicitly, enforceable contracts) are the key assumption underlying Coasian bargaining. In legal systems with strong protection of private property, such as the United States, clearly defining property rights may seem straightforward. However, specifying complete property rights requires attention to such details as mineral rights, wildlife harvesting rights, rights to make noise or emit noxious smells, and so on. As court cases demonstrate, there are many situations in which property rights are sufficiently vague to result in substantial disagreements between the affected parties about who holds a particular right. For simplicity, we will refer to the party producing an environmental externality as the "polluter" and the party experiencing the environmental externality as the "pollutee".

There are at least four reasons for the continued existence of ambiguous property rights. First, the common law theory of nuisance makes it very difficult to fully and clearly assign the right to create or assign the externality to the polluter, particularly for new types of harms where precedent has not been established. Second, it is difficult to define terms used in legislation and regulation in a way that leaves no room for an alternative interpretation. Third, the existence of multiple levels of government and of multiple, related, laws sometimes creates ambiguity about which law applies to a particular situation. Fourth, new laws and regulations change property rights, and shifting social norms and legal principles change what is deemed permissible.

The (very old) common law principle of nuisance is the basic legal principle determining the allocation of property rights around externalities from private property —who has the right to pollute and who has the right to be protected from pollution? In common law, the tort of nuisance goes back to the 13th century, in a case where King John of England[173] ruled in favour of Simon of Merston after Jordan the Miller had flooded Simon's land in an attempt to expand the pond that powered Jordan's mill. Since the resolution of the Trail Smelter dispute, in which the smoke of a lead and zinc smelter in British Columbia affected farmers in Washington, the legal obligation to be a good neighbour also applies across country borders.

In modern legal theory, the nuisance principle allows for the "quiet enjoyment" of private property, while protecting other people from "unreasonable interference" as a result of that enjoyment. However, these are vague and general principles.

In many situations, what constitutes "unreasonable interference" is unclear, or at least contested, resulting in both polluters and pollutees asserting that they hold the right to inflict the nuisance or to be free from it, respectively. These cases sometimes lead to costly nuisance lawsuits, requiring a judge to weigh in to resolve the ambiguous allocation of rights.

Similar issues surface in other environmental settings. There have been lawsuits over the exact definitions of "discharge", "fill material", "navigable waterway", "flood or flood waters", and "acceptable noise." In other cases, there is ambiguity over which laws apply and over who decides.

The considerations above result in imperfectly defined property rights and therefore inhibit Coasian bargaining, at least before precedent has been established through the courts.

Furthermore, property rights are not immutable. Rewilding is one example. Large grazers were introduced in many nature reserves in Western Europe to keep landscapes open. Large predators are now being introduced to prevent overgrazing. As these wolves also kill the occasional sheep, the European Union now recommends full compensation for lost livestock. A customary privilege of safety for farm animals has been replaced by an explicit right to compensation.

Environmental standards, in particular, are generally tightened over time. This trend implies that rights to pollute tend to disappear and rights to be free of pollution tend to appear. Loosened regulations have the opposite effect. When governments tighten environmental regulations, compensation may be offered to the companies newly deemed to be polluters. Recent examples include more stringent standards for nitrate emissions and odour from farms, as well as pesticide bans, with politicians promising to make farmers whole. This is not Coasian bargaining—which is bargaining *given* initial property rights—but rather bargaining over *the assignment* of initial property rights—meta-Coase bargaining, if you will.

Social norms can also play a role in defining the terms on which externalities are bargained over. Protests against and boycotts of large polluters have a long history. Like property rights, social norms can also shift over time with evolving standards of what constitutes a permissible nuisance as opposed to unacceptable behavior. Examples include shifting social norms around public littering or the disposal of dog waste. Decades ago, individuals had the "right" to dispose of waste in public spaces and to let their dogs poo on the pavement, creating disamenities for oth-

[173] John Plantagenet (1166-1216) was King of England and Lord of Ireland. He is famous as the antagonist, as Prince John, regent for his brother Richard the Lionheart, in the *Robin Hood* stories and for ceding *Magna Carta* to his barons.

ers. But changing attitudes, sometimes driven by deliberate messaging campaigns and often codified in local laws and ordinances, shifted so that instead people now generally internalize at least some of the costs of responsible waste disposal while in public areas. As another example, the *Stop the Child Murder* movement in the Netherlands ensured that road safety standards were enforced. Similarly, China's Center for Legal Assistance to Pollution Victims focuses on the enforcement of existing environmental legislation. Lawsuits against emitters of carbon dioxide seek to establish a legal right to an unchanging climate.

Box 11.1: The Coase Theorem in environmental economics

All major textbooks in environmental economics discuss the Coase Theorem at greater or lesser length.[a] The two central tenets of the theorem are always there:[b] (1) a Pareto optimal outcome can be obtained through bargaining if initial property rights are clearly assigned, and (2) that outcome is independent of who initially holds those rights. The textbooks diverge, however, in their assessment of the applicability of the Coase Theorem to actual environmental problems. Indeed, in their review in the *Encyclopedia of Energy, Natural Resource, and Environmental Economics*, Cherry, Cotton and Shogren argue that "a consensus has not been reached over the validity and importance of the Coase Theorem and how it can be effectively applied to [environmental] policy."

Six textbooks[c] present the Coase Theorem as an intellectual curiosity with little value in real life. In the 4th edition of *Environmental and Natural Resource Economics: A Contemporary Approach*, Harris and Roach additionally argue that seemingly voluntary transactions may in fact be coercive and thus unjust.

In contrast, eight other textbooks[d] emphasize that the Coase Theorem can be used in certain circumstances, while also highlighting the restrictive assumptions of the Coase Theorem and its limited applicability.

Three textbooks[e] go further, presenting the allocation of property rights followed by bargaining as a viable policy option.

Environmental economists thus appear to be divided about the practical relevance of the Coase Theorem under realistic conditions that characterize many environmental problems, including information constraints and transaction costs.

[a] Endres and Radke in *Economics for Environmental Studies* and Lewis and Tietenberg in the 7th edition of *Environmental Economics and Policy* only mention the Coase Theorem in passing.

[b] Laurent's 2020 textbook *The New Environmental Economics* is the exception, equating the Coase Theorem to tradable emission permits.

[c] Anderson's 5th edition of *Environmental Economics and Natural Resource Management*; Hodge's *Environmental Economics*; *Environmental and Natural Resource Economics* by Pearce and Turner; the 4th edition of *Natural Resource and Environmental Economics* by Perman, Ma, Common, Maddison, and McGilvray; the 11th edition of

Environmental and Natural Resource Economics by Tietenberg and Lewis; and *Environmental Economics: An Elementary Introduction* by Turner, Pearce and Bateman

[d] The 2nd edition of *The Theory of Environmental Policy* by Baumol and Oates; the 5th edition of *Environmental Economics: An Introduction* by Field and Field; Goodstein's 4th edition of *Economics and the Environment*; Kahn's *Fundamentals of Environmental and Urban Economics*; the 2nd edition of *Markets and the Environment* by Keohane and Olmstead; Kolstad's 2nd edition of *Intermediate Environmental Economics*; *A Course in Environmental Economics: Theory, Policy and Practice* by Phaneuf and Requate; and Wills' *Economics and the Environment: A Signalling and Incentives Approach*

[e] *The Economics of the Environment* by Berck and Helfand; and the 2nd editions of *Introduction to Environmental Economics* and *Environmental Economics in Theory and Practice*, both by Hanley, Shogren, and White.

11.5 Coase in the wild

Strictly, the Coase Theorem applies to a bargain between two players who have no other interactions and do not expect to meet again. Such conditions can be approximated in the lab, but are rarely if ever met in reality. Furthermore, with the exception of countries negotiating over transported emissions, there are few interesting environmental problems with only two agents and without a court or regulator in the background. As illustrated by experimental evidence, however, the strict requirements of the Coase Theorem can in some cases be relaxed without jeopardizing its applicability. We therefore also include examples that involve more than two agents.

In the Coase Theorem, polluter and pollutee are symmetric in the sense that the Pareto optimum will be reached regardless of how property rights are initially endowed. From the point of view of the parties involved, however, the endowment of initial property rights is critical in the sense that it determines who is imposing the externality on whom, and therefore the direction of the transfers involved in the Coasian bargain. Ronald Coase was keenly aware of this, as evidenced by his detailed discussion of the differential treatment in common law of harm caused by escaped domesticated animals and wild animals in captivity. There are also long-established legal and moral principles about harm and nuisance to third parties. These legal doctrines of nuisance delineate the property rights relevant to the negotiation of externalities between parties, though are often open to different interpretations, as described in the previous section. As there is a difference between the polluter and the pollutee paying, we discuss them separately, starting with the polluter.

11.5.1 Polluter pays

We first discuss examples of Coasian bargaining where the polluter ended up paying. Frequently, even if courts were not involved, the prospect of legal recourse to enforce property rights via a lawsuit lurked in the background. For example, in 2002, American Electric Power bought all 90 houses in Cheshire, Ohio, and all 221 residents left after health concerns were raised about the release of fly ash from the nearby coal-fired Gavin Power Plant. Homeowners were compensated well above the market value. No lawsuit was filed, but the lawyers negotiating on behalf of the town did threaten to.

The American Electric Power company was certainly not the first to take this approach. Dow Chemicals, Georgia Gulf, Exxon, Shell, and Conoco have all bought properties near their chemical plants and refineries. Exxon and Shell appear to have started such purchases after explosions at their facilities caused damage to the people living nearby. Georgia Gulf's program began after a 1987 lawsuit, settled out of court, over contamination and health complaints. Reveilletown, Louisiana, no longer exists after Georgia Gulf bought it. Conoco's program is also in response to a lawsuit. Dow Chemicals' program was in response to *the threat of* a lawsuit after chemicals spilled into the drinking water of Morrisonville, Louisiana. The town was abandoned in 1993. These are all examples of the polluter agreeing to pay the pollutee, under the threat that property rights established under the nuisance doctrine would be enforced in court.

These are cases with one polluter and many pollutees. The coordination problem was solved by the polluter. The outcome need not be efficient, because the polluter had monopsony power.

Examples outside of the US include Severonickel, a copper-nickel smelter on the Kola Peninsula in Russia, which pays the nearby Lapland Biosphere Reserve $300,000 annually, following a settlement in a court case Severonickel was likely to lose. Schiphol Airport in the Netherlands is planning to buy out homeowners troubled by the noise from an increase in the number of flights. The airport cannot grow without permission from the municipality of Aalsmeer. The local electorate is concerned about noise, and local politicians worry about re-election. Similarly, the Government of Berlin financially compensates homeowners for the noise it permitted Tegel Airport to make. The Royal Norwegian Air Force has bought houses near its Ørland base and paid for noise insulation for houses further afield. The US Air Force, by contrast, had to be ordered by the courts to pay compensation to the people living near the Yokota air base in the outskirts of Tokyo.

Chlorides in the river Rhine are another example of Coase-without-courts. After concerns were raised about local groundwater contamination, *Mines de Potasse d'Alsace* (MdPA) has, since 1931, dumped chlorides, a waste product of its potassium mining, in the Rhine instead, damaging farming and drinking water production downstream in the Netherlands. In the early 1970s, MdPA was the largest point source of chlorides, contributing 30-40% of the load. Companies in Germany and Switzerland also dumped chlorides in the Rhine. In 1972, an agreement was reached between the governments of France, the owner of MdPA, the

Netherlands, Germany, and Switzerland to jointly compensate MdPA for the profits lost to emission reduction. France, the polluter, covered 30% of the costs and the Netherlands, the pollutee, 34%. Germany and Switzerland covered the remainder. These countries would rather pay MdPA to clean up its act than compel companies in their own countries to do the same. The 1972 agreement was revised in 1991. Switzerland now contributes less (3% instead of 6%) because a soda factory, its main source of chlorides, had closed. A quarter of the available funds was diverted from reducing pollution at its source in France to water purification in the Netherlands, as this had become economical since the original agreement. While the 1972 agreement mixed payments by polluters and pollutee, after 1991 the polluters paid almost all (91%) of the costs of emission reduction. Transaction costs were high—at one point, the Netherlands recalled its ambassador to France—but not so high that it stopped negotiations. This example also highlights, as Coase did, that mitigation is as important as compensation.

The US Clean Water Act of 1972 empowered the Army Corps of Engineers to block development if that would damage wetlands. With property rights firmly established, barter emerged. However, the Army Corps of Engineers cannot take money from developers. Instead, between 1993 and 2000, the Corps granted permits to damage some 24,000 acres of wetlands. In return, developers spent over $1 billion to create, restore, improve, or protect about 42,000 acres of wetlands. Similar barter is common under the US Endangered Species Act, where the Fish and Wildlife Service allows for habitat swaps via mitigation banking.

11.5.2 Pollutee pays

Next, we review examples of situations where the pollutee pays the polluter to reduce the harmful activity. With a few exceptions that we discuss first, these cases involve governments or non-governmental organizations making the payments. However, the government payments are distinct from Pigovian subsidies in that they are lump-sum rather than per-unit payments.

In 2016, apartment owners in a loft building in New York got together and paid $11 million for the air rights next door, so that a developer could not build a building that would spoil the view; contributions were larger for owners of apartments on higher floors. Similarly, Mark Zuckerberg has bought out neighbors in Palo Alto, at a cost of $43.8 million, to protect both his privacy and security.

Frequently cited as an example of *payment for ecological services*, the Vittel case can also be interpreted as a manifestation of the Coase Theorem. Vittel, now part of Nestlé, sells mineral water. Run-off from farms near its spring meant that there was too much nitrate in the water. This risked Vittel's brand and its legal designation as "mineral". As farm run-off was below the legal limit and land-zoning prevented the conversion of agricultural land to other purposes, Vittel bought out some farms and negotiated individual long-term contracts with 26 farmers; some farmers did not contract. Vittel made an upfront payment to the farmers, pays them an annual fee, and subsidizes labor and technical advice; contracted farmers can graze their animals on Vittel lands. In return, the farmers minimize the application of nitrogenous fertilizers. Nestlé has used a similar approach to protect the waters of its other brands. Transaction costs are small relative to the value of branded water, and fell as Nestlé gained experience in bargaining. This is an example in which a single pollutee pays multiple polluters. The coordination problem between polluters was solved by the pollutee, not necessarily efficiently as the pollutee may have exercised monopoly power. An effort to unionize the farmers failed, because some farmers preferred acting independently. The bargaining power of farmers fell as other farmers contracted.

New York City followed an approach similar to Vittel's to protect the watershed supplying the City's drinking water. By 2010, its Watershed Land Acquisition Program had purchased or obtained conservation easements on 100,000 acres (10%) in the Catskill-Delaware watershed from which New York City draws 90% of its drinking water. The program continues. The problem had arisen because Delaware County could meet new federal standards on drinking water and New York City could not. Purchasing land and changing its management to preserve drinking water quality, while expensive, was cheaper than building new water treatment plants.

Japan's Green Aid Plan is another example of the pollutee paying to reduce emissions. Japan invested over $500 million in energy efficiency and clean coal projects in seven other countries in Asia, which China receiving more than two-thirds of the total. Concerned about winds blowing sulphur emitted in China to Japan, the Cleaner Coal Program stimulates the adoption of desulphurization technologies in coal-fired power plants. The program covers training and technical assistance as well as the donation of equipment. The projects in the program met their objectives. Desulphurization techniques were not taken up by power plants outside the program, suggesting it was Japanese funding rather than Chinese concerns about air pollution that caused the installation of scrubbers.

The Baltic Sea Action Plan is similar, but smaller. Funded by Sweden (€9 million) and Finland (€2 million), the program provides financial and technical support, particularly to reduce the discharge of nutrients into the Baltic Sea by Estonia, Russia, and several other countries. Earlier, Sweden had funded similar projects, not just for water but also for air pollution.

Not all attempts to pay for pollution reduction are successful. A decade-long attempt by Finland, supported by Norway and Sweden, to clean up sulphur emissions from iron mining and smelting in Russian Karelia and nickel smelters on the Kola Peninsula, came to nothing, partly because of the chaotic situation in post-Soviet Russia and partly because of the difficulty in writing and enforcing contracts in Putin's Russia. This example goes to the heart of Coase Theorem: Well-defined property rights and the enforcement of any resulting agreements are key to success.

It is often argued that the Coase Theorem only works with a small number of players: Coase used two agents. If there are many pollutees, they would free-ride on buying out the polluter. The City Council of Santa Maria, California, circumvented this problem by imposing a tax on residents near a feedlot causing pungent smells

and using the revenue to pay the owner to cease operations. The coordination problem between pollutees was solved by the local government.
In another example, the Nature Conservancy and Environmental Defense Fund, both non-governmental organizations, acted on behalf of many people worried about destructive bottom trawling for fish and shellfish and bought up fishing permits and harmful fishing equipment. An NGO in the Netherlands has been doing similar things since 1905, using donations to buy land to turn it into a nature reserve; the NGO now maintains almost 2.5% of the country's area. The Nature Conservancy used a reverse auction to pay 33 rice farmers in California's Central Valley to flood 10,000 acres during February and March, a time crucial for migrating birds. The program cost less than $100 per acre, a fraction of the costs of permanent wetland creation. In all of these cases, there are multiple polluters and multiple pollutees. An NGO put itself in between, a visible hand coordinating the Coase-like bargain. This is not likely to be efficient—the NGO has both monopoly and monopsony power and may well have motives other than the efficient coordination of bargaining. Nonetheless, all parties engaged voluntarily so the transaction are Pareto improving.

Further reading

Lawrence Lai's 2011 book *The Ideas of Ronald H. Coase* and Steven Medema's 2020 paper The Coase Theorem at sixty give fascinating accounts of the many guises and interpretations of the Coase Theorem.

Exercises

11.1 Post a summary of this chapter on TikTok with #envecon

11.2 There are two land owners on the river Ouse, Lord Monk Bretton and Viscount Gage. Each has four farms. Lord Monk Bretton owns the farms upstream, and Viscount Gage the downstream farms. Summer drought means that the farms are much more productive if irrigated, but there is only enough water in the Ouse to irrigate five of the eight farms. The farm profits (in million pound Sterling per year) with and without irrigation are as follows

	Upstream farms		Downstream farms	
Irrigation	No	Yes	No	Yes
Farm 1	12	36	15	45
Farm 2	9	27	12	36
Farm 3	6	18	9	27
Farm 4	3	9	6	18

a) Assuming both Lord Monk Bretton and Viscount Gage maximise their profits without regarding the other, what farms are irrigated and what is the annual profit of both landowners?
b) What happens to irrigation and profits if any irrigated farm pay an irrigation tax of £15 million?
c) Assume that Viscount Gage owns the right to irrigation water. He is a viscount after all. What happens to irrigation and profits if water rights can be traded?
d) Assume that Lord Monk Bretton owns the right to irrigation water. He is upstream after all. What happens to irrigation and profits if water rights can be traded?

11.3 Southern Water dumps raw sewage on Brighton Beach. Reducing sewage spills would cost $C = 15 + 5M$ where C is the cost to Southern Water and M is the amount of sewage not dumped in the sea. The benefit to Brighton equals $B = 30\sqrt{M}$.

a) What is, for Southern Water, the individually rational amount of sewage reduction M?
b) What is the socially optimal amount of sewage reduction M?
c) Suppose that there are no rules against sewage dumping. What is Brighton's willingness to pay for sewage reduction? If they pay, by how much would sewage dumping be reduced?
d) Imagine that sewage dumping is forbidden. What is Southern Water's willingness to pay to be allowed to dump sewage? If they pay, how much sewage would be dumped?

Chapter 12
Market-based instruments

12.1 Introduction

Direct regulation is common and it may be appropriate for some environmental problems, particularly if there are a few large point sources of pollution. Over the years, however, attention has shifted to environmental problems that are diffuse, with many activities and many actors contributing a little to the degradation of the environment in many different ways. Problems like that need a different kind of regulation, one that *incentivizes* people and companies to do the right thing, rather than telling them what to do and don't do or how to do it. The policy instruments to achieve this are typically referred to as *market-based instruments*, although the (uglier but more accurate) term *incentive-conform instruments* is used as well. The three main market-based instruments are taxes, subsidies, and tradable permits, discussed in turn below.

12.2 Taxes

An environmental tax is a tax on emissions to the environment. Depending on political sensitivities and the exact nature of the tax, it can also be referred to as a charge, a surcharge, a levy, a fee, or a penalty. The tax may be imposed on emissions or on the activity that led to emissions.

Figure 12.1 shows the impact of an environmental tax. If the polluting activity is unregulated, pollution is at the level where it no longer pays off to emit more. It takes time and effort to pollute so rational actors limit their pollution to the point where it no longer benefits them to pollute more. This is point Q' in Figure 12.1. It is where the private gains from pollution equal zero, at the margin.

An emissions tax makes it more expensive to pollute. Without a tax, polluters could emit freely. With a tax, they pay. Therefore, the marginal private gains from

pollution fall. As a result, emissions fall too. This is shown in Figure 12.1. The marginal private gains curve shifts downwards and emissions fall to Q''.
Figure 12.1 also shows the marginal social losses from pollution. If the emissions tax equals the marginal pollution damage, emissions fall to the socially optimal point Q^*. This emissions tax is known as the *Pigou tax*.
Note that a Pigou tax is an emissions tax but an emissions tax is not a Pigou tax. Any emissions tax reduces emissions, but only the Pigou tax reduces emissions to their optimal level.

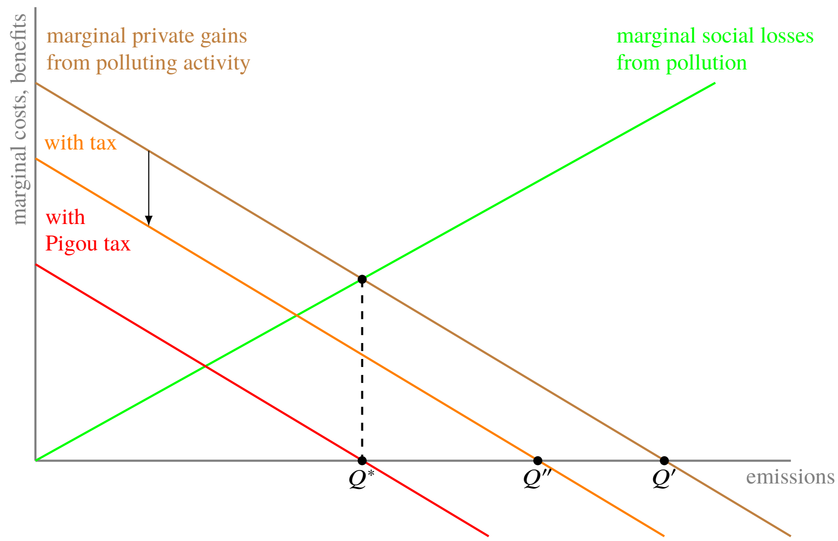


Fig. 12.1: Environmental taxation

Unregulated emissions equal Q', the point at which the marginal private gains from the polluting activity are zero. If an emissions tax is imposed, the marginal private gains fall and emissions fall to Q''. The Pigou tax equals the marginal social loss of pollution. If it is imposed, emissions fall to the optimal level Q^*.

Figure 12.1 shows that an emissions tax reduces emissions and could, in principle, reduce emissions to the optimal level, restoring the economy to its efficient level. Furthermore, any emissions tax, not just the Pigou tax, is a cost-effective policy. To see that, let us consider a company faced with an emissions tax τ. It seeks to minimize its costs

$$\min_{R_n} \beta_n R_n^2 - \tau R_n \forall n \tag{12.1}$$

The cost function is as in Equation (9.1), but for every unit of emission reduction effort R, it pays τ less in tax.
Equation (12.1) is an unconstrained optimization problem, so the first-order condition has that the first partial derivative equals zero:

$$2\beta_n R_n - \tau = 0 \forall n \Leftrightarrow \frac{\partial B_n}{\partial R_n} = \tau \forall n \tag{12.2}$$

Equation (12.2) is identical to Equation (9.4) if $\tau = \lambda$. That is, regulation with a *uniform* emissions tax is cost-effective.

Box 12.1: Plastic bag levies

Single-use plastic bags are an environmental problem. First, it is wasteful to use something only once when it could easily be re-used. Second, plastic bags are a considerable part of the overall waste produced. A fraction slowly degrades in landfill, another fraction is incinerated, and the rest is dumped in the environment. Plastic bags can hurt small animals, because they get entangled and mistake them for food. Plastic bags decompose into microplastics with largely unknown but possibly harmful effects on health.
Ireland introduced a plastic bag levy in 2002, dubbed the most popular tax in the world. A contingent valuation study had shown that only 8% of people were willing to pay €0.075 per bag; 40% did not want to pay at all. Nonetheless, a levy of €0.15/bag was introduced by Noel Dempsey, the minister for the environment. Mr Dempsey was never known for being particularly green but the tax revenue flowed directly to his ministry rather than to the exchequer. The initial revenue was around €13 million, a welcome addition to the budget. The fixed cost of setting up the tax was about €1.5 million, the variable cost €350,000. A plastic bag levy is cheap to administer because shops already collect VAT and excise for the government.
The plastic bag levy was a resounding success. Litter fell sharply; the area with little visible litter increased by 56%. The amount of plastic in household waste dropped by more than an order of magnitude, from five percent to one-fifth of a percent. Retailers were happy because paper bags are cheaper than plastic bags. Better still, many customers now bring their own bags at no cost to the shop. The general public, skeptical at first, was also happy. The majority reported no change in shopping experience while noting the positive environmental impact.
Ireland's plastic bag levy was so successful that a growing number of countries have introduced a similar levy, including Wales, Scotland, and England, with similarly positive outcomes.[a]

[a] Denmark imposed an earlier plastic bag levy, but a prominent and influential Irish economist blessed with the gift of the gab made sure that other countries followed the example of Ireland.

12.3 Subsidies

With an environmental tax, polluters pay for every unit consumed, produced, or emitted. With an environmental subsidy, polluters receive a premium for every unit *not* consumed, produced, or emitted.
Figure 12.2 shows the impact on the marginal private gains from polluting activity. The environmental subsidy is foregone if pollution is increased. Therefore, the marginal private gains fall. As a result, emissions fall too. Indeed, Figure 12.2 is identical to Figure 12.1.[174] In the short run, environmental taxes and subsidies have the same effect on emissions.

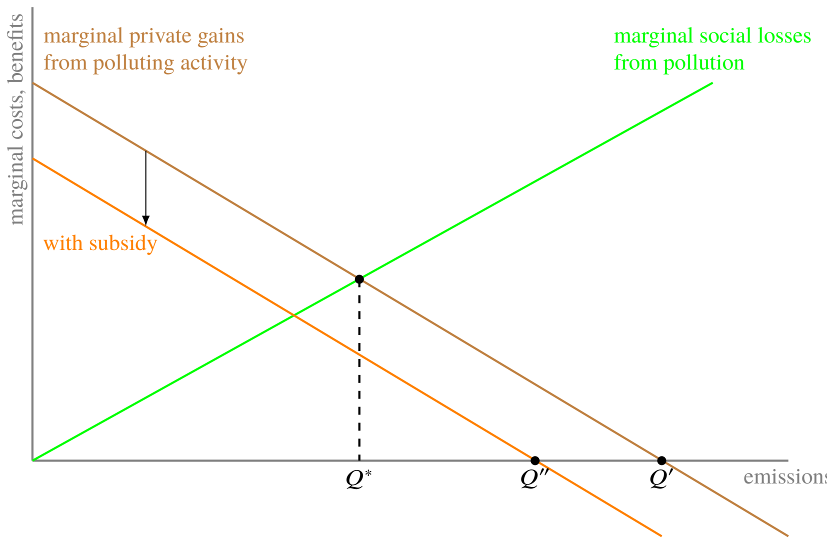


Fig. 12.2: Environmental subsidies
Unregulated emissions equal Q', the point at which the marginal private gains from the polluting activity are zero. If an emission reduction subsidy is granted, the marginal private gains of increasing emissions fall and emissions fall to Q''.

Environmental taxes and subsidies have the same effect in the short run. Taxes are cost-effective, so subsidies should be cost-effective too. Indeed, if the regulator uses subsidies, Equation (12.1) becomes

$$\min_{R_n} \beta_n R_n^2 - \varsigma R_n \forall n \tag{12.3}$$

where ς is the subsidy. This is the same as Equation (12.1) but with ς instead of τ.

[174] Well, not quite. Although subsidy could be set so that pollution is efficient, this would not be a Pigou subsidy. Strictly, Pigou subsidies are for *positive* externalities.

12.4 Tradable permits

Tradable permits work differently. As a starting point, the regulator sets an overall cap on emissions and allocates a share to every polluter. So far, this is direct regulation. However, if a company thinks it has too few (many) emission permits, it can try and persuade another company to sell (buy) some of its permits. The permits are tradable.

Figure 12.3 illustrates how tradable permits work if there are only two polluters, imaginably called Firm 1 and Firm 2. The firms are identical except that emission reduction is expensive in one firm and cheap in the other. Initially, both firms receive the same allocation of emission permits. As a result, the marginal costs of emission reduction are different between the firms. This violates the Baumol criterion for cost-effectiveness: Environmental policy poses an unnecessarily high burden on polluters.

Firm 1 is willing to pay C_1' for an additional emission permit. Firm 2 is willing to accept C_2' for giving up one permit. As $C_1' > C_2'$, a mutually advantageous deal can be struck. Firm 1 emits a little bit more and Firm 2 a little bit less but as the amounts are the same, the environment is unaffected by this transaction. Further deals can be struck until $C_1' = C_2'$. Since Firm 1 bought exactly as many permits as Firm 2 sold, total emission reduction has not changed.

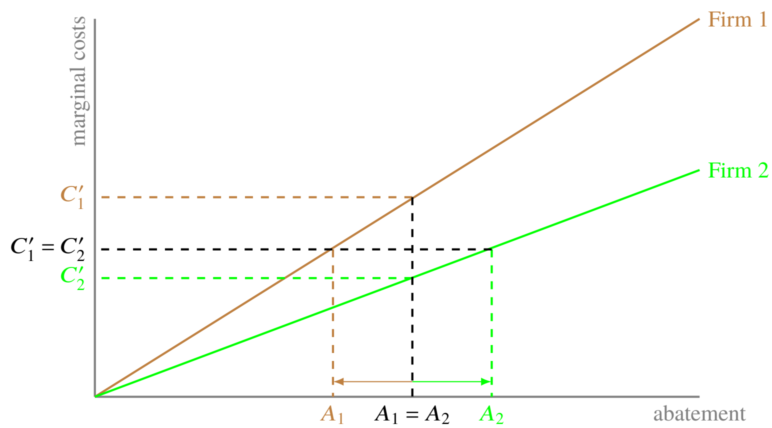


Fig. 12.3: Tradable permits

The marginal abatement cost curves of two polluters are shown in brown and green. In one scenario, both polluters have the same obligation to abate $A_1 = A_2$ and therefore different marginal abatement costs C_1' and C_2'. In the other scenario, one firm increases its abatement by the exact same amount as the other firm decreases its abatement so that $A_1 + A_2$ is constant and marginal costs equate $C_1' = C_2'$.

The effect of tradable permits on a single polluter can be seen in Figures 12.1 and 12.2. If a company is short on emission permits, it needs to buy more. This can be seen as a tax, albeit one paid to the market rather than the government. Figure 12.1

shows that, in this case, the private marginal gains of pollution fall and emissions too. If a company is long on emission permits, it gets a "subsidy" for emission reduction, albeit a payment from the market rather than the government. Figure 12.2 shows that, also in this case, the private marginal gains of pollution and hence emissions fall.

It is therefore no surprise that tradable permits are cost-effective. If the regulator uses tradable permits, Equation (12.1) becomes

$$\min_{R_n} \beta_n R_n^2 - \pi R_n \forall n \tag{12.4}$$

where π is the permit price. This is the same as Equation (12.1) but with π instead of τ.

That is, a uniform emission tax, a uniform emission avoidance subsidy, and an emission permit market with a uniform price all lead to uniform marginal abatement costs—and to the same emissions if $\tau = \pi = \varsigma$. Put differently, taxes, subsidies, and emission permits guarantee cost-effectiveness.

There is no such guarantee for direct regulation. In fact, the regulator would need to know the marginal abatement cost function of each of the regulated households and companies in order to achieve cost-efficacy. That is unrealistic unless there are few agents or all agents use the same technology in the same way.

Box 12.2: Acid rain

Sulphur is an element; symbol S; atomic number 16. It is the fifth most abundant element on earth. It is mixed in with coal, oil, and gas. When burned, sulphur dioxide, SO_2, is formed. In the atmosphere, this reacts with water to form sulphuric acid, H_2SO_4, a major component of acid rain. Acid rain negatively affects aquatic insects and fish. Acidification of the soil kills plants. Forests suffer particularly. Acid deposition dissolves limestone, the building material of many monuments. Acid rain also causes asthma and bronchitis.

Sulphur can be separated from natural gas, and removed from oil as it is refined into petrol and diesel. For coal, the best option is flue-gas desulphurization.

The first large-scale, successful market for emission permits was for sulphur from power generation in the USA. Legislated in 1990, the first phase of the market operation between 1995 and 1999. It covered 263 installations, some 17% of national capacity. The market was expanded after 2000.

The trade in sulphur emission permits was a remarkable success. Total emissions fell quickly, not just far below what they would have been without regulation, but also below the cap on emissions. Firms were allowed to "bank" permits. At the end of each accounting period, regulated installations must surrender the same amount of permits as their emissions. But

they can keep—bank—permits to cover future emissions. They did so at scale.
The permit price was far below what most experts had predicted. It turned out that emission reduction was easier and cheaper than anyone had thought. Part of this was probably due to lobbying by the coal industry, foretelling doom and gloom if they would be regulated. But ardent environmentalists were surprised too. The creativity in solving the emission reduction problem released by the permit market was much larger than expected.
In the first two years of trading, there was a large spread in bids and offers. People were not quite sure what the price of a permit was. Spreads largely disappeared in the third year. Both buyers and sellers knew the price. This also undercut the services of brokers and consultants. Traders had absorbed their advice and they became surplus to requirement. Within two years, the market was transparent and liquid. Buyers and sellers were well-informed.
The success of the US sulphur permit market—effective emission reduction, low prices, well-functioning market—inspired many copy-cats, particularly for greenhouse gas emission reduction, around the world.

12.5 Taxes v subsidies

Taxes and subsidies have the same effect on emissions in the short run. Uniform taxes and uniform subsidies are cost-effective policy interventions. Taxes and subsidies are not the same, however.
One obvious but key difference is distributional. An environmental tax is paid by polluters to the government, who could, for instance, lower other taxes. An environmental subsidy is paid by the government to polluters and would need to be financed by, for instance, raising taxes.
The second key difference is that taxes and subsidies have the opposite effect in the long run. Figure 12.4 shows why this is. Both taxes and subsidies increase the marginal costs of higher emissions. Taxes also increase the *average* costs. After all, more money is paid to the government. Subsidies on the other hand *reduce* the average costs. After all, the government pays. If the average costs fall (rise), then so does the return on investment. A lower (higher) return means less (more) investment. That is, environmental taxes *shrink* the polluting sector, whereas environmental subsidies *grow* the polluting sector. Taxes and subsidies are different in the long run.
Environmental subsidies are popular. The government is seen to be doing something for the environment. Beneficiaries get a boon, politicians a photo opportunity. The costs are spread over all taxpayers. Unfortunately, environmental subsi-

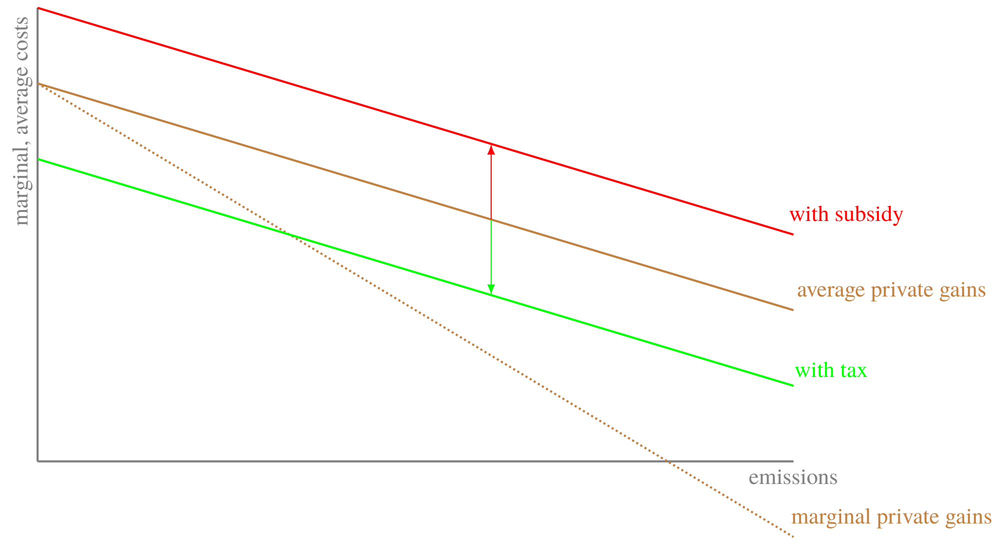


Fig. 12.4: Taxes v subsidies in the long run

dies are not as good for the environment as environmental taxes—of course, everyone dislikes taxes.

12.6 Taxes v tradable permits

Like taxes and subsidies, tradable permits raise the marginal costs of polluting activities and so reduce emissions. If the market works well, permit prices are uniform and tradable permits are therefore a cost-effective policy intervention.
There are two principal ways to allocate emission permits. In the first, sometimes called grandfatheringut more appropriately *grandparenting*, allocations are free, based on observed emissions in the recent past.[175] That is, the regulator may take emissions in the year 2020 as a basis and give every emitter an initial allocation that is a fixed proportion of their 2020 emissions. This may sound like a subsidy but it is not as polluters need to surrender permits, equal to their actual emissions, at the end of the accounting period.[176]
Grandparenting is a popular method for allocating emission permits because, although introducing a new regulation, it essentially confirms the status quo. Polluters need a permit where they used not to need one, but the permit is free so the

[175] Grandparents, both grandmothers and grandfathers, are wont to give presents, often looking to the past for inspiration.

[176] Yeah, I know. Getting something for free at the start of the year and returning it at the end is an interest-free loan.

apparent cost is administrative. Confirmation of the status quo implies, of course, that the worst offenders get the most lenient treatment; and that fast-growing companies are put at a disadvantage. Repeated grandparenting gets messy quickly.
Permit auctions are the main alternative to grandparenting. Instead of giving away permits for free, the regulator sells them to the highest bidder. Tradable emission permits are then very much like an emission tax: The costs of emissions increase at the margin, and polluters pay the government. There is a difference, though. Permit prices are volatile, prices vary from day to day. Taxes are stable, changing once a year or less frequently.
The Coase Theorem holds that the initial allocation of permits affects neither the final allocation nor the permit price.

12.6.1 Prices v quantities

There is another difference between taxes and tradable permits: They respond differently to lobbying or mistakes by the regulator. This is illustrated by Figure 12.5. Let us assume that the marginal benefits of emission reduction are known and as shown by the green curve. If the marginal costs are known too and as in the brown curve, the optimal emissions tax would be $\tau*$. Alternatively, the regulator could put the optimal cap on emissions Q^*.
Now assume that the regulator is lobbied by industry and convinced that abatement costs are higher than they really are. This is the orange curve in Figure 12.5. Then the rational (if ill-informed) decision would be to impose a more lenient, higher cap on emissions $Q' > Q^*$. There is *under*regulation. However, if the regulator instead opts for an emissions tax, there is *over*regulation as the tax imposed would be higher $\tau' > \tau*$.[177]
This asymmetry in response to misinformation provides a way to assess under what circumstances we would prefer taxes over tradeable permits or the other way around. This is based on work by Martin Weitzman.[178]
Figure 12.5 shows that price instruments—taxes—and quantity instruments—tradable permit—respond differently to mistakes with or manipulation of the marginal costs of emission abatement. Figure 12.6 shows the welfare implications of these mistakes. The underregulation with tradable permits is to the advantage of polluters

[177] If you intend to become a lobbyist for industry, the moral of the story is this: If the regulator plans to impose a system of tradable permits, you should argue that emission reduction is difficult and expensive. On the other hand, if the regulator plans to levy an emissions tax, you should argue that emission reduction is cheap and easy. Indeed, during the pilot phase of the European Union Emission Trading System, two companies manipulated the market by swapping permits at an exaggerated price. This may have contributed to the later overallocation of permits and a collapse of the permit price.

[178] Weitzman (1942-2019) taught at Yale, MIT, and Harvard. He is famous for stealing horse manure and contributions to welfare, discounting, uncertainty, nature conservation, and instrument choice.

and to the disadvantage of the environment. Regulation is suboptimal and the latter is larger than the former. Figure 12.6 shows the net loss.

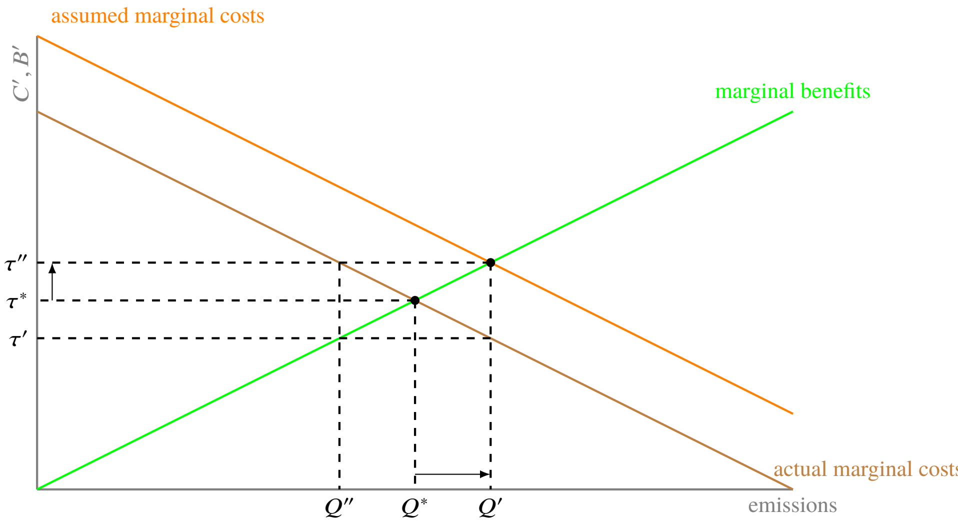


Fig. 12.5: Prices v quantities

If the *assumed* marginal costs of emission reduction are higher than the *actual* marginal costs, then the regulator would *under*regulate with a quantity instrument $Q' > Q*$ but *over*regulate with a price instrument $\tau' > \tau*$.

The overregulation with taxes is to the disadvantage of polluters and to the advantage of the environment. Regulation is again suboptimal and the latter is smaller than the former. Figure 12.6 shows the net loss. Although the distribution is different, the net loss of overregulation equals the net loss of overregulation. From a social perspective, mistakes with taxes and tradable permits are equally painful. However, Figure 12.6 is a special case. Particularly, the marginal cost curve and the marginal benefit curve are equally steep.
Figure 12.7 shows the respective welfare losses if the marginal benefits are steeper than the marginal costs. This reduces the underregulation with permits and increases the overregulation with taxes. The net losses move in the same direction.
Figure 12.8 shows the case where the marginal benefits are shallower than the marginal costs. This increases the underregulation with permits and the associated welfare loss and increases overregulation with taxes and its welfare loss.

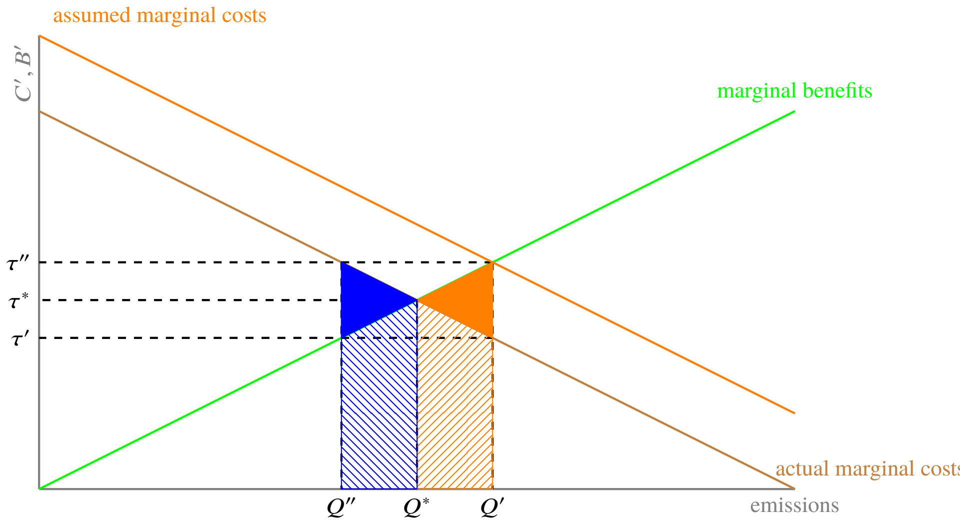


Fig. 12.6: Welfare effects

Underregulation with a quantity instrument would lower abatement costs (dashed orange area) but increase environmental damage (dashed plus filled orange area). The net social loss is the filled orange area. Overregulation with a price instrument would increase abatement costs (dashed plus filled blue area) but lower environmental damage (dashed blue area). The net social loss is the filled blue area.

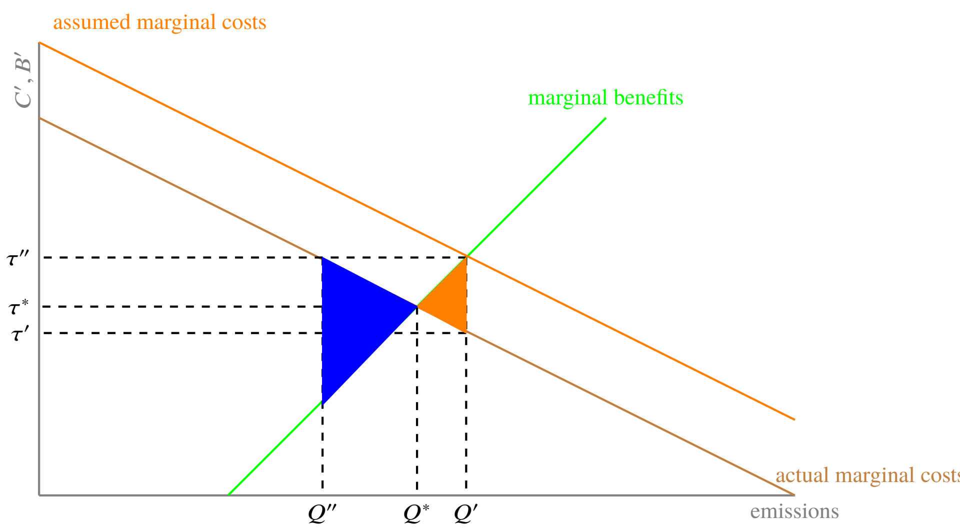


Fig. 12.7: Welfare effects, steep marginal benefits

If the marginal benefit curve becomes steeper, underregulation with a quantity instrument and associated welfare loss become less pronounced and overregulation with a price instrument and associated welfare loss more pronounced.

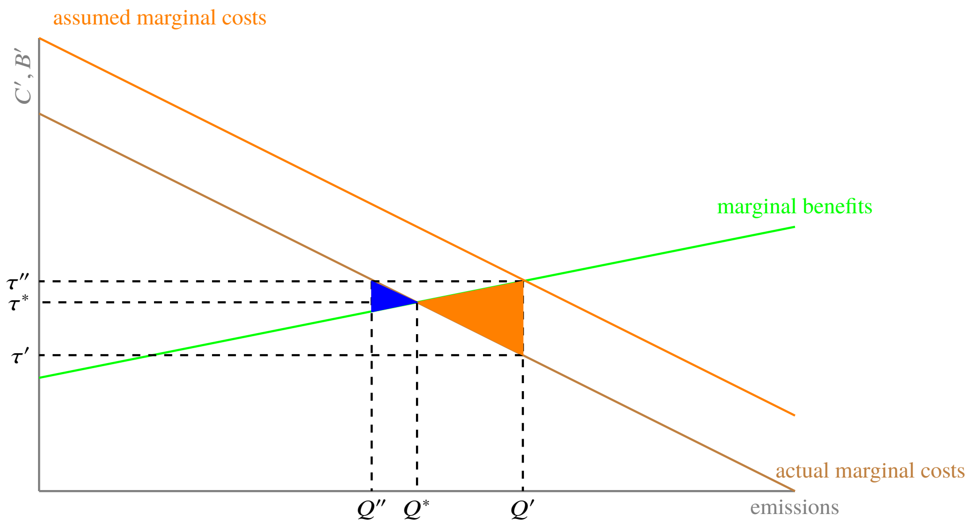


Fig. 12.8: Welfare effects, shallow marginal benefits
If the marginal benefit curve becomes shallower, underregulation with a quantity instrument and associated welfare loss become more pronounced and overregulation with a price instrument and associated welfare loss less pronounced.

This is the *Weitzman Theorem*.[179] If the marginal benefits are steeper (shallower) than the marginal costs, then mistakes with a quantity (price) instrument are less costly than mistakes with a price (quantity) instrument.
In other words, relatively shallow marginal benefits argue for an emissions tax, relatively steep marginal benefits for tradable permits.

12.7 Market power

The optimal tax on an externality, the Pigou tax, is typically derived under the assumption that there is a single market distortion. In that case, the Pigou tax equals the marginal damage done. This result needs modification for multiple market imperfections.
Assume a demand function and an inverse demand function

$$q = \bar{\pi} - \pi \Leftrightarrow \pi = \bar{\pi} - q \tag{12.5}$$

[179] Well. It is the graphical representation of the Weitzman Theorem with linear marginal costs and benefits and one-sided errors. The actual Weitzman Theorem is not limited to linearity and errors can go either way. Note that Weitzman did not write about environmental regulation at all, but rather about the choice between a market economy based on price signals and a planned economy based on quantities.

where q is the quantity demanded, π is the price, and $\bar{\pi}$ is a parameter, the choke price.
If the costs of making q is quadratic, the profit function is

$$\Pi = \pi q - 0.5q^2 - \tau q \tag{12.6}$$

where τ is a tax on production. A price-taker would maximize (12.6) assuming that p is constant:

$$\frac{\partial \Pi}{\partial q} = \pi - q - \tau = 0 \Rightarrow q = \pi - \tau \tag{12.7}$$

Equating supply (12.7) and demand (12.5) in a Cournot equilibrium $q = q$, we find that

$$\bar{\pi} - \pi = \pi - \tau \Leftrightarrow \pi = \frac{\bar{\pi} + \tau}{2} \Rightarrow q' = \frac{\bar{\pi} - \tau}{2} \tag{12.8}$$

A monopolist would maximize (12.6) assuming that π varies with q

$$\frac{\partial \Pi}{\partial q} = \pi + \frac{\partial \pi}{\partial q} q - q - \tau = \pi - 2q - \tau = 0 \Rightarrow q = \frac{\pi - \tau}{2} \tag{12.9}$$

In the Cournot equilibrium

$$\bar{\pi} - \pi = \frac{\pi - \tau}{2} \Leftrightarrow \pi = \frac{2\bar{\pi} + \tau}{3} \Rightarrow q'' = \frac{\bar{\pi} - \tau}{3} \tag{12.10}$$

Comparing (12.8) to (12.10) we note two things. First, the monopolist supplies less, one-third less in this example. This is not news: A monopolist suppresses supply to raise the price. The second thing to note is that the response of the monopolist to the emissions tax is muted: A company with market power responds differently to government regulation than a company without market power. In this example, a unit tax increase leads to a reduction in supply of 1/2 in a perfect market but 1/3 in a monopoly.
Total welfare is given by consumer surplus plus profit plus government revenue minus external cost:

$$\begin{aligned} W = \int_0^q (\bar{\pi} - x)\mathrm{d}x - \pi q + \pi q - 0.5q^2 - \tau q + \tau q - \psi q = \\ -0.5(\bar{\pi} - x)^2|_0^q - 0.5q^2 - \psi q = \bar{\pi} q - 0.5q^2 - 0.5q^2 - \psi q = \\ (\bar{\pi} - \psi)q - q^2 \end{aligned} \tag{12.11}$$

where ψ measures the damage done, at the margin, by the externality.
Maximizing total welfare (12.11) we find optimal consumption

$$q = \frac{\bar{\pi} - \psi}{2} \tag{12.12}$$

A comparison to (12.8) immediately reveals that the optimal tax $\tau = \psi$. That is, the Pigou tax equals the marginal damage.

However, equating (12.12) to (12.9) leads to $\tau = \frac{3}{2}\psi - \frac{1}{2}\bar{\pi}$. The tax serves two functions: It corrects the externality and it takes away the effect of monopoly power.[180] We would expect the monopolist to be taxed less than the price-taker. After all, the regulator needs to reduce production to correct for the externality but increase production to correct for market power.

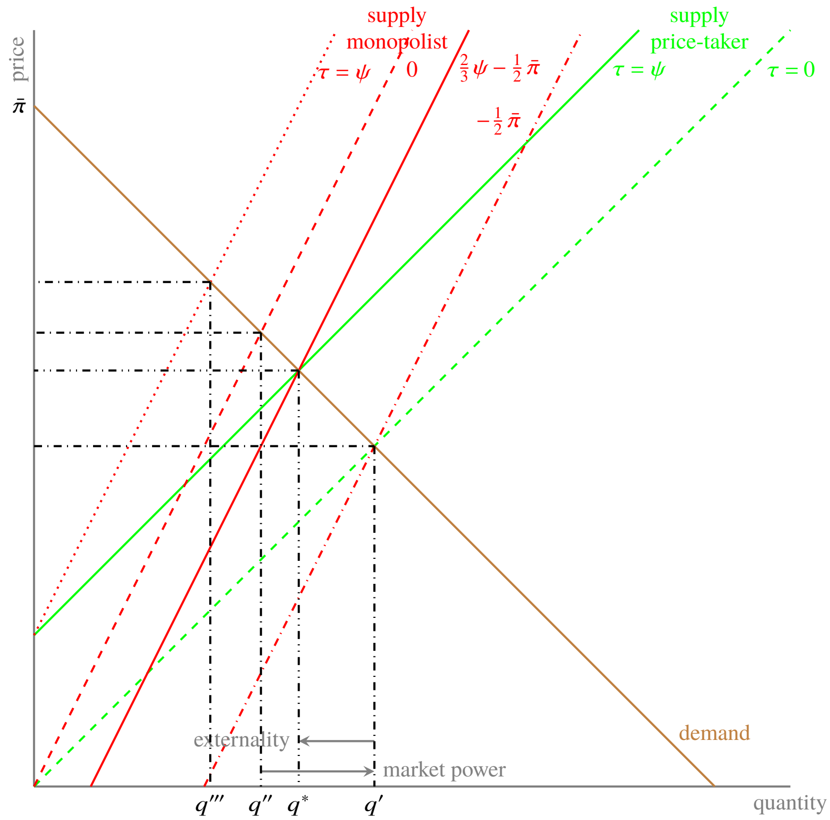


Fig. 12.9: Market power and environmental taxation

The demand for the polluting product is in green. Its supply by a price-taking producer is in green, with and without the Pigou tax $\tau = \psi$. Monopolistic supply is in red, without a tax, with the Pigou tax, and with the optimal tax $\tau = \frac{3}{2}\psi - \frac{1}{2}\bar{\pi}$.

Figure 12.9 illustrates this. There are two cases for the price-taker, with and without the Pigou tax. The supply curve of the monopolist is steeper than the supply curve of the price-taker. Figure 12.9 shows four cases for the monopolist. In the un-

[180] A single policy instrument cannot typically solve two problems. It can in this case because the model is almost linear, and because both problems require a change in the level of production. It would still be better to break-up the monopoly and impose the Pigou tax.

regulated case, the monopolist suppresses supply to drive up the price. If the Pigou tax is imposed, production and hence pollution falls, but not by as much in the case of a price-taker. Correcting for market power requires a subsidy. This is the third case shown. The optimal tax corrects for both market power and externality. In this case, the tax is negative, that is, a subsidy.

12.8 Production vs sale taxes

Above, the environmental tax was levied on production or sale. There is no reason for this. The government may just as well tax the sale of the polluting product. In that case, the profit function becomes

$$\Pi = (\pi - \tau)q - 0.5q^2 = \pi q - 0.5q^2 - \tau q \tag{12.13}$$

This is the same as Equation (12.6) so nothing has changed.

12.9 Production vs consumption taxes

Above, the environmental tax was levied on production or sale of the polluting product. There is no reason for this. The government may just as well tax consumption.

Then the demand function and inverse demand function become

$$q = \bar{\pi} - \pi - \tau \Leftrightarrow \pi = \bar{\pi} - \tau - q \tag{12.14}$$

The profit function is now

$$\Pi = \pi q - 0.5q^2 \tag{12.15}$$

so that

$$\frac{\partial \Pi}{\partial q} = \pi - q = 0 \Rightarrow q = \pi \tag{12.16}$$

Equating supply (12.16) and demand (12.14)

$$\bar{\pi} - \pi - \tau = \pi \Leftrightarrow \pi = \frac{\bar{\pi} - \tau}{2} \Rightarrow q' = \frac{\bar{\pi} - \tau}{2} \tag{12.17}$$

The quantity produced is the exact same as in Equation (12.8). Nothing has changed by shifting the environmental tax from producer to consumer.

The demand function for a monopolist is

$$\frac{\partial \Pi}{\partial q} = \pi - 2q = 0 \Rightarrow q = \frac{\pi}{2} \tag{12.18}$$

In the Cournot equilibrium

$$\bar{\pi} - \pi - \tau = \frac{\pi}{2} \Leftrightarrow \pi = \frac{2\bar{\pi} - 2\tau}{3} \Rightarrow q'' = \frac{\bar{\pi} - \tau}{3} \tag{12.19}$$

Compared to Equation (12.10), we see that production has changed by shifting the tax from production to consumption!
Note the double insight. (*i*) Environmental taxes are different between perfect and imperfect markets. (*ii*) Production and consumption taxes are equivalent in a perfect market but not in an imperfect market.

12.10 Prior tax distortions

However, this assumes that there is a single tax, on pollution. Let us introduce a profit tax ς. Other tax payments are typically not tax deductible, so the profit function is now

$$\Pi = \left(\pi q - 0.5q^2\right)(1 - \varsigma) - \tau q \tag{12.20}$$

with an environmental tax and

$$\Pi = \left(\pi q - 0.5q^2\right)(1 - \varsigma) \tag{12.21}$$

without.
A price-taker's supply function

$$q = \pi - \frac{\tau}{1 - \varsigma} \tag{12.22}$$

with a production tax and $q = \pi$ with a consumption tax.
In the Cournot equilibrium, with a consumption tax, we find again that $q' = \frac{\bar{\pi} - \tau}{2}$.
However, with a production tax, we have that

$$q' = \frac{\bar{\pi} - {}^{\tau}/_{1-\varsigma}}{2} \tag{12.23}$$

That is, the prior tax distortion due to the profit tax breaks the equivalence between the environmental tax on production and the environmental tax on consumption, even if there is no market power.
The broader insight is as follows. Environmental taxation is simple in an economy with a single imperfection—one externality. The policy prescription is straightforward: Impose the Pigou tax, and it does not really matter on whom. That simplicity disappears if there are multiple imperfections, be it due to market power or prior tax distortions.

12.11 Adverse selection

Consider local pollution. Suppose that there are two types of polluters, one with a high cost and the other with a low cost of emission reduction. Because pollution is local, the optimal strategy is to differentiate regulation between low- and high-cost polluters. Figure 12.10 shows this. High-cost polluters would face a higher tax but be allowed to emit more. Low-cost polluters would face a lower tax and deeper emission cuts.

Figure 12.10 also shows the case of a uniform tax, which is too low for high-cost polluters and too high for low-cost polluters, and the resulting welfare losses. A uniform tax would decrease emissions of the low-cost polluter, where relatively little damage is done, and increase emissions of the high-cost polluter, where relatively more damage is done. This is a clear loss for the environment. The decreased costs for the high-cost polluter are larger than the increased costs for the low-cost polluter, but the net fall in costs is smaller than the net increase in environmental damages.

A uniform tax is suboptimal in this case. However, the regulator may have no choice. It could be that anti-discrimination rules or norms prevent tax differentiation. It may also be that the regulator does not know which polluters are high-cost and which are low-cost. Let's further examine the latter case.

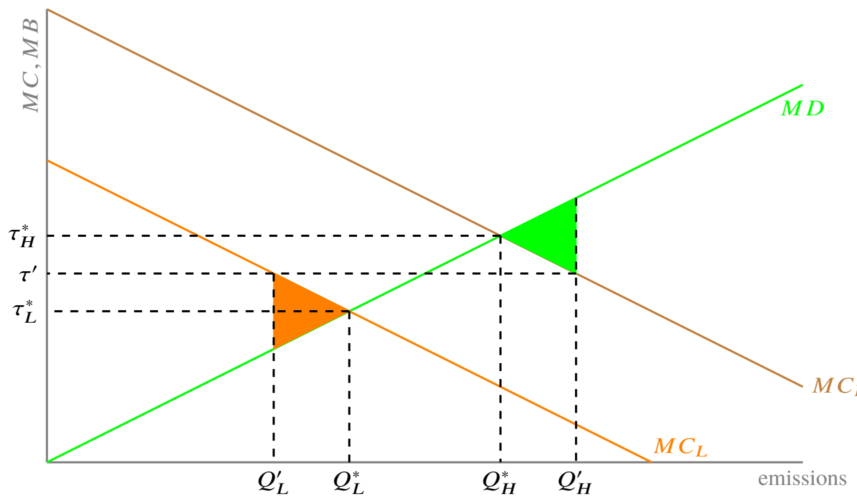


Fig. 12.10: Local pollution regulation with high- and low-cost abatement

Marginal damages of emissions MD are in green. Marginal costs of emission reduction MC are in brown for the high-cost polluter and in orange for the low-cost polluter. Optimal emissions Q and taxes τ are denoted by an asterisk *. The emission levels that correspond to the uniform tax τ' are denoted by a prime $'$. The social welfare loss of uniform taxation is given by the orange and brown triangles.

The regulator does not know which polluters are high-cost or low-cost. High-cost polluters get a more lenient target. Figure 12.11 shows the gains from pretending to be a high-cost polluter when you are in fact a low-cost one. Low-cost polluters get a more stringent target. Figure 12.11 also shows the loss from pretending to be a low-cost polluter when you are in fact a high-cost one.

Suppose that the regulator decides to give a subsidy S_H (S_L) to polluters that self-identify as high-cost (low-cost). Target differentiation tends to be legal if based on an objective criterion. This rule extends to self-declared information. Conditional grants are commonplace too, as are conditional capital subsidies. The regulator needs to combine targets and subsidies so that polluters reveal their true costs.

High-cost polluters get a more lenient target and therefore do not be incentivized with a subsidy: $S_H = 0$. They may, however, declare to be low-cost if the subsidy is high enough. Therefore $C_H(Q_H) < C_H(Q_L) - S_L$.

Low-cost polluters would pretend to be high-cost if the leniency of the target is worth more than the subsidy. Therefore $C_L(Q_L) - S_L < C_L(Q_H)$.

Combining these two conditions, the subsidy should satisfy $C_L(Q_L) - C_L(Q_H) < S_L < C_H(Q_L) - C_H(Q_H)$. This puts an upper and a lower bound on the subsidy to low-cost polluters.

The key insight, however, is that subsidies should go to low-cost polluters, while high-cost polluters get more lenient targets.

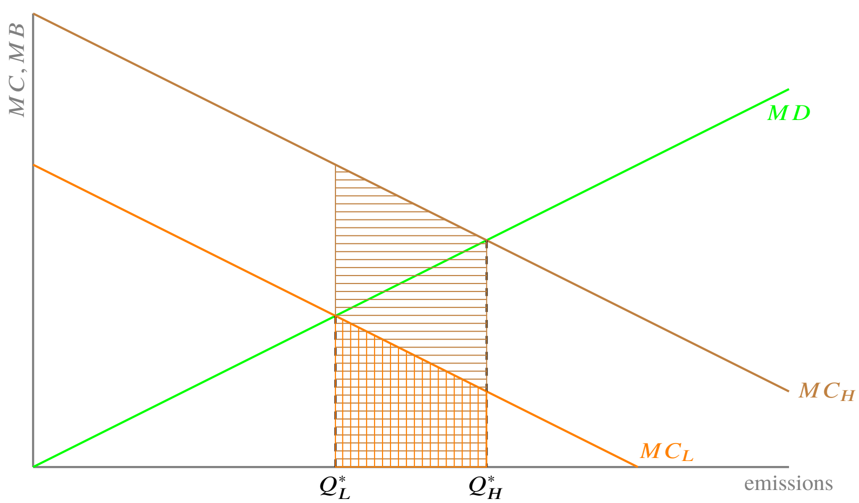


Fig. 12.11: Costs of misinforming the regulator

Marginal damages of emissions MD are in green. Marginal costs of emission reduction MC are in brown for the high-cost polluter and in orange for the low-cost polluter. The area with the brown horizontal lines denotes the cost of pretending to be low cost when you are high cost. The area with the orange vertical lines denotes the gain of pretending to be high cost when you are low cost.

12.12 Enforcement

So far, we have assumed that people and firms obey the law and pay their taxes. If so, regulation is effective. An emissions tax increases the costs of emitting at the margin. Emissions fall. But what if polluters break the law, ignore the tax, and do not cut their emissions? We first look at the case of an emission standard.

12.12.1 Standards

Let us consider a firm with production costs $C(M)$, where costs C fall as emissions M rise. A fine $F(M)$ is imposed if emissions exceed the imposed standard S and the firm gets caught. The fine consists of a fixed penalty D and a variable penalty f that increases with excess emissions:

$$FM = \begin{cases} \pi f(M-S)+D & \text{if } M > S \\ 0 & \text{if } M \leq S \end{cases} \tag{12.24}$$

where π is the probability of being caught.

Figures 12.12 and 12.13 illustrate this. Figure 12.12 shows the case with a fine that is sufficiently high. If emissions exceed the standard, the expected costs rise because of the fixed penalty. The variable penalty is such that the costs are lowest if emissions equal the standard.

Figure 12.13 shows the case with a fine that is too low. If emissions exceed the standard, the expected costs initially rise with the fixed penalty. However, the variability penalty is not high enough to offset the falling production costs and total costs fall—and even fall below the costs for emissions equal to the standard. It is therefore optimal to have emissions above the standard and risk getting fined.

Suppose it is optimal to exceed the standard; see Figure 12.13. The total cost is then

$$TC(M) = C(M) + \pi f(M-S) + D \tag{12.25}$$

Costs are minimized if

$$\frac{\partial TC}{\partial M} = \frac{\partial C}{\partial M} + \pi f = 0 \Rightarrow -C_M = \pi f \tag{12.26}$$

That is, the marginal costs of emission reduction equal the fine times the probability of being caught.

In the optimum, the marginal costs equal the marginal benefits

$$-C_M = \pi f = B_M \Rightarrow f = \frac{B_M}{\pi} \tag{12.27}$$

That is, the optimal fine is the Pigou tax divided by the probability of catching the polluters who break the law and exceed their emission standard.

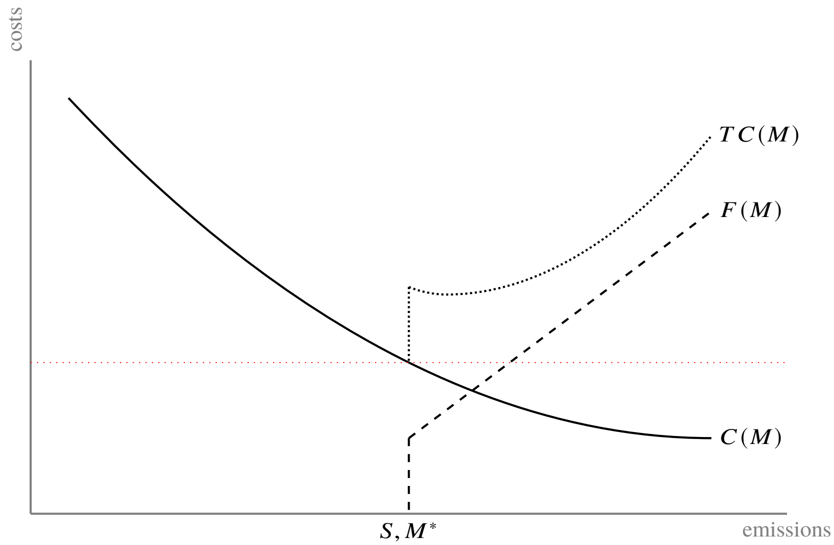


Fig. 12.12: Total costs with an effective fine

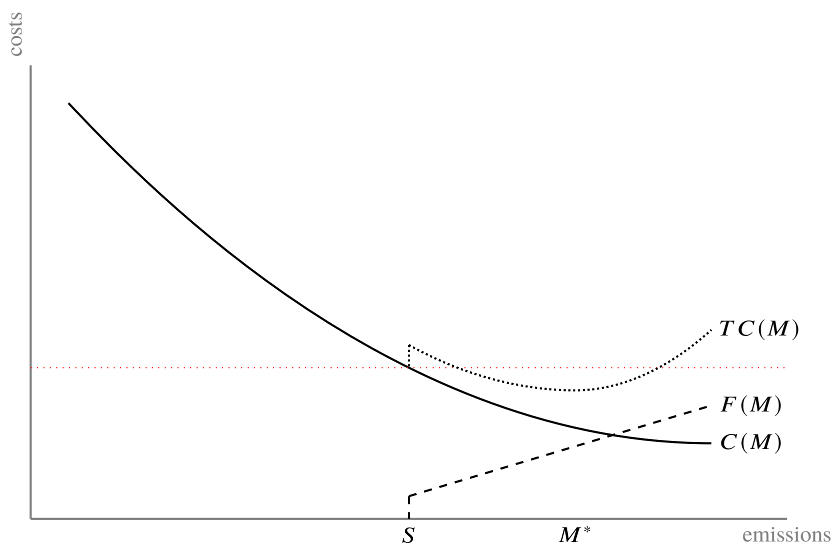


Fig. 12.13: Total costs with an ineffective fine

12.12.2 Taxes

Let us now look at an emissions tax τ. If the polluter complies with the tax:

$$TC(M) = C(M) + \tau M \tag{12.28}$$

. Minimizing costs then leads to the first-order condition $-C_M = \tau$. Emissions are set so that the marginal costs of production equal the emissions tax.
Emissions may be underreported by an amount U. If the polluter is caught underreporting, which happens with probability π, she needs to pay the tax τ plus a fine f which increases with the extent of underreporting, say $f = 0.5\varphi U$. Then, the total cost function is

$$\begin{aligned} TC(M) = C(M) + (1-\pi)\tau(M-U) + \pi(\tau + fU)U = \\ = C(M) + (1-\pi)\tau M - \tau U + 0.5\pi\varphi U^2 \end{aligned} \tag{12.29}$$

The polluter now makes three decisions: How much to emit (as before) and whether and how much to underreport.
Whether or not to underreport emissions follows from comparing (12.28) to (12.29). A lower tax bill is the benefit of underreporting, but this comes at the risk of a fine. The polluter underreports if

$$0.5\pi\varphi U^2 < \tau U \tag{12.30}$$

That is, tax compliance is achieved by either a high probability π of being caught or a large fine φ if so. At the same time, a higher emissions tax leads to greater non-compliance.
Suppose that the regulator did not get this message and the polluter decides to underreport. Two decisions remain, how much to emit and how much to report, so there are two first-order conditions. For emissions, this is

$$\frac{\partial TC}{\partial M} = \frac{\partial C}{\partial M} + \tau(1-\pi) = 0 \Rightarrow -C_M = \tau(1-\pi) \tag{12.31}$$

Setting the marginal costs equal to the marginal benefits

$$-C_M = \tau(1-\pi) = B_M \Rightarrow \tau = \frac{B_M}{1-\pi} \tag{12.32}$$

Above, the optimal fine is the Pigou tax divided by the probability of being caught. As all reported emissions are tax, the optimal tax is the Pigou tax divided by *one minus* the probability of being caught.
The first-order condition for cost-minimizing underreporting is

$$\frac{\partial TC}{\partial U} = -\tau + \pi\varphi U = 0 \Rightarrow U = \frac{\tau}{\pi\varphi} \tag{12.33}$$

That is, underreporting increases with the emissions tax but decreases with the probability of being caught π and the severity of the fine φ. Figure 12.14 illustrate this trade-off.

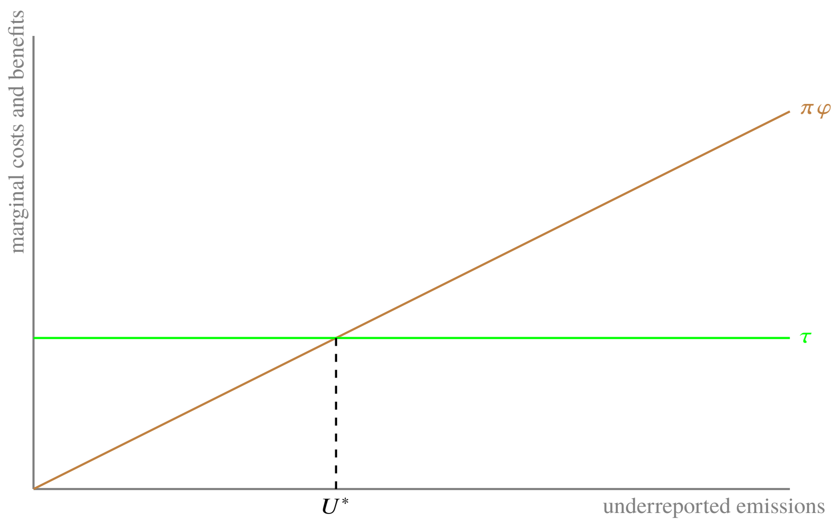


Fig. 12.14: Marginal costs and benefits of underreporting emissions

Further reading

IDEAS/RePEc has a curated bibliography.

Exercises

12.1 Post a summary of this chapter on TikTok with #envecon

12.2 Consider an economy of two firms and two consumers. The two firms pollute. Firm 1 has a marginal savings function of $MS_1(e_1) = 5 - e_1$, where e is the quantity of emissions from this firm. Firm 2's marginal savings function is $MS_2(e_2) = 8 - 2e_2$. Each of the two consumers has marginal damage $MD_i(e) = e = e_1 + e_2$.

a) Graph the firm-level and aggregated marginal savings functions.
b) Graph the aggregate marginal damage function.
c) What is the optimal level of pollution?

d) What is the Pigou tax?
e) What are the optimal emissions from each firm?

12.3 The Fireyear and Goodstone Rubber Companies are two firms located in the rubber capital of the world. These factories produce finished rubber and sell that into the highly competitive world market at the fixed price of £60 per ton. The process of producing a ton of rubber results in air pollution that affects the city. The relationship between rubber output and pollution is fixed and immutable. Fireyear's cost function is $300 + 2Q_F^2$, Goodstone's $500 + Q_G^2$. Total pollution equals $E_F + E_G = Q_F + Q_G$. Marginal damage from pollution equals £12 per ton.

a) In the absence of regulation, how much rubber would be produced by each firm? What is the profit of each firm? How much pollution would there be? What is the value of that pollution?
b) The city government decides to impose an environmental tax on pollution. What is the optimal tax? How does that affect rubber production? Profits? Pollution? The value of pollution?
c) Suppose that the mayor changes his mind and grants an environmental subsidy for pollution reduction instead. What is the optimal subsidy? How does that affect rubber production? Profits? Pollution? The value of pollution?
d) The government changes its mind again and decides to impose a cap-and-trade system. Each company gets, for free, an initial allocation of 18 tons. What is the permit price? How does that affect rubber production? Profits? Pollution? The value of pollution?
e) The government changes its mind yet again. It maintains the cap-and-trade system, but Fireyear gets an initial allocation of 27 tons while Goodstone gets only 9. What is the permit price? How does that affect rubber production? Profits? Pollution? The value of pollution
f) Compare and contrast the results for tax, subsidy and tradable permits.

12.4 Graphically derive Weitzman's Theorem on prices and quantities if the regulator assumes that emission reduction costs are *lower* than they actually are.

Chapter 13
Environmental Kuznets Curve

13.1 Mechanisms

The late Alan Krueger[181] used to joke that, although he was a labour economist, his most-cited paper is in environmental economics. I could return the favour. Although Alan's reputation is in causal analysis, his most famous paper is an association.

The Kuznets Curve is named after Simon Kuznets.[182] Kuznets argued that poor societies are egalitarian, that societies first grow more unequal as they grow richer but that societies become more egalitarian again as they grow richer still.

Alan Krueger and Gene Grossman[183] argued that poor societies are clean, that societies first grow dirtier as they grow richer but that societies become cleaner again as they grow richer still. See Figure 13.1. They called this the *Environmental Kuznets Curve*, often abbreviated to EKC.

Economic growth has a number of effects on environmental pollution and natural resource use:

13.1 *Scale* More economic activity means more pollution and more resource use.
13.2 *Composition* Industry typically imposes a greater environmental burden than agriculture and services.
13.3 *Technology* New technologies are often less resource-intensive, but may introduce new environmental issues.
13.4 *Demand* Richer people are willing to pay more for environmental care.
13.5 *Governance* Richer countries tend to have governments that are better able to deliver on policy priorities.

---

[181] Krueger (1960-2018) taught economics at Princeton University. He would have shared the 2021 Nobel Memorial Prize with David Card.

[182] Kuznets (1901-1985) taught economics at the U Penn, Johns Hopkins and Harvard. He won the 1971 Nobel Memorial Prize for his work on economic development. He defined Gross Domestic Product.

[183] Grossman (1955-) teaches economics at Princeton. He mainly studies international trade.

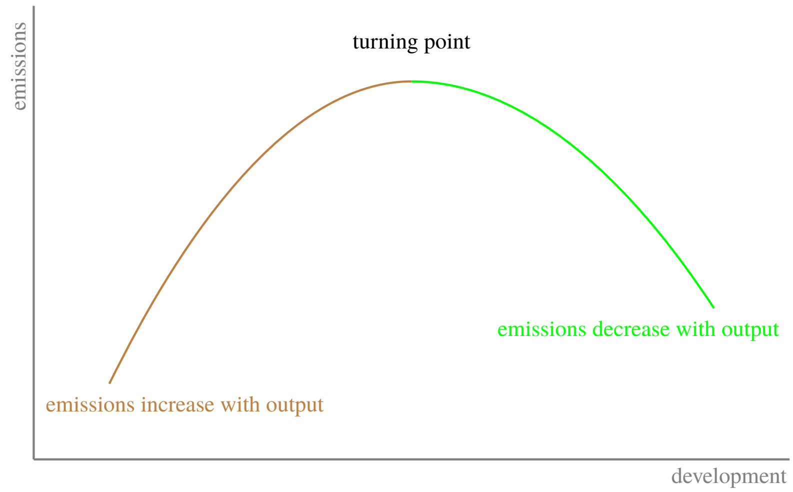


Fig. 13.1: The Environmental Kuznets Curve

Some of these effects imply that richer means cleaner, some imply that richer means dirtier, and some can go either way.

International trade further complicates the relationship between growth and the environment. International trade stimulates economic growth and changes the economic structure of trading partners. It encourages the spread of technologies. Foreign direct investment typically comes with foreign know-how, including knowledge of environmental protection. As foreign investors need to protect their reputation at home, they do not just bring expertise but also attitudes and standards.

Products are often made to the highest specification of all the markets in which they are sold. It is typically more profitable to make a single product that can be sold everywhere, including the place with the strictest environmental standards on final products, than to differentiate products between markets. A single product saves on design costs and training of production managers, and it hedges against fluctuations in demand in the various markets.

However, international trade also allows for production to be shifted to the country with the laxest regulation. Just like labour-intensive production has moved to countries where wages are low, energy-intensive production shifts to places where energy is cheap—and energy is cheaper where environmental standards are weaker. There are tax havens in the world; there are pollution havens too. In fact, politicians may opt to weaken standards in order to attract foreign direct investment just like multinationals may choose locations for their pliable leaders. Other countries may have no choice but to follow. A race to the bottom would result.

It is therefore no surprise that the —large and growing—empirical literature on the Environmental Kuznets Curve is inconclusive (see below). Results are different, depending on the indicator of environmental quality; the time period, the countries or economic sectors included; the model specification; the estimator used;

whether the analysis is done over time or between countries; and whether international trade and investment is considered.
If anything, an Environmental Kuznets Curve can be seen in the data for local environmental problems that are directly harmful to human health. Environmental problems that are global, or affect nature rather than humans do not seem to follow the Environmental Kuznets Curve.
Even if the data reveal an Environmental Kuznets Curve, the results should be interpreted with care. The analysis shows an association rather than a causal relationship. Beyond the turning point, the environment does not get cleaner because we grow richer. The policy implication is not that we should get rich quick and the environment will be fine. Rather, the environment is cleaned-up because people no longer tolerate a dirty environment, take action themselves and demand that politicians do the same. Economic growth creates a demand and opportunities for environmental policy. For all his revolutionary work on causality in empirical economics, Krueger's most-cited paper is an unidentified reduced-form.
That the Environmental Kuznets Curve has no bearing on policy is best illustrated with an example. The Netherlands is often seen as a great country for cyclists. Many people think it was always so. That is a mistake. Old photographs of Amsterdam in the 1950s show a city where the traffic was dominated by cyclists, much like it is today. But photos of Amsterdam in the 1960s and 1970s show a city full of cars, much like other cities across the world. More recent photos see the return of the cyclist. There is an Environmental Kuznets Curve for car traffic in Amsterdam—low when poor, high when richer, low when richer still.
But that is not what happened in cities in other countries, many of which are still dominated by cars. In the 1950s and 1960s, in the Netherlands and elsewhere, car ownership and use rose rapidly, as did traffic accidents and deaths. The Dutch campaign for road safety gained momentum after the teenage son of an influential journalist was killed while riding his bike. Its main slogan was *End Child Murder*. That campaign included road blockades, die-ins, and Rutger Hauer—the biggest movie star in the country—seen being cool on a bike. That put so much pressure on the local authorities[184] that measures were taken to make cycling safer—dedicated cycle lanes, integration of rail and bike, regulation of equipment, and liability in case of accidents. This led, over time, to the Netherlands as we know it now. Countries like Belgium, Denmark, and Germany have followed a similar path as the Netherlands did as has, belatedly, Paris. The recent transformation of Paris underlines that the uptake of cycling has little to do with vague notions of culture and a lot with the availability of infrastructure.
Elsewhere, cycling is seen as sport rather than transport, as a niche activity rather than something for the masses. Bikes are occasionally dismissed as toys for children. England is a prime example. Cycling is a popular sport, but the cycling association has always resisted dedicated cycle lanes because that would restrict

---

[184] The pro-cycling campaign also supported the reform of local governance from its earlier patrician style to more direct democracy. A scandal around soil pollution was another important element in that reform. Governance shapes environmental pollution, but pollution also shapes governance.

the freedom of cyclists to go wherever they want. Dedicated cycle lanes are being built, sometimes overengineered, but mostly in places that are popular with tourists—rather than to connect residential areas with places of work and study.

13.2 Empirical evidence

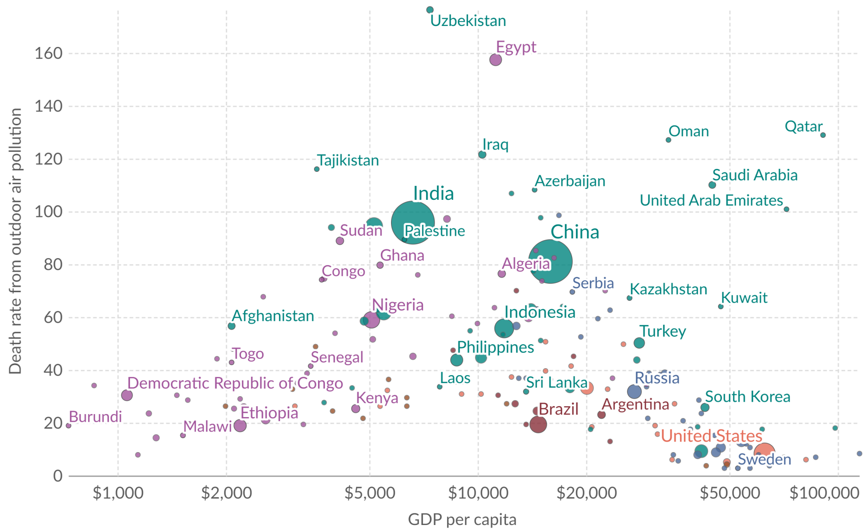
13.2.1 Across countries

Figure 13.2 shows an example of the Environmental Kuznets Curve between countries with different levels of development. The horizontal axis has average per capita income for a large number of countries. It is measured in purchasing-power-parity dollars, correcting for different price levels, so that it reflects actual living standards. The vertical axis shows the number of premature deaths due to air pollution, per 100,000 inhabitants.
Death rates are low in very poor countries, such as Burundi, despite low-quality health care. Death rates rise until a maximum of 0.175% is reached around $7500 per person per year in Uzbekistan. Death rates lowest in rich countries such as the UK (11/100,000) and the USA (9/100,000). This is the combined result of stringent environmental standards and excellent health care.
Figure 13.2 also shows that the link between income and air pollution is not automatic. Rich countries on the Arabian Peninsula suffer high death rates. This is because the immigrant labour population does not enjoy the same level of environmental protection and health care as does the native population. Income *enables* high standards but does necessitate them.

13.2.2 Over time

Figure 13.3 shows global emissions of sulphur dioxide over time. Sulphur dioxide causes acid rain; see Box 12.2. Global emissions were less than 2 million tonnes of SO_2 per year in 1850, with virtually all emissions concentrated in industrializing Europe. Emissions rose to over 150 Mt/SO_2 in 1980, with Europe accounting for 47% of global emissions. After that, emissions started falling as coal-fired electricity started to be replaced by gas-fired power and anti-acidification policies and measures started to take effect. The decline in emissions accelerated after 1990 when the Soviet Union collapsed and the heavy industry of Eastern Europe with it.
Figure 13.3 thus illustrates the Environmental Kuznets Curve. Emissions were low when mostly people were poor and primarily worked the land. Emissions rose with prosperity and a shift in economic activity to manufacturing. However, as people got richer still the market shifted to less polluting activities and environmental policies kicked in.

Fig. 13.2: Air pollution deaths, 2019.



Death rates are measured as the number of premature deaths attributed to outdoor particulate matter air pollution per 100,000 individuals. Gross domestic product (GDP) per capita is measured in constant international Geary-Khamis dollars. Circle size is proportional to population size. Source: Hannah Ritchie and Max Roser, 2024, Our World in Data.

Figure 13.3 also reveals the limitations of a blind faith in the Environmental Kuznets Curve: Sulphur dioxide emissions in Asia were still rising in 2010, making up the majority (53%) of global emissions. However, satellite measurements show that emissions in China fell by almost 90% between 2011 and 2021, although emissions in India are still increasing, albeit slowly and from a much lower base.

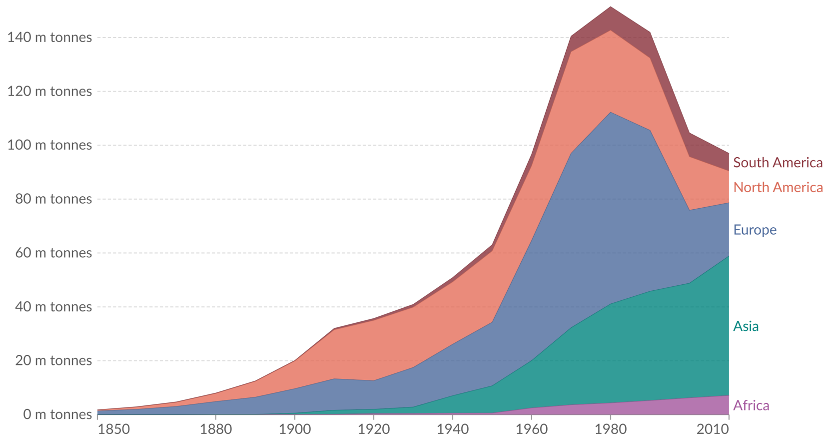
Further reading

IDEAS/RePEc has a curated bibliography.

Exercises

13.1 Post a summary of this chapter on TikTok with #envecon
13.2 Look at the World Bank data on PM2.5. Can you see something like an Environmental Kuznets Curve over time? Over space? What are the main drivers of PM2.5 emissions? How do these drivers vary with economic growth and development?

Fig. 13.3: Sulphur dioxide emissions by year and region.



Source: Hannah Ritchie, 2017, Our World in Data.

Chapter 14
Environmental justice

14.1 Mechanisms

The chapter on the Environmental Kuznets Curve discusses how pressures on the environment differ *between* countries or over time and how differences in wealth, priorities, and access to technologies can explain some of these differences.

It stems to reason, therefore, that there are also differences in environmental pressures *within* countries, that is, between people. It is important to distinguish between direct emissions, the emissions that originate in the household, and indirect emissions, which arise from the things bought by the household. Richer people affect the environment differently than poorer people. Richer people consume more, live in bigger houses, own more appliances and gadgets, and take more and farther holidays. They also own newer and better equipment, and live and work in different places. Besides income, households also differ in other respects. Larger households consume more, but less per head because of economies of scale in heating and cooking. Households with infant, disabled, or elderly members tend to spend more time at home—and therefore need more heating fuel but less transport fuel. Ethnic minorities and recent immigrants are more likely to live in inner cities, in older, poorly insulated houses but with good public transport. Like with the Environmental Kuznets Curve between countries, it is therefore not possible to draw general, universally applicable conclusions. But while the empirical literature shows mixed results, some stylized facts emerge.

First, environmental pollution is often associated with essential goods and services: agriculture, energy, transport, water, waste. By definition, poorer people tend to spend a greater share of their income on essentials than do richer people. Richer people may well spend more in an absolute sense[185] but less relative to their budget. Environmental policy makes these essential goods more expensive, be it

[185] Recall, though, that it is expensive to be poor. If you do not have access to transport, you cannot shop around for a better deal. If you live from hand to mouth, you cannot buy products cheaply in bulk and you may not have space to store them anyway. If you have a poor credit record, you pay as you go for communication and electricity.

directly with taxes or indirectly by telling households and companies to switch to cleaner but more expensive technologies. The costs of environmental policy thus tend to fall disproportionally on the poor.

Second, environmental pollution also tends to fall disproportionally on the poor, and environmental policy thus tends to disproportionally benefit the poor. The relationship between income and pollution is complicated, as sketched above, but the broad pattern is that the rich tend to be less exposed to pollution. This is partly because they are better able to protect themselves. The chapter on revealed preferences discusses defensive expenditure—double glazing, air filters, bottled water. All these things cost money—this is key in valuing environmental services—those who can *afford* better protection are better protected. That chapter also discusses hedonic pricing: Houses are more expensive in cleaner environments. The rich congregate in the nice parts of town and country, the poor are left with areas that are polluted, flood-prone, noisy.

Third, siting decisions disadvantage the disenfranchised. Hazardous and polluting facilities are not located randomly. Decisions to clean-up or protect some places before other places are not random either. Instead, decisions to site a plant or create a nature reserve are made after long deliberation, often following intense debate with local and sometimes national politicians and pressure groups. This means that people with political or media connections, people who can organize a local protest, people who can formulate a threat of legal action, are more likely to come out well. Such people tend to be richer and, importantly, part of the politically dominant group. For instance, a third (and fourth) runway for Heathrow Airport is best placed on the grounds of Windsor Castle, as the increase in noise would affect a few people—but as these people are well-connected, this option is politically impalatable. Political dominance is different in different countries. It is organized partly by race in the USA, by class in the UK, by caste in India, by religion in Israel, and by tribe in Ethiopia. But however a polity may be structured, the disenfranchised are disadvantaged, also when it comes to environmental hazards.

Fourth, while many environmentalists lean to the political left and identify as progressive, the environmental movement has a more chequered history, as touched upon in the first chapter, a history that environmentalists tend to disregard. So it came to be that the Green Party of Germany in their election campaign of 2021 sang to the tune of *Kein schöner Land*. The original lyrics are outright nationalistic—no country is as beautiful. The song was the anthem of the *Wandervogel*, one of the precursor organizations of the Nationalist Socialist German Workers' Party, better known by its acronym *Nazi*. Some in the early environmental movement argued that nature would wash the great unwashed while others sought to protect the environment from the barbarous crowds. In practice, a day in the woods was reserved for the leisured class as it still often is. The World Wide Fund for Nature (WWF) was founded, by former members of the *Hitlerjugend* and the *Afrikaner Broederbond*, to keep the natives off the African hunting grounds of the European elites. WWF still seems to rate the welfare of the pygmy sloth over the welfare of the Baka. When neo-Maltusians warn about population growth, they refer to the high birth rates in Africa and Asia. When people worry about climate migrants, they are not concerned about Americans retiring in Florida or Europeans in Portugal. They worry about darker-skinned people coming to our shores.

The relationship between environment and race is thus a complicated one. Minorities suffer most from pollution, are deprioritized by environmentalists, and disproportionally benefit from and pay for environmental policy. How this exactly pans out is an empirical question.

Note that there is no *biological* basis for these differences between minorities and majorities. The human body's response to environmental contaminants does not vary in a systematic way between races and ethnicities, with one exception. The hole in the ozone layer increases UVB radiation. Lighter-skinned people are more prone to develop skin cancer as a result. Indeed, reduced skin pigmentation is a physiological adaptation to increase the synthesis of vitamin D for farmers under the weak European sun.[186] Tellingly, the hole in the ozone layer is one of the few success stories in solving global environmental problems.

Similarly, there is little difference between the sexes but large differences between the genders. Women tend to spend more time at home than men and are therefore more exposed to indoor air pollution and less exposed to outdoor air pollution. Women tend to be responsible for the collection of water and firewood and therefore suffer most from scarcity. This has nothing to do with female biology, and everything to do with gendered roles in society.

There is one exception to this. We used to use phosphates as detergents until we grew concerned about its effects on eutrophication or hypoxia (see Box 9.1). Phosphate in washing powder were replaced by endocrine disruptors (see Box 14.1). As male and female hormones differ, these pseudo-hormones have different effects on the sexes.

Box 14.1: Pseudo-hormones

"Endocrine disruptors" is the technical term for a class of substances more intuitively known as pseudo-hormones. The endocrine system consists of the glands (thyroid, ovaries, testes and more) and the hormones that regulate your body. You do not want that disrupted.

Humans are exposed to endocrine disruptors through residual pesticides on foods, paints and varnishes, cosmetics and personal care products, clothing, and microplastics.

Pseudo-hormones cause a range of problems. Sperm quality, fertility, and abnormal genitalia are the obvious ones, but the list of issues also includes cancers, obesity, diabetes, learning disabilities, immune function, and more. Already disadvantaged groups, such as ethnic minorities, are disproportionally exposed. See Weiss et al. (2023) and references therein.

These problems are not limited to humans. We share much of our bodily functions with other animals. Pseudo-hormones replaced phosphates in detergents (see Box 9.1) and so end up in waste- and surface waters. Aquatic animals thus face disproportionate exposure.

[186] Hunter-gatherers in Europe were dark-skinned, getting their vitamin D from red meat.

Endocrine disruptors are a relatively recent environmental problem—the term was coined only in 1991—and have yet to attract widespread attention and regulatory action. The impact of pseudo-hormones is hard to pin down because of the complexities in exposure and effects, while any symptom has multiple potential causes. Besides, the number of suspected endocrine disruptors runs in the tens of thousands. A few have been taken off the market.

14.2 Empirical evidence

14.2.1 United Kingdom

In 2002, Julii Brainard and colleagues published a paper on Birmingham. They combined the finest spatial resolution of the 1991 Census with detailed data on traffic and air quality. They found that the average White Brummie was exposed to 2091 μg m^{-3} of carbon monoxide and 22.10 μg m^{-3} of nitrogen dioxide. Ethnic Asians, on the other hand, experienced 2824 μg m^{-3} CO and 27.16μg m^{-3} NO_2 while concentrations were 2919 μg m^{-3} CO and 27.05μg m^{-3} NO_2 for Blacks.
In a 2015 paper, Daniela Fecht and colleagues use similar methods and data to study Birmingham, Bristol, Leeds, Liverpool, London and Sheffield. The concentration difference between the most and least deprived 20% of neighbourhoods in England was 1.5 μg m^{-3} for PM10 and 4.4 μg m^{-3} for NO_2. The differences between white and non-white neighbourhoods was with 3.0 μg m^{-3} for PM10 and 10.1 μg m^{-3} for NO_2. They found similar results for the Netherlands.
Cathryn Tonne and colleagues improve on the results above in a paper published in 2018: They study some 45,000 individuals in London, and distinguish between pollution at home and during the usual commute. Poorer Londoners are more exposed to nitrogen dioxide at home, but less exposed on the road. Asians live in the dirtier parts of relatively clean neighbourhoods, but the difference with Whites disappears in dirty neighbourhoods. Blacks are exposed to more NO_2 everywhere in London.

14.2.2 United States of America

While there is some evidence for racial disparities in environmental exposure in the UK, there is a lot in the USA. This is partly because there is more and better data for that country and partly because race has been a much more contentious issue in the USA than in most other countries. The literature on environmental justice in the USA is very large, but the contribution by economists is more limited.

Jonathan Colmer and colleagues documented in 2020 that the average concentration of PM2.5 fell from about 24 μgm^{-3} in 1981 to about 7 μgm^{-3} in 2016, an impressive improvement. In mostly black neighbourhoods, the concentration was around 8 μgm^{-3} in 2016, down from some about 26 μgm^{-3} in 1981. This compares to around 20 μgm^{-3} in 1981 and about 6 μgm^{-3} in 2016 in mostly white neighbourhoods. Differences narrowed, but did not disappear. In a follow-up paper, Janet Currie and colleagues corrected these estimates for differences in household and neighbourhood characteristics. The racial gap remained, and was found to be statistically significantly different from zero in all years in the study.

In a 2024 paper, Laura Bakkensen and colleagues cast a wider net. The report that non-whites are not just exposed to more particulate matter, but also to ozone and other air pollutants. They tend to live closer to hazardous waste sites and contaminated land. They live more often in houses with lead paint (see Box 1.1).

Not all is bad for African-Americans. In a 2024 paper, George Galster and colleagues find that Blacks face a lower risk of flooding. However, Native Americans are particularly exposed to inland flood risk, and Hispanics to coastal floods.

Jonathan Hoffman and colleagues study the current impact of past decisions, in a paper published in 2020. They consider 108 cities across the USA that had industrial policies in the 1930s. Zones were introduced. Investment was encouraged in some zones, and discouraged in others. The latter were lined in red on a map—this practice became known as *redlining*. They used satellite data between 2014 and 2017 to estimate temperature, tree cover, and impervious surface area. They found significant differences. Areas that were favoured 80 years early had greater tree cover, more permeable ground and, hence, lower flood risks and lower temperatures. Redlining in the 1930s increased the risk of floods and heatwaves. The temperature in the redlined zones was 2.5°C higher. Redlining was done in the Jim Crow era. Racism was sort-of legal then. Areas with a high proportion of African-American were redlined. These traditionally black neighbourhoods typically still see a high proportion of ethnic minorities.

Further reading

IDEAS/RePEc has a curated bibliography.

Exercises

14.1 Post a summary of this chapter on TikTok with #envecon

14.2 Çoker and colleagues investigate differences in meat consumption between ethnic groups in the UK. Why is this relevant for the environment and for environmental policy?

14.3 Look at the ethnicity map of England and Wales. How does this correlate with the Green Belt and National Parks? Traffic noise and pollution?

Chapter 15
Environmental accounting

15.1 GDP and its discontents

Gross Domestic Product (GDP) is a measure of economic activity. It was defined in 1925 by Simon Kuznets.[187] In 1932, Kuznets wrote

> the welfare of a nation can scarcely be inferred from a measurement of national income

Kuznets' warning notwithstanding, many non-economists and even some economists use GDP as a welfare indicator. It is not. This follows immediately from the three alternative ways to measure GDP. GDP can be measured as

- **Total effective demand** Gross Domestic Product equals private consumption plus public expenditure plus gross investment plus exports minus imports.
- **Total value added** Gross Domestic Product equals value added in all economic sectors (e.g. agriculture, manufacturing and services), plus Value Added Tax.
- **Total income** Gross Domestic Product equals labour income plus capital income plus state revenue plus amortization of debt.

That is, GDP is a measure of the size of the economy. Private consumption and government provision of public goods directly contribute to human welfare, but other things matter too. GDP per capita is thus an incomplete proxy for welfare. It is not just an underestimate, it is an overestimate too: Investment and international trade do not directly add to welfare.
Although GDP was designed as an indicator of economic activity, it is incomplete. Anything not traded on legal markets is outside the scope of GDP. Marijuana is outside the GDP of most countries,[188] even though there is a market with consumers, retailers, wholesalers, importers, exporters, and producers. Homework and growing food for own consumption—and so all subsistence farming—are not market transactions therefore excluded from GDP. Economists used to joke that

---

[187] See footnote 182.

[188] Legalizing pot is a bit of a nightmare for statisticians, as it causes a break in the time series of GDP.

marrying your housekeeper would reduce GDP but we do not think this is funny anymore.
GDP was never intended to measure economic welfare. Buying medicine is included, but feeling sick is excluded. Air pollution is not in GDP, and neither is a stroll in the park. GDP counts total income, but it is silent on the distribution of income. Free speech and the rule of law are omitted.
There is another problem with GDP: It counts gross investment. Additions to the capital stock are included, but subtractions are not. Breaking and fixing a window thus grows GDP. This is known as *Bastiat's broken window fallacy*.[189] The solution is the *Net Domestic Product*, which equal GDP minus depreciation. Unlike GDP, NDP counts the broken window, not just its repair.

15.2 Mismeasuring productivity growth

If GDP per capita is an incomplete measure of economic welfare, then measures of productivity growth based on GDP are biased too.
To see this, let us assume that there are two factors of production, labour L and environment E, so that economic output Y is given by

$$Y = Af(L,E) \tag{15.1}$$

where A is total factor productivity. If all input factors change a little bit, then

$$Y + \Delta Y = (A + \Delta A) f(L + \Delta L, E + \Delta E) \tag{15.2}$$

Linearize the production function

$$f(L + \Delta L, E + \Delta E) \approx f(L,E) + \frac{\partial f}{\partial L}\Delta L + \frac{\partial f}{\partial E}\Delta E \tag{15.3}$$

If we substitute that back in and subtract Y on the left-hand side of the equation and $Af(L,E) = Y$ on the right-hand side, we find

$$\Delta Y \approx \Delta A f(L,E) + \frac{\partial f}{\partial L}\Delta L + \frac{\partial f}{\partial E}\Delta E \tag{15.4}$$

Now divide everything by Y

$$\frac{\Delta Y}{Y} \approx \frac{\Delta A}{A} + \frac{L}{Y}\frac{\partial f}{\partial L}\frac{\Delta L}{L} + \frac{E}{Y}\frac{\partial f}{\partial E}\frac{\Delta E}{E} \tag{15.5}$$

---

[189] Claude-Frédéric Bastiat (1801-1850) was a Classical economist from the south of France, a staunch critic of protectionism and government intervention. He developed the concept of *opportunity cost*.

Assuming that the economy is efficient, the condition for production efficiency implies that the input price p_L equals the output price p_Y times the marginal product of labour:

$$p_L = p_Y \frac{\partial f}{\partial L} \Leftrightarrow \frac{p_L}{p_Y} = \frac{\partial f}{\partial L} \tag{15.6}$$

Ditto for the environment. Then

$$\frac{L}{Y}\frac{\partial f}{\partial L}\frac{\Delta L}{L} = \frac{L}{Y}\frac{p_L}{p_Y}\frac{\Delta L}{L} = \frac{p_L L}{p_L L + p_E E}\frac{\Delta L}{L} =: s_L \frac{\Delta L}{L} \tag{15.7}$$

The second step follows because the value of output equals he value of inputs $p_Y Y = p_L L + p_E E$. s_L is the input share of labour.
Ditto for the environment, so

$$\frac{\Delta A}{A} \approx \frac{\Delta Y}{Y} - s_L \frac{\Delta L}{L} - s_E \frac{\Delta E}{E} \tag{15.8}$$

Now divide both sides of the equation by Δt and define $\dot{X} = {}^{\Delta X}/_{\Delta t}$ to find the growth rate of the Solow[190] residual:

$$\frac{\dot{A}}{A} \approx \frac{\dot{Y}}{Y} - s_L \frac{\dot{L}}{L} - s_E \frac{\dot{E}}{E} \tag{15.9}$$

The rate of technological progress equals the rate of output growth minus the rates of input growth times their value shares.
Now that we have re-capped growth accounting, let us consider the situation where one of the inputs into production is hard to measure and therefore omitted. Then

$$Y = A^* f(L) \tag{15.10}$$

Implicitly, if we omit E, we assume that

$$\frac{\dot{E}}{E} = \frac{\dot{L}}{L} \Rightarrow \frac{\dot{A}^*}{A^*} = \frac{\dot{Y}}{Y} - \frac{\dot{L}}{L} \tag{15.11}$$

If, in fact,

$$\frac{\dot{E}}{E} = \frac{\dot{L}}{L} - B \tag{15.12}$$

then

$$\frac{\dot{A}}{A} = \frac{\dot{Y}}{Y} - s_L \frac{\dot{L}}{L} - s_E \frac{\dot{E}}{E} + s_E B = \frac{\dot{Y}}{Y} - \frac{\dot{L}}{L} + s_E B \Rightarrow \frac{\dot{A}^*}{A^*} = \frac{\dot{A}}{A} - s_E B \tag{15.13}$$

That is, if the missing input grows more sluggishly ($B > 0$) than the included input, then we understate technological progress. This makes intuitive sense. There is an unmeasured drag on output. It cannot be explained by sluggish input growth, so total factor productivity seems to grow more slowly than it really does.

[190] See footnote 42.

Of course, if the environment improves rapidly ($B < 0$), we *over*state technological progress.

15.3 The welfare significance of national product

Attempts to come up with complements to GDP, measures of economic welfare rather than economic activity, are often *ad hoc*, but there is some theory to guide that effort.
Let us assume that we want to maximise the net present utility of consumption:

$$\max_{C(t)} \int_{t=0}^{\infty} U(C(t))e^{-\rho t} \mathrm{d}t \tag{15.14}$$

where $C(t)$ is consumption at time t, U is the utility function and rho is the pure rate of time preference. This maximization is subject to the constraints

$$Q(t) = Q(K(t)) \tag{15.15}$$

where production Q is a function of capital stock K, which follows the equation of motion

$$\frac{\partial K}{\partial t} =: \dot{K}(t) = -\delta K(t) + I(t) = -\delta K(t) + Q(K(t)) - C(t) \tag{15.16}$$

where I is investment. Note that the right-hand side of Equation (15.16) incorporates Equation (15.15) so that there is only one constraint on optimization.
In order to find the optimum, form the current-value Hamiltonion

$$\mathcal{H}(t) = U(C(t)) + \lambda(t)\dot{K}(t) \tag{15.17}$$

Note that the Hamiltonian is measured in utils.
The first-order condition for dynamic efficiency is

$$\dot{\lambda}(t) - \rho\lambda(t) = \frac{\partial \mathcal{H}}{\partial K} \tag{15.18}$$

We will ignore this condition. The first-order condition for static efficiency is

$$\frac{\partial \mathcal{H}(t)}{\partial C(t)} = U_C(t) + \lambda(t)\frac{\partial \dot{K}(t)}{\partial C(t)} = 0 \Rightarrow U_C(t) = \lambda(t) \tag{15.19}$$

The *maximized* Hamiltonian is therefore

$$\mathcal{H}(t) = U(C(t)) + U_C(t)\dot{K}(t) \approx U_C(t)C(t) + U_C(t)\dot{K}(t) \tag{15.20}$$

This implies

$$\frac{\mathcal{H}(t)}{U_C(t)} \approx C(t) + \dot{K}(t) \tag{15.21}$$

On the left-hand side, we divide the Hamiltonion by marginal utility. This transforms the left-hand side from utils to money. The right-hand side equals consumption plus the change in the capital stock, or consumption plus investment minus depreciation. This is the Net Domestic Product. It now has a welfare interpretation: NDP equals the monetized, linearized Hamiltonian. The NDP is what we seek to optimize in the short run, while taking the long-term implications into account. This insight is due to a young Martin Weitzman.[191]

15.4 The welfare significance of environmental product

An older Weitzman[192] extended the analysis to the environment.
Let us assume that utility depends on material consumption C and the state of nature N. We thus want to maximize

$$\max_{C(t),P(t)} \int_{t=0}^{\infty} U(C(t), N(t)) e^{-\rho t} \mathrm{d}t \tag{15.22}$$

subject to the constraints

$$\dot{K}(t) = -\delta K(t) + Q(K(t)) - C(t) - P(t) \tag{15.23}$$

and

$$\dot{N}(t) = \vartheta N(t) + P(t) \tag{15.24}$$

where ϑ is the natural regeneration rate of nature and P is the expenditure on nature conservation. This expenditure cannot be used for consumption or investment and therefore also appears in the equation of motion for capital. As we have two constraints, there are two co-state variables. The current-value Hamiltonian is

$$\mathcal{H}(t) = U(C(t), N(t)) + \lambda(t)\dot{K}(t) + \mu(t)\dot{N}(t) \tag{15.25}$$

Investment in nature conservation is a choice variable. We therefore have two first-order conditions for static efficiency—one for each choice variable—and two first-order conditions for dynamic efficiency—one for each stock variable. The dynamic ones are Equation (15.18) and

$$\dot{\mu}(t) - \rho\mu(t) = \frac{\partial \mathcal{H}}{\partial N} \tag{15.26}$$

These do not interest us here.

---

[191] See footnote 178.

[192] Martin Weitzman published his first paper in 1965. Although he showed an early interest in public goods and energy, he did not publish his first paper on environmental issues until 1992.

The first-order conditions for static efficiency are Equation (15.19) and

$$\frac{\partial \mathcal{H}(t)}{\partial P(t)} = -\lambda(t) + \mu(t) = 0 \Rightarrow \mu(t) = \lambda(t) \tag{15.27}$$

Following the same logic as above, the maximized Hamiltonian is

$$\mathcal{H}(t) = U(C(t), N(t)) + U_C(t)\dot{K}(t) + U_C(t)\dot{N}(t) \tag{15.28}$$

Therefore

$$\mathcal{H}(t) \approx U_C(t)C(t) + U_N(t)N(t)\frac{U_C(t)}{U_C(t)} + U_C(t)\dot{K}(t) + U_C(t)\dot{N}(t) \tag{15.29}$$

so that

$$\frac{\mathcal{H}(t)}{U_C(t)} \approx C(t) + N(t)\frac{U_N(t)}{U_C(t)} + \dot{K}(t) + \dot{N}(t) \tag{15.30}$$

The term ${}^{U_N}/_{U_C}$, the marginal utility of nature over the marginal utility of consumption, is the price of nature. So, if we care about both material consumption and nature, then the welfare equivalent to the Net Domestic Product equals consumption plus *the amenity value for nature* plus net investment in capital minus *net growth of natural capital*. This is known as the *Environmental Domestic Product*.
In sum, if we only care about material consumption, then the Net Domestic Product is an appropriate welfare indicator, one that accounts for current welfare (measured by consumption) and future welfare (measured by the change in the capital stock). However, if we care about both material consumption and the natural environment, then the appropriate welfare indicator adds the monetised value of the environment and the change in the natural capital stock.
Of course, we can redo the analysis with any number of attributes to the utility function—we could add knowledge and the company of friends, and human and social capital. That would complicate the notation without adding insight: There would be more terms in Equation (15.30) to reflect the things we value and net investment in corresponding stocks.
Note that the Environmental Domestic Product adds changes in the physical capital stock to changes in the natural capital stock. It assumes that the two are perfectly substitutable. The Environmental Domestic Product is a measure of weak sustainability.

15.5 Environmental products in practice

Well before Weitzman provided the theoretical underpinning of the Environmental Domestic Product, William Nordhaus[193] and James Tobin[194] proposed an *ad hoc* measure that is very similar: The *Measure of Economic Welfare*. The Measure of Economic Welfare equals Net Domestic Product minus economic bads (pollution control, repairs) and regrettable necessities (police, defense) plus household production, illegal production, and leisure. Although the authors described their proposal as primitive and experimental, it was very influential and was reincarnated under such names as the *Index of Sustainable Economic Welfare*, the *Genuine Progress Indicator*, the *Sustainable Net Benefit Index*, and the *Measure of Domestic Progress*.
The indicator that is now most widely used is *Adjusted Net Savings*, formerly known as *Genuine Savings* This measure is adopted by the World Bank, who collect data that are consistent over time and between countries. Genuine Savings is, in theory, defined as net investment in manufactured capital, plus net investment in human capital, minus net depreciation of natural capital. That is, Adjusted Net Savings expands the Environmental Domestic Product by including education.
Theory is not practice. Because of data limitations, Adjusted Net Savings as currently reported includes gross savings and depreciation, depletion of mineral, energy and forest resources, damage by particulate matter and carbon dioxide, and expenditure on education.
Note that Adjusted Net Savings omits consumption. It does not account for current welfare but only for the potential to generate future welfare. It therefore has an immediate interpretation for weak sustainability. Positive Adjusted Net Savings are weakly sustainable, negative Adjusted Net Savings are unsustainable.
The United Nations Statistics Division maintains the *System of National Accounts*. Its purpose is to ensure the comparability of economic statistics between countries. In 2012, it launched the *System of Environmental Economic Accounting* (SEEA). These are so-called satellite accounts. Satellite accounts are compatible with the national accounts and provide additional information.
The SEEA comprises several elements. The *Ecosystem Accounts* includes data on the extent and condition of ecosystems, the ecosystem services provided, the monetary value of these services, and the value of the stock of ecosystem service providers. The *Agriculture, Forestry, and Fisheries Accounts* are separate, recording yields in both physical volumes and monetary values and the associated stocks (or assets), also in both physical and economic terms. The *Energy Accounts* follow the same rule. Flows and stocks of energy are recorded in both joules and dollars. The *Water Accounts* are somewhat different. Physical stocks and flows are

[193] William D. Nordhaus (1941-) is a professor of economics at Yale University. He won the 2018 Nobel Prize for his work on the economics of climate change.

[194] James Tobin (1918-2002) taught economics at Yale University, winning the Nobel Prize in 1981. He is known for his work on the demand for liquidity, the Tobit for regression analysis of censored data, Tobin's Q as a company's value, and the Tobin tax on the market in foreign currency.

included, but monetary values are more limited—partly because so many water "transactions" are outside the market (e.g., rain), and partly because water is sacred in a number of cultures.

Those are the core accounts. The SEEA also encourages countries to construct *Air Emission Accounts*, which only extends to physical amounts. The *Land Accounts* record land use as well as the monetary returns on different types of land use. The *Material Flow Accounts* do not add anything new, but rearrange the material in the other accounts so as to get an overview of the physical amounts of material that are extracted, exported and imported—and, by addition and subtraction, used domestically. Finally, the *Environmental Activity Accounts* collect data on expenditure on environmental protection, on the production of environmental goods and services, and on environmental taxes and subsidies.

Together, the SEEA provides a fairly complete account of the interactions between the economy and the environment. Unfortunately, few countries collect all necessary data and many collect none at all.

Box 15.1: Gross ecosystem product

The Gross Ecosystem Product (GEP) is an attempt to extend the national accounts of China. The GEP uses the values of 21 different services. It carefully distinguishes between those services that are provided for free, such as the sequestration of carbon dioxide in forests, and services that require co-production by humans, such as agricultural crops.

A pilot project in Qinghai found that the GEP was roughly equal to GDP in 2000. That is, the value added by ecosystems was about as large as the value added to humans. However, GDP grew faster so that it was about a third larger than GEP in 2015.

15.6 Alternative indicators

Over the years, many alternative indicators have been proposed. Few of them gained much traction, were collected for short periods of time or for a handful of countries. Two indicators are successful, however, in that they are widely available and used.

The *Human Development Index* (HDI) excludes environmental concerns, but it is instructive as an exercise in index construction. The HDI consists of three subindices: gross domestic product per capita, life expectancy at birth, and education, which in turn equals two-thirds times the adult literacy rate plus one-third times the enrollment rate of school children. The three subindices are rescaled such that the worst performing country scores zero and the best performing one scores one. The HDI is the average of the three subindices.

This is odd. It is not so much an index of development in the absolute sense of the word. It is a positional score. That is, if a country improves on all three scores, but less fast than the rest of the world, then its HDI will fall—even if income, longevity, and education have all improved. Furthermore, the relative weights of the three subindices vary from year to year as they depend on the relative distance between the worst and best performing countries. If, for instance, the gap in longevity narrows but the education gas widens, then small differences in life expectancy get highlighted and large differences in human capital are discounted. These problems notwithstanding, the HDI is often seen as a credible alternative to GDP per capita.

The *Ecological Footprint* is all about the environment. Unlike the weakly sustainable measures reviewed above, it is an indicator of *strong sustainability*, at least to some extent. The Ecological Footprint was proposed by Mathis Wackernagel[195] and William Rees[196] in 1990. The Ecological Footprint seeks to express all pressures we put on the environment into its equivalent amount of land. It then compares this to the amount of land available.

The results are shocking. Before 1970, humans used less than the amount of land available. Since 1971, we have used more than that. In 2022, the latest available data, we used 1.71 Earths—but we have only one! Human activity comes at the expense of environmental destruction.

The Ecological Footprint is calculated as follows. The amount of land needed for our buildings, crops and animals is straightforward. For fisheries, the Ecological Footprint uses the land area needed to husband the equivalent amount of animal protein. The land equivalent for carbon dioxide emissions is the land required to grow trees that would sequester the emitted CO_2. This is a key assumption. Carbon dioxide emissions make up 53% of the global Ecological Footprint in 2019, the latest available data. It is a debatable assumption: There are other ways to sequester carbon dioxide, or to reduce emissions.

The Ecological Footprint ignores other environmental issues. Like all indicators reviewed above, it is incomplete. It does not assume that human capital can substitute for natural capital. It does, however, assume that different forms of natural and environmental capital are substitutable. The only thing that matters is the total amount of land available.

By using land as the yardstick, the Ecological Footprint reminds us of the Physiocrats. They disagree on another point. Jean-Francois Quesney was no fan of Jean-Baptiste Colbert and his mercantilism. Quesney favoured trade. The Ecological Footprint frowns on it.

Above, I state that we consume the services of 1.71 Earths per year. Alternatively, we consume all we have in the first 213 days of the year. After 1 August, *Earth Overshoot Day*, we are running down our capital stock. The Footprint Network also promotes *Country Overshoot Day*, the day at which a country uses more than it is big. Country Overshoot Day comes early in small countries that trade a lot, such as Qatar (11 February) and Luxembourg (20 February). The argument that a

[195] Wackernagel (1962-) is an activist.

[196] Rees (1943-) taught ecology and planning at the University of British Columbia.

country should live off what is in its territory can easily be interpreted as an argument against international trade and for protectionism.

Further reading

The first chapters of *Capitalism without Capital: The Rise of the Intangible Economy* by Jonathan Haskel and Stian Westlake contain a lucid introduction to the national accounts. Jan Bebbington and colleagues edited a 2021 *Handbook of Environmental Accounting*. Steven Bragg's 2024 book *Environmental Accounting* focuses on corporate accounting.

Exercises

15.1 Post a summary of this chapter on TikTok with #envecon
15.2 The derivation in Section 15.2 assumes two factors of production: labour and the environment. Would the results change if we added capital?
15.3 The Office of National Statistics publishes data on environmental taxes in the UK. Look at Table 1. What are the largest sources of environmental tax revenue? How has this shifted over time? Look at Table 4. What part of the economy paid most in environmental taxes? How has this shifted over time?
15.4 The ONS also publishes statistics on atmospheric emissions of heavy metals. What are the major sources of lead? How has this changed over time? Why do you think that is?

Appendix A
Optimization in continuous time

A.1 Discrete time

You are familiar with constrained optimization. If we want to find the optimal consumption path in a production economy, you could

$$\max_{C_0, C_1, \ldots} \sum_t U(C_t)(1+\rho)^{-t} \text{ s.t. } \Delta K_t = -\delta K_t + (Q(K_t) - C_t) \tag{A.1}$$

where U denotes utility, C_t consumption in year t, ρ the utility discount rate, K_t the capital stock at time t, δ the depreciation rate, and Q the production function.
In order to solve this, form the Lagrangian:

$$\mathcal{L} = \sum_t U(C_t)(1+\rho)^{-t} - \lambda_t \left(-\delta K_t + Q(K_t) - C_t - \Delta K_t\right) \tag{A.2}$$

The Lagrangian is the objective function minus the Lagrange multiplier times the constraint-rearranged-to-equal-zero.
The first-order conditions are

$$\frac{\partial \mathcal{L}}{\partial C_t} = U_{C_t} + \lambda_t = 0 \forall t \tag{A.3}$$

and

$$\frac{\partial \mathcal{L}}{\partial \lambda_t} = 0 \Leftrightarrow \Delta K_t = I_t - \delta K_t \forall t \tag{A.4}$$

where I_t is investment in year t.
The problem with these first-order conditions is that they are not particularly informative. For instance, we find that the shadow price of capital, λ_t, should be equal to the marginal utility of consumption, U_{C_t}, at every point in time—this follows from Equation (A.3)—but we discern nothing about the evolution of the shadow price over time. Equation (A.4) reproduces the equation of motion of capital, rather than its price.

A.2 Continuous time

You could also write the maximisation problem in continuous time

$$\max_{C(t)} \int_t U(C(t))\mathrm{e}^{-\rho t}\mathrm{d}t \text{ s.t. } \dot{K}(t) = -\delta K(t) + (Q(K(t)) - C(t)) \tag{A.5}$$

There are a few differences between Equations (A.1) and (A.5). Instead of a summation over time, we have an integral. Recall that a Riemann integral is summation in infinitisimally small steps. Instead of subscripts to denote time, variables are now functions of time. This is just a convention. Instead of the discount factor $(1+\rho)^{-t}$ we have $\mathrm{e}^{-\rho t}$. In the former, ρ is the annual discount rate. Measuring time in annual time steps is arbitrary. Instead of solar years, you could measure time in lunar months, or in days, hours, minutes, or seconds. If the time step goes to zero, $(1+\rho)^{-t}$ approaches $\mathrm{e}^{-\rho t}$. Finally, $\dot{K}(t)$ replaces ΔK_t. The latter is the difference between two periods, $\Delta K_t = K_{t+1} - K_t$. The former is the change at time t, $\dot{K}(t) = \frac{\partial K(t)}{\partial t}$. Although the notation has changed to account for the fact that we are working in continuous rather than in discrete time, our representation of the system has not changed.

You cannot use the methods developed by Joseph-Louis Lagrange to find an optimum in continuous time. Instead, you have to use the methods of William Rowan Hamilton and Lev Pontryagin. So, in order to solve this, we form the Hamiltonian, or more specifically, the current-value Hamiltonian[1]:

$$\mathcal{H} = U(C(t)) + \eta(t)\dot{K}(t) \tag{A.6}$$

The Hamiltonian consists of three elements. The first element is the current value of the objective function. That is, get rid of the integral. Only take the bit that you integrate, in this case $U(C(t))$. The second bit is known as the co-state variable, $\eta(t)$, which is a shadow price just like the Lagrange multiplier. The third part is the left-hand-side of the constraint, $\dot{K}(t)$. Compared to the Lagrangian, the Hamiltonian is considerably simpler.

This simplicity helps greatly with the first-order conditions. There are two. The first is

$$\frac{\partial \mathcal{H}}{\partial C(t)} = U_{C(t)} - \eta(t) = 0 \tag{A.7}$$

The first first-order condition has that the first partial derivative of the Hamiltonian to the control variable be equal to zero, just like in Lagrange's constrained optimization. As with the Lagrangian, this says that the shadow price of capital should equal the marginal utility of consumption. This is because we sacrifice consumption to invest so as to accumulate capital used to produce consumption goods.

The second first-order condition has no analogue with Lagrange. It is

[1] Mathematicians and physicists are better used to the present-value Hamiltonian. The results are the same. The current-value Hamiltonian is more readily interpreted for economic problems.

$$\dot{\eta}(t) - \rho\eta(t) = \frac{\partial\mathcal{H}}{\partial K(t)} = \eta(t)\left(Q_{K(t)} - \delta\right) \tag{A.8}$$

That is, the first partial derivative of the Hamiltonian to the constrained stock variable equals the change in its co-state variable minus the discount rate times the co-state variable.

This can be rewritten as

$$\frac{\dot{\eta}(t)}{\eta(t)} = Q_{K(t)} - \delta + \rho \tag{A.9}$$

The left-hand side is the proportional rate of change of the shadow price of capital. This is a variable with an economic interpretation. It is the equation of motion of the *price* of capital.

The elements on the right-hand side are intuitive too: the marginal productivity of capital $Q_K(t)$, the depreciation rate δ, and the utility discount rate ρ. Equation (A.9) thus says that the value of capital should increase with its productivity, and fall with depreciation, and rise with discount rate. The last result may not be intuitive. If the discount rate is higher, you care less about the future, therefore invest less, and thus have less but more valuable capital as a result.

A.3 Conclusion

Optimization in continuous time is daunting at first sight. However, it is just a trick. Constrained optimization is a trick. Form the Lagrangian. Write down the first-order conditions. Continuous time optimization is a trick too, albeit a different one. Form the Hamiltonian. Write down the first-order conditions. The good thing about the Hamiltonian is that its first-order conditions immediately lead to economic insight.

Index