Climate Economics

Economic Analysis of Climate, Climate Change and Climate Policy

Third Edition

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to Irena Sendler

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Preface

The first edition of this book had been 13 years in the making. I started teaching the economics of climate change in Hamburg in 2001, and had been hampered by the lack of a good textbook ever since. My biggest thanks are therefore to the students in Hamburg, Amsterdam, Sussex and Rome who suffered through my attempts to master the material that lies in front of you.

Writing the second edition took less time. Students complained about parts that were unclear, incomplete, or wrong. Colleagues did the same. The state-of-the-art moved slightly forward. Policy changed more. The third edition followed the same path, and I added more material for master's students and PhD candidates.

My thoughts on the economics of climate change and climate policy have benefitted from discussions with and papers by many people. I name a few: David Anthoff, Doug Arent, David Bradford†, Ian Burton, Carlo Carraro, Bill Cline, Hadi Dowlatabadi, Tom Downing, Sam Fankhauser, Jan Feenstra†, Brian Fisher, Reyer Gerlagh, Christian Gollier, Paul Gorecki, Cameron Hepburn, Huib Jansen†, Matt Kahn, Klaus Keller, Charlie Kolstad, Sean Lyons, David Maddison, Alan Manne†, Rob Mendelsohn, Bill Nordhaus, Steve Pacala, David Pearce†, Roger Pielke Jr, Katrin Rehdanz, Rich Richels, Roberto Roson, Tom Rutherford, Tom Schelling†, Steve Schneider†, Joel Smith, Ferenc Toth, Harmen Verbruggen, Marty Weitzman†, John Weyant, and Gary Yohe.

A number of people made useful comments on draft versions and the first and second edition, including David Anthoff, Francesco Bosello, Valentina Bosetti, Alice Branagan, Elena Buzzi, Ana Chavez Moreira, Iscen Duan, Alex Dubgaard, Francisco Estrada, Carlos Vladimir Fajardo Peña, Alice Favero, Maggie Jiang, Ruby Lawrence, Mike Mastandrea, Guy Meunier, Hom Pant, Paul Pelzl, Georgia Scott, Lance Wallace, Bob Ward, Tim Worstall, and three anonymous referees. David Anthoff inspired Chapter 13, and wrote the first draft of its text. The team at Edward Elgar is fantastic, and Sarah Brown stood out for her work on the second edition.

It is common to devote books about climate change to one's children or grandchildren. I don't see why. My parents told me to think for myself, to work hard, and to get an education. I try to pass this on to my kids, and I'm sure they'll be fine, if I succeed, regardless of what the climate throws at them.

Instead, as a warning against the hubris that pervades climate research and policy, I dedicate this book to the memory of Irena Sendler, *Righteous among the Nations*.

Introduction

This is a textbook on the economics of climate, climate change, and climate policy. The book is structured as follows. Chapter 1 reviews the science of climate change. Chapter 2 discusses sources of and scenarios for greenhouse gas emissions, and technical options for emission reduction. Chapter 3 turns to the costs of emission reduction, and Chapter 4 to policy instruments for emission reduction. Chapter 5 is about the impacts of and adaptation to climate change, and about the economic valuation of goods and services not traded on markets. Chapter 6 treats the economic impact of climate change. Chapter 7 discusses the relationship between climate (change) and development. Chapter 8 is on optimal emission reduction policy. Chapters 9, 10 and 11 discuss the effect of aggregation (over time, over possible states of the world, and over people, respectively) on optimal climate policy. Chapter 12 discusses non-cooperative climate policy.

Chapter 14 is an overview and summary. It provides a basis for a single, one-hour lecture on the economics of climate change and gives a taste of the controversies around climate policy.

Compared to the second edition, material has been updated where needed and modified for clarity where students complained. New material can be found in Chapters 3 (distribution of costs), 4 (second best regulation), 6 (weather shocks), **??**ch:development) (culture), 8 (tipping points, backstops, green paradox), 9 (endogenous population), 11 (Epstein-Zin preferences) and 12 (Lindahl equilibrium, linked games, dynamic games). The previous editions had a short chapter on adaptation policy. This has been split between chapters 5, 7 and 8.

Every chapter starts with its key messages. These come in the form of tweets with #climateeconomics. Accuracy is sacrificed for brevity. I find that tweeting my core message before a class or lecture helps me to focus on what I want and need to say. There is an online quiz for each chapter, designed for revising the material covered, again with a focus on the core messages. Both tweets and quizzes help the students distinguish the forest from the trees.

There is a resource site https://rtol.github.io/ClimateEconomics/ which has quizzes for revising each chapter. That site also has slides to accompany each chapter, links to videos of lectures, and other materials.

Chapters end with suggestions for further reading and exercises. The exercises are designed to expand on the text. There are three sets. First, there are classical exercises such as "calculate this" and "why would that be?" Second, there are reading assignments for presentation and discussion. Third, there is a set of instructions to build an integrated assessment model and use it to shed light on climate policy. This set of exercises is gathered in Chapter 13. Which set of exercises (if any) to use depends on the structure and aims of modules and courses.

The material is presented at four levels. Prerequisite material is marked with one star*. This should have been covered in an earlier module. It is here presented for completeness and to refresh readers' memories. Basic material is marked with two stars**. This is suited for a course at bachelor's level. Advanced material is marked with three stars***. This is suited for a course at master's level. Specialist material is marked with four stars****. This is suited for a course at PhD level. In every chapter, there is a reading exercise (for each of the three levels) and suggestions for further reading. The listed papers together form a reader at PhD level.

Graphs were drawn by the author unless otherwise indicated.

Chapter 1

The science of climate change

Thread

- The 3 most important anthropogenic greenhouse gases, ambient CO_2, CH_4 and N_2O, have risen since the Industrial Revolution. #climateeconomics
- The global mean surface air temperature and global mean sea level have gone up too, and snow pack down. #climateeconomics
- Greenhouse gases are transparent to visible light from the sun, but opaque to infrared radiation from Earth. #climateeconomics
- With greenhouse gases in the atmosphere, it is easier for energy to enter the planet than to leave it. #climateeconomics
- Higher greenhouse gas concentrations imply warming, but how much is uncertain as there are many, complex feedbacks. #climateeconomics
- Human CO_2 emissions are a tiny fraction of natural emissions, but natural emissions are balanced by natural uptake. #climateeconomics
- By 2100, the global mean temperature will probably be 1–6 degrees Celsius higher than now, depending on scenario and model. #climateeconomics
- Warming will be more pronounced towards the poles, in winter, at night, and over land. #climateeconomics
- Some places and times will see more rain, other places and times less. Downpours may well become heavier. #climateeconomics
- Tropical storms will probably not extend their range or increase their frequency. Storms everywhere will intensify. #climateeconomics
- Water expands as it warms, and sea levels rise. Land ice melts. By 2100, the sea will probably rise by 0.2–0.6 metres. #climateeconomics
- As more CO_2 dissolves in water, oceans will become less akaline. #climateeconomics

1.1 Processes**

The 3 most important anthropogenic greenhouse gases, ambient CO_2, CH_4 and N_2O, have risen since the Industrial Revolution.

Figure 1.1 shows observations[1] of the atmospheric concentration of the three main anthropogenic[2] greenhouse gases—carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)—over two periods: From the start of the Industrial Revolution (say, 1850 CE) to today, and from the start of the agricultural revolution (say, 8000 BC) to today. Since the start of the Industrial Revolution, ambient greenhouse gases have been on the rise. The increase in the last 150 years is quite unusual given the experience of the last 12,000 years.

The global mean surface air temperature and global mean sea level have gone up too, and snow pack down.

Figure 1.2 shows observations of the global mean surface air temperature, the temperature of the upper ocean and the air over the ocean, the temperature of the troposphere, the ocean heat content, the global mean sea level, the extent of arctic sea ice, the average snow cover in the northern hemisphere, the mass balance of glaciers, and humidity. Temperature, humidity, and sea level have gone up over the last 150 years, and snow and ice have declined. This is exactly as one would expect if greenhouse gas concentrations are rising (although climate could also have changed for other reasons), for reasons explained now.

Greenhouse gases are transparent to visible light from the sun, but opaque to infrared radiation from Earth.

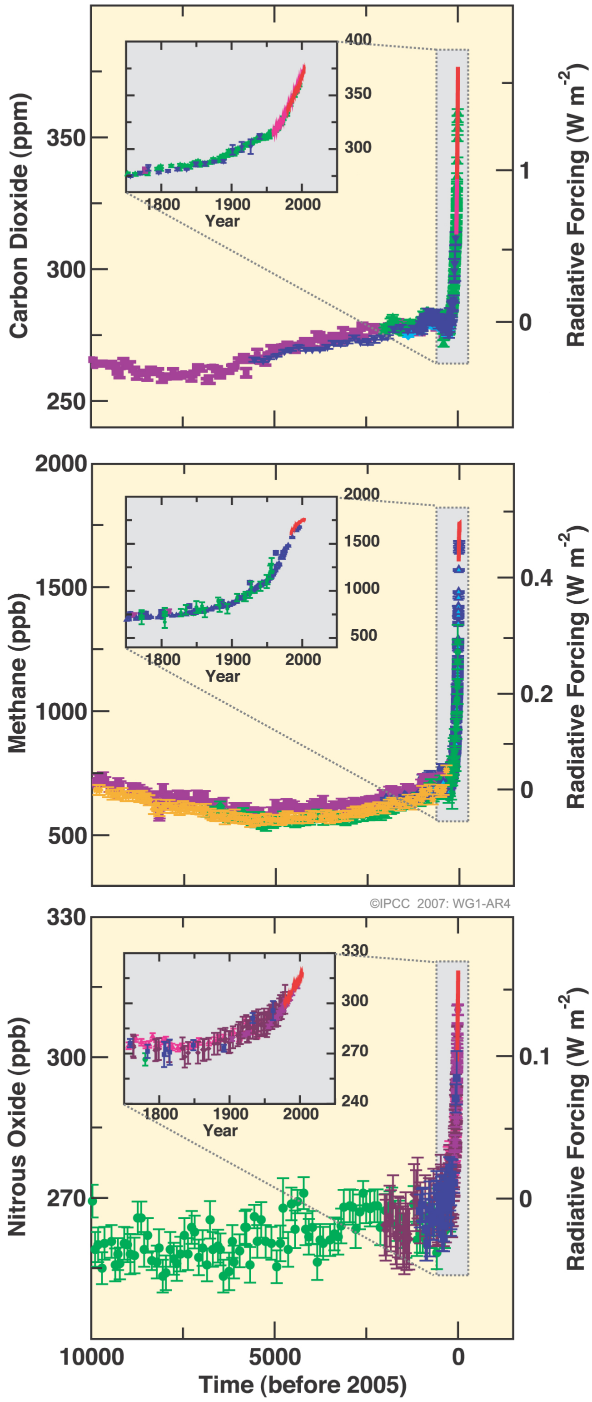
Figure 1.3 illustrates why more greenhouse gases in the atmosphere would lead to global warming. The sun sends energy into space in every direction. Some of that energy is in the part of the spectrum that is visible to the human eye, and some of that energy reaches Planet Earth. The planet is in energy balance: It receives as much energy as it emits, at least on average. If not, the planet would forever heat or cool and would have evaporated or frozen over a long time ago. Earth therefore must emit energy. Earth does not emit visible light—it is dark at night, the ground does not light up—but it does emit infrared radiation. Greenhouse gas molecules are, by definition, transparent to visible light[3] but intransparent to infrared radiation. That is, solar energy passes unhindered through the atmosphere, but infrared radiation is absorbed by greenhouse gas molecules. These molecules get excited, but later return to their base state, emitting energy as infrared radiation in any direction. That is the crucial part of the greenhouse effect. Infrared radiation from Planet Earth is directed towards outer space. Infrared radiation from greenhouse gas molecules can go anywhere, including back to the planet's surface.

With greenhouse gases in the atmosphere, it is easier for energy to enter the planet than to leave it.

[1] Measuring the composition of the atmosphere is a recently developed skill. Older measurements are obtained as follows. As snow falls on ice caps, little bubbles of air are trapped and sealed in the newly formed ice. Older air can be found in older ice, deeper in the ice cap. The atmospheric concentration of ancient times can be reconstructed from cores drilled from the ice. Such reconstructions are imperfect, both with regard to their timing and the assumption that air bubbles are hermetically sealed.

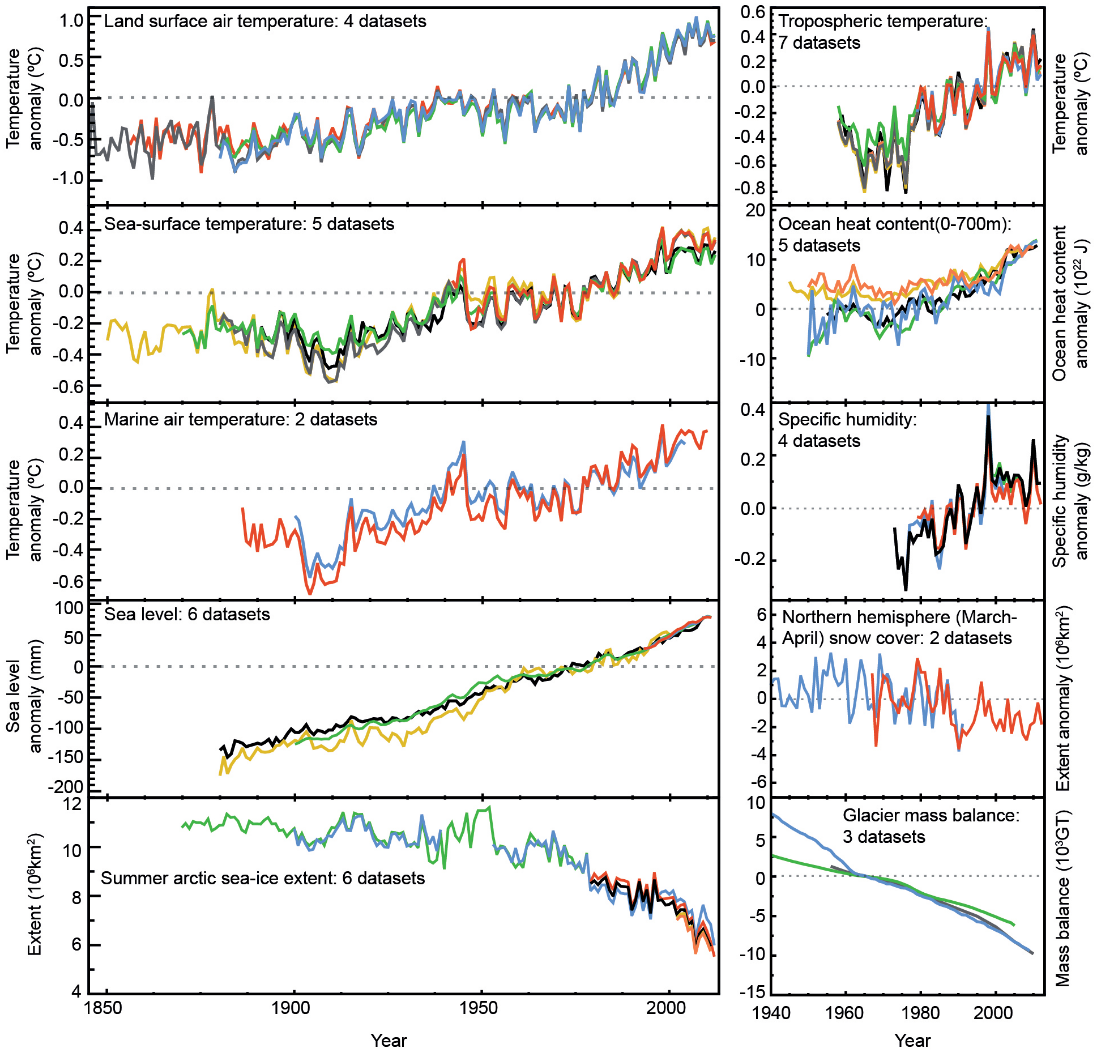
[2] "anthropogenic" is from the Greek word for human being, *anthropos*, and the Greek word for born to, *genes*; anthropogenic thus means "from human origin".

[3] The frequent pictures in the media notwithstanding, you cannot photograph carbon dioxide emissions. These are pictures of water vapour.



Source: IPCC WG1 AR4 SPM.

Figure 1.1: Atmospheric concentrations of the three main anthropogenic greenhouse gases



Source: IPCC WG1 AR5 TS.

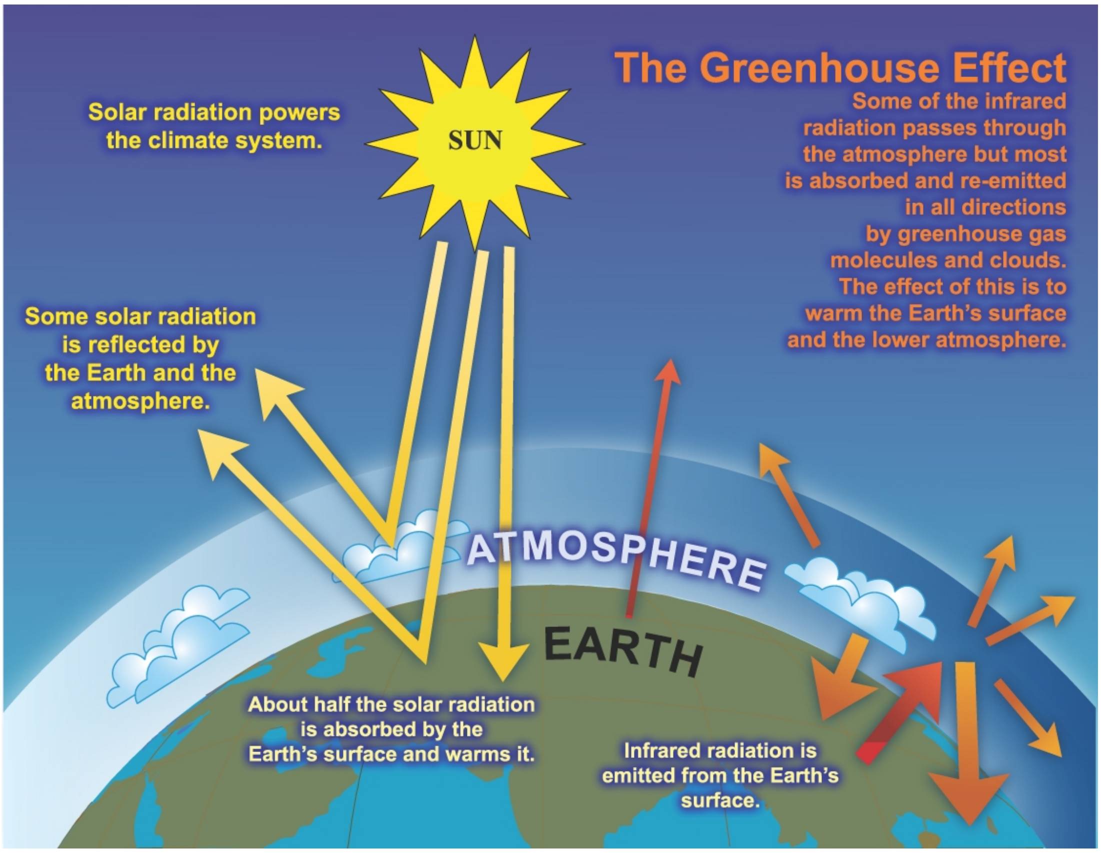
Figure 1.2: Observed temperature, sea level, sea ice, humidity, snow pack, and glacier mass

Therefore, if there are greenhouse gases in the atmosphere, it is harder for energy to leave the planet than if there are no such gases. If the atmospheric concentration of greenhouse gases is constant, the planet is still in energy balance—incoming energy equals outgoing energy—but more energy is stored on the planet: It is warmer.

The science of the greenhouse effect is old and well-established. The warming effect of the atmosphere was first described by Joseph Fourier in 1827. Eunice Foote identified carbon dioxide as a potent greenhouse gas.[4] John Tyndall figured out the key role of infrared radiation in 1861, and added further details later in the 1860s. In 1896, Svante Arrhenius[5] reckoned that the burning of fossil fuels would increase the concentration of carbon dioxide in the atmosphere

[4]Her gender attracted more attention than her finding.

[5]Arrhenius won the 1903 Nobel Prize for Chemistry for the electrolytic theory of dissociation.



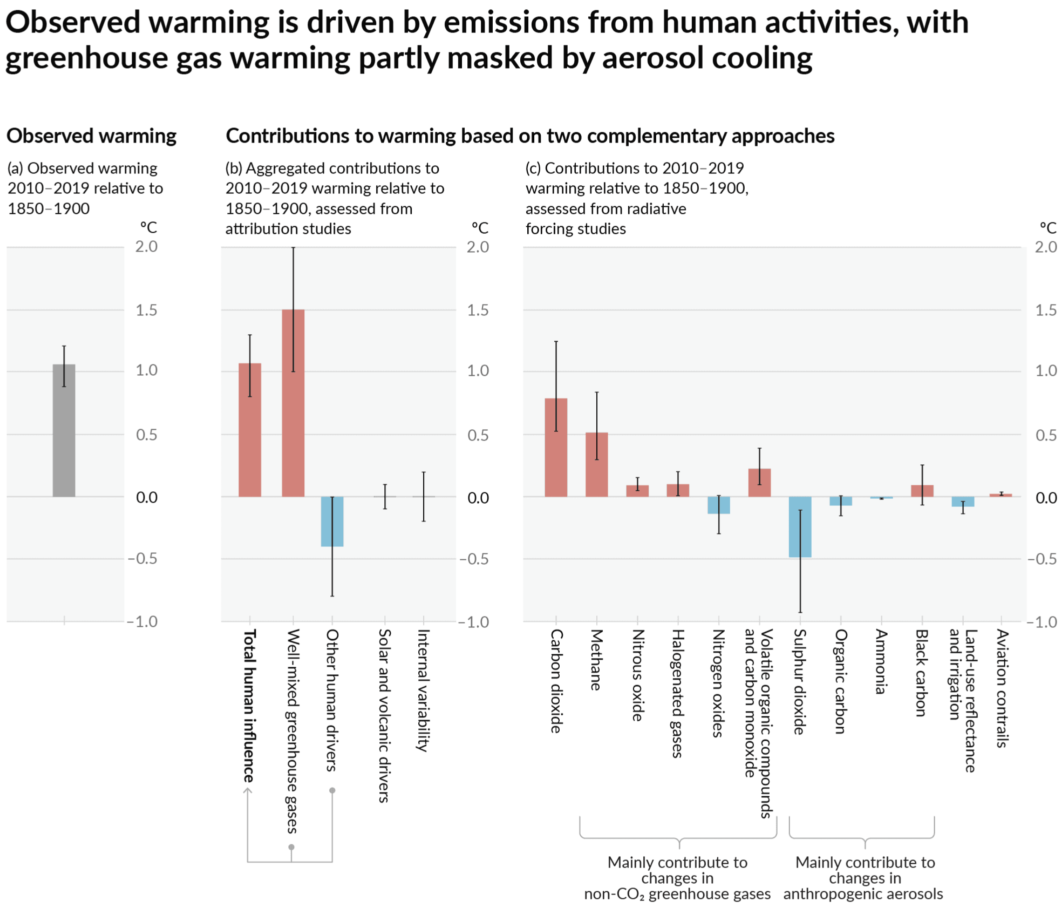
Source: IPCC WG1 AR4 SPM.

Figure 1.3: The greenhouse effect

—a prediction first confirmed by Charles Keeling in 1970—and that this would enhance the greenhouse effect, create an energy imbalance, and warm the planet—first confirmed in 1993 by Richard Tol and Aart de Vos. Figures 1.1 and 1.2 show that this is indeed, at least qualitatively, the case: Higher carbon dioxide concentrations imply warming.

Although the first principles are simple and well-understood, there are complications, some of which are illustrated in Figure 1.4. It shows radiative forcing, the *change* in energy per square metre, since 1750, due to the enhanced greenhouse effect and other factors. Carbon dioxide is by far the most important substance in the change in the Earth's energy balance. It is also relatively well-known, the main uncertainty being the atmospheric concentration in pre-industrial times. Put together, the other anthropogenic greenhouse gases have contributed about two-thirds as much as carbon dioxide to the total radiative forcing. Relative uncertainty is about as large.

But the human interference with the climate system does not end there. Ozone is a greenhouse gas too. It is not emitted by human activities, but results from interactions in the atmosphere with substances that are emitted by humans. Near the surface, ozone concentrations are higher than they used to be because of precursor emissions from transport and agriculture. Higher up in the atmosphere, ozone concentrations are lower because of emissions of chlorofluorocarbons.



Source: IPCC WG1 AR6 SPM.

Figure 1.4: Radiative forcing and its components since pre-industrial times

Water vapour too is a greenhouse gas, in fact the most important of them all, but its concentration is only marginally affected by human activity: The breakdown of methane (CH_4) in the atmosphere increases the concentration of water vapour (H_2O) (and carbon dioxide (CO_2)).

Box 1.1: Carbon and carbon dioxide

Carbon dioxide and other greenhouse gases are often referred to simply as carbon. This is fine as a colloquial short-hand. Many greenhouse gas do contain carbon, from carbonic acid to methane to the halogenated fluorocarbons. Not all do, though. Laughing gas and water vapour are powerful greenhouse gases without a hint of carbon. Short-hands can be misleading. We worry about carbon dioxide in the atmosphere, not about carbon dioxide per se. The carbon dioxide in your lungs is perfectly innocent. If you get drowsy in a crowded, poorly ventilated room, that is because the carbon dioxide concentration is too high, but the levels required for that will never be observed outside. Some 18% of your body is elemental carbon. The carbon cycle takes carbon through its various transformations—from the essential in organisms to the useful in fossil fuels to the climate-altering as an atmospheric gas to the acidifying when dissolved in water. Some people have even taken to confusing the properties of elemental carbon, which is pretty much indestructible, with the properties of carbon dioxide, which any plant routinely destroys. Short-hands are fine if you understand they're not the real thing.

Humans have also changed the albedo, which determines the amount of energy reflected by the surface of Planet Earth. Soot has made snow and ice darker than they used to be, thus absorbing more energy. Less snow and ice also means a darker surface. On the other hand, trees, dark in colour, have been replaced by grass, light in colour. People congregate in cities, which are hotter than the surrounding countryside, not just because machines and bodies generate heat but also because hard surfaces radiate it. Fossil fuel combustion also emits aerosols, which directly affect radiation passing through the atmosphere and play a role in cloud formation (and thus indirectly affect the radiative balance). The water vapour from aircraft also forms clouds—contrails—but their contribution to global warming is minimal. Humans affect the nutrient cycles (nitrogen, phosphate) and so vegetation, albedo and carbon cycle.

Besides the human influences on the climate, there are natural effects as well. Volcanic eruptions can have a rather large, but typically short-lived impact. There is no reason to believe that there is a long-term trend in volcanic activity. There is a trend in the energy output of the sun, but this is small compared with the changes in greenhouse gas concentrations.

Our confidence in the radiative forcing of greenhouse gas emissions is higher than in other radiative forcing, partly because the physics and chemistry of the relevant process is not completely understood (as it is much more complex than the greenhouse effect) and partly because data for pre-industrial times are spotty. The uncertainty about total radiative forcing is one of the reasons climate science is complicated: We do not know exactly how much the radiative balance has changed, so we cannot exactly how much Earth should have warmed.

Complications do not stop there. The uncertainty about climate change is much larger than the uncertainty about radiative forcing. The degree of global warming is determined by the amount of radiative forcing and a number of feedbacks in the climate system. Most importantly, warmer air contains more water vapour, and water vapour is a greenhouse gas. The first feedback is positive: Warming leads to more warming. The big uncertainty is about cloud formation. Clouds can keep the heat of the sun out (as on a summer's day), but also the warmth of the earth in (as in a winter's night). Different cloud types have different effects, as have clouds at different heights. The physics of cloud formation is rather complex and operates at a spatial scale much finer than can be resolved by climate models. Different models therefore use different cloud parameterizations,[6] which behave roughly the same in the current climate but differently in altered climates.

> Higher greenhouse gas concentrations imply warming, but how much is uncertain as there are many, complex feedbacks.

The oceans are another major uncertainty. If the atmosphere warms, so do the waters at the ocean surface. If surface waters warms, so do the waters deeper down. The speed at which energy dissipates into the ocean determines the speed at which the atmosphere warms in response to the enhanced greenhouse effect. The rate of ocean warming depends on a complex

[6] Climate models are partly based on physics and partly based on statistical relations fitted to experimental or observational data; the latter are referred to as parameterizations.

pattern of horizontal and vertical currents. The slow dynamics of the deep ocean induce semi-regular cycles in the temperature of the atmosphere with characteristic life-times of years and decades, maybe longer. Observations of the deep ocean are few and recent, so ocean circulation models are poorly constrained by data.

Model uncertainty is reflected in Figure 1.5. It shows—globally, over land, over ocean, for the seven continents—the observed mean surface air temperature, and for the seven ocean basins, smoothed over time, for the 20th century. Figure 1.5 also shows the range of model reconstructions for two sets of scenarios: One with all known radiative forcing, and one with natural forcing only. If all forcing is included, the observed warming is somewhere in the middle of the predicted range of warming. If anthropogenic forcing is omitted, the observed warming is outside the predicted range. This indicates that it is unlikely, but not impossible, that the observed warming is not, at least partially, to blame on human activity.

> Human CO_2 emissions are a tiny fraction of natural emissions, but natural emissions are balanced by natural uptake.

Figure 1.6 depicts the carbon cycle, relating the stocks and flows of carbon dioxide. In pre-industrial times, the main exchanges of CO_2 were between the atmosphere, the ocean, and terrestrial vegetation. Each stores a large amount of CO_2. CO_2 fluxes are large too, as vegetation grows in Northern spring and summer and dies back in Northern fall and winter. There is far less land in the Southern Hemisphere. There is another large stock of carbon in fossil fuels. In natural circumstances, this stock does not play a significant part in the carbon cycle. However, human exploitation has mobilized this carbon. Emissions of CO_2 from fossil fuel combustion are small compared with natural emissions—but unlike natural emissions, there is no counterbalancing flux. Although human emissions are partly absorbed by vegetation and ocean, the atmospheric concentration of CO_2 has increased, enhancing the greenhouse effect.

Figure 1.6 illustrates yet another complexity in climate science: Key parts of the carbon cycle depend on the climate, notably plant growth. That is, CO_2 emissions change the climate and the climate changes CO_2 emissions. This effect would be especially large if climate change leads to forest dieback. It does not stop there, unfortunately. Swamps release CH_4, as does melting permafrost.

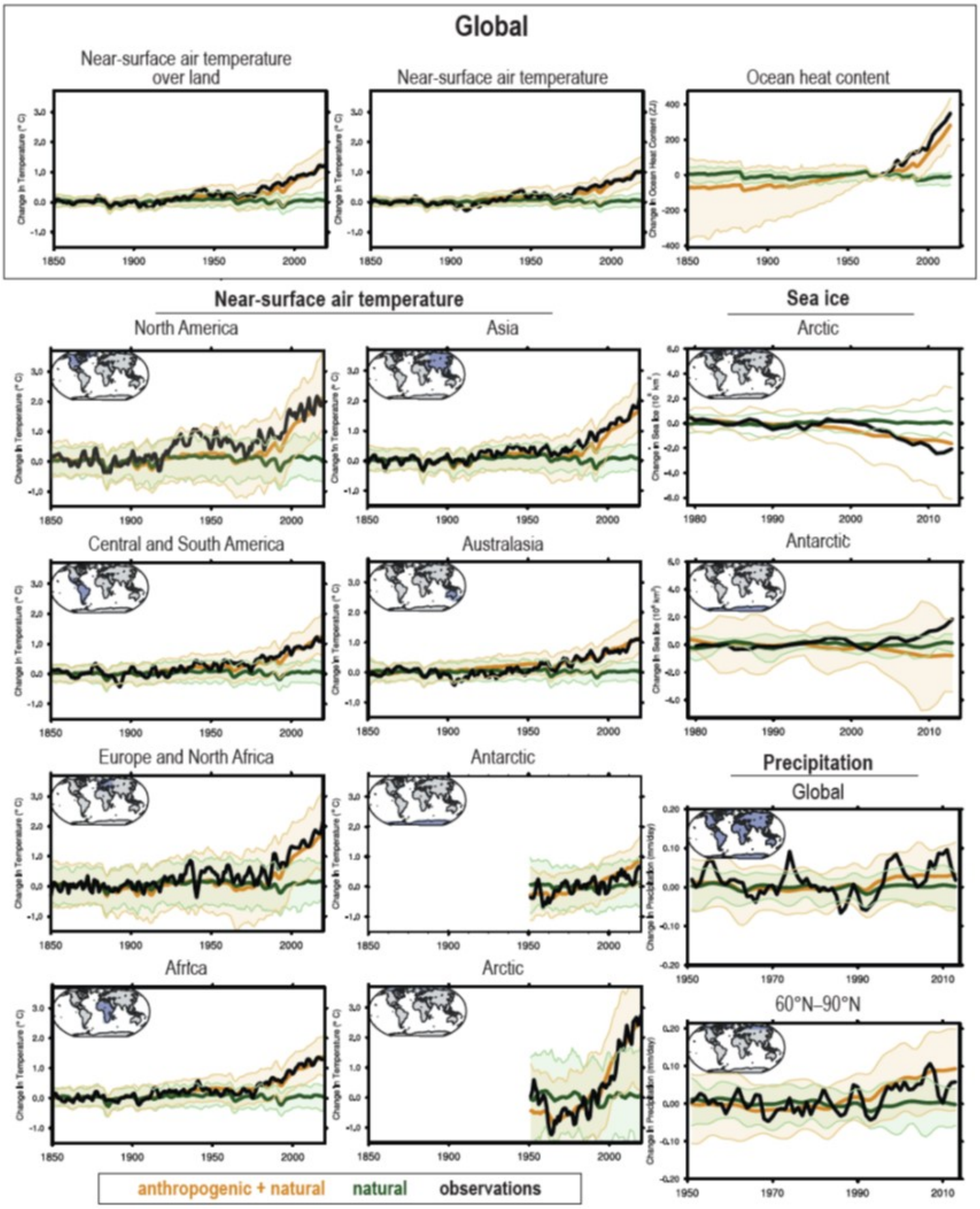
1.2 Projections**

> By 2100, the global mean temperature will probably be 1–6 degrees Celsius higher than now, depending on scenario and model.

Figure 1.5 shows model reconstructions of the 20th century. Figure 1.7 applies the same models to the 21st, 22nd and 23rd centuries for a range of emission scenarios (see Chapter 2). Over the 21st century, global warming will probably be between 0.2 and 5.8℃, on top of the 0.8℃ warming in the 20th century. In the longer run, if we burn all fossil fuel resources, global warming may exceed 12℃.

Box 1.2: Predictions and scenarios

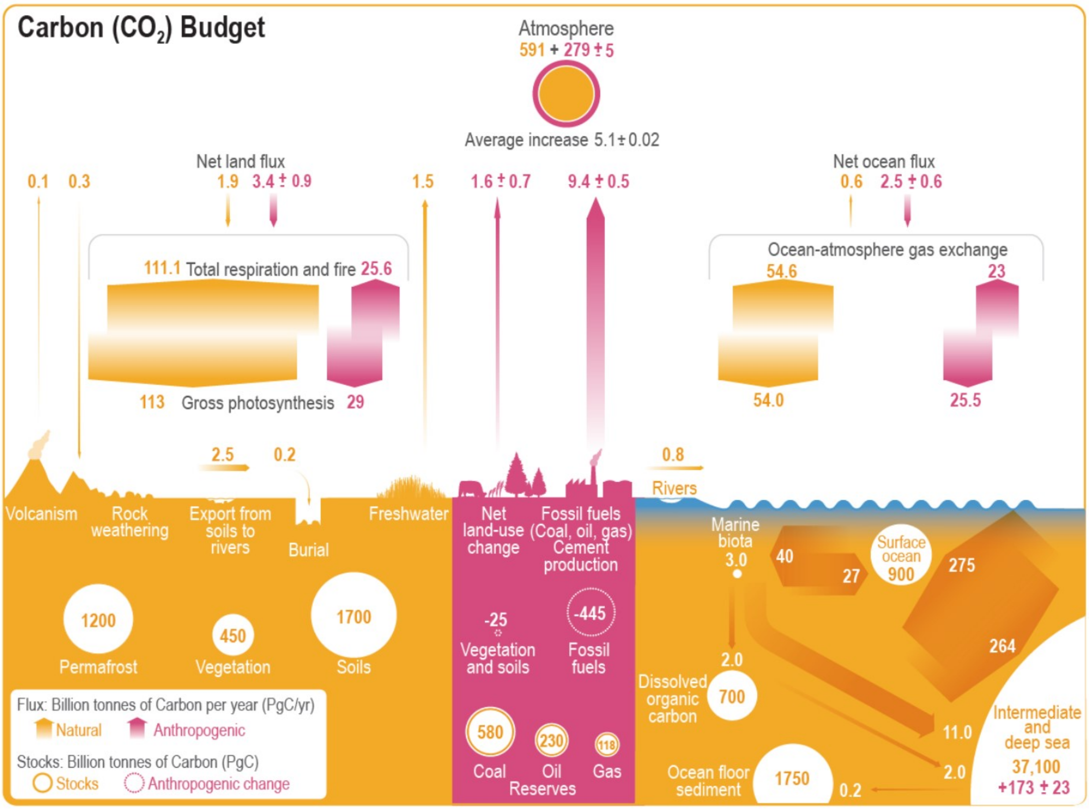
Successful prediction is the ultimate aim of positive research. Prediction comes in gradations. "The sun will rise tomorrow at 5:28 am" is an *unconditional* prediction (and wrong in most places at most days). "The Earth will warm by 3℃ if the atmospheric concentration of carbon dioxide doubles" is a *conditional* prediction: It depends on the change in atmospheric carbon dioxide—hence "if". Conditional predictions are silent on



Source: IPCC WG1 AR5 SPM.

Figure 1.5: Observed and modelled mean surface air temperatures, sea ice, and rainfall

the plausibility of the conditions. If our description of future events is incomplete, as it



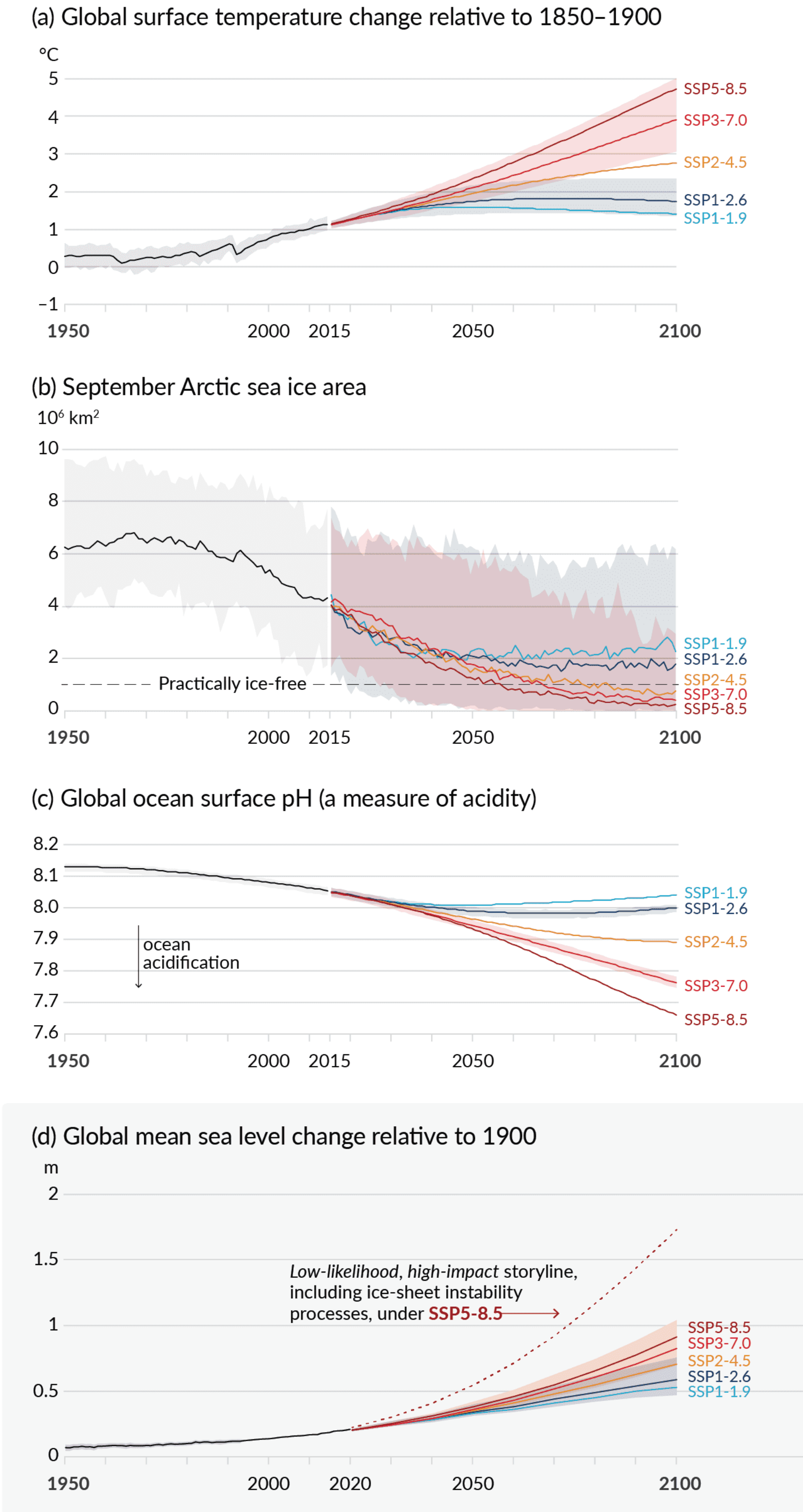
Source: IPCC WG1 AR6 Chapter 5.

Figure 1.6: The carbon cycle

is in most cases and certainly in climate change, predictions are necessarily conditional. In climate research, people prefer the terms "scenario" over "conditional prediction". A scenario is a not implausible, internally consistent way in which the future may unfold, according to one definition. Another definition refers to scenarios as storylines. Scenarios of future emissions are conditional predictions, in a way, but system boundaries are not well understood—the prediction is conditional on something vague—and relative probabilities are not estimated. A scenario is a conditional prediction that does not speak its name.

Projections of future climate change are predictions conditional on future emissions, and conditional on the initial state of the climate. Because this initial state is not known completely and precisely, and because the climate system (and climate models) is chaotic,[a] a projection is a realization from a stochastic process. It is not the mean or the mode or a known percentile of a probability density.

Predictions play a different role in normative research, of course. There is the *Lucas Critique*: Optimal decision rules of economic agents vary systematically with changes in policy. In other words, a prediction in a self-aware system will change the system. More practically, predictions are conditional on policy, and often aim to change policy. "If



Source: IPCC WG1 AR6 SPM.

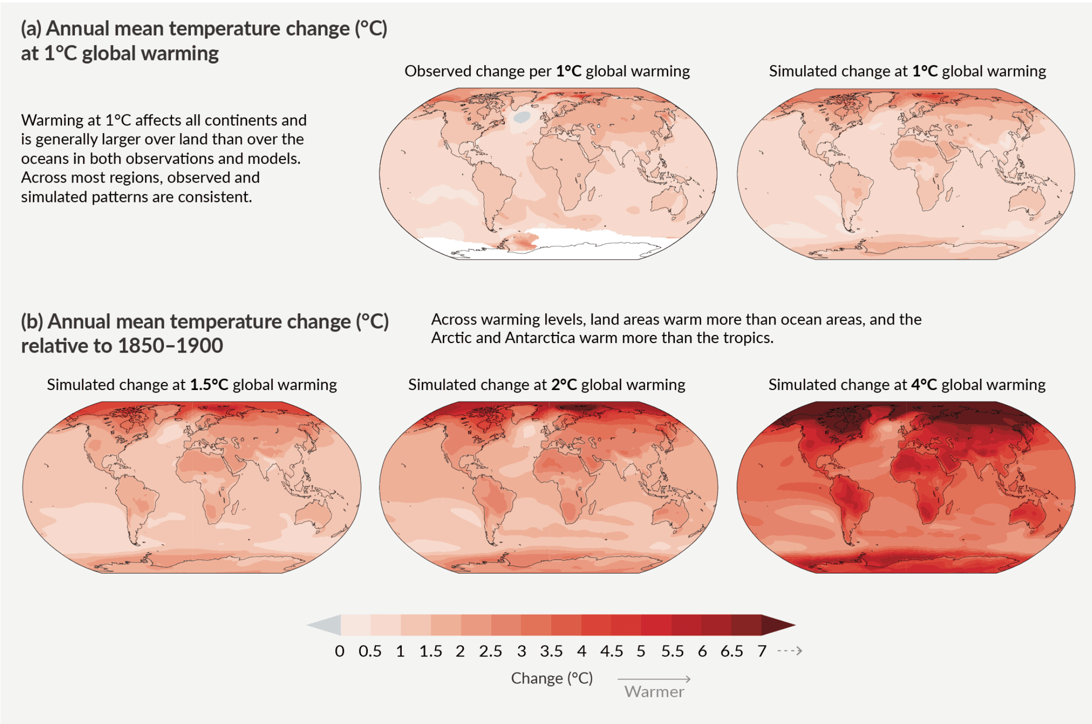
Figure 1.7: The global mean surface air temperature, sea ice, ocean acidity and sea level as observed and projected

you do not intervene, dear policy maker, bad things will happen." In a policy context, predictions are often intended to be self-defeating prophesies. A false prediction is thus a sign of success rather than failure.

[a]Chaos refers to the behaviour of systems of non-linear differential equations.

Warming will be more pronounced towards the poles, in winter, at night, and over land.

Figure 1.8 shows the spatial pattern of warming. Warming is more pronounced over land than over water, and towards the poles. Warming is more pronounced in the further future, and if greenhouse gas emissions are higher. Not shown in Figure 1.8, warming is more pronounced in winter than in summer, and at night than at day. Models agree on these broad patterns.

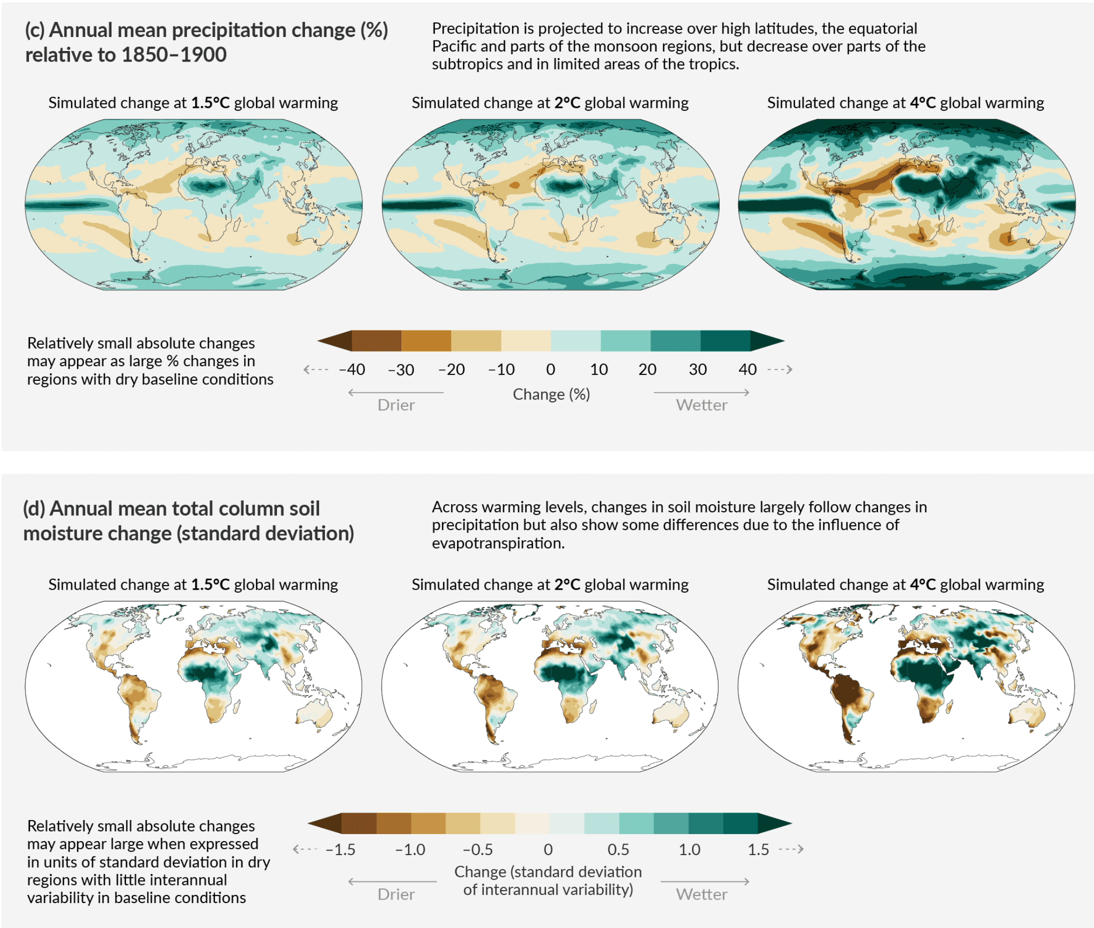


Source: IPCC WG1 AR6 SPM.

Figure 1.8: The spatial pattern of projected warming

Some places and times will see more rain, other places and times less. Downpours may well become heavier.

Figure 1.9 shows the projected changes in precipitation (rain and snow) and soil moisture. The latter is more important for agriculture. There is little agreement on the pattern of changes in rainfall. On large parts of the globe, models do not even agree on the sign of change. However, (sub)tropical areas are likely to get drier and higher latitude areas wetter—this implies that, in the southern hemisphere, more rain will fall over sea (which is no use). In temperate areas, winters will get wetter and summers drier. Changes in rainfall tend to get larger as we look further into the future, although sign reversals are not uncommon. As it gets warmer, rainfall will tend to get more intense, with heavier downpours in between longer dry spells.



Source: IPCC WG1 AR6 SPM.

Figure 1.9: The spatial and seasonal pattern of projected changes in precipitation and soil moisture

> Tropical storms will probably not extend their range or increase their frequency. Storms everywhere will intensify.

Storms, both in the tropics and elsewhere, are likely to become more intense too. Maximum wind speeds will probably increase. There is no reason to assume that the frequency of storms will change much; or that tropical storms will extend their area.

> Water expands as it warms, and sea levels rise. Land ice melts. By 2100, the sea will probably rise by 0.26–0.82 metres.

Water expands if it gets warmer. Sea levels will therefore rise. This is a surprise to some people. After all, tea does not visibly shrink as it cools down. However, the ocean is on average three kilometres deep. If ocean water expands by 0.01%, then sea levels rise by 30 cm. The projected sea level rise over the 21st century—see Figure 1.7—due to thermal expansion is somewhere between 10 and 33 cm. The melting of small ice caps and glaciers will add another 4–23 cm to sea level rise. Although glaciers are impressive to the human eye—and their disappearance dramatic—they contain little water relative to the oceans. The melting of floating ice, common around the North Pole, does not contribute to sea level rise, because that ice already displaces sea water. The large ice caps and shelves on Greenland and Antarctica rest on land and do contain a substantial amount of water. If the West-Antarctic Ice Shelf would melt or slide into the sea—the latter could happen much more quickly—sea levels would rise by 5–6 metres. If the Greenland ice cap would melt, sea levels would rise by 6–7 metres. If the ice on East-Antarctica would melt, sea levels would rise by some 60 metres. The ice on West-Antarctica and Greenland may not survive the current millennium but will most likely make it to the end of the century. Greenland ice melt would add 1–23 cm to sea level rise. Because of increased snowfall, the Antarctic ice caps may lower sea level by as much as 7 cm, although rapid disintegration could add up to 16 cm by the end of the century.

Sea level rise is not spatially uniform as shown in Figure 1.10. This is because warming is not spatially uniform and water is transported by ocean currents, because ice melt and freshwater discharge are spatially heterogenous, and because air pressure changes differ from area to area. The volume of ice in Antarctica is such that gravity pulls water to the South Pole. Should that ice melt, sea levels would on average rise by 70 metres or so. Sea level rise in Europe would be some 100 metres as the water is more evenly distributed over the globe.

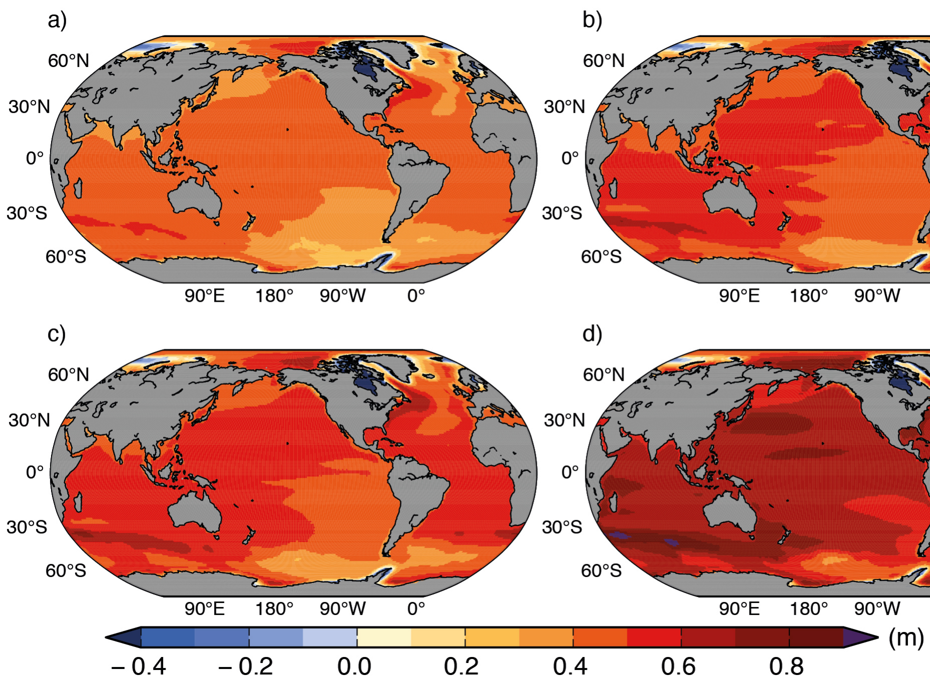
As more CO_2 dissolves in water, oceans will become less alkaline.

Figure 1.6 shows that there is a lot of CO_2 in the ocean. Marine biota contain only a relatively small amount of carbon. The bulk of the carbon is dissolved in water. The partial pressure of CO_2 in the atmosphere equals the partial pressure of CO_2 in the ocean. Thus if there is more CO_2 in the atmosphere, there will be more CO_2 in the ocean. The proper name of carbon dioxide (dissolved in water) is carbonic acid. Higher CO_2 concentrations in ocean waters therefore imply a more acidic ocean, or rather a less alkaline one—see Figure 1.7—affecting all species with an exoskeleton and their predators.

Further reading

Every six years, Working Group I of the Intergovernmental Panel on Climate Change publishes a major assessment of the natural science of climate change. The information is layered, with a Summary for Policy Makers with high-level information, Technical Summaries with more detail, and multiple chapters with a lot of detail and references to the underlying literature. These reports can be found at the http://www.ipcc.ch/. Mark Maslin's *Climate Change: A Very Short Introduction* (2014) is highly regarded, as is Steve Earle's *A Brief History of the Earth's Climate* (2022).

Climate research is rather controversial. Good introductions to the controversy are Mike Hulme's book *Why We Disagree About Climate Change: Understanding Controversy, Inaction, and Opportunity* (2009), Donna Laframboise's book *The Delinquent Teenager Who Was Mistaken For The World's Top Climate Expert* (2011), Andrew W. Montford's book *The Hockey Stick Illusion: Climategate and the Corruption of Science* (2010), and Michael Shellenberger's *Apocalypse Never* (2020).



Source: IPCC WG1 AR5 Chapter 13.

Figure 1.10: The spatial pattern of projected sea level by the end of the 21st century for four scenarios

Chapter 2

Emissions scenarios and options for emission reduction

Thread

- Fossil fuel combustion is the main source of CO_2. Per unit of energy, coal emits most, followed by oil and gas. #climateeconomics
- Land use change and cement production are other sources of CO_2. Specialized industries emit halocarbons. #climateeconomics
- Methane results from paddy rice, livestock, waste, and gas leakage, nitrous oxide from agricultural soils. #climateeconomics
- CO_2 emissions equal population times income per capita times energy use per output times emissions per unit of energy. #climateeconomics
- World CO_2 emission +2.1%/year 1965–2020: population +1.6%, income +1.7%, energy per GDP −0.9%, CO_2 per energy -0.3%. #climateeconomics
- Scenarios are not implausible, internally consistent descriptions of alternative futures #climateeconomics
- Existing scenarios of future greenhouse gas emissions do not reflect the full range of historical experience. #climateeconomics
- There is not enough conventional oil and gas to substantially change climate. Future climate is driven by their replacements. #climateeconomics
- Reduced population and economic growth would reduce emissions, but few elected governments would opt for this. #climateeconomics
- Technological change reduces emissions but current effort would need to be trebled to stabilize emissions. #climateeconomics
- Behavioural change reduces emissions too, but habits are hard to change and market imperfections waste a lot of energy. #climateeconomics

- Carbon-free fuels are another option but nuclear and hydropower are unpopular. #climateeconomics
- Renewables are expensive; volatile and unpredictable; and bring their own environmental problems. #climateeconomics
- CO_2 can be captured and stored at a price. Scale, permanence, and safety are issues. CCS is an end-of-pipe solution. #climateeconomics
- Slowing deforestation would reduce emissions but if that were easy it would have been done long ago. #climateeconomics
- Geoengineering is a risky option. There are concerns about who would decide to geoengineer the global climate. #climateeconomics

2.1 Sources of greenhouse gas emissions**

There are a number of different greenhouse gases. Figure 1.4 shows their relative contribution since pre-industrial times. Figure 2.1 shows the relative contributions in the year 2010.

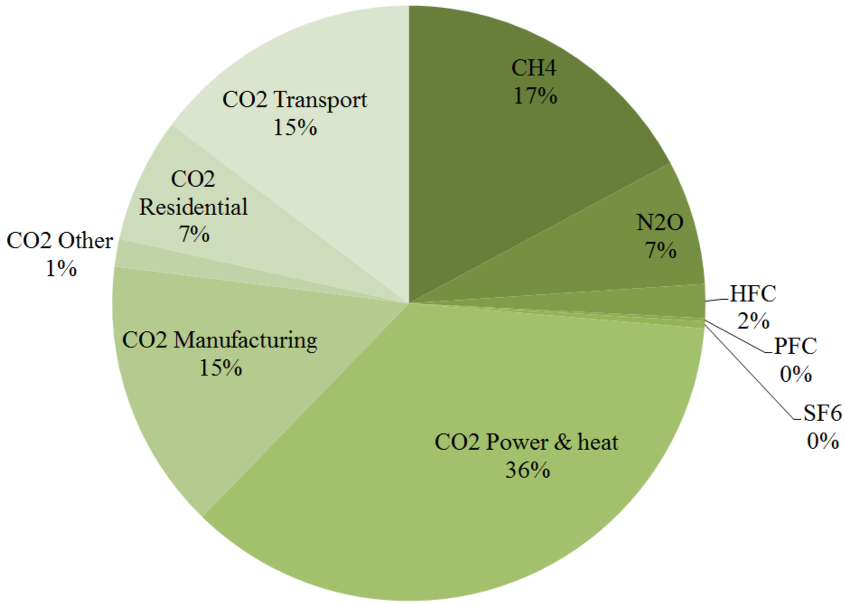


Figure 2.1: Global greenhouse gas emissions by gas and source in 2010

Fossil fuel combustion is the main source of CO_2. Per unit of energy, coal emits most, followed by oil and gas.

Carbon dioxide is the most important anthropogenic greenhouse gas. Fossil fuel combustion is the main source of CO_2. Fossil fuels are hydrocarbons. You need to add energy to break the chemical bond between the carbon and the hydrogen. Both are then oxidized, to CO_2 and H_2O, respectively. As new chemical bonds form, energy is released—more energy than was needed to break hydrogen from carbon. CO_2 emissions are thus intrinsic to the process: You cannot get energy out of fossil fuel without forming CO_2. Emissions can be reduced by using fossil fuels more efficiently, or by using non-fossil energy instead.

Fossil fuels come in a number of varieties. Peat emits most CO_2 per unit of energy (99–117 tCO_2/TJ), followed by coal (98–109 tCO_2/TJ), oil (73–77 tCO_2/TJ), and natural gas (56–58 tCO_2/TJ). Emissions from fossil fuel combustion can thus be reduced by switching from peat and coal to gas.

> Land use change and cement production are other sources of CO_2. Specialized industries emit halocarbons.

Land use change is another major source of CO_2. Plants are made of hydrocarbons too. As tall trees have been replaced by small grass, less carbon is stored in terrestrial vegetation. A substantial part of the wood was burned and CO_2 formed. Emissions can be reduced by slowing deforestation. Land use emissions are negative in much of Europe and North America because of reforestation.

Cement production is the least important source. CO_2 is vented as limestone is transformed to cement. As with fossil fuel combustion, this is intrinsic to the process. You need to lose carbon to turn lime into cement. Different building materials are needed to reduce emissions.

> Methane results from paddy rice, livestock, waste, and gas leakage, nitrous oxide from agricultural soils.

Methane is the next most important greenhouse gas. Ruminants (cows etc.) are a main source. Grass and meat are both hydrocarbons, but there are more hydrogen atoms per carbon atom in grass than in meat. Excess hydrogen is dangerous. When combined with oxygen, it forms hydroxyl radicals (OH), which are highly reactive and thus destructive. In an oxygen-starved environment such as a cow's stomach, hydrogen turns to hydrogen gas (H_2), which lifts zeppelins. Ruminants have therefore formed a symbiotic relationship with methanogenic bacteria, sacrificing one useful carbon atom to remove four damaging hydrogen atoms. The methane is then burped out. This is an ancient relationship, shared by a large number of grazing animals. Marsupials (kangaroos etc.) use a different solution: acetate ($C_2H_3O_2$) rather than methane (CH_4). This is less efficient: Marsupials sacrifice 2 carbons to get rid of 3 hydrogens, ruminants lose 8 hydrogens for 2 carbons. Considering the evolutionary distances between cows and kangaroos, milk production would be hard to achieve without emitting methane, and meat production without methane would be very different. However, feed supplements, particularly seaweed, could reduce methane emissions. A larger and more diverse supply of milk and meat substitutes too would cut emissions.

When plant material rots in an aerobic environment (with oxygen), CO_2 is formed. In an anaerobic environment (without oxygen), CH_4 is formed. Paddy rice is thus another major source of methane, as roots exude nutrients into waterlogged soils. Paddy rice is the most productive grain crop. Switching to other crops would reduce methane emissions, but would also reduce food production. Genetic manipulation may be more promising. The introduction of a barley gene leads the rice plant to channel more nutrients into grain production, increasing yields while reducing methane emissions.

Landfills, too, are anaerobic environments with a lot of organic material and thus high methane emissions. Emissions can be reduced by diverting organic waste to composting or incineration; or by capping the landfill, capturing the methane, and flaring it or using it to substitute natural gas.

Natural gas is another word for methane. Methane leaks into the atmosphere from natural gas exploitation and transport. Gas is often found together with coal and oil, and is emitted from their exploitation as well (unless flared, which gives off carbon dioxide). Emissions would fall if leaks are fixed and if gas is used rather than flared.

Nitrous oxide is the third most important anthropogenic greenhouse gas, primarily emitted from agricultural soils that have been treated with nitrogenous fertilizers. emission reduction is thus hard without affecting food production. That said, farmers routinely use too much fertilizer.

There are also a range of industrial greenhouse gases. Most of these are artificial: They do not occur naturally. Most were invented after World War II to serve particular purposes—coolants, propellants, solvants. Other gases are by-products of industrial processes—semiconductor manufacturing and packaging material are two important examples. Although the absolute volumes of these emissions are small, these gases tend to be particularly potent greenhouse gases and some have an atmospheric life-time that is measured in tens of thousands of years. Emission reduction is feasible through the development of substitute processes or products, and in select cases through improved waste management.

2.2 Trends in carbon dioxide emissions**

CO_2 emissions equal population times income per capita times energy use per output times emissions per unit of energy.

All identities are right, but some are useful. The *Kaya Identity*[1] helps to understand trends in emissions. If applied to carbon dioxide from fossil fuel combustion, it looks as follows:

$$M = N\frac{Y}{N}\frac{E}{Y}\frac{M}{E} \tag{2.1}$$

where M denotes emissions, N number of people, Y Gross Domestic Product, and E primary energy use. Thus the Kaya Identity has that emissions equal the number of people times per capita income times energy intensity (energy use per unit of economic activity) times carbon intensity (emissions per unit of energy use). This is an identity. On the right-hand side of Equation (2.1), N cancels N, Y Y and E E so that $M = M$. This is true.

Kaya's is a useful identity, and perhaps more so if expressed in proportional growth rates. Take logs on both side of Equation (2.1) and the first partial derivative to time. Then

$$\frac{\partial \ln M}{\partial t} = \frac{\partial \ln N}{\partial t} + \frac{\partial \ln {}^{Y}/_{P}}{\partial t} + \frac{\partial \ln {}^{E}/_{Y}}{\partial t} + \frac{\partial \ln {}^{M}/_{E}}{\partial t} \tag{2.2}$$

As

$$\frac{\partial \ln X}{\partial t} = \frac{1}{X}\frac{\partial X}{\partial t} = \frac{\dot{X}}{X} \tag{2.3}$$

we have that the growth rate of emissions equals the growth rate of the population plus the growth rate of per capita income plus the growth rate of energy intensity plus the growth rate of carbon intensity.

[1]The Kaya Identity is named after Yoichi Kaya, then a professor of engineering at the University of Tokyo. Kaya proposed the identity during a 1993 talk at the Conference on Global Environment, Energy and Economic Development. The Kaya Identity was already widely used when Kaya published it in 1997 in the conference proceedings.

World CO_2 emission +2.1%/year 1965–2020: population +1.6%, income +1.7%, energy per GDP −0.9%, CO_2 per energy -0.3%.

Figure 2.2 shows global carbon dioxide emissions between 1965 and 2020. CO_2 emissions rose by 2.1% per year. Why? The Kaya Identity allows us to interpret past trends. Population growth was 1.6% per year over the same period. Emissions per capita thus rose by 0.5% per year. Per capita income rose by 1.7% per year, again slower than the emissions growth rate. However, total income thus rose by 3.3% per year, considerably faster than emissions. In other words, the economy grew faster than emissions. This is primarily because the energy intensity of production fell by 0.9% per year. The carbon intensity of the energy system fell too, by 0.3% per year. In other words, population and income growth drove emissions up. This was partly offset by improvements in energy efficiency and a switch to less carbon-intensive fuels.

Trends were not steady over the period. For instance, energy efficiency improved by only 0.1% per year between 1965 and 1979. After 1979, the second oil crisis, this accelerated to 1.5% per year. Carbon intensity fell by 0.4% per year between 1965 and 1999. as oil and gas increasingly replaced coal, but rose by 0.4% per year between 1999 and 2011, as the coal-driven economies of China and India grew rapidly. Since then, it has fallen by 0.9% per year, as natural gas and renewables boomed.

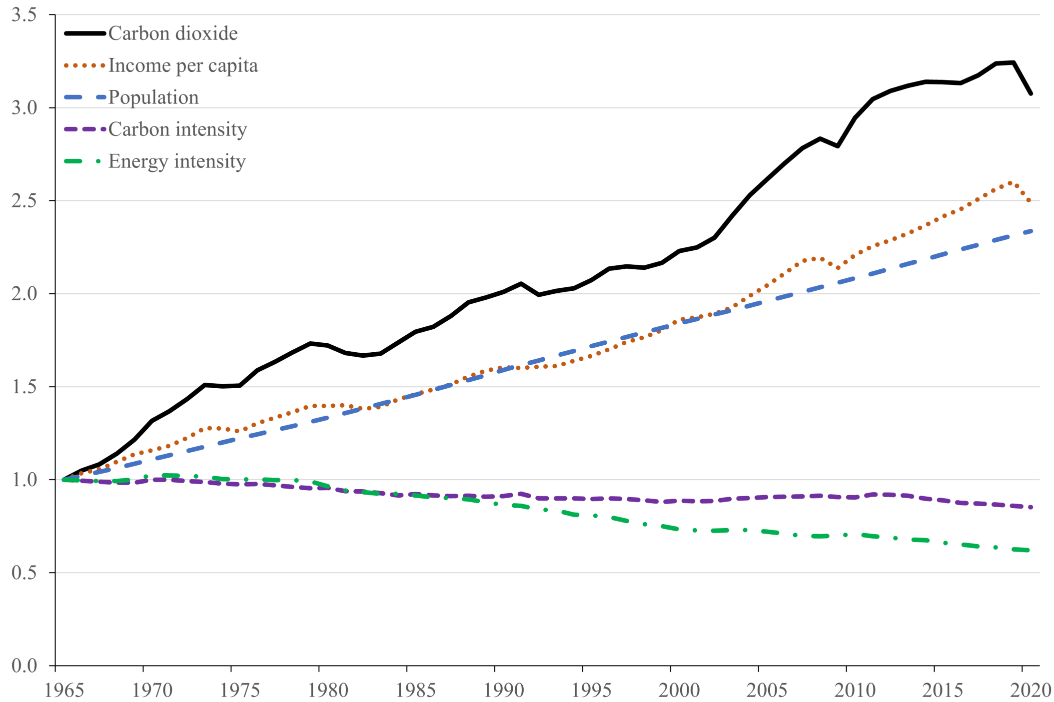


Figure 2.2: Global carbon dioxide emissions and its constituents

The Kaya Identity also allows us to project emissions into the future. We need to build a scenario of population growth, economic activity, energy use, and energy supply. See Section 2.3.

Finally, the Kaya Identity allows us to assess how emissions can be cut. We would need to reduce population or income, or improve energy or carbon efficiency. See Section 2.4.

2.3 Scenarios of future emissions**

Scenarios are not implausible, internally consistent descriptions of alternative futures.

Figure 1.7 shows four alternative scenarios of future climate change—see Box 1.2 for a discussion of forecasts, scenarios and projections. These scenarios are based on assumptions about population, economy, and technology. Such assumptions are not independent of one another. For example, poorer people tend to have shorter lives and more children. As people have fewer children, the number of workers rises relative to the total population, boosting economic growth.

Technological progress is a key driver of economic growth. Although our understanding of the processes of long-term development has considerably improved in recent decades, it does not permit any confidence in forecasts over a century or longer, particularly since institutions play such an important role, and institutional change is hard to predict. Therefore, scenarios are built instead. Scenarios are not predictions. Scenarios are not-implausible, internally consistent storylines of how the future might unfold.

As stated above, the Kaya Identity is useful for organizing future scenarios. Emission scenarios must include the number of people, but may also have their age structure—because that drives decisions on consumption and saving and hence economic growth—their education—because that drives labour productivity and hence growth—and urbanization—because that drives travel and transport and hence energy use. Emission scenarios must include per capita income, but may also have the structure of the economy—because certain sectors use more energy per unit value added than others—and expenditure patterns—because a beef- and rice-based diet emits more methane than a mutton- and wheat-based diet. Emission scenarios must include the energy intensity of economic production, and may include a range of primary and final energy sources and carriers—because emissions are more easily reduced in electrified transport than in liquid-fuel based transport. Emission scenarios must include the carbon intensity of the energy sector, and thus details of the supply and demand for a range of different energy sources and their transformations and transport. Emission scenarios should also include land use, agriculture, and the economic sectors that emit industrial greenhouse gases.

There are two types of scenarios for climate change. In one, there is no climate policy. These are typically referred to as "business-as-usual" scenarios, although the fact that there has been climate policy for three decades now in some countries increasingly makes this a misnomer. In the other type of scenario, there is climate policy. We will return to the latter in Chapter 8.

Figure 2.3 shows a key example of business-as-usual scenarios: the Shared Socioeconomic Pathways (SSPs). Values are for the world as whole. The scenarios are broken down according to the Kaya Identity. The scenarios started in the year 2010. For comparison, the observed values for 1970–2010 are shown too. These scenarios were implemented with six alternative models. Figure 2.3 shows the mean plus or minus twice the standard deviation across these models.

Existing scenarios of future greenhouse gas emissions do not reflect the full range of historical experience.

There are five scenarios for each variable. However, two pairs of the population scenarios are really close together, while the income scenarios are more evenly spaced. This implies that the SSPs assume that population growth is independent of per capita income, an assumption at odds with everything we know about fertility and mortality. All scenarios of per capita income show exponential growth, and most very rapid growth, even though some parts of the

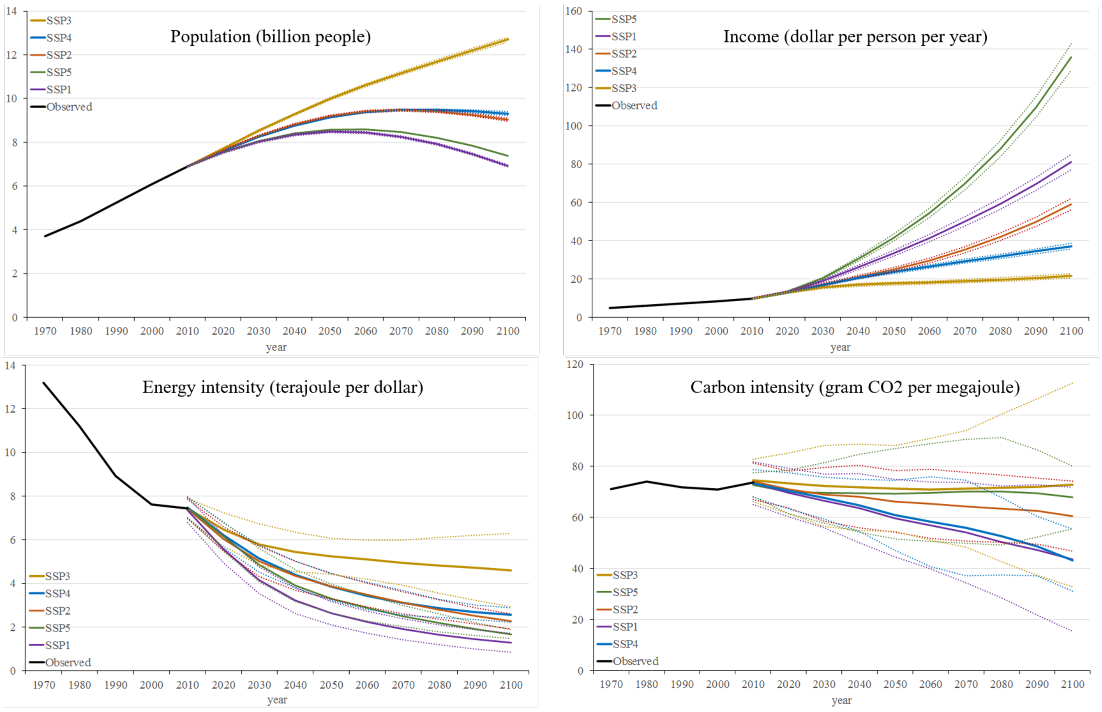


Figure 2.3: The SSP scenarios for the world broken down according to the Kaya Identity

world have enjoyed little growth in the past. In the most pessimistic scenario, per capita income will roughly double. In 2100, the world average will be similar to the average income in Portugal in 2015. In the most optimistic scenario, per capita income will rise 14-fold. The world average in 2100 will be well above the 2015 average in Luxembourg. All scenarios show a steady improvement of energy efficiency, often at a rate that exceeds the experience of the last 40 years. Most scenarios show a steady fall in carbon intensity, even though recent history showed both decreases and increases. That said, the relative price of renewables to fossil fuels is now such that a decrease in carbon intensity seems more likely. A prolonged increase in carbon dioxide, as shown by some models, seems particularly implausible as it assume that conventional oil and gas, when depleted, will be replaced by coal. While technically feasible through gasification and liquification, this does require tapping into coal resources that are expensive to develop, for example those on Antarctica. Although peculiar, the SSP scenarios form the basis of much research on climate change, its impacts, and policies to reduce greenhouse gas emissions. The scenario with highest emissions is used most often even if least likely.

> There's not enough conventional oil and gas to substantially change climate. Future climate is driven by their replacements.

The availability of fossil fuels is a crucial part of any scenario of future carbon dioxide emissions. Figure 2.4 shows estimates of the reserves and resources of fossil fuels by type. The estimates are taken from the World Energy Council's Survey of Energy Resources of 2010, when the shale gas revolution was tentatively reaching beyond the borders of the USA and the shale oil revolution was in its infancy. Reserves can be profitably exploited with current technology at current prices and costs. Resources are known or suspected to be there, and may become commercial in the future. Figure 2.4 reveals that conventional oil and gas reserves are relatively small: 317 billion tonnes of oil equivalent. In 2009, total primary energy use was 11.6 GTOE. There is therefore enough conventional oil and gas to cover energy demand for another 27 years. Figure 2.4 also reveals, however, that there are plenty of other types of fossil fuels, including coal of course but also large resources of unconventional liquids and gases.

The second panel of Figure 2.4 shows the carbon dioxide emissions that would result if these fossil fuels were burned. For comparison, global 2008 emissions were 30 billion tonnes of CO_2. We can keep up current emissions for 100 years or more. The third panel shows the impact on the atmospheric concentration, should all available fossil fuels be burned at once. Conventional oil and gas can contribute only about 100 ppm. Other fossil fuels, reserves and resources, are worth another 1500 ppm.

This implies that the climate problem is not driven by conventional oil and gas, but rather by what will *replace* conventional oil and gas when they run out. The future energy sector will therefore be very different. Different companies and countries will dominate. Technologies will be different too, and trillions of dollars will need to be invested in new equipment and infrastructure. This will need to be done regardless of climate change. The scale of transformation is of the same order of magnitude as that is needed for climate policy, and the timescale is similar too.

2.4 Options for emission reduction**

The Kaya Identity identifies the main options for emission reduction.

> Reduced population and economic growth would reduce emissions, but few elected governments would opt for this.

Fewer people is the first option, harking back to Thomas Malthus. Some murderous regimes in Africa and the Middle East actively seek to reduce the population of their countries. Few democratic countries would seek to emulate this in the name of climate policy. Indeed, population policy is controversial in most democracies—although less so among environmentalists.[2] China, however, has often put forward its one-child policy as one of its major contributions to climate policy—although that policy dates back to a time when climate change was hardly recognized as a problem, and has recently been relaxed.

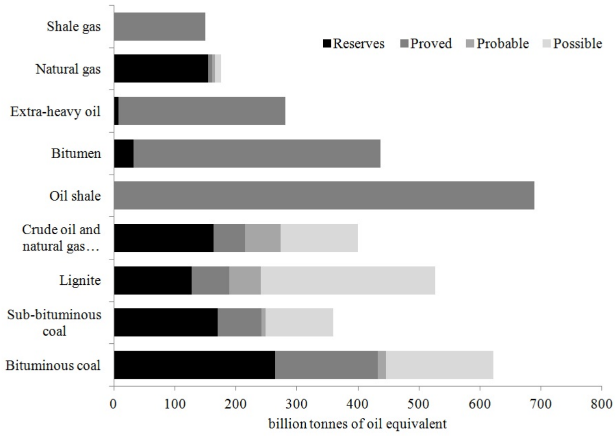
Slower economic growth is the second option. The collapse of the former Soviet Union and its aftermath has shown that reducing the level of per capita income is an effective way of cutting greenhouse gas emissions. See Figure 2.5. The Great Recession further demonstrated the power of economic growth over emissions growth. The fall in carbon dioxide emissions in Europe is primarily due to its lacklustre economic performance. Economic recession is a powerful way to cut emissions. However, promoting slower economic growth is not recommended to a politician seeking re-election.

That leaves us with just two of the four terms in the Kaya Identity.

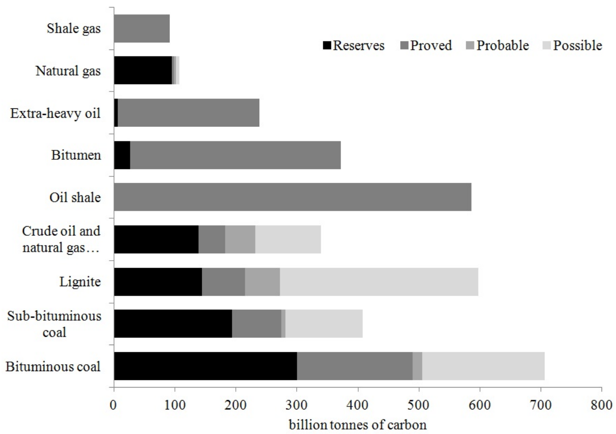
> Technological change reduces emissions but current effort would need to be trebled to stabilize emissions.

Energy efficiency improvements have kept the rise of carbon dioxide emissions in check (see Figure 2.2). Energy efficiency is likely to further improve in the future regardless of climate policy. This is because energy is a cost. A gadget that is the identical to its competitor but

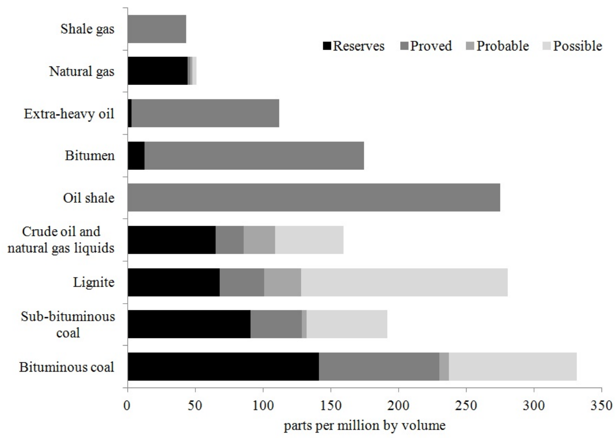
[2]Beware when someone calls for fewer children. All too often, fewer children means fewer black and brown children.



(a) Energy



(b) Emissions



(c) Concentrations

Figure 2.4: Fossil fuel reserves and resources as estimated for 2010 (top panel), their carbon content (middle panel), and implied carbon dioxide concentrations (bottom panel)

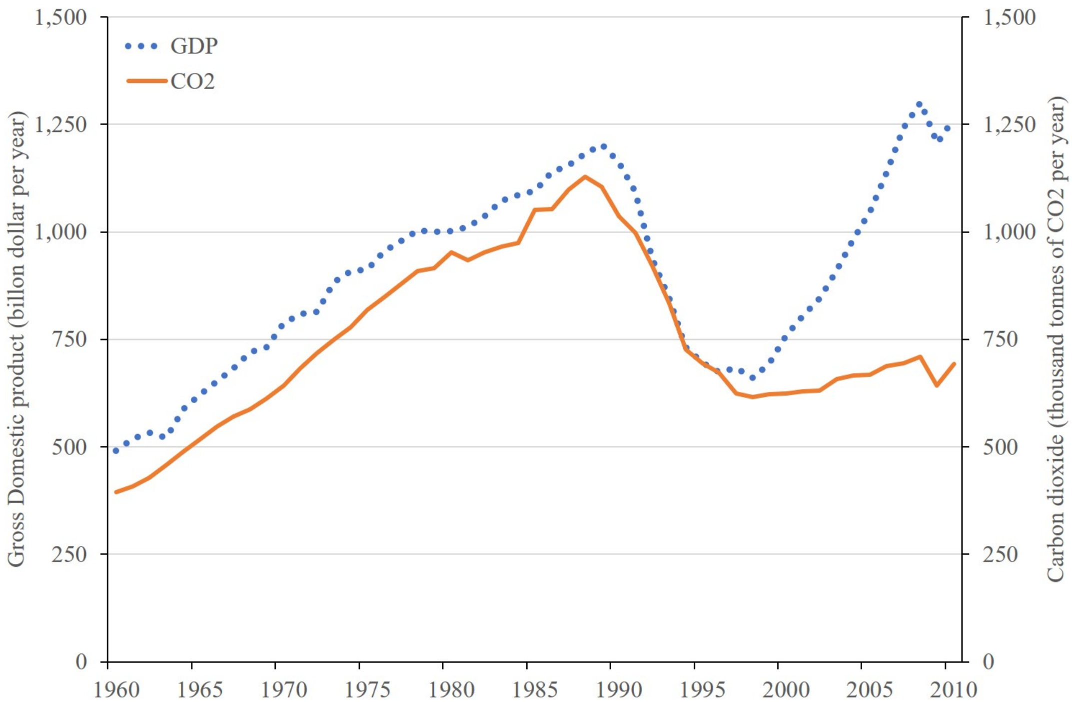


Figure 2.5: Gross domestic product and carbon dioxide emissions in the Soviet Union and successor states

uses less energy is more appealing to customers. You get the same service at a lower price. Companies therefore invest in improving the energy efficiency of their products. Ditto for the production process. Costs go down ff you can make the same stuff with less energy. The same is true for household energy use.

Energy efficiency improvement does not necessarily imply reduced energy use. For instance, the fuel efficiency of the US car fleet was roughly constant between 1980 and 2010. This is a remarkable feat of engineering as, over the same period, the size and weight of cars increased considerably. The gains in fuel efficiency were used not to reduce energy use, but rather to increase comfort, status and an illusion of safety.

There is also the *rebound effect*, first formulated by William Stanley Jevons. Better energy efficiency means lower energy costs means higher energy use. Improving the insulation of homes, for instance, means that it is cheaper to heat the house. This often leads to higher indoor temperatures at the expense of reduced energy use. Better fuel efficiency means it is cheaper to drive a long distance. This leads to longer or more frequent drives. Estimates of the size of the rebound effect vary widely. This is no surprise as energy is used for so many different things in so many different ways. Typical estimates have that the rebound effect is 10–20%. That is, increased energy demand offsets one-tenth to one-fifth of the initial reduction in energy use.

Behavioural change reduces emissions too, but habits are hard to change and market imperfections waste a lot of energy.

Besides technical change, behavioural change can also reduce emissions. Engineers reckon that some 30% of energy used serves no purpose.[3] It is, however, easier to identify energy waste than to reduce it. People may boil a kettle full of water to make a single cup of tea. People may leave the light on in the bathroom. Most would agree they should not, but do it anyway. It is hard to get rid of energy waste. Government awareness campaigns are not particularly effective, and social pressure can be unpleasant.

Energy is also wasted because of misaligned incentives. A university lecturer is responsible for turning off teaching equipment at the end of class, but the money thus saved will disappear into the overall budget of the college. A landlord is responsible for building maintenance, but the tenant pays the energy bills. The costs of wall insulation cannot usually be recouped from increased rents, because running costs are not typically known to prospective renters.[4] If the rental market is tight, landlords have little reason to invest in maintenance. Solving these *principal–agent* problems—the principal pays the bills, the agent makes the decisions—make for nice exercises in industrial organization, but reality is more resistant.

Lower energy demand is another form of behavioural change. People can put on a sweater and turn down the thermostat. They can move closer to work and cycle instead of drive. They can shower less. They can go for a holiday in Brighton rather than Bangkok. Only a small minority is prepared to make these changes for a better climate.

> Carbon-free fuels are another option but nuclear and hydropower are unpopular.

The carbon intensity of the energy sector is the fourth component of the Kaya Identity. The carbon intensity is improved by switching from high-carbon energy sources to low- or no-carbon energy. In recent years, power generation in the USA has switched from coal to gas and carbon dioxide emissions fell as a result. This was done because the shale gas revolution brought abundant and cheap natural gas. In Europe, the opposite has happened. With a population wary of fracking, cheap American coal has replaced natural gas and emissions have gone up. Japan and Germany have taken it a step further, replacing carbon-free nuclear power by gas, coal and even lignite.

There are several carbon-free energy sources. Hydropower and nuclear power are proven technologies. Both are controversial. Hydropowerrenewable energy!hydropower needs a reservoir, displacing people and land that may be used for agriculture or nature conservation. With nuclear power, people worry about nuclear waste and safety—problems of the past, if you ask me, but the resulting escalation of costs is a concern—and about the proliferation of nuclear material and knowledge for military application. Because of this, there is limited scope for a large expansion on nuclear and hydropowerrenewable energy!hydropower.

> Renewables are expensive; volatile and unpredictable; and bring their own environmental problems.

Besides hydropowerrenewable energy!hydropower, there are many other renewables sources of energy. Some renewables are confined to small niches, such as geothermal energy and tidal power. Other renewables are more widely applicable. Wind power is a key part of the carbon dioxide emission reduction strategy in many countries. Onshore wind power is 25–50% more expensive than coal- and gas-fired electricity—although approaching grid parity[5] in some areas.

[3] This should be taken with a grain of salt. Experts also reckon that 30% of food is wasted, 30% of mobile data, and 30% of health spending.

[4] Energy labels go some way to solving this problem.

[5] A source of electricity is at grid parity if it can compete with other electricity supplies without government support.

Offshore wind is more expensive still. There has been some progress in reducing the costs, but as wind is an established technology, breakthroughs are not expected. Cost savings come from economies of scale, better materials, and improved control. Besides the costs, wind power is intermittent and unpredictable. Backup generators are needed to prevent blackouts. On top of that, there is opposition to the visual intrusion of wind turbines, and turbines kill bats and birds.

Solar power is another key part of many an emission reduction policy. Apart from niche applications, solar power is expensive still, but costs have fallen faster and are likely to continue to fall rapidly. This is because photovoltaic power piggybacks on technological progress in materials science and semiconductors. Intermittency is less than with wind, but photovoltaics do not work in the dark. Solar panels contain nasty chemicals and should be carefully disposed at the end of their life time. Concentrated solar power, where sunlight is used to heat a material like water or salt, does have the momentum to be a reliable and dispatchable energy source, and it is at or near grid parity in sunny places with cheap land. Realized temperatures are rising, so that concentrated solar power can be used not just for power generation but also in industrial applications such as the production of steel.

Biomass is the most widely used renewable source of energy, but primarily in its traditional forms—wood, dried dung. Unlike wind and solar power, bioenergy can be used to substitute the liquid fuels that propel most vehicles, ships and aircraft. The first generation of modern biofuels are expensive, and the materials used are often edible. Bioenergy use thus drives up the price of food. There is much research into second- and third-generation bioenergy, but little commercial application. Second-generation bioenergy would use the same materials, thus directly competing with food production, but with improved processing. Fossil fuels are plant material nicely dried, compacted and converted by Mother Nature over millions of years. Biomass energy is recent plant material that needs to be gathered, dired, compacted and converted by people and their machines. As this is relatively new, progress can be expected in bringing down the costs. Third-generation bioenergy uses different or modified source material. Over the last 10,000 years, we have optimized plants for food, but we have never much bothered with optimizing plants for energy. Rapid progress can therefore be expected, particularly now that genetic engineering is routine. However, although there regularly is exciting news from the lab, there has yet to be successful commercialization.

2.5 Beyond the Kaya Identity***

There are a number of other options not captured by the Kaya Identity. Above, the Kaya Identity was interpreted for carbon dioxide emissions from fossil fuel combustion.

> CO_2 can be captured and stored at a price. Scale, permanence, and safety are issues. CCS is an end-of-pipe solution.

The Kaya Identity is about the structural causes of emissions and structural solutions. There is also an end-of-pipe solution: Carbon capture and storage (CCS). In CCS, carbon dioxide is separated before, during, or after burning. It is then captured and transported to be stored in a safe place. Carbon capture requires capital and energy. In a conventional power plant, the investment cost of a power plant with capture is some 25% higher than that of a similar plant without, and some 30% of the energy output of the plant will be devoted to carbon capture. The costs of carbon capture can be brought down with a radical redesign of power plants, for example the Allam Cycle, but that is as yet untested at scale. Transport of CO_2 is costly too. According to some estimates, if we want to capture all carbon dioxide from power generation, the transport network would be several times bigger than the network for oil and gas, because CO_2 is less dense. The main issues with storage are permanence and safety. There is little point in storing carbon dioxide if it leaks out again. Sudden releases of carbon dioxide would endanger animal and human life.

> Slowing deforestation would reduce emissions but if that were easy it would have been done long ago.

Besides the emissions from fossil fuel combustion, land use change also releases carbon dioxide. Reducing such emissions requires slowing down the pace of deforestation, or even reversing it. There are other reasons for doing so. Tropical forests are rich in biodiversity. Forests upstream protect against floods downstream. Mangrove forests shield coasts from waves and wind, and provide food and shelter for animals. Agroforestry promotes soil conservation and crop diversification. Yet, despite many attempts to slow deforestation, it has continued apace. This suggests that it is difficult and expensive. Unless a more lucrative alternative is offered to those that decide to chop down trees and burn forests, they will continue.

Note that climate policy may even accelerate deforestation. Bioenergy needs land. Palm oil plantations in Southeast Asia replace virgin forest. Sugarcane farms in South America push other crops onto pasture land, and pasture into the rainforest.

As discussed above, methane emissions are intrinsic to the production of dairy, rice, and certain types of meat. Although technical measures can be used to reduce emissions by a little bit, more substantial emission reduction requires volume measures—less dairy, less rice, different or less meat. Reducing nitrous oxide emissions requires more judicial use of fertilizers and other crop management practices, lest food production fall. Methane from waste disposal and mining can be captured and either flared or burned as a fuel. Almost all emissions can be captured with sufficiently high investment. Similarly, leaks in gas pipes can be fixed to any standard one is willing to pay for. Industrial gases can be replaced with other substances, which at present are either more expensive or perform worse.

> Geoengineering is a risky option. There are concerns about who would decide to geoengineer the global climate.

Finally, there is geoengineering. The aim of geoengineering is not to prevent climate change, but rather to change the climate back. There are many ways to achieve this, from spraying water over the oceans to putting aerosols in the atmosphere and mirrors in space. Geoengineering sounds attractive at first sight, as it is cheap and does not require a large number of countries to cooperate. However, uncertainty is one of the main features of climate science. If we do not really know the consequences of putting carbon dioxide in the atmosphere, do we think we know how much sulphur aerosols we should put where to offset the impact of carbon dioxide? Even if successful, geoengineering is risky. With climate change solved, how do you convince policy makers to continue to invest in geoengineering for decades, maybe centuries on end? There are political risks in the short run, too. A mirror in the L1 Lagrangian point would deflect sunlight and cool Earth. It would be a feat of engineering that is within reach for NASA, ESA and JAXA. Who would operate that mirror? Joe Biden, Xi Jinping, or Ursula von der Leyen? Would we trust them to use this power wisely? Putting aerosols into the atmosphere is much simpler. A fleet of four large transport planes could put enough material in the air to substantially cool the planet. A small country like the Maldives could do this, or a mid-sized corporation. Aerosols can also be shot into the atmosphere using cannon, putting geoengineering within reach of terrorist organizations. Governance is a key concern.

Further reading

Every six years, Working Group III of the Intergovernmental Panel on Climate Change publishes a major assessment of options for emission reduction. The information is layered, with a Summary for Policy Makers with high-level information, Technical Summaries with more detail, and multiple chapters with a lot of detail and references to the underlying literature. These reports can be found at http://www.ipcc.ch/. In 2000, the IPCC released a Special Report on Emissions Scenarios, which can be found at the same site. More recent IPCC scenarios are referred to as *Representative Concentration Scenarios* and *Shared Socio-Economic Pathways*; see van Vuuren et al., *Climatic Change* (2011) and Riahi et al., *Global Environmental Change* (2017).

The best discussion of carbon-free energy sources is *Sustainable Energy—without the hot air* by David MacKay†(2015). Oliver Morton's *The Planet Remade—How geoengineering could change the world* (2016) is a excellent overview of all aspects of geoengineering. If you want to read about energy in general, no one beats Vaclav Smil, particularly his *Beginner's Guide* (2017), *Energy Transitions* (2016), and *Energy and Civilization* (2017). Bill Gates' *How to Avoid a Climate Disaster* is strong too.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tda.html.

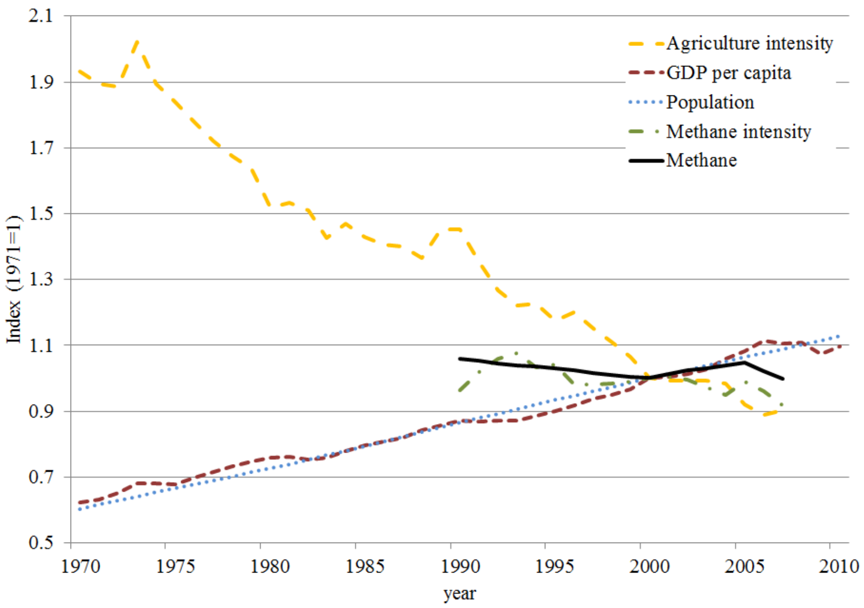
Exercises

2.1. Between 1971 and 2013, how fast should energy efficiency improvements have been to keep global carbon dioxide emissions constant? And carbon efficiency improvements? How do these numbers compare with the observed trend?

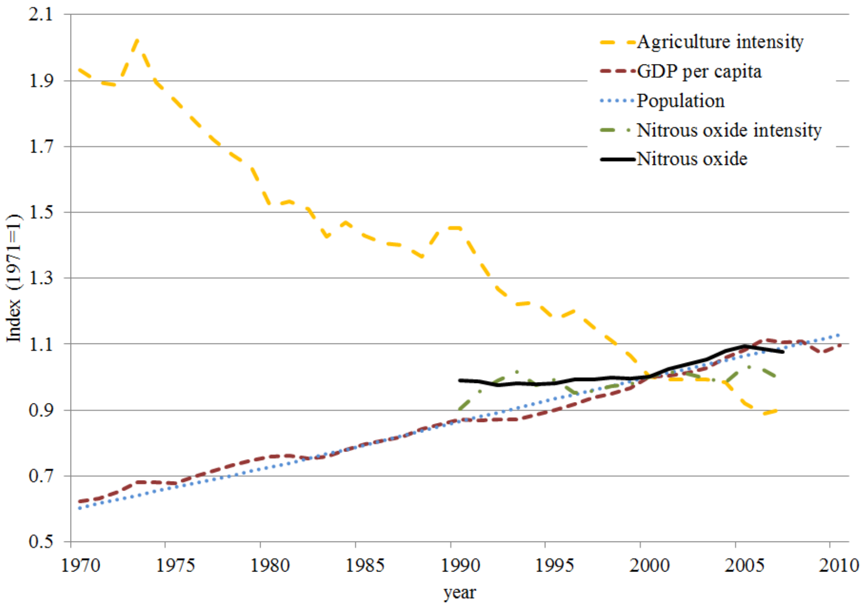
2.2. Figure 2.6 shows the Kaya Identity for agricultural emissions of methane and nitrous oxide. How is the Kaya Identity defined in these graphs? Discuss the results. How would you define the Kaya Identity in this case?

2.3. Read and discuss:

- **D. Helm, R. Schmale and J. Philips (2007), Too Good to be True? The UK's Climate Change Record.
- **D. Diakoulaki and M. Mandaraka (2007), Decomposition analysis for assessing the progress in decoupling industrial growth from CO_2 emissions in the EU manufacturing sector, *Energy Economics*, 29, 636–664.
- ***G.P. Peters and E.G. Hertwich (2008), CO_2 embodied in international trade with implications for global climate policy, *Environmental Science and Policy*, 42 (5), 1401–1407.
- ***G. Baiocchi and J.C. Minx (2010), Understanding changes in the UK's CO_2 emissions: A global perspective, *Environmental Science and Technology*, 44, 1177–1184.
- ****M.D. Webster et al. (2003), Uncertainty analysis of climate change and policy responses, *Climatic Change*, 61, 295–320.
- ****M.D. Webster and C.-H. Cho (2006), Analysis of variability and correlation in long-term economic growth rates, *Energy Economics*, 28 (5–6), 653–666.



(a) methane



(b) nitrous oxide

Figure 2.6: Global emissions of methane (top panel) and nitrous oxide (bottom panel) from agriculture and its constituents

Chapter 3

Abatement costs

Thread

- Emission reduction costs money as it forces companies and households to use more expensive energy and dearer technology. #climateeconomics
- The economy can be fully decarbonized at negligible cost if policy design is smart and abatement is gradual. #climateeconomics
- Differences between abatement cost estimates are large, reflecting different assumptions on emissions without policy. #climateeconomics
- Models also differ on the degree of adjustability of the economy, and the responsiveness of R&D to climate policy. #climateeconomics
- The two degrees target may be physically impossible. It is infeasible without stringent policy in all large countries now. #climateeconomics
- An initially low but rising carbon tax stabilizes the climate. A stringent target requires a high initial carbon tax. #climateeconomics
- Capital stock turnover, technological progress, discount rate and carbon cycle argue for a slow start to abatement. #climateeconomics
- Abatement costs money in a perfect market. In an imperfect market, abatement costs money too. #climateeconomics
- Climate policy may reduce market imperfections and this would at least partly offset the cost of abatement. #climateeconomics
- The revenue of a carbon tax or permit auction could be used to improve the structure of the tax system. #climateeconomics
- Taxes are more distortionary if the tax base is narrower, price elasticities higher, and initial tax level higher. #climateeconomics
- In EU (US), the tax burden should be shifted from labour (capital) to emissions. This may even stimulate growth. #climateeconomics
- Smart climate policy requires a political system capable of delivering smart fiscal reform. This is in short supply. #climateeconomics

3.1 The costs of emission reduction**

Emission reduction costs money as it forces companies and households to use more expensive energy and dearer technology.

Emission reduction costs money. There are various ways to look at this. Without climate policy, greenhouse gas emissions are free. With climate policy, emissions are not. What used to be free is no longer. We used to be able to dump greenhouse gas emissions in the atmosphere, without cost, without constraint. No more. We used to freely choose what energy to use and what food to eat. No longer. Therefore, costs have gone up or consumption down.

Alternatively, you can look at this mathematically. Climate policy imposes a new constraint on a maximization problem. If the constraint bites—that is, if emissions are lower than they otherwise would have been—the objective function must fall. Put yet another way, climate policy forces people and companies to use different technologies and different fuels than they would have without climate policy. Without climate policy, these technologies and fuels are available, but people choose not to use them, or not to the same extent. More specifically, climate policy gets people and companies to invest more in energy savings than they would of their own volition, and gets them to switch to more expensive energy sources. That costs money.

As with any other policy, it is difficult to estimate the costs of climate policy. Most climate policy analysis is done *ex ante*—before the fact. We study a hypothetical situation, or rather, two hypothetical situations, as a cost estimate is the difference in welfare with and without the policy. If we evaluate the impact of past policy, we observe only one history. The "history" without policy is a counterfactual—what would have happened if. Cost estimates therefore must rely on models. We compare two model runs for *ex ante* policy analysis, and we compare a model run with reality for *ex post* policy evaluation. Cost estimates are only as good as the models used.

Not all models are equally good. Some analysts claim that all investments in energy savings are because of climate policy—although in fact energy efficiency has always been improving, well before the advent of climate policy (see Figure 2.2). Famously, President George W. Bush once promised to improve energy efficiency by 14% over a decade—even though the historical trend is 18% per decade in the USA. Similarly, other people claim that all investment in renewable energy can be ascribed to climate policy. Truth is, renewable energy is commercially viable in an increasing number of applications and place. Solar power, for instance, has long beaten other sources of electricity if the distance to the grid is sufficiently large, and may soon outcompete coal and gas everywhere.

The economy can be fully decarbonized at negligible cost if policy design is smart and abatement is gradual.

Estimates of emission reduction costs vary widely, partly because all estimates are model based, and partly because modellers have not used existing climate policy for model calibration. Most studies agree, however, that a complete decarbonization of the economy can be achieved at a reasonable cost if policies are smart, comprehensive and gradual. These conditions are further discussed below and in Chapter 4.

Models disagree, however, on how much emission reduction would cost. This is illustrated in Table 3.1: emission reduction costs vary by an order of magnitude. There are various reasons for this. Modellers make different assumptions about what options are available to reduce greenhouse gas emissions, and at what cost. Obviously, if a model omits an option—say, hydrogen fuel-cells for private transport—or assumes that its costs are high, then that model will find that emission reduction is more expensive. Vice versa, if a model assumes that an option exists—say, unlimited capacity for carbon storage—or puts its costs at a lower level than what is commonly believed, then that model will find that emission reduction is less expensive.

Table 3.1: The total costs (10^{12} \$) of greenhouse gas emission reduction

Target	650 ppm		550 ppm				450 ppm			
Approach	below		above		below		above		below	
Non OECD	now	later	now	later	now	later	now	later	now	later
Model 1	-0.2	0.5	4.8	6.4	5.1	7.4	36.2	78.6	54.4	X
Model 2	13.4	18.8	30.4	48.2	30.9	64.1	123.4	X	X	X
Model 3	23.8	18.9	33.9	26.3	38.0	X	56.7	X	X	X
Model 4	1.4	1.2	3.8	5.1	5.1	10.2	X	X	X	X
Model 5	15.6	17.3	29.7	X	32.7	X	X	X	X	X
Model 6	7.2	7.8	16.2	29.8	18.8	35.7	X	X	X	X
Model 7	2.2	6.5	4.4	9.1	10.9	X	11.9	X	X	X
Model 8	2.2	na	5.9	na	12.4	na	27.9	X	X	X
Model 9	2.4	3.1	5.3	6.7	6.5	X	15.5	32.8	25.7	X
Model 10	13.0	12.8	44.3	59.8	44.3	59.8	X	X	X	X
Model 11	1.9	2.6	27.9	39.7	32.1	64.5	X	X	X	X

Notes: Costs are the net present value of the abatement costs over the 21st century. Costs are given in trillions of dollars. Results are presented for 11 different models and model variants, and for 3×2×2 policy scenarios with different stabilization targets (in parts per million of carbon dioxide equivalent), different approaches to those targets (from below, that is the target caps concentrations at all times, or from above, that is the target holds for 2100 but may be exceeded in the interim), and for different participation (non-OECD countries start to reduce their emissions in the near future or later in the century). Infeasible scenarios are marked X.

Source: L.E. Clarke, J.A. Edmonds, V. Krey, R.G. Richels, S.K. Rose and M. Tavoni (2009), 'International climate policy architectures: Overview of the EMF22 international scenarios', *Energy Economics*, 31 (S2), S64–S81.

Models also differ on the degree of adjustability of the economy, and the responsiveness of R&D to climate policy.

The rate of technological change is a key determinant of future emission reduction costs. The difference in the costs between carbon-neutral energy (solar, wind, nuclear) and carbon-emitting energy (coal, oil, gas), for instance, is a key assumption: emission reduction would be cheap if solar is only slightly more expensive than coal. That cost difference is reasonably well known for the present and past, but has to be assumed for the future. If technology advances faster in carbon-neutral energy than in carbon-emitting energy—say, solar is getting cheaper faster than coal—abatement cost are lower. Different models make different assumptions about the rates of technological progress.

Some models assume that progress in carbon-saving technologies accelerates in response to climate policy. Other models do not have such a response. The latter models thus have slower technological progress in energy efficiency and renewables, and higher costs of emission reduction. Some models assume that there is no opportunity cost to accelerating technological progress in energy; others do include an opportunity cost. Perhaps there are highly educated taxidrivers, who would make a real contribution to the next generation of solar cells if only there were government support. But perhaps hiring clever people to work on solar power means that they will not work in medicine. These alternative assumptions further explain the wide range in cost estimates.

If a model assumes high price elasticities, high substitution elasticities, and rapid depreciation of capital, its cost estimates will be lower than of a model with low price elasticities, low substitution elasticities, and slow turnover of the capital stock. The latter model assumes that the world of energy use is set in its carbon-intensive ways, which makes it hard and expensive to change course.

Differences between abatement cost estimates are large, reflecting different assumptions on emissions without policy.

Finally, some models assume that, in the scenario without climate policy, greenhouse gas emissions will not grow very fast. Consequently, emission targets are within easy reach. Other models assume rapidly rising emissions, so that a large effort is needed to meet emissions targets.

Table 3.1 shows results for different policy scenarios. There is one minor variation: Is the long-term target an upper bound for the concentrations in all years, or only in the final year? This makes a difference in any model, as the latter case has fewer constraints than the former case. However, there is so much momentum in both the carbon cycle and the energy system that the difference is small. Besides, you would have to rely on the natural processes in the carbon cycle to remove the excess carbon dioxide from the atmosphere. That puts a limit on the extent of the overshoot: In most cases, it is optimal to approach the target from below.

Some of the models in Table 3.1, however, assume that biomass power plus carbon capture and storage is a viable option at scale. This is negative-carbon-energy: Plants take up carbon dioxide when growing. In a biomass-fired power plant, roughly the same amount of carbon dioxide is released again. But if the carbon is captured and stored, the net effect is that you remove carbon dioxide from the atmosphere. This implies that you can correct excess emissions from earlier years towards the end of the century. In this case, you can overshoot the target in the intermediate years to a larger extent, and costs are saved.

Participation of poorer countries in climate policy is another variation in the policy scenarios shown in Table 3.1. In some scenarios, every country starts to reduce its emissions from 2015 onwards. In other scenarios, only rich countries do, and poorer countries start considerably later. This has a large impact on the estimated cost of emission reduction. If a fraction of emission is excluded from abatement, the rest will have to be reduced more to meet the same target. As emission reduction costs are more than linear in emission reduction effort, this necessarily drives up the total costs. Furthermore, many of the cheaper emission reduction options can be found in poorer countries, partly because these economies tend to rely on older, less efficient technology, and partly because money buys more in poorer countries.

The two degrees target may be physically impossible. It is infeasible without stringent policy in all large countries now.

The concentration target is the third policy variation in Table 3.1. The more stringent the target, the higher the cost—and costs rise very rapidly from the more lenient to the more ambitious targets. For the most stringent targets, a number of models do not report. That can be for one of three reasons. First, the representation of the carbon cycle disallows the model to meet the target. Second, the representation of emissions and emission reduction disallows the target. Third, the model can meet the target, but the costs are so exorbitant that the modeller refused to report the results. Whatever the reason—physical, technical or political —the most stringent target in Table 3.1 may well be beyond reach. This is as expected: There are always things than cannot be done. However, the 450 ppm CO_2eq target in Table 3.1 corresponds to a 50–50 chance of meeting the 2°C target of the United Nations (see Box 8.1).

Table 3.2 complements Table 3.1. It shows results for the same set of models and the same set of scenarios, but now for the marginal abatement costs. This is best thought of as the carbon tax imposed on all greenhouse gas emissions from all economic activities in all (participating) countries in 2015. Per policy scenario, the models again disagree by an order of magnitude. The initial carbon tax required for meeting the least stringent target is modest, but this escalates with increased stringency.

Figure 3.1 repeats part of the information in Table 3.2, highlighting the spread of model results for a single target. Figure 3.2 shows a different cross-section, averaging across models to highlight the impact of different targets, approaches to that target, and participating.

Table 3.2: The marginal costs ($\$/tCO_2eq$) of greenhouse gas emission reduction

Target	650 ppm		550 ppm				450 ppm			
Approach	below		above		below		above		below	
Non OECD	now	later	now	later	now	later	now	later	now	later
Model 1	3	5	8	13	10	24	77	214	1297	X
Model 2	20	43	51	147	52	239	260	X	X	X
Model 3	14	16	27	28	27	X	28	X	X	X
Model 4	1	1	11	12	16	92	X	X	X	X
Model 5	13	27	43	X	52	X	X	X	X	X
Model 6	9	13	29	154	35	256	X	X	X	X
Model 7	6	35	7	35	26	X	15	X	X	X
Model 8	6	na	12	na	27	na	70	X	X	X
Model 9	4	7	8	10	14	X	20	53	101	X
Model 10	10	11	40	67	30	67	X	X	X	X
Model 11	3	6	4	36	22	131	X	X	X	X

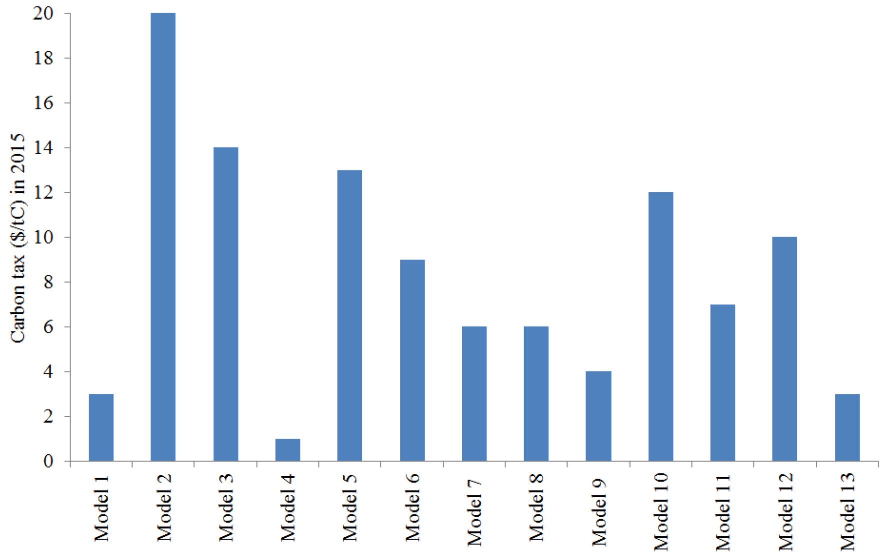
Notes: Marginal costs are for 2020, and apply (uniformly) to the participating countries only. Marginal costs are given in dollars per tonne of carbon dioxide equivalent. Results are presented for 11 different models and model variants, and for 3×2×2 policy scenarios with different stabilization targets (in parts per million of carbon dioxide equivalent), different approaches to those targets (from below, that is the target caps concentrations at all times, or from above, that is the target holds for 2100 but may be exceeded in the interim), and for different participation (non-OECD countries start to reduce their emissions in the near future or later in the century). Infeasible scenarios are marked X.

Source: L.E. Clarke, J.A. Edmonds, V. Krey, R.G. Richels, S.K. Rose and M. Tavoni (2009), 'International climate policy architectures: Overview of the EMF22 international scenarios', *Energy Economics*, 31 (S2), S64–S81.

Table 3.2 shows the increase in energy prices in dollars per tonne of carbon dioxide, a unit with which not everyone is intimately familiar. Therefore, Table 3.3 translates $\$/tCO_2$ into local currency per unit of energy use. That is, Table 3.3 specifies how much a carbon tax would add to a liter of gasoline, a bag of coal, and a kilowatt-hour of electricity in selected countries.

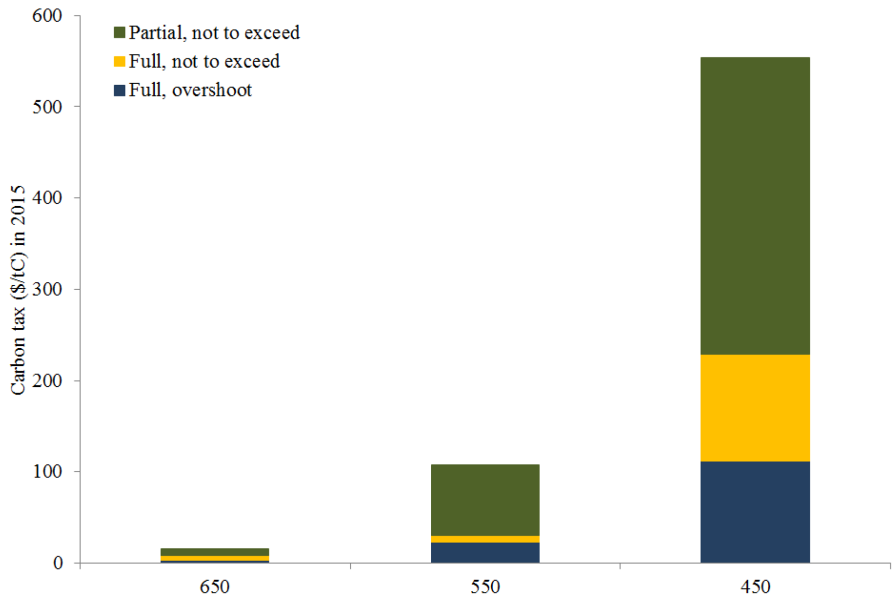
> An initially low but rising carbon tax stabilizes the climate. A stringent target requires a high initial carbon tax.

Table 3.2 shows the required carbon tax in 2020. The carbon tax is assumed to increase over time. Figure 3.3 provides insight into the allocation of emission reduction effort over time. Figure 3.3 shows the emissions trajectories to meet five alternative targets at the lowest possible costs. It contrasts the least cost trajectories to arbitrary trajectories for four of the five targets. Figure 3.4 shows the cost differences, which vary between 10% and 60% depending on



Note: Carbon tax needed in 2015 to meet, with full participation, a 650 ppm CO_2eq target in 2100.

Figure 3.1: The marginal costs of emission reduction for different models



Note: Carbon tax, averaged across models, needed in 2015 to meet alternative targets in 2100 (or throughout the 21st century) with different participation rates.

Figure 3.2: The marginal costs of emission reduction for different targets

Table 3.3: Carbon dioxide emissions per unit of energy use and price increase due to a \$100/tC carbon tax

Fuel	Unit	Brazil	China	Germany	France	India	Japan	UK	USA
		Emissions per unit							
Petrol	$kgCO_2/l$	2.312	2.312	2.312	2.312	2.312	2.312	2.312	2.312
Diesel	$kgCO_2/l$	2.668	2.668	2.668	2.668	2.668	2.668	2.668	2.668
Gas	$kgCO_2/kWh$	0.184	0.184	0.184	0.184	0.184	0.184	0.184	0.184
Coal	$kgCO_2/kg$	2.383	2.383	2.383	2.383	2.383	2.383	2.383	2.383
Power	$kgCO_2/kWh$	0.076	0.794	0.451	0.097	1.239	0.437	0.487	0.544
		carbon tax							
tax	LC/tCO_2	64	168	21	21	1784	2715	17	27
tax	LC/tC	235	617	76	76	6540	9955	64	100
		Price increase per unit							
Petrol	LC/l	0.148	0.389	0.048	0.048	4.123	6.276	0.040	0.063
Diesel	LC/l	0.171	0.449	0.055	0.055	4.758	7.243	0.047	0.073
Gas	LC/kWh	0.012	0.031	0.004	0.004	0.327	0.498	0.003	0.005
Coal	LC/kg	0.153	0.401	0.049	0.049	4.250	6.470	0.042	0.065
Power	LC/kWh	0.004	0.125	0.009	0.002	1.697	1.126	0.008	0.014

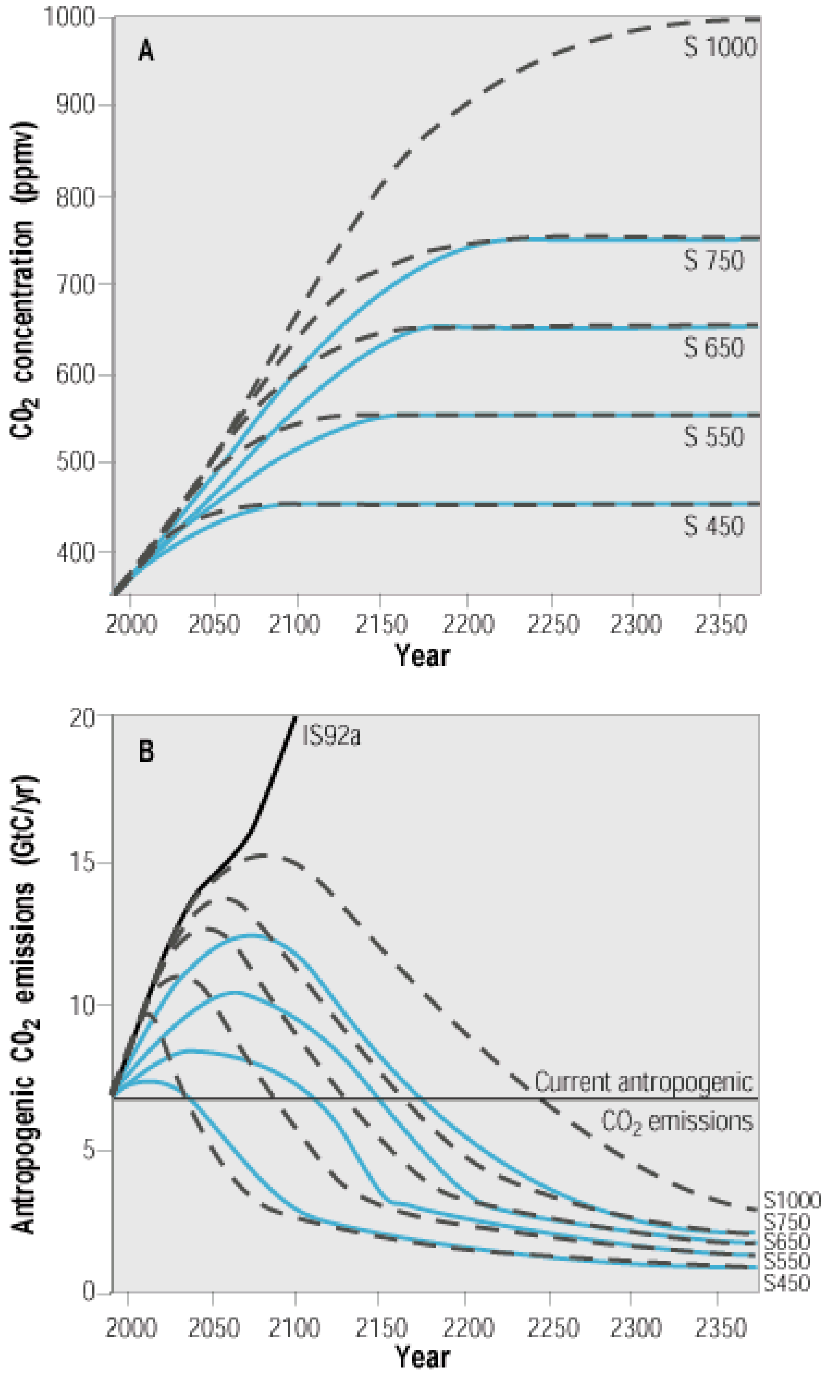
Note: LC = local currency: real, renminbi, euro, euro, rupiah, yen, pound sterling, dollar.

the model. As the net present value of the costs of emission reduction is measured in trillions of dollars, a 10% cost savings is worth pursuing. The main difference between the two sets of trajectories is that the arbitrary ones start with radical emission cuts whereas the least cost trajectories begin with modest abatement that accelerates over time.

There are four reasons why money is saved if emission reduction targets are lenient at first while becoming more stringent over time. Greenhouse gas emissions are to a large degree determined by things that change only slowly, such as machinery and buildings, technology blueprints, and location choice. Emission reduction requires changes in behaviour and technology, but behaviour and technology are constrained by durable consumption goods and invested capital. A carbon tax does not reduce the emissions of those households and companies that continue to use the same cars, live and work in the same place and in the same building, and operate the same machinery. In those cases, a carbon tax simply imposes a penalty on investment decisions made in earlier, pre-climate-policy times. In other words, rapid emission reduction implies capital destruction, particularly rapid emission reduction that was unexpected when investment decisions were made. This is a deadweight loss to the economy. This deadweight loss falls over time as capital turns over, so that the carbon tax can increase without inducing excessive costs.

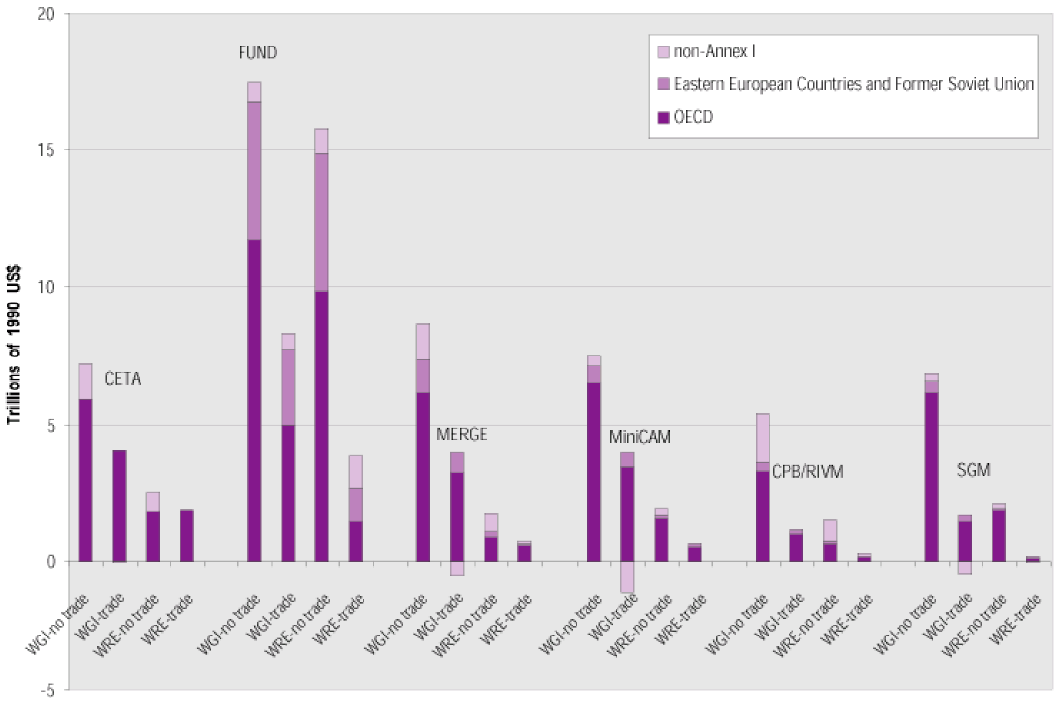
> Capital stock turnover, technological progress, discount rate and carbon cycle argue for a slow start to abatement.

Technological change is another reason why emission reduction is expensive in the short term but cheaper in the medium to long term. Carbon-neutral energy is still immature technology. Although fossil fuel technology continues to progress, it is well developed and all the easy improvements have been made. Although there has been rapid progress in oil and gas exploitation, this has been about unlocking relatively expensive reserves, such as shale oil and gas. In contrast, we can still expect major technological breakthroughs with solar power and bioenergy. Furthermore, the easily accessible sources of fossil fuels are getting exhausted. So, over time, we expect the costs of fossil fuels to rise and the costs of renewables to fall. As the costs of emission reduction are driven by the difference in costs between fossil and renewable energy, abatement costs should fall over time.



Source: IPCC WG3 AR3.

Figure 3.3: Alternative pathways to stabilization of carbon dioxide concentrations in the atmosphere



Note: WRE corresponds to the black lines in Figure 3.3, WGI to the blue lines.

Source: IPCC WG3 AR3.

Figure 3.4: The costs of alternative pathways to stabilization of carbon dioxide concentrations in the atmosphere

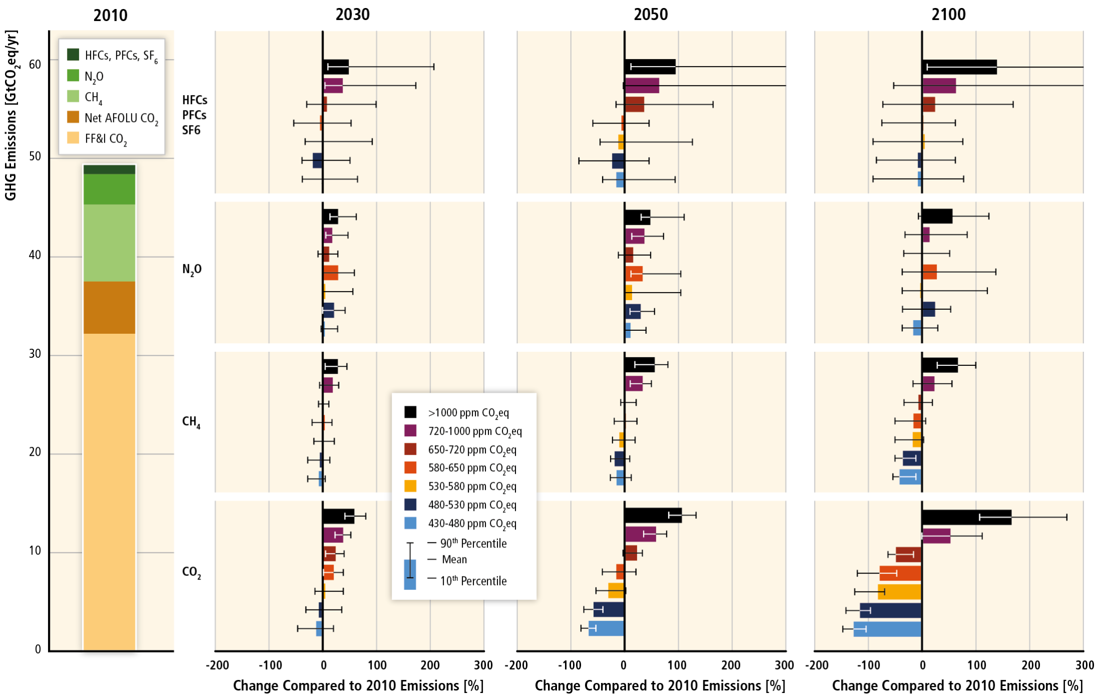
Third, emission reduction costs in the future are discounted. The discount rate makes that costs incurred in the future are less important than costs incurred today. Postponing emission reduction reduces the net present value of the costs.

Fourth, emissions are degraded in the atmosphere. Climate policy targets typically refer to the long term, say the year 2100. Emissions in 2090 are more important to concentrations in 2100 than emissions in 2020. Put differently, later emission reduction is more effective than earlier emission reduction. Atmospheric degradation thus functions as a discount rate, so that it is better to reduce emissions later.

3.2 Negative emissions**

Many cells in Table 3.1 are marked X, denoting that the target is deemed infeasible for physical, technical, economic or political reasons. The results in Table 3.1 are somewhat older. There is a political demand for the analysis of ambitious climate targets. Modellers have met that demand by expanding options for negative emissions. This includes negative carbon energy—biomass with carbon capture and storage—and direct air capture—artificial photosynthesis to remove carbon dioxide from the atmosphere.

Figure 3.5 shows just how much emissions will need to be cut in order to meet the more ambitious targets. In only two of the seven policy scenarios, emissions will continue to grow relative to 2010. In four scenarios, global emissions will be below 2010 by 2050. In two scenarios, emissions will need to fall by 2030. In the same two scenarios, emissions will be net negative by 2100. In 2010, carbon dioxide emissions were about 33 billion tonnes a year. Averaged across models, for the most ambitious policy target, in 2100, carbon dioxide emissions are over *negative* 6 billion tonnes per year.



Source: IPCC WG3 AR5 Chapter 6.

Figure 3.5: Greenhouse gas emissions relative to 2010 for three time slices, seven concentration targets, and four (groups of) emissions

Figure 3.6 shows the chance of staying below 2℃ global warming, the upper limit of acceptable climate change according to the Paris Agreement (see Box 8.1). It reveals that the probability of meeting this internationally agreed target rapidly falls if greenhouse gas concentrations exceed 550 ppm CO_2e. A concentration of 450 ppm CO_2e would give a 90% chance of meeting the target. In the summer of 2016, the concentration of CO_2 alone was 404 ppm. Adding the other greenhouse gases, the total concentration was 489 ppm CO_2e. This explains why negative emissions are necessary.

As they grow, energy crops remove carbon dioxide from the atmosphere. This requires and deserves a carbon subsidy. If we take the above 6 $GtCO_2$ and a carbon tax of \$1,500/tCO_2,[1] the net carbon subsidy will thus be 9 trillion dollars per year. Economic activity is projected to reach between 200 and 1,300 trillion dollars per year, with \$600 10^{12} in the middle of the range. Carbon subsidies may thus pose a very substantial burden on either the public finances or taxpayers. In the central estimate, there would be a 1.5% levy on income to finance net

[1]This is the best guess from the Fifth Assessment Report of the IPCC Working Group III.

carbon emissions, comparable to current spending on defence. But there are also scenarios that put negative carbon emissions at 40 $GtCO_2$ and the carbon tax at \$6,000/tCO_2—putting the cost of the carbon removal subsidy on par with expenditure on health care. Besides the cost, incidence is problematic too. Energy crops will be grown in monoculture on large farms, probably corporate farms, and certainly heavily mechanized farms. Processing will similarly be done by large firms. It is hard to imagine an electoral strategy that would sustain a stream of large subsidies to agri-energy multinationals, particularly if negative carbon energy is successful and the threat of climate change recedes.

Even though models have converged on the necessity of negative emissions to meet the targets of the Paris Agreement, they have not converged on the cost of doing so. Figure 3.7 shows that estimates of the marginal costs of greenhouse gas emission reduction differ by an order of magnitude, as do the total costs.

3.3 Distribution of costs**

The estimates reviewed above reflect what climate policy would cost the average person. The distribution of costs is important too. Greenhouse gas emissions result from energy and food. Both are necessary goods. If income increases, expenditure on energy and food increases too, but not by as much as income. The income elasticity is greater than zero but smaller than one.

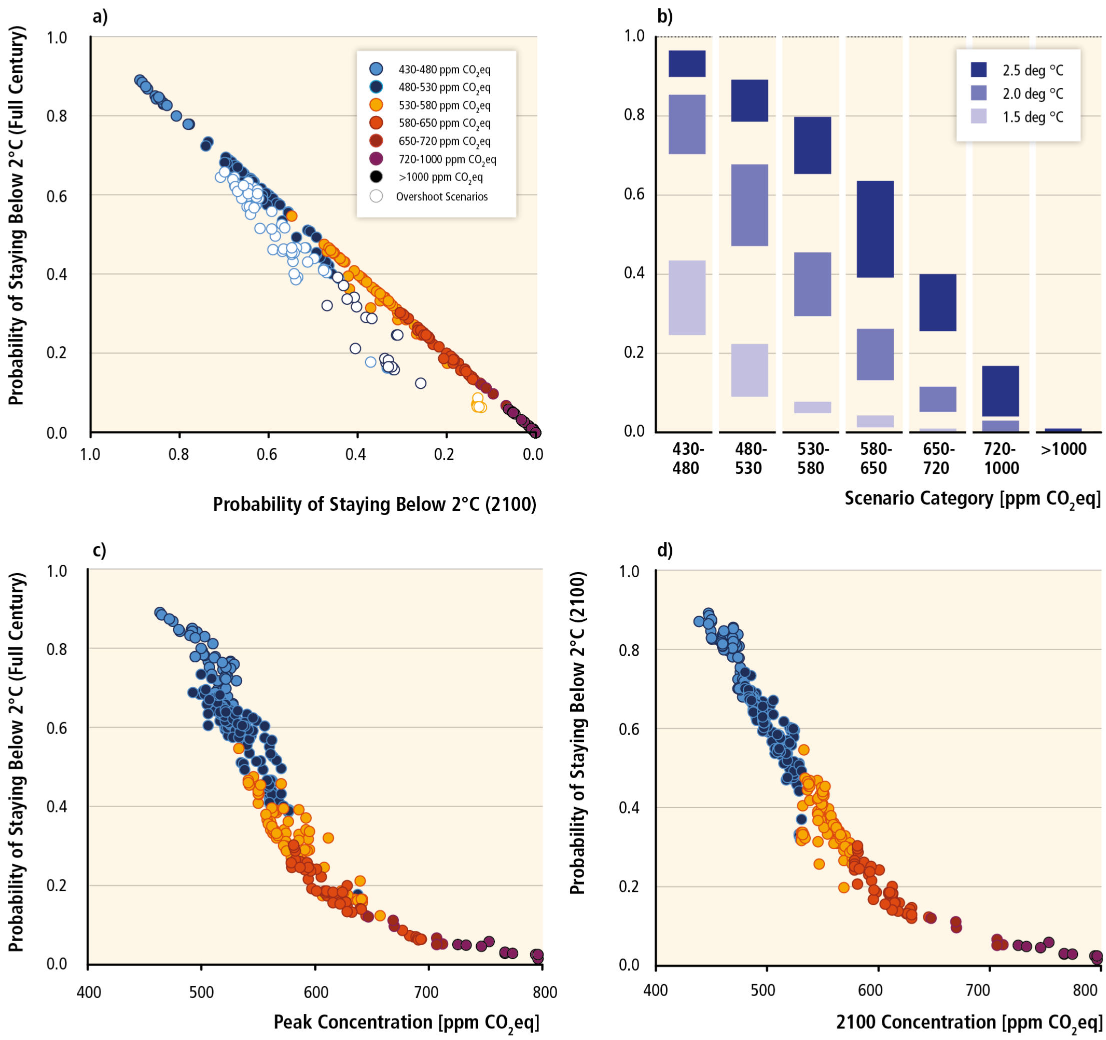
Climate policy makes energy and food more expensive, perhaps explicitly by levying a carbon tax, perhaps implicitly by imposing technology standards. This disproportionally hurts the poor, who spend a higher share of income on energy and food, use older, less fuel-efficient appliances, and have fewer options to switch to cheaper alternatives.

More expensive energy makes everything in the economy more expensive, as energy is used to make, transport, and store things. This exacerbates the disproportionate impact on the poor, who tend to save little and are thus hit harder by price inflation. If we leave out the direct expenditure on energy for heating, light and transport, the poor tend to spend their money on more energy-intensive goods and services than do the rich.

Because of this, climate policy is often seen to be regressive: It hits the less well-off hardest. This is sometimes used as an argument against climate policy. It can also be used as an argument for a carbon tax. A carbon tax ensures that climate policy is not unnecessarily expensive; see Chapter 4. The costs on the poor are still disproportional, but lower than they could have been. A carbon tax also brings revenue to the government, which can be used to offset its negative impacts, for instance by increasing benefits and tax credits and reducing tax rates. The same argument can be made for auctioned tradable permits.

The regressivity of climate policy is not as clear cut as it seems. There are two counterveiling forces that may dampen the disproportionate impact on the poor, or even make climate policy progressive. The income of the poor mostly consists of wages and government transfers. Richer people also earn from capital, and this is the dominant source at the top of the income distribution. Energy and capital are close complements. Electricity is of no use without a lightbulb or a laptop to use it. Gasoline is useless unless you have a car to propel. This implies that a tax of energy—and a tax on carbon dioxide emissions is a tax on fossil energy—reduces the returns on capital. Machines are less profitable if more expensive to run. A explicit tax on energy is an implicit tax on capital. Profits fall, and dividends. Stock prices are lower too. This disproportionally affects the rich.

There is a second effect. If energy is more expensive and the returns on capital fall, then it is less attractive to automate production. Capital and energy are, to a degree, substitutes for labour. Climate policy thus increases the demand for labour, particularly for jobs that

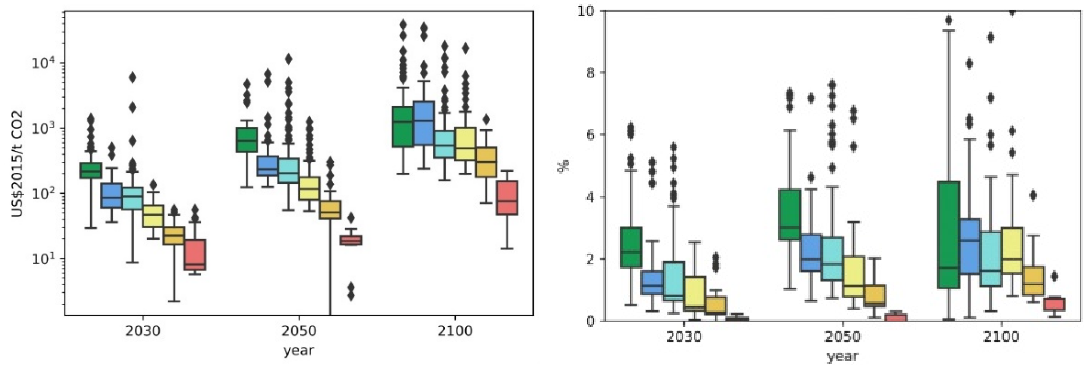


Note: The top right panel groups the scenarios of the top left panel, showing the 10–90% confidence range over the scenarios; this panel also adds results for the chance of staying below 1.5°C and 2.5°C warming.

Source: IPCC WG3 AR5 Chapter 6.

Figure 3.6: The probability of staying below 2°C global warming in the 21st century versus in the year 2100 (top panels), the peak concentration of greenhouse gases (bottom left panel), and the 2100 concentration of greenhouse gases (bottom right panel)

could also have been done by machines. These jobs tend to be less well-paid. On top of that, renewable energy is more labour-intensive than fossil fuels. More people are needed, particularly for installation and maintenance. Both of these mechanisms would lead to higher employment and higher wages, especially in the lower parts of the income distribution.



Note: From left to right, the green scenarios stay below 1.5℃ warming; the dark blue scenarios overshoot but return to 1.5℃ before 2100; the light blue scenarios stay below 2.0℃ with a 2 in 3 chance; the yellow scenarios stay below 2.0℃ with a 1 in 2 chance; the dark yellow scenarios stay below 2.5℃ with a 1 in 2 chance; the orange scenarios stay below 3.0℃ with a 1 in 2 chance

Source: IPCC WG3 AR6 Chapter 3.

Figure 3.7: The marginal (left panel) and total (right panel) costs of climate policy in 2030, 2050 and 2100.

3.4 Negative abatement costs**

There are claims that the costs of emission reduction are negative —that is, that it would be possible to save emissions and save money at the same time. Some of the claims are the result of bad accounting. Two common mistakes are the following. First, people confuse the technological change that is part of the no-policy scenario with the accelerated technological change in the policy scenario. As we saw in Chapter 2, the no-policy scenario indeed contains a large number of actions that are both commercially viable and reduce emissions. Energy efficiency improves over time, also in the absence of climate policy. Because these investments are commercially viable, they do not need policy support —and it is thus wrong to attribute them to climate policy.

Another common mistake is to underestimate the costs of investment. Most greenhouse gas emission reduction requires an upfront investment (e.g., wall insulation, solar panel) in return for lower energy costs later. The discount rate is thus crucial in determining whether this investment is worthwhile. Some analysts assume that households and companies can borrow money at the same rate of interest as the government can. In fact, private rates of interest tend to be higher than public ones. That makes investment less attractive. As another example, well-established technologies have acquired a reputation and a dense network of mechanics for installation, maintenance and repair. New technologies lack those, a cost that is easily overlooked.

Non-economists may also claim that a reduction in fossil fuel imports would be good for the economy. Jean-Baptise Colbert, finance minister to Louis XIV, was an early proponent of import substitution as a strategy for economic growth—mercantilism—but the theory was discredited a long time ago. Import substitution policies were largely abandoned in the 1980s. Substituting cheap imported energy with expensive domestic energy slows economic growth. Protected infant industries tend not to create competitive companies, but rather companies that are adept at lobbying and rent-seeking. The balance of payments holds, of course, so reduced imports imply reduced exports, reduced foreign investment, exchange rate adjustments and so on.

That said, there may be genuine reasons why the costs of emission abatement may be different than suggested by Tables 3.1 and 3.2—perhaps smaller or even negative. The models in these tables are either optimization models or equilibrium models. Recall that a market equilibrium corresponds to a Pareto optimum. If the no policy scenario is an optimum, any policy intervention bears a cost. If you start at the top, the only way is down.

In reality, however, the no-climate-policy case is characterized by many market imperfections and policy distortions. Climate policy may overcome some of these, and this would reduce its costs. However, climate policy may also interact with pre-existing distortions, and this would increase its costs.

> Abatement costs money in a perfect market. In an imperfect market, abatement costs money too.

A carbon tax is one way to implement climate policy. Like any tax, a carbon tax is distortionary. In an undistorted market, rational actors find a Pareto optimum. A tax changes the choices people make, and leads that market to an equilibrium with lower welfare. The welfare loss is a measure for the degree of distortion of the tax.

> Climate policy may reduce market imperfections and this would at least partly offset the cost of abatement.

However, a carbon tax brings revenue too, and that revenue could be used to reduce other, more distortionary taxes. Taxes are distortionary because they distort behaviour, moving people and companies away from the Pareto optimum, making them do things they would rather not.

> Taxes are more distortionary if the tax base is narrower, price elasticities higher, and initial tax level higher.

Taxes are more distortionary if they are higher, if price elasticities are higher (because behaviour is more responsive), and if the tax base is narrower (as fewer people are affected, by definition, then, for the same revenue, the behaviour of those people is further distorted). A carbon tax starts from a low level, price elasticities are low, and a carbon tax has a broad base. It is therefore not particularly distortionary (even though it is specifically designed to change behaviour). If the carbon tax revenue is used to reduce another tax, there may well be a benefit—and that benefit may more than offset the initial cost of abatement. This is known as the *revenue-recycling effect*.

> The revenue of a carbon tax or permit auction could be used to improve the structure of the tax system.

Let us assume that the revenue of the carbon tax is used to reduce the labour tax. A labour tax drives a wedge between the marginal productivity of the worker—the willingness to pay of the employer for the employee's efforts—and the marginal value of leisure—the willingness to accept compensation for the employee for giving up leisure. A labour tax thus reduces welfare and employment. Reducing the labour tax using the revenues of the carbon tax then increases welfare and employment.

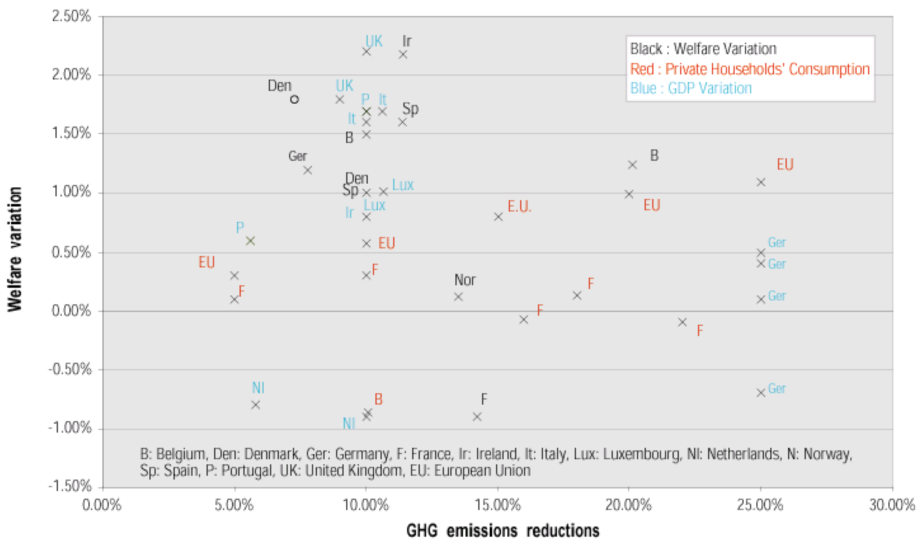
There is third effect,[2] however: The *tax-interaction effect*. A carbon tax increases the price of energy. As energy use is ubiquitous, all other prices increase too. The real wage falls—that is,

[2]The first effect is emission reduction, the second revenue recycling.

the reward for labour falls. In other words, the revenue-recycling effect implies a smaller wedge between marginal productivity and marginal leisure but the tax-interaction effect leads to a large wedge. The carbon tax, through its effect on prices, increases the distortionarity of the labour tax. There are theoretical models in which the tax-interaction effect is necessarily larger, in absolute terms, than the revenue-recycling effect. Applied models show mixed evidence.

In EU (US), the tax burden should be shifted from labour (capital) to emissions. This may even stimulate growth.

Figure 3.8 illustrates this, comparing three alternative welfare measures and twelve European countries for a single carbon tax and a single carbon-tax recycling scheme: the reduction of payroll taxes. In the majority of cases, welfare increases. If payroll taxes fall, companies would hire more workers. Figure 3.9, which is taken from the same study, confirms this. However, these benefits are not automatic. Figure 3.10 shows the results for the same carbon tax again but different recycling options. Depending on the country (or rather, its pre-existing fiscal policy), revenue recycling brings larger or smaller benefits. Comparing Figure 3.8 and Figure 3.10, you may conclude that a payroll tax reduction is best. Table 3.4 shows that that conclusion is unfounded. Table 3.4 shows results for the USA. In Europe, labour taxes tend to be high and are thus a prime target for a beneficial reduction. In the USA, tax reform that stimulates savings and investment is more desirable.

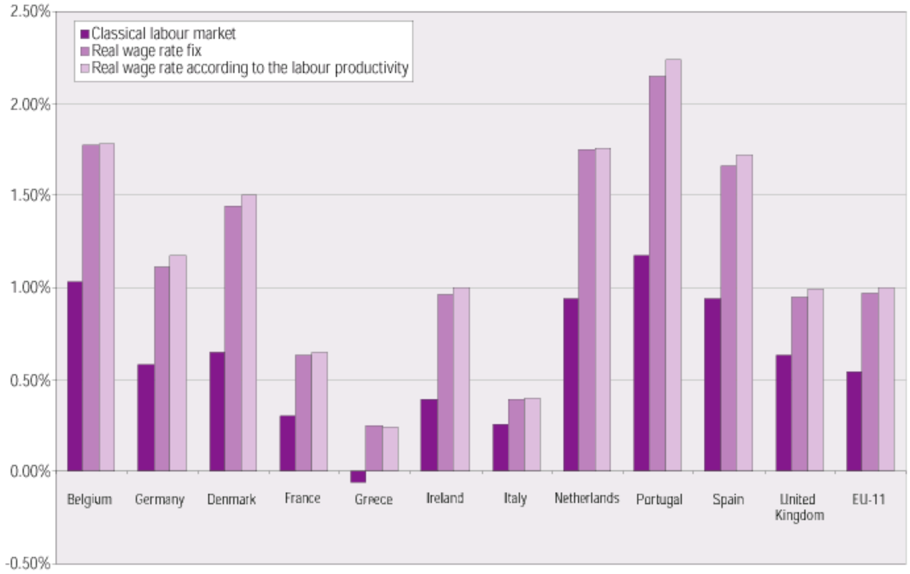


Source: IPCC WG3 AR3 Chapter 8.

Figure 3.8: The impact of climate policy on welfare for different European countries for alternative welfare measures

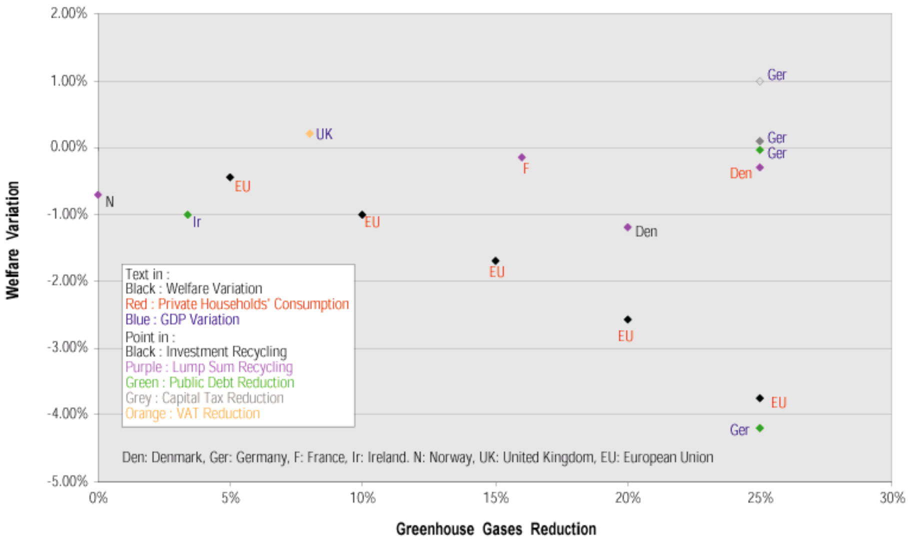
Smart climate policy requires a political system capable of delivering smart fiscal reform. This is in short supply.

In sum, the revenue of a carbon tax may be used to reduce other taxes and this would bring benefits that at least partially offset the costs of emission reduction. If the tax reform is well-tailored to the specific circumstances of the fiscal system, then that benefit may be substantial.



Source: IPCC WG3 AR3 Chapter 8.

Figure 3.9: The impact of climate policy on employment for different European countries for alternative models of the labour market



Source: IPCC WG3 AR3 Chapter 8.

Figure 3.10: The impact of climate policy on welfare for different European countries for alternative welfare measures and for alternative ways to recycle the carbon tax revenue

It is not the case that any use of the revenue is beneficial: It may be used to increase hand-outs to friends and allies of the government. It is also not the case that any tax reform is equally

Table 3.4: The costs of emission reduction in USA according to four models, for alternative carbon tax revenue recycling options

	Model 1	Model 2	Model 3	Model 4
Lump sum transfer to households	-0.58	-0.46	-0.62	-0.24
Increase government spending	-0.40	- 1.02		-0.24
Reduce personal income tax	-0.56	-0.53	-0.16	-0.16
Reduce corporate income tax	0.40	-0.11	0.60	-0.17
Reduce payroll tax				-0.18
Reduce payroll tax paid by employer	-0.58	-0.53		
Reduce payroll tax paid by employee	0.19	-0.25		
Increase investment credit	1.55	1.67		0.00

beneficial. The benefits that exist in theory are not necessarily realized in practice.

Further reading

Every six years, Working Group III of the Intergovernmental Panel on Climate Change publishes a major assessment of the costs of emission reduction. The information is layered, with a Summary for Policy Makers with high-level information, Technical Summaries with more detail, and multiple chapters with a lot of detail and references to the underlying literature. See their website: http://www.ipcc.ch/. The Energy Modelling Forum regularly organizes model comparison exercises on abatement costs. Recent and relevant are EMF36, EMF25, EMF22 and EMF21. See http://emf.stanford.edu/research/.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tdb.html.

Exercises

3.1. Table 3.1 shows the total cost of greenhouse gas emission reduction. Calculate the average across the 11 models. Calculate the average extra costs for delayed participation by non-OECD countries. Calculate the average extra costs for approaching the target from below. Calculate the average extra costs of making the target more stringent by 100 ppm.

3.2. Assume that emission reduction costs are quadratic in relative emission reduction $C = \alpha R^2$, where C denote costs, R relative emission reduction, and $\alpha = 1$ is a parameter. Suppose that the emissions target is $T = (1-R)E$, where $E = 100$ are baseline emissions. Compute the costs of reducing emissions by 1, 10 and 100 units. Compute the change in costs of emission reduction if the cost parameter is 10% higher, i.e., $\alpha = 1.1$. Compute the change in costs if baseline emissions are 10% higher, i.e., $E = 110$.

3.3. The results in Table 3.1 vary widely. How would you go about testing which model is correct?

3.4. Read and discuss:

- **M. Wise, K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos and J. Edmonds (2009), Implications of limiting CO_2 concentrations for land use and energy, *Science*, 324, 1183–1186.

- **T.C. Schelling (1996), The economic diplomacy of geoengineering, *Climatic Change*, 33, 303–307.
- ***S. Barrett (2008), The incredible economics of geoengineering, *Environmental and Resource Economics*, 39, 45–54.
- ***G.C. van Kooten, A.J. Eagle, J. Manley and T. Smolak (2004), How costly are carbon offsets? A meta-analysis of forest carbon sinks, *Environmental Science and Policy*, 7, 239–251.
- ***R. Martin, L.B. de Preux and U.J. Wagner (2014), The impact of a carbon tax on manufacturing: Evidence from microdata, *Journal of Public Economics*, 117, 1–14.
- ***M. Fowlie, M. Greenstone and C. Wolfram (2018), Do energy efficiency investments deliver? Evidence from the Weatherization Assistance Program, *Quarterly Journal of Economics*, 133, 1597–1644.
- ****K.C. Meng (2017), Using a Free Permit Rule to forecast the marginal abatement cost of proposed climate policy, *American Economic Review*, 107, 748–784.
- ****M. Goes, N. Tuana and K. Keller (2011), The economics (or lack thereof) of aerosol geoengineering, *Climatic Change*, 109, 719–744.
- ****R.N. Lubowski, A.J. Plantinga and R.N. Stavins (2006), Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function, *Journal of Environmental Economics and Management*, 51, 135–152.
- ****L.H. Goulder (1995), Environmental taxation and the double dividend: A reader's guide, *International Tax and Public Finance*, 2, 157–183.
- ****S.A. Smulders and M. de Nooij (2003), The impact of energy conservation on technology and economic growth, *Resource and Energy Economics*, 25, 59–79.

Chapter 4

Policy instruments for emission reduction

Thread

- Direct regulation is the government telling people and companies what (not) to do, and how (not) to do it. #climateeconomics
- Direct regulation works fine if there are few, similar sources of emissions. It does not work for greenhouse gases. #climateeconomics
- Direct regulation was successful, it made the career of current environmental leaders, and so it is still popular. #climateeconomics
- Taxes, subsidies and tradable permits reward emission reduction, but the decision whether and how is private. #climateeconomics
- A target is met at its lowest possible cost if taxes, subsidies or tradable permits are used. #climateeconomics
- Taxes increase costs, subsidies reduce costs. Over time, subsidies thus lead to an expansion of the polluting sector. #climateeconomics
- With permit trade, emissions are known but costs are not. With taxes, marginal costs are known but emissions are not. #climateeconomics
- (Mistakes with) annual national emissions do not matter much for a global stock pollutant. Emission certainty is worth little. #climateeconomics
- Cost certainty is worth a lot. Therefore, taxes are better suited for climate policy than tradable permits. #climateeconomics
- There are various ways to allocate permits: auction, equal per capita, to the polluters, to the victims of pollution. #climateeconomics
- The initial allocation of permits provides opportunities for politicians to hand out favours. #climateeconomics

- The willingness to pay to pollute equals the willingness to accept compensation for not polluting. #climateeconomics
- The willingness to accept compensation for pollution equals the willingness to pay for reduced pollution. #climateeconomics
- The market allocation of permits is therefore independent of the initial allocation. Efficiency and equity separate. #climateeconomics
- The price of carbon should rise with the interest rate plus the rate of atmospheric decay if there is a constraint on the concentration of CO_2. #climateeconomics
- The price of carbon should rise with the interest rate plus the rate of atmospheric decay minus the rate of climate deterioration if net present welfare is maximized. #climateeconomics
- Emission permits traded across borders require that importing countries recognize the permits of exporting countries. #climateeconomics
- The EU ETS is a large, international emission permit market. It suffered from avoidable teething problems. #climateeconomics
- Enforcement is the greatest challenge for the EU ETS, as it relies on judicial strength of individual Member States. #climateeconomics
- The Clean Development Mechanism appears to have led to neither development not emission reduction. #climateeconomics
- Technological progress in renewable energy, energy efficiency and agriculture drives the costs of climate policy. #climateeconomics
- Diverting R&D towards energy and agriculture would be expensive as these are small sectors in the economy. #climateeconomics
- R&D is best stimulated by patents, prizes, and taxes. Governments are bad at picking winners. #climateeconomics

4.1 The justification of public policy*

The *First Welfare Theorem* has that a competitive equilibrium is a Pareto optimum. The intuition is as follows. As Aristotle noted, a voluntary exchange is Pareto improving: Both parties are at least as well off as without the exchange. Why else would they agree to it? A sequence of voluntary exchanges thus improves welfare. If there is no additional exchange possible that satisfies all parties involved, then we must be in a Pareto optimum—but the market must also be in equilibrium as no further exchanges take place.

The First Welfare Theorem can be used to argue that the government should leave the market well alone, as any intervention would be Pareto inferior. There are a number of exceptions to this, but I here give only one. If there are externalities, the market equilibrium is not a Pareto optimum. The intuition is simple. An externality is an unintended and uncompensated impact on a third party. If two agents voluntarily agree on an exchange, that exchange must be Pareto improving. However, if this exchange unintentionally hurts a third party, and the two exchange parties do not make good the damage (nor cancel the exchange), then the exchange is no longer Pareto superior. A sequence of such exchanges would not lead to a Pareto optimum.[1]

The emission of carbon dioxide clearly is an externality. We burn fossil fuel to generate electricity, heat houses and propel cars. We do not burn fossil fuel to emit carbon dioxide. Emissions are thus *unintentional* (even if intrinsic to the process; see Section 2.1). Climate change does affect the welfare of people all over the world (cf. Chapter 6). These people are *not compensated* by the emitters of carbon dioxide.

In the presence of externalities, government intervention can improve welfare and is thus justified. The best intervention is the Pigou tax, named after Arthur Pigou, professor of political economy at University of Cambridge in the 1920s. The Pigou tax internalizes the externality. The emitters pay a tax on their emissions. This tax is exactly equal to the marginal damage done. This restores the Pareto optimum.

4.2 Direct regulation*

The regulator has many ways to affect emissions. Each of these instruments has different properties, which makes them more or less suitable for solving some problems than others.

> Direct regulation was successful, it made the career of current environmental leaders, and so it is still popular.

Direct regulation is probably the most common form of environmental policy. Direct regulation has been highly successful in the OECD. In the 1960s and 1970s, the environment in Europe and North America was filthy. It is no longer. The clean-up of the environment was largely done by direct regulation. This means that environmental regulators have a substantial amount of experience with these instruments, while senior regulators fondly recall the past successes of direct regulation. Even though times have changed and current environmental problems are different, environmental regulation lags behind. Furthermore, direct regulation allows bureaucrats to expand bureaucracies, as is in their interest.

> Direct regulation is the government telling people and companies what (not) to do, and how (not) to do it.

Direct regulation is also known as command and control. Essentially, the regulator goes in and tells households and companies what (not) to do and how (not) to do it. The regulator would be able to come up with sensible instructions if she has detailed knowledge of the regulated activity, which requires that there are either only a small number of agents or a small number of technologies in use. Direct regulation is essentially a one-size-fits-all solution. Regulation is homogenous because of capacity constraints within the regulator, and because administrative fairness demands that everyone is treated the same. This is fine unless there is substantial heterogeneity among the regulated.

> Direct regulation works fine if there are few, similar sources of emissions. It does not work for greenhouse gases.

There are different forms of direct regulation:

- The regulator may proscribe or forbid certain inputs into the production process, or put standards on the amount of input used.

[1] If the externality is positive no Pareto optimum is reached either, as the third party could sacrifice part of her windfall to incentivize more of the externality.

- The regulator may proscribe of forbid certain technologies used in the production process, or put standards on performance.
- The regulator may put limits on selected outputs of the production process, or put requirements on the products.
- The regulator may put limits on the timing of certain activities, or on their location.

For example, the US government have mandated that car fuel should be a blend of petrol and bioethanol. Car fuel may not contain lead. Car engines have to be equipped with catalytic convertors and meet fuel-efficiency standards. Power plants may only emit a certain amount of sulphur. Toys for infants may not contain carcinogenic material. Planes are not allowed to take off or land between 11 pm and 6 am. New buildings cannot be built in nature reserves. CFCs may not be made, sold, bought or used.

4.3 Market-based instruments*

> Taxes, subsidies and tradable permits reward emission reduction, but the decision whether and how is private.

Market-based or incentive-compatible policy instruments are the main alternative to direct regulation. Taxes and subsidies are the oldest instruments. With a tax, there is a charge, levy or penalty for every unit of the offending substance (or a proxy) used, produced, or emitted. With a subsidy, there is monetary reward for every unit of the offending substance not used, not produced, or not emitted.

In the short run, taxes and subsidies have the same effect on, say, emissions. With a subsidy, every tonne of emissions avoided will bring a reward. With a tax, every tonne of emissions avoided will reduce the tax burden, that is, bring a reward.

Taxes and subsidies have different distributional effects. With a tax, money flows from households and companies to the government. With a subsidy, money flows from the government to households and companies.

> Taxes increase costs, subsidies reduce costs. Over time, subsidies thus lead to an expansion of the polluting sector.

Because of that, taxes and subsidies also have different effects on emissions in the medium run. An emission tax increases the average cost of doing business in a particular sector. Investment flows elsewhere and the emitting sector shrinks (relative to what its size would have been without the tax). An emission avoidance subsidy reduces the average cost of doing business in that sector. Additional investment flows there, and the emitting sector expands (relative to what its size would have been without the subsidy).

Tradable permits are a more recent addition to the set of instruments available to the regulator. With tradable permits, the regulator sets an overall cap on consumption, production, or emissions. Let us focus on the last. The overall emissions cap is then split into units and each emitter receives a certain amount of permits to emit. So far, this is direct regulation. However, if a company finds that it has too few permits, it may buy additional permits from a company that has too many.

The price for emission permits that is formed on its market works just like a tax. For every unit of additional emissions, a company either has to buy an additional permit (which is a cost) or can sell fewer of the permits it holds (which is a cost too). For every unit of emissions avoided, a company either can sell more permits (which is a benefit) or has to buy fewer permits in the market (which is a benefit too).

The main advantage of market-based instruments is that the regulator does not specify how emissions are reduced. That decision is left to household and companies. The regulator does specify, however, that emissions are reduced.

Box 4.1: Emissions trade in practice: US Northeast

The *Regional Greenhouse Gas Initiative* (RGGI) is an emission permit market covering Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont for CO_2 emissions from power generation within these nine states. All power generating facilities with a capacity of 25 MW or greater are included, which is essentially all power generators. All permits are auctioned, with the proceeds going to programmes for energy efficiency and renewables. Permits are valid for a three year period, but can be banked for later periods. Exact regulations vary from state to state, but permits are traded freely between states.
Emissions fell by 40% between 2005, when the market started, and 2013. Emissions are mandated to fall by a further 2.5% per year until 2020. Permit prices have varied between \$2 and \$7 per short ton of CO_2, the price peak in 2015 coinciding with a downwards adjustment of the emissions cap. Prices are low because cheap shale gas outcompetes coal for power generation, and because the states each have initiatives to promote renewable electricity.
Originally, New Jersey was also part of RGGI. It stopped issuing new emission permits in 2012, but committed to uphold the validity of permits issued before 2012. The other states continued to recognize New Jersey permits, including permits issued for the years 2012–4, even though New Jersey does not. This raised the emissions cap, but maintained the legal integrity of the cap. This demonstrates that an interjurisdictional permit market can cope with the departure of a member.
New Jersey rejoined in 2018. Pennsylvania joined in 2022, North Carolina may soon.

4.4 Cost-effectiveness*

A target is met at its lowest possible cost if taxes, subsidies or tradable permits are used.

The costs of emission reduction are uniform at the margin if taxes, subsidies or tradable permits are used. This is an important characteristic. Let us consider a social planner, who seeks to reduce emissions at a minimum cost to society:

$$B = \sum_n B_n = \sum_n \beta_n R_n^2 \tag{4.1}$$

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

$$\min_{R_n} \sum_n B_n \text{ s.t. } \sum R_n \geq R \tag{4.2}$$

Form the Lagrangian

$$\mathcal{L} = \sum_n \beta_n R_n^2 - \lambda(\sum_n R_n - R) \tag{4.3}$$

and take the first partial derivative to the policy instruments (i.e., the emission reduction effort) to derive the first-order conditions for optimality:

$$\frac{\partial \mathcal{L}}{\partial R_n} = 2\beta_n R_n - \lambda = 0 \, \forall n \Rightarrow \frac{\partial C_n}{\partial R_n} = \lambda \, \forall n \tag{4.4}$$

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 either is 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.[2] Besides productive efficiency, we also care about allocative and cross-efficiency, which are captured by cost-efficacy if, as is usual in the context of climate policy, applied at the macro-scale.

Now let us consider a company faced with an emissions tax τ. It seeks to minimize its costs

$$\min_{R_n} \beta_n R_n^2 - \tau R_n \forall n \tag{4.5}$$

The cost function is as in Equation (4.1), but for every unit of emission reduction effort R, it pays τ less in tax.

Equation (4.5) is an unconstrained optimization problem, so the first-order condition has that the first partial derivative equals zero:

$$2\beta_n R_n - \tau = 0 \forall n \Leftrightarrow \frac{\partial B_n}{\partial R_n} = \tau \forall n \tag{4.6}$$

Equation (4.6) is identical to Equation (4.4) if $\tau = \lambda$.

If the regulator uses tradable permits, Equation (4.5) becomes

$$\min_{R_n} \beta_n R_n^2 - \pi R_n \forall n \tag{4.7}$$

where π is the permit price. This is the same as Equation (4.5) but with π instead of τ.

If the regulator uses subsidies, Equation (4.5) becomes

$$\min_{R_n} \beta_n R_n^2 - \varsigma R_n \forall n \tag{4.8}$$

where ς is the subsidy.

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.

[2]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.

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.

Uniformity can be deceptive. There are two types of combustion engine: Diesel and Otto. Suppose that the government imposes minimum fuel-efficiency on petrol cars. This makes cars more expensive. A long-distance commuter would avoid a lot of carbon dioxide emissions. Someone who drives to church once a week would avoid few emissions. There is thus a large difference in average costs per unit of emission avoided, even if the regulation is seemingly uniform.

Box 4.2: Emissions trade in practice: California and Quebec

Since 2013, California has had a market for greenhouse gas emission permits. It covers power generators and importers, industrial facilities, and fuel distributors who emit at least (the equivalent of) 25,000 metric tonnes of carbon dioxide. Permits are valid for three years, but can be banked for later. Most permits are grandparented, but additional permits are auctioned every three months. The auctions have a reserve price of \$10/tCO_2e (in 2012, rising with inflation). This puts a floor under the permit price. There is also a strategic reserve, 1% of the total emission allocation in 2013 but eventually rising to 7%. If the permit price reaches defined thresholds (\$40, 45, 50/tCO_2e in 2013, rising with inflation), the permits in the strategic reserve will be auctioned. This puts a cap on the permit price. These design elements thus find a compromise between the cost certainty of a carbon tax and the emission certainty of tradable permits.
Permits started trading in September 2011—well before they had to be surrendered to the *California Air Resources Board* to legitimize emissions—at around \$22/tCOtCO_2e.The price fell to below \$12/tCO_2e in late 2014. Permits traded around \$15/tCO_2e in August 2017. These prices are much closer to the price floor than to the price ceiling, and prices are low too in the light of California's goal to reduce emissions by 15% between 2015 and 2020. Prices are low because California has a range of other policies to reduce greenhouse gas emissions. Overlapping regulation increases the costs of meeting any target. Other climate policies can be seen as lowering the baseline from which cap-and-trade needs to reduce emissions. As the gap between baseline and target emissions shrinks, the cost of emission reduction falls and so does the marginal cost, i.e., the price of emission permits.
California is part of the *Western Climate Initiative* together with British Columbia, Manitoba, Ontario and Quebec. Quebec created a greenhouse gas emission permit market in 2013 with much the same design and regulations as the Californian market, and the two markets were linked in 2014. Ontario is set to follow in 2018. This illustrates international trade in government licences is feasible, also between subnational jurisdictions, provided that all governments involved want to make this happen and regulations are mutually compatible.

4.5 Second-best regulation***

Above, we derive the first-order condition for cost-effectiveness: Abatement costs should be equated across polluters at the margin. This condition in fact only holds if there are no distortions in the market before regulation to reduce greenhouse gases. If there is market power, or pre-existing regulation, or any other market imperfection, then the carbon tax, say, should be not be uniform, but rather correct for how the carbon tax increases market power, interacts with other regulation, or affects any other market imperfection. If the carbon tax is not corrected, then regulation is said to be *second-best*—as opposed to *first-best*.

4.5.1 The cost of suboptimal regulation

However, regulation can also be second-best because it is ill-designed. There may be exemptions to a carbon tax, or subsidies may be differentiated between different segments of the market. Using the equations above, the effect of this kind of second-best regulation can readily be assessed. Equation (4.4) has that marginal abatement costs should be equal. Assuming the quadratic abatement cost function of Equation (4.1), we have that

$$2\beta_n R_n = \lambda = 0 \forall n \Leftrightarrow R_n^* = \frac{\lambda}{2\beta_n} \forall n \tag{4.9}$$

so that the costs of emission reduction equal

$$B_n^* = \beta_n {R_n^*}^2 = \beta_n \left(\frac{\lambda}{2\beta_n}\right)^2 \forall n \tag{4.10}$$

Because B_n^* are the costs in the cost-effective solution, any other allocation of the emission reduction effort R_n has to lead to a higher total cost—this follows trivially from Joseph Louis Lagrange's work on the calculus of variations.

With the functional forms chosen, we can readily illustrate this for two polluters. Assume that polluter 1 does d more, and polluter 2 does d less:

$$B_1^{**} = \beta_1 \left(\frac{\lambda}{2\beta_1} + d\right)^2 ; B_2^{**} = \beta_2 \left(\frac{\lambda}{2\beta_2} - d\right)^2 \tag{4.11}$$

Total emission reduction stays the same. The cost increase for polluter 1 is

$$\Delta B_1 = B_1^{**} - B_1^* = \beta_1 \left(\frac{2\lambda d}{2\beta_1} + d^2\right) = \lambda d + \beta_1 d^2 \tag{4.12}$$

That is, the cost increase equals the square of the deviation from the optimum plus twice the cross-product of the deviation and the costs in the optimum.

For polluter 2, costs change by

$$\Delta B_2 = B_2^{**} + B_2^* = \beta_2 \left(-\frac{2\lambda d}{2\beta_2} + d^2\right) = -\lambda d + \beta_2 d^2 \tag{4.13}$$

The cost fall equals the squared deviation *minus* the cross-product. In other words, the costs for polluter 1 increase faster than the costs for polluter 2 fall.

The total cost increase therefore equals

$$\Delta B = \Delta B_1 + \Delta B_2 = \lambda d + \beta_1 d^2 + \lambda d - \beta_2 d^2 = (\beta_1 + \beta_2) d^2 \tag{4.14}$$

In words, the total costs of emission reduction increase with the square of the deviation from the first-best emission reduction allocation.

4.5.2 The Pigou tax under monopoly

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

$$q = \bar{\pi} - \pi \Leftrightarrow \pi = \bar{\pi} - q \tag{4.15}$$

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

$$\Pi = \pi q - 0.5q^2 - \tau q \tag{4.16}$$

where τ is a tax on production. A price-taker would maximize (4.16) assuming that p is constant:

$$\frac{\partial \Pi}{\partial q} = \pi - q - \tau = 0 \Rightarrow q = \pi - \tau \tag{4.17}$$

Equating supply (4.17) and demand (4.15), we find that

$$\bar{\pi} - \pi = \pi - \tau \Leftrightarrow \pi = \frac{\bar{\pi} + \tau}{2} \Rightarrow q = \frac{\bar{\pi} - \tau}{2} \tag{4.18}$$

A monopolist would maximize (4.16) assuming that π varies with q

$$\frac{\partial \Pi}{\partial q} = \bar{\pi} - 2q - q - \tau = 0 \Rightarrow q = \frac{\bar{\pi} - \tau}{3} \tag{4.19}$$

Comparing (4.18) to (4.19) 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:

$$\begin{aligned} W = \int_0^q (\bar{\pi} - x)\mathrm{d}x - \pi q + \pi q - 0.5q^2 - \tau q + \tau q - \psi q = \\ -0.5(\bar{\pi} - x)^2|_0^q - 0.5q^2 - \psi q = \bar{\pi} q - 0.5q^2 - 0.5q^2 - \psi q = \\ (\bar{\pi} - \psi)q - q^2 \end{aligned} \tag{4.20}$$

where ψ measures the damage done, at the margin, by the externality.

Maximizing total welfare (4.20) we find optimal consumption

$$q = \frac{\bar{\pi} - \psi}{2} \tag{4.21}$$

A comparison to (4.18) immediately reveals that the optimal tax $\tau = \psi$. That is, the Pigou tax equals the marginal damage.

However, equating (4.21) to (4.19) 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.[3] 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.[4]

[3]A single policy instrument cannot typically solved 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.

[4]There would be a third factor for a non-linear benefit function: There is less pollution in a monopoly.

4.5.3 Regulatory capture

Above, we maximize total welfare, consumer surplus plus profit minus external cost. The social planner is not beholden to lobbyists or special interests. This can readily be changed in a Peltmanesque model of regulatory capture, where the social planner puts undue weight $\vartheta > 0$ on the interests of producers.

Total welfare is then:

$$W = \bar{\pi}q - 0.5q^2 - \pi q + (1+\vartheta)(\pi q - 0.5q^2 - \tau q) + \tau q - \psi q \tag{4.22}$$

Note that the transfers πq and τq do not cancel, as these are transfers to and from a priviliged party. This complicates the analysis.

Substituting the demand (4.15) and supply (4.17) equations, we obtain indirect welfare

$$V = 0.5(\bar{\pi} - \pi)^2 + 0.5(1+\vartheta)(\pi - \tau)^2 + \tau(\pi + \psi) - \tau^2 - \psi\pi \tag{4.23}$$

Finding the optimal tax rate then requires

$$\frac{\partial V}{\partial \tau} = -(1+\vartheta)(\pi - \tau) + (\pi + \psi) - 2\tau = 0 \Rightarrow \tau = \frac{\psi - \vartheta\pi}{1 - \vartheta} \tag{4.24}$$

This reduces to $\tau = \psi$ for $\vartheta = 0$.

Imposing the market clearing condition (4.15) = (4.17), we find

$$\pi = \frac{1-\vartheta}{2-\vartheta}\bar{\pi} - \frac{\psi}{2-\vartheta} \tag{4.25}$$

and

$$\tau = \frac{\psi}{1-\vartheta}\frac{2-2\vartheta}{2-\vartheta} - \frac{\vartheta}{2-\vartheta}\bar{\pi} \tag{4.26}$$

which again reduces to $\tau = \psi$ for $\vartheta = 0$.

In a way, this is a trivial result. A social planner who does not maximize social welfare, does not impose a Pigou tax. This is not a route into normative analysis. But Equation (4.24) is a route into positive analysis: Environmental taxes that deviate from the Pigou tax can be interpreted as an undue weight given to special interests, or as the degree to which the regulator has been captured by industry. We do not know the Pigou tax, of course, but we do observe that different industries, and different companies within the same industry, face different regulations—often as the result of successful special pleading.

4.5.4 Prior tax distortions

The analysis of optimal environmental taxation with prior tax distortions is more complicated.

The first-best

Let us consider an economy with $i = 1, 2, ..., N$ identical agents and 2 goods, a clean one q_c^i and a dirty one q_d^i. Assume that the production of the dirty good causes emissions $M = \sum_i q_d^i = Nq_d^i$, which reduce utility. The utility function of agent i is

$$U^i = U(1 - S^i, q_c^i, q_d^i, M) \tag{4.27}$$

where $1 - S^i$ is the leisure enjoyed by agent i and S^i is her labour supply.

To keep things simple, let's assume there is one factor of production, labour, and a linear production function. Then

$$\chi_c \sum_i q_c^i + \chi_d \sum_i q_d^i = \sum_i S^i \tag{4.28}$$

As individuals are all the same, we can drop the superscripts and simplify the macro-economic budget constraint to

$$\chi_c N q_c + \chi_d N q_d = NS \Leftrightarrow \chi_c q_c + \chi_d q_d = S \tag{4.29}$$

Construct the Lagrangian

$$\mathcal{L} = NU(1-S, q_c, q_d, M) - \lambda \left(\chi_c N q_c + \chi_d N q_d - NS\right) \tag{4.30}$$

The first-order conditions are

$$\frac{\partial \mathcal{L}}{\partial S} = -N\frac{\partial U}{\partial S} + N\lambda = 0 \Rightarrow U_S = \lambda \tag{4.31}$$

That is, the marginal cost of labour, or the marginal value of leisure, equals the shadow price of total expenditure, since labour is the only factor of production.

$$\frac{\partial \mathcal{L}}{\partial q_c} = N\frac{\partial U}{\partial q_c} - N\lambda\chi_c = 0 \Rightarrow \frac{U_{q_c}}{U_S} = \chi_c \tag{4.32}$$

That is, the marginal value of consumption equals marginal productivity.

$$\frac{\partial \mathcal{L}}{\partial q_d} = N\frac{\partial U}{\partial q_d} + N^2\frac{\partial U}{\partial M} - N\lambda\chi_d = 0 \Rightarrow \frac{U_{q_d}}{U_S}\left(1 + N\frac{U_M}{U_{q_d}}\right) = \chi_d \tag{4.33}$$

That is, the marginal value of consumption needs to corrected for the marginal value of the externality.

Now let us introduce producer prices $w = 1$, π_c and π_d and taxes $\tau_w = 0$, τ_c and τ_d, so that the consumer prices are $w = 1$, $(1+\tau_c)\pi_c$ and $(1+\tau_d)\pi_d$. The consumer's budget constraint is then

$$(1+\tau_c)\pi_c q_c + (1+\tau_d)\pi_d q_d = S + Q \tag{4.34}$$

where Q is an income transfer from the government, which is independent of consumer behaviour.

If N is large, then $\partial M/\partial q_d \approx 0$ so that the first-order conditions for the consumer are

$$\frac{U_{q_j}}{U_S} = (1+\tau_j)\pi_j \text{ for } j = c, d \tag{4.35}$$

Profit maximization by competitive firms implies that producer prices equal marginal costs $\pi_j = \chi_j$. That is, in a competitive equilibrium, both consumers and producers ignore the externality.

The government does not, however. Comparing Equation (4.35) to (4.32) and (4.33), we find that $\tau_c = 0$ and

$$\tau_d = -N\frac{U_M}{U_{q_d}} \tag{4.36}$$

That is, the social planner imposes a tax if the externality is negative $U_M < 0$ and a subsidy if the externality is positive $U_M > 0$, just as Pigou proposed.

The second-best

The indirect utility function is the utility from the agents' best response

$$V(\tau) = U(S(\tau), q_c(\tau), q_d(\tau), M(\tau)) \tag{4.37}$$

The first partial derivative to the product taxes are

$$\frac{\partial V}{\partial \tau_j} = -U_S \frac{\partial S}{\partial \tau_j} + U_{q_c} \frac{\partial q_c}{\partial \tau_j} + U_{q_d} \frac{\partial q_d}{\partial \tau_j} + NU_M \frac{\partial q_d}{\partial \tau_j} \tag{4.38}$$

We know from Equation (4.31) that $U_S = \lambda$ and from Equation (4.35) that $U_{q_j} = U_S(1+\tau_j)\pi_j$, so that

$$\frac{\partial V}{\partial \tau_j} = -\lambda \frac{\partial S}{\partial \tau_j} + \lambda(1+\tau_c)\pi_c \frac{\partial q_c}{\partial \tau_j} + \lambda(1+\tau_d)\pi_d \frac{\partial q_d}{\partial \tau_j} + NU_M \frac{\partial q_d}{\partial \tau_j} \tag{4.39}$$

Taking the first derivative of Equation (4.34), we find that

$$\frac{\partial S}{\partial \tau_j} = (1+\tau_c)\pi_c \frac{\partial q_c}{\partial \tau_j} + (1+\tau_d)\pi_d \frac{\partial q_d}{\partial \tau_j} + \pi_j q_j \tag{4.40}$$

Substitution gives

$$\frac{\partial V}{\partial \tau_j} = -\lambda \pi_j q_j + NU_M \frac{\partial q_d}{\partial \tau_j} \text{ for } j = c, d \tag{4.41}$$

We are now ready to study product taxation in the second-best.

The fiscal market imperfection is the simplest possible. There is a certain amount of money needed to run the government. This does not create utility or disutility. It does not create jobs. There simply is a hole in the economy. The social planner's budget constraint is then

$$N\tau_c q_c + N\tau_d q_d = Q_G \tag{4.42}$$

Form the Lagrangian

$$\mathcal{L} = NV(\tau) - \kappa(N\tau_c q_c + N\tau_d q_d - Q_G) \tag{4.43}$$

to find the first-order conditions

$$\frac{\partial \mathcal{L}}{\partial \tau_c} = -\lambda \pi_c q_c + NU_M \frac{\partial q_d}{\partial \tau_c} - \kappa \left(\tau_c \frac{\partial q_c}{\partial \tau_c} + \tau_d \frac{\partial q_d}{\partial \tau_c} + q_c \right) = 0 \tag{4.44}$$

and

$$\frac{\partial \mathcal{L}}{\partial \tau_d} = -\lambda \pi_d q_d + NU_M \frac{\partial q_d}{\partial \tau_d} - \kappa \left(\tau_c \frac{\partial q_c}{\partial \tau_d} + \tau_d \frac{\partial q_d}{\partial \tau_d} + q_d \right) = 0 \tag{4.45}$$

This is a system of two equations in two unknown, but there is no general solution. However, we can find an implicit solution in τ_j:

$$\tau_c = \frac{\left(NU_M \frac{\partial q_d}{\partial \tau_d} - (\lambda\pi_d + \kappa)q_d\right) \kappa \frac{\partial q_d}{\partial \tau_c} - \left(NU_M \frac{\partial q_d}{\partial \tau_c} - (\lambda\pi_c + \kappa)q_c\right) \kappa \frac{\partial q_d}{\partial \tau_d}}{\kappa^2 \left(\frac{\partial q_d}{\partial \tau_d} \frac{\partial q_c}{\partial \tau_c} - \frac{\partial q_d}{\partial \tau_c} \frac{\partial q_c}{\partial \tau_d} \right)} \tag{4.46}$$

and

$$\tau_d = \frac{\left(NU_M \frac{\partial q_d}{\partial \tau_c} - (\lambda\pi_c + \kappa)q_c\right) \kappa \frac{\partial q_c}{\partial \tau_d} - \left(NU_M \frac{\partial q_d}{\partial \tau_d} - (\lambda\pi_d + \kappa)q_d\right) \kappa \frac{\partial q_c}{\partial \tau_c}}{\kappa^2 \left(\frac{\partial q_d}{\partial \tau_d} \frac{\partial q_c}{\partial \tau_c} - \frac{\partial q_d}{\partial \tau_c} \frac{\partial q_c}{\partial \tau_d} \right)} \tag{4.47}$$

This simplifies to

$$\tau_c = \frac{(\lambda\pi_d + \kappa)q_d\frac{\partial q_d}{\partial \tau_c} - (\lambda\pi_c + \kappa)q_c\frac{\partial q_d}{\partial \tau_d}}{\kappa\left(\frac{\partial q_d}{\partial \tau_d}\frac{\partial q_c}{\partial \tau_c} - \frac{\partial q_d}{\partial \tau_c}\frac{\partial q_c}{\partial \tau_d}\right)} \tag{4.48}$$

Note that, even though q_c can be substitute for or complement of q_d, that is $\partial q_c/\partial \tau_d \neq 0$, the clean good should not be taxed for the externality caused by the dirty good. Furthermore,

$$\tau_d = \frac{(\lambda\pi_c + \kappa)q_c\frac{\partial q_c}{\partial \tau_d} - (\lambda\pi_d + \kappa)q_d\frac{\partial q_c}{\partial \tau_c}}{\kappa\left(\frac{\partial q_d}{\partial \tau_d}\frac{\partial q_c}{\partial \tau_c} - \frac{\partial q_d}{\partial \tau_c}\frac{\partial q_c}{\partial \tau_d}\right)} - \frac{U_{q_d}}{\kappa}N\frac{U_M}{U_{q_d}} \tag{4.49}$$

The first part of Equation (4.49) is just like Equation (4.48): A tax needs to be raised on products to cover the costs of government and the two goods are treated in exactly the same way.

The second part of Equation (4.49) is different from Equation (4.36): Instead of increasing the tax on the dirty good by its marginal damage, as you would do in the first-best, in the second-best the Pigou tax is multiplied by the ratio of the marginal value of the dirty good to the marginal value of the public budget. The optimal tax in the first-best is not the same as the optimal tax in the second-best. The Pigou tax should be corrected for prior tax distortions.

Box 4.3: Emissions trade in practice: China

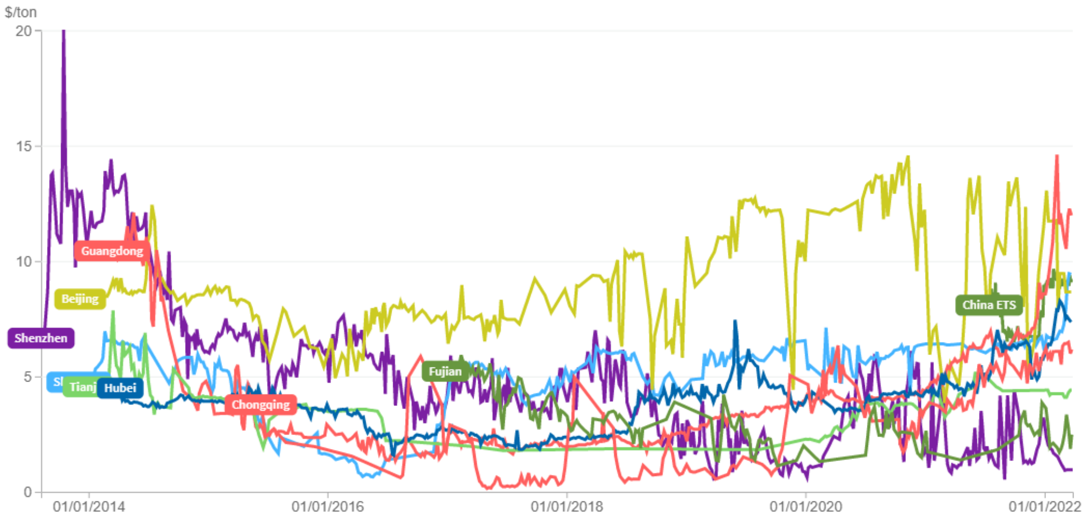
China has trialed emissions trading from 2011 on in the provinces of Guangdong and Hubei, and the cities of Beijing, Tianjin, Shanghai, Chongqing and Shenzhen. Together, the seven pilot schemes cover about a third of all carbon dioxide emissions from China. The pilots are deliberately different so as to maximize learning. Since August 2021, there is also a national market, but Figure 4.1 shows that prices have yet to converge.

A number of issues have emerged. First, China does not have a cap on emissions. If there were a cap on emissions, the number of emission permits would have followed trivially. Instead, China has a target for the emission intensity of the economy. The number of permits follows once GDP is known, but statistics on energy use and hence emissions typically become available before statistics on economic activity. The pilot schemes therefore tried absolute targets by economic sectors, combined emission intensity targets with *projected* GDP, or a mix of these two approaches.

The pilot schemes cover the *direct* emissions from fossil fuel burned within the seven jurisdictions, plus the *indirect* emissions from electricity generated anywhere in China if that electricity is used within the covered jurisdiction. This is essentially a border tax adjustment for power trade, noting that the border is not an international one. This complicates target setting.

The third issue is that energy markets in China are heavily regulated, if not owned and planned outright by city and provincial governments. Permit trade works by appealing to the animal spirits of private operators seeking profit. In China, electricity companies in particular operate by bureaucratic mandate. This makes it hard, if not impossible, to adjust their operations to reflect the price of carbon. Similarly, retail prices are typically regulated, if not set by the local governments—and it is thus not possible to pass the costs of carbon onto the final users so as to induce them to save energy.

Monitoring and enforcement are perhaps the biggest issues. Statistics of energy use and greenhouse emissions show large discrepancies in China. Different estimates can easily deviate by 30% or more. Companies are supposed to match their emissions to their permits, but this is difficult if emissions are not known with precision. Enforcement is more problematic still. China has an ambivalent attitude towards private property—and emission permits are private property—and its legal system has had many problems adjudicating and enforcing property rights. In the pilot programmes, regulators frequently punished non-compliant emitters by imposing or strengthening unrelated regulations, or rewarded compliant emitters with handouts from unrelated subsidy schemes. While this is a workaround to incentivize compliance in the emission permit market, it undermines the unrelated regulations so used.



Source: ICAP Allowance Price Explorer.

Figure 4.1: The price of greenhouse gas emission permits in China

4.6 Dynamic efficiency****

Section 4.4 derives the condition for static efficiency: A uniform carbon price. The costs of emission reduction are at its lowest if every emitter faces the same abatement costs at the margin. The Baumol condition follows from a cost-minimization problem, and the realization that the constraint is on *total* emissions, rather than the emissions from an individual household or company, and that its shadow-price is therefore equal for all. You could also see this as an arbitrage condition: If one company can reduce its emissions for \$90/tCO_2 and another company for \$110/tCO_2, then surely it would be mutually advantageous to have the former company reduce harder and the latter company less hard.

This arbitrage principle also works over time. If it costs \$100/tCO_2 this year to reduce emissions and \$100/tCO_2 next year, then it would be cheaper not to reduce emissions by that much this year, put the money in the bank, and work harder next year. Arbitrage suggests that the carbon price should rise at the rate of interest. It is not quite as simple as the dynamics of carbon cycle and climate also play a role. Below, we derive the conditions for dynamic efficiency under two or three alternative problem definitions.

4.6.1 Emission reduction as an *efficiency* problem

Climate policy can be looked at as an efficiency problem. Emissions add to concentrations. Welfare depends on the concentration of greenhouse gases in the atmosphere. Cutting emissions affects output. The problem can be formalized as follows. Let us maximize net present welfare:

$$\max_{C(t),M(t)} W = \int_t U(C(t), L(t))e^{-\rho t}\,\mathrm{d}t \tag{4.50}$$

where W is net present welfare, U is instantaneous utility, C is consumption, L is the atmospheric concentration of carbon dioxide, Y is economic output, K is capital, and M is emissions, subject to

$$\dot{K} = Y(t) - C(t) = Y(K(t), M(t)) - C(t) \tag{4.51}$$

and

$$\dot{L} = -\delta L(t) + M(t) \tag{4.52}$$

The current-value Hamiltonian is

$$\mathcal{H} = U(C(t)) + \kappa\dot{K} + \lambda\dot{L} = U(C(t), L(t)) + \kappa(Y(K(t), M(t)) - C(t)) + \lambda(M(t) - \delta L(t)) \tag{4.53}$$

The first-order conditions are

$$\frac{\partial \mathcal{H}}{\partial C} = \frac{\partial U}{\partial C} - \kappa = 0 \Rightarrow U_C = \kappa \tag{4.54}$$

$$\frac{\partial \mathcal{H}}{\partial M} = \kappa\frac{\partial Y}{\partial M} + \lambda = 0 \Rightarrow Y_M = -\frac{\lambda}{\kappa} \tag{4.55}$$

$$\dot{\kappa} = \rho\kappa - \frac{\partial \mathcal{H}}{\partial K} = \rho\kappa - \kappa\frac{\partial Y}{\partial K} \Rightarrow \frac{\dot{\kappa}}{\kappa} = \rho - Y_K \tag{4.56}$$

$$\dot{\lambda} = \rho\lambda - \frac{\partial \mathcal{H}}{\partial L} = \rho\lambda - \frac{\partial U}{\partial L} + \lambda\delta \Rightarrow \frac{\dot{\lambda}}{\lambda} = \rho + \delta - \frac{U_L}{\lambda} \tag{4.57}$$

That is, marginal utility U_C equals the shadow price of capital κ, or the return on savings equals the return on investment; see Equation (4.54). The marginal cost of emission reduction Y_M (in money) equals the shadow price of the atmospheric concentration λ (in utils, normalized by marginal utility $\kappa = U_C$ to convert to money); see Equation (4.55). The growth rate of the shadow price of capital is the difference between the pure rate of time preference ρ and the return to capital Y_K; see Equation (4.56).

> The price of carbon should rise with the interest rate plus the rate of atmospheric decay minus the rate of climate deterioration if net present welfare is maximized.

The growth rate of carbon tax, the shadow price of the atmospheric carbon dioxide concentration λ, is the discount rate ρ plus the rate of atmospheric degradation δ, minus the marginal damage of climate change U_L over the shadow price; see Equation (4.57). The marginal damage is given in utils per concentration; the shadow price too is in utils per concentration; the final term on the right-hand side of Equation (4.55) is therefore unitless like ρ and δ. This term measures the rate of change of the severity of climate change—it is the ratio of the marginal increase in the damages of climate change over the marginal value of those damages. Taken together, the shadow price of emissions is higher if we care less about the future (ρ), if the future is less problematic because emissions are dissipated (δ), and if the marginal welfare impacts are lower (U_C). That is, the carbon tax should grow at the discount rate plus the rate of depletion of carbon dioxide from the atmosphere minus the rate of deterioration of climate change. The intuition behind the *subtraction* is this: If the damages of climate change are getting worse, then you should not postpone the taxation of greenhouse gas emissions. The carbon tax should start high, but not grow that rapidly.

4.6.2 Emission reduction as a *cost-effectiveness* problem

Climate policy can also be looked at as a cost-effectiveness problem. Emissions add to concentrations. There is an agreed upper limit on the concentration of greenhouse gases in the atmosphere. This can be formalized as zero damages below the threshold, and arbitrarily high damages above. Cutting emissions affects output. The problem can then be formalized as follows. We still want to maximize net present welfare as specified by (4.50) but now specify

$$\begin{array}{ccc} U = U(C) \Rightarrow \frac{\partial U}{\partial L} = 0 & & L \leq \overline{L} \\ & \text{for} & \\ U = \underline{U} & & L > \overline{L} \end{array} \tag{4.58}$$

subject to (4.51) and (4.52).

> The price of carbon should rise with the interest rate plus the rate of atmospheric decay if there is a constraint on the concentration of CO_2.

The current-value Hamiltonian is (4.53). The first-order conditions are (4.54), (4.55), (4.56) and

$$\dot{\lambda} = \rho\lambda - \frac{\partial \mathcal{H}}{\partial L} = \rho\lambda + \lambda\delta \Rightarrow \frac{\dot{\lambda}}{\lambda} = \rho + \delta \text{ for } L \leq \overline{L} \tag{4.59}$$

That is, marginal utility equals the shadow price of capital or the return on savings (as above). The marginal cost of emission reduction (in money) equals the shadow price of the atmospheric concentration (as above). The growth rate of the shadow price of capital is the difference between the pure rate of time preference and the return to capital (as above). The growth rate of the carbon tax, the shadow price of the atmospheric concentration, is the discount rate plus the rate of atmospheric degradation—*without* the marginal damage of climate change.

Climate policy can be looked at as a waste disposal or a resource problem. Equation (4.58) puts a cap on the concentration of carbon dioxide in the atmosphere, and thus a cap on accumulated emissions. You can interpret this as some finite disposal capacity, with every emission degrading some of that capacity. The result is the same: The carbon price should rise with the discount rate plus the rate at which carbon dioxide degrades from the atmosphere, because that is the rate at which disposal capacity is added.

4.6.3 Summary

Comparing the above results, the following insights emerge. If we impose a constraint on concentrations, then the carbon price should rise at the rate of discount plus the rate of CO_2 removal from the atmosphere (until the target is met). If we view greenhouse gas emissions as a waste disposal or a resource problem, with a fixed capacity, the same result emerges. However, if we seek to maximize welfare, the carbon price should rise at the rate of discount plus the rate of atmospheric removal but minus the rate at which the climate problem gets worse. Cost-benefit analysis thus calls for a slower increase in the price or carbon than cost-effectiveness analysis.

4.7 Environmental effectiveness*

Besides cost-effectiveness, environmental effectiveness is the other main criterion for environmental policy. A policy intervention is useless unless it reduces emissions by at least roughly the desired amount. Tradable emission permits, if monitored and enforced, guarantee environmental effectiveness, as there is a cap on total emissions. Taxes and subsidies have no such guarantee. Unless the regulator knows the marginal abatement cost curve of each emitter, the regulator cannot accurately predict how companies and households will respond to either a tax or a subsidy. The regulator therefore does not know by how much emissions will be reduced.

Direct regulation covers many different policy interventions, some of which have relatively certain environmental results. An emission cap per installation is an example, although more installations may be built. Sometimes, emission caps only hold for installations above a threshold size, and companies may opt for more, smaller installations in response.

If direct regulation targets inputs or technologies, behavioural change may partly defy the environmental goals. Improved energy efficiency, for instance, lowers the effective price of energy services and may lead to increased energy use rather than reduced emissions—the so-called rebound effect first discussed by W.S. Jevons in 1865. For instance, building insulation may lead to warmer homes rather than lower energy use.

4.8 Taxes versus tradable permits under uncertainty**

With permit trade, emissions are known but costs are not. With taxes, marginal costs are known but emissions are not.

We have seen above that tradable permits lead to a certain environmental outcome, but the permit price and hence the costs of abatement are unpredictable. Vice versa, the marginal cost of abatement is known for an emission tax and this puts an upper bound on the total costs of abatement. However, the effect on the environment is uncertain. The *Weitzman Theorem* provides guidance which is worse.

Figure 4.2 shows a standard benefit–cost analysis. The marginal costs of abatement rise as emissions are cut further. The marginal benefits of abatement fall with emission reduction. The optimal tax is set where the marginal cost curve crosses the marginal benefit curve. The optimal emission target is set at the same point.

Now suppose that the government believes that emission reduction is more expensive than it really is. If the government uses a quantity instrument, it underregulates: The emissions target is higher than it should be, because the regulator believes that the costs are higher than they are. However, if the government uses a price instrument, it overregulates: The emissions tax is higher than it should be because the regulator believes that the efficacy is lower than it is.

Figure 4.2 shows the associated welfare losses. The underregulation with a quantity instrument leads to a welfare loss for the environment and a welfare gain for the emitter; the latter is larger than the former. The net welfare loss is denoted in blue. The overregulation with a price instrument leads to a welfare loss for the emitter and a welfare gain for the environment; the latter is larger than the former. The net welfare loss is denoted in pink.

In Figure 4.2 the net welfare loss due to overregulation exactly equals the net welfare loss due to underregulation. (The distributional effects are, of course, different.) This is by construction. Figure 4.3 repeats the exercise, but with a steeper marginal benefit curve. The net welfare loss of underregulation falls, and the net welfare loss of overregulation rises. Figure 4.4 repeats

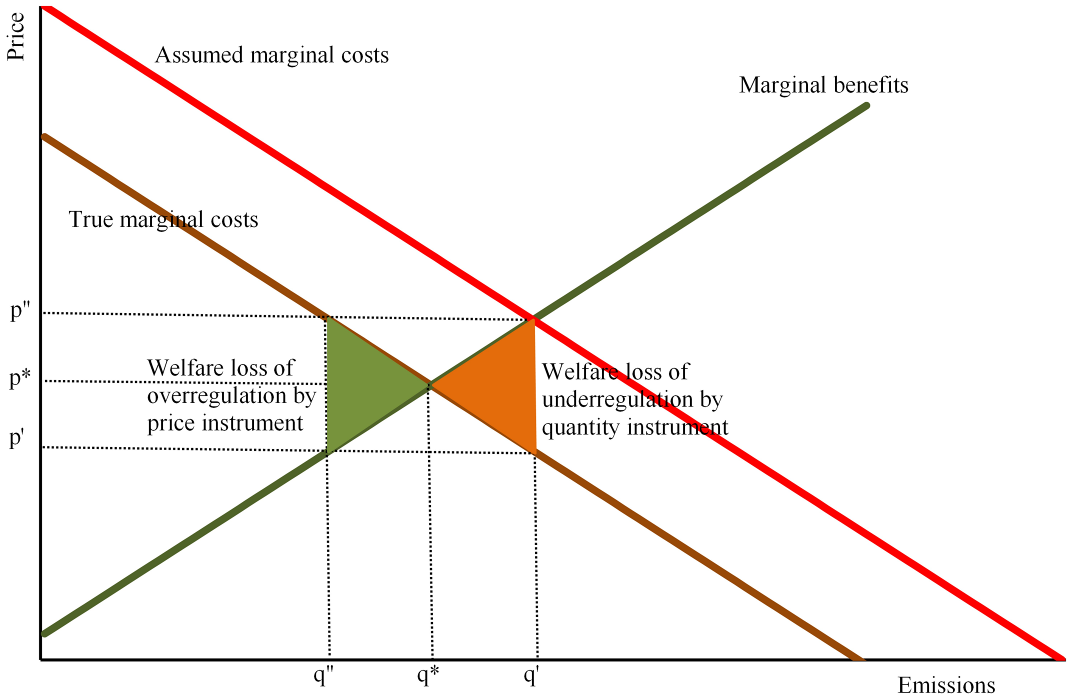


Figure 4.2: Welfare losses for price and quantity instruments if the regulator assumes abatement costs that are too high

the exercise once more, but with a shallower marginal benefit curve. The net welfare loss of underregulation rises, and the net welfare loss of overregulation falls.

> (Mistakes with) annual national emissions do not matter much for a global stock pollutant. Emission certainty is worth little.

Figures 4.2, 4.3 and 4.4 illustrate one particular case, but the insight is much more general. If the marginal benefit cost curve is steeper (less steep) than the marginal abatement cost curve, then mistakes with quantity (price) instruments are less costly than mistakes with price (quantity) instruments. This is the Weitzman Theorem.

> Cost certainty is worth a lot. Therefore, taxes are better suited for climate policy than tradable permits.

Climate change is driven by the stock of emissions. That implies that the marginal impacts of climate change do not change much if emissions are reduced or increased by a little. The effect of a change in emissions is dampened by the stock of emissions. In other words, the benefit cost curve is shallow. The marginal costs of emission reduction do, however, vary with emissions. Therefore, for a stock problem like climate change, mistakes with a price instrument (tax) are less costly than mistakes with a quantity instrument (tradable permits). In other words, mistakes with the quantity of emissions do not matter much. After all, climate change is driven by global emissions, accumulated over decades and centuries. Mistakes with the price of emissions do matter, as the costs of emission reduction directly affects people and companies. The regulator should therefore levy a carbon tax, rather than create a market for emission permits.

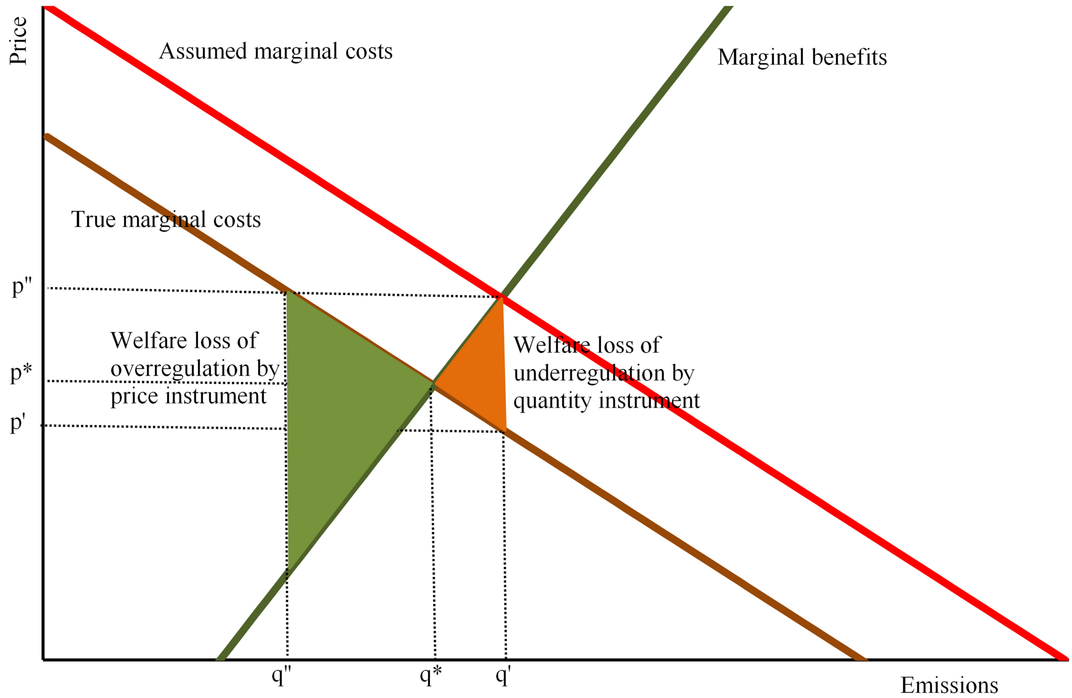


Figure 4.3: Welfare losses for price and quantity instruments if the regulator assumes abatement costs that are too high and the marginal benefit curve is steeper than the marginal cost curve

The Weitzman Theorem fell on deaf ears. International tax harmonization is a political non-starter, even in the otherwise tightly integrated European Union. New taxes are anyway toxic in some jurisdictions. Tradable permits therefore play a substantial role in actual and planned climate policy around the world.

4.9 Initial allocation of permits**

With tradable permits, as described above, the regulator sets an overall cap on emissions. The overall emissions cap is then split into units and each emitter receives a certain amount of permits to emit. If a company finds that it has too few permits, it may buy additional permits from a company that has too many. But how does the government get the newly created permits to the appropriate emitters?

> There are various ways to allocate permits: auction, equal per capita, to the polluters, to the victims of pollution.

There are many ways in which the initial allocation of emission permits can be implemented. I discuss the four basic ones.

Grandparenting (sometimes called grandfathering) of permits is by far the most popular choice. Permits are allocated, for free, on the basis of emissions in the recent past.[5] This method is popular because it confirms the status quo. Large emitters are faced with a new regulation,

[5]That is, gifts are given with an eye to the past, just like grandfathers do. This explains the original name, still in use, although grandmothers are much like grandfathers in this regard.

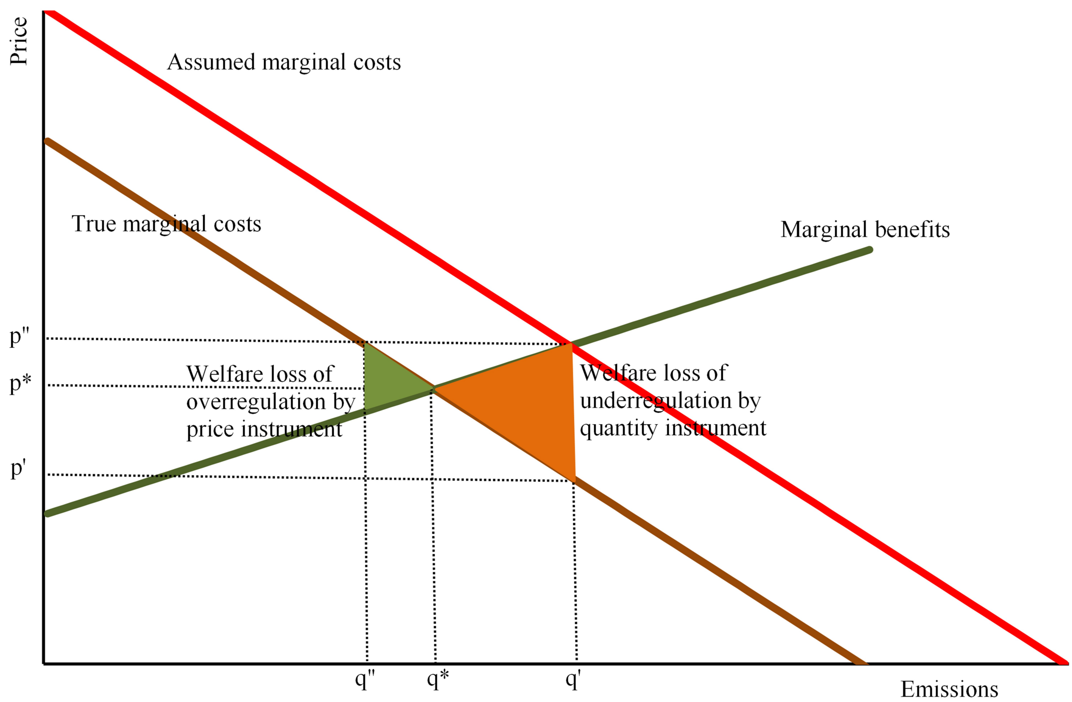


Figure 4.4: Welfare losses for price and quantity instruments if the regulator assumes abatement costs that are too high and the marginal benefit curve is shallower than the marginal cost curve

but get a large amount of free permits in return. No money changes hands. Grandparenting is also unfair. Bad behaviour (large emissions) in the past is rewarded with a large allocation, while good behaviour (low emissions) is punished. Fast-growing companies are disadvantaged relative to slow-growing companies.

> The initial allocation of permits provides opportunities for politicians to hand out favours.

In 2012, the aviation industry became part of the EU ETS. Emission permits were grandparented based on the actual emissions, per airline, in 2005. The two big discount airlines, easyJet and Ryanair, grew rapidly between 2005 and 2012, whereas the three big incumbents, British Airways, Lufthansa, and Air France, grew more slowly. The two discounters fly newer, more fuel-efficient planes. They also have a higher load factor, that is, they pack more people in a plane. They fly point-to-point, avoiding energy-intensive take-offs and landings, and avoid congested airports. Per passenger kilometre, on the same route, the discounters thus emit less carbon dioxide than the incumbent airlines. Nonetheless, the initial allocation of permits is relatively generous towards the incumbents, and will thus lead to a transfer of wealth from the discounters to the incumbents. The formerly state-owned incumbents, of course, have a much closer relationship to the regulator.

Greenhouse gas emissions are externalities: unintended and uncompensated consequences of economic activity. The welfare loss of an externality follows from the fact that it is uncompensated. An alternative way to allocate emission permits is thus to give them to the victims. This would help to restore efficiency (see Sections 4.1 and 4.6.1) and it adheres to a basic notion of fairness: If you want to emit carbon dioxide, you would have the buy the right to do so from someone who would be hurt by your act. It would be complicated to allocate emission permits in this manner. Victims would need to be identified and their relative damage estimated. Most of the victims of climate change are yet to be born, so their likely ancestors will need to be found. This allocation is also politically impractical. The majority of victims live in poor countries, while emissions are concentrated in rich countries. A large transfer of wealth would be the result. Some argue that this is desirable anyway, but politically it is a non-starter.

Alternatively, emission permits may be allocated on a per capita basis. This corresponds to a basic notion of fairness: Everyone is treated the same. At a deeper level, it may not be fair at all. People in colder countries need more energy, and they live there because of choices their ancestors made, not knowing about climate change and climate policy. Disabled people often need more energy too. A per capita allocation of emission permits has a basis in international law too: The atmosphere is the common property of humankind. In this view, the government has committed an injustice by grandparenting permits. It expropriated us, the people, and gave what is rightfully ours to private companies. A per capita allocation is unrealistic, however, because it would imply a large transfer of wealth.

One of the main issues with any free allocation of emission permits is that the market starts without a price. In the beginning, no one quite knows what permits are worth. The market is thin and erratic as a result. Therefore, as a fourth alternative way to initially allocate emission permits, an auction may be organized. Permits are sold to the highest bidder. Traders know the price. The regulator gains a substantial amount of revenue that it can use to lower taxes, to compensate victims, or to put in the president's bank account. In a distributional sense, auctioned permits are equivalent to taxes.

In practice, regulators often opt for a mix of grandparenting and auctioning. This does not upset the status quo so much, has an initial price signal, and new entrants to the market can purchase permits.

4.10 Initial and final allocation of permits*

Figure 4.5 depicts a barter trade between two people. One agent benefits from a polluting activity, and the other suffers from pollution. A social planner would set the level of pollution where the marginal benefits of the polluting activity equal the marginal costs of pollution.

> The willingness to pay to pollute equals the willingness to accept compensation for not polluting.

Alternatively, the regulator may allocate explicit property rights to either party and organize a market. Suppose that the pollutee has the right to a pristine environment. The polluter then has to compensate the pollutee. As long as the marginal benefit of the polluting activity is greater than the marginal loss, the two parties should be able to strike a mutually advantageous deal. It is in both parties' best interest to agree on that level of pollution where the marginal costs equal the marginal benefits. This is illustrated in Figure 4.6.

> The willingness to accept compensation for pollution equals the willingness to pay for reduced pollution.

Now suppose that the polluter has the right to pollute. The pollutee then has to compensate the polluter for emission reduction. As long as the marginal loss of reducing the polluting activity is greater than the marginal benefit of reduced pollution, the two parties should be able to strike a mutually advantageous deal. It is in both parties' best interest to agree on that

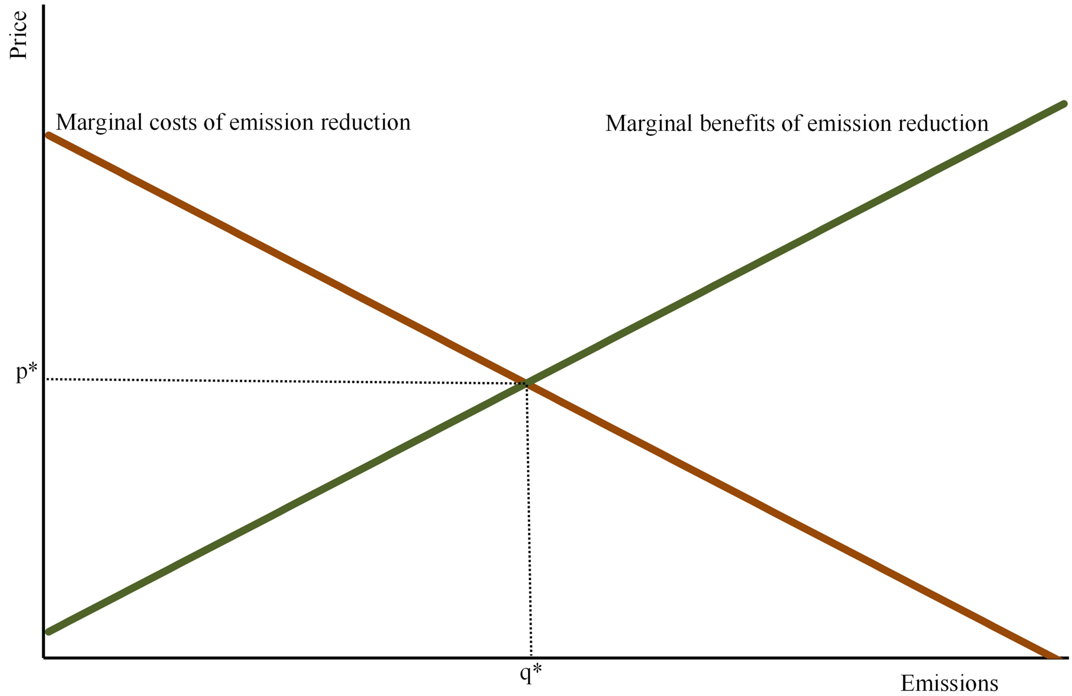


Figure 4.5: Marginal costs and benefits of emission reduction, optimal quantity and optimal price

level of pollution where the marginal costs equal the marginal benefits. This is illustrated in Figure 4.7.

> The market allocation of permits is therefore independent of the initial allocation. Efficiency and equity separate.

Figures 4.6 and 4.7 illustrate the environmental interpretation of the Coase Theorem. More generally, the Coase Theorem states that the initial allocation of property rights does not affect the final allocation. That is, regardless of who intially gets the tradable emission permits, the market allocates them in the same way. The distributional consequences—equity—are different in the two cases, but independent of the market allocation—efficiency—which is the same. The Coase Theorem separates equity (who pays what) and efficiency (who does what).

Known examples of the Coase Theorem mostly involve state actors. This is probably because private settlements attract little attention and scrutiny. For example, the daughters of our neighbours like to invite their friends over for an early morning singsong by the pool. They always bring us flowers the day after, when their hangover is cured. This is not officially recorded.

In the Trail Smelter Case, which predates the Coase Theorem, compensation was paid by a Canadian company to US farmers for the damage done by transboundary air pollution. A potash mine in France similarly compensated farmers and drinking water companies in the Netherlands for salt dumped in the Meuse, a transboundary river. In both cases, compensation required judicial review (which is how we know about them). American Electric Power, a utility, bought out all the homeowners in a hamlet as compensation for violating air pollution standards. Finland and Sweden pay other countries around the Baltic Sea to reduce discharges

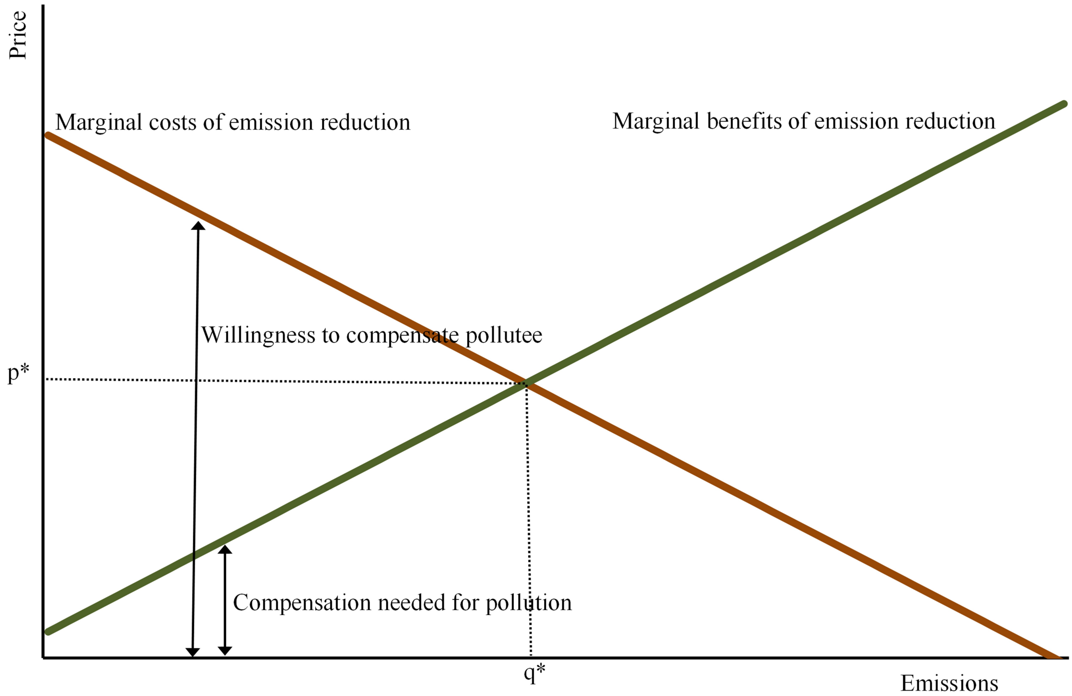


Figure 4.6: Marginal costs and benefits of emission reduction if there is a right to zero pollution

of a range of pollutants. Finland paid the Soviet Union to clean up transboundary air pollution from nickel mining on the Kola peninsula, Sweden helped the Baltic states to do the same, and Japan made similar contributions in kind and in cash to China and the Koreas. New York City bought land upstream to protect its water supplies. In all these cases, economic agents sort out a specific externality among themselves.

Box 4.4: Emissions trade in practice: The EU Emissions Trading System

The *EU Emissions Trading System* (or Scheme as it used to known; EU ETS) is the largest market for emission permits in the world, and the only multinational one. The EU ETS is now in its third phase. The first phase, 2005–2007, was primarily a test phase. The second phase, 2008–2012, helped Europe meet its commitments under the Kyoto Protocol. The current, third phase, 2013–2020, reflects the EU's unilateral commitments to control greenhouse gas emissions.

> The EU ETS a large, international emission permit market. It suffered from avoidable teething problems.

The EU ETS covers the emissions of 11,000 installations (not companies) in 31 countries. Some 45% of all greenhouse gas emissions fall under the EU ETS. Included are carbon dioxide from power and heat generation, metal production, pulp and paper, bulk chemicals, and mineral products; nitrous oxide from the production of acids; and perfluorocarbons from aluminium production. carbon dioxide from intra-Union aviation is also covered; coverage of extra-Union flights is suspended. There is a double selection.

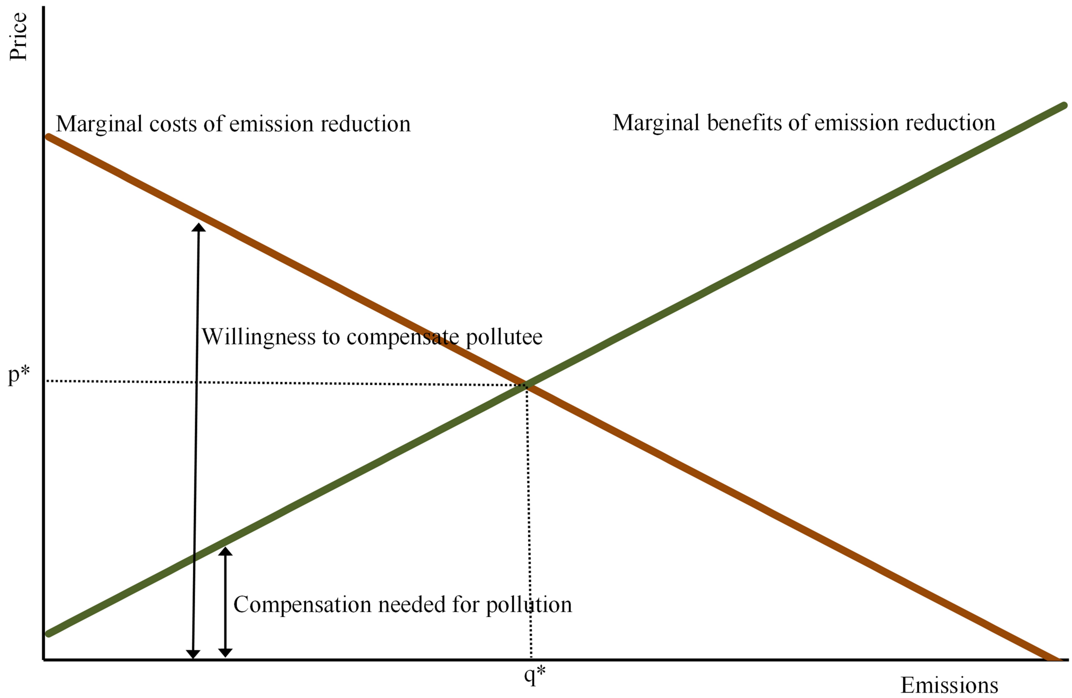


Figure 4.7: Marginal costs and benefits of emission reduction if there is a right to unlimited pollution

Besides the sectoral/gas criteria listed above, only installations that emit more than a threshold are included.

Permit markets can be created at any point in the production cycle. In an upstream market, emission permits would be needed for the exploitation and importation of fossil fuels. The problem is that there tend to be few companies in these sectors, so that market power is an issue. In a downstream market, emission permits would be needed for the consumption of goods and services in which carbon dioxide is embedded. This would be administratively costly as there are so many participants. Some people would find it difficult to manage their individual carbon account. The EU therefore opted for a mid-stream market.

Emission permits are held in electronic registries. Permits can be traded over-the-counter (that is, directly between two emitters), on a number of exchanges, and via brokers. Derivatives markets quickly appeared. More recently, permits can be bought at auctions too.

Emission permits are fungible within each phase. That is, emission permits for the third phase can be used at any time between 2013 and 2020. Between phase 2 and 3, emission permits can be banked but not borrowed. That is, a 2008–2012 emission permit is still valid after 2012. A 2013–2020 emission permit, on the other hand, was not valid before 2013 but will presumably be valid after 2020.

Initially, permits were grandparented, that is, allocated for free to companies on the basis of past emissions. Over time, more and more permits are auctioned. In 2013, 40%

of permits were auctioned. This should rise to 100% in 2020. These permit auctions are the second direct source of revenue for the European Commission.

The EU ETS has had a number of teething problems, some of which could have been avoided. Initially, permits were allocated by the Member States. As the EU ETS covers only about half of the emissions, and constraints on the other half are not enforced, every Member State allocated more permits to its companies than it should have, in the hope of creating a new export industry. When the market collapsed under the oversupply, the European Commission took over the allocation of permits.

In the beginning, VAT treatment of permits was different between Member States. Carousel fraudsters bought permits in countries with no VAT and sold them in countries with VAT. Instead of transferring the VAT to the rightful treasury, the company was folded and the monies laundered. Several people ended in jail. Many more are probably lazing in the sun. Since 2010, VAT treatment has been harmonized.

There were administrative problems too. Several electronic registries were hacked, and trading had to be suspended. In Romania, the civil servant in charge of emissions monitoring went on maternity leave and was not replaced. Monitoring is essential for the integrity of the permits. The United Nations Framework Convention on Climate Change—the UNFCCC for short—duly suspended Romania. Lithuania and Slovakia were also suspended for irregularities in emissions monitoring. The EU ETS did not follow suit.

> Enforcement is the greatest challenge for the EU ETS, as it relies on judicial strength of individual Member States.

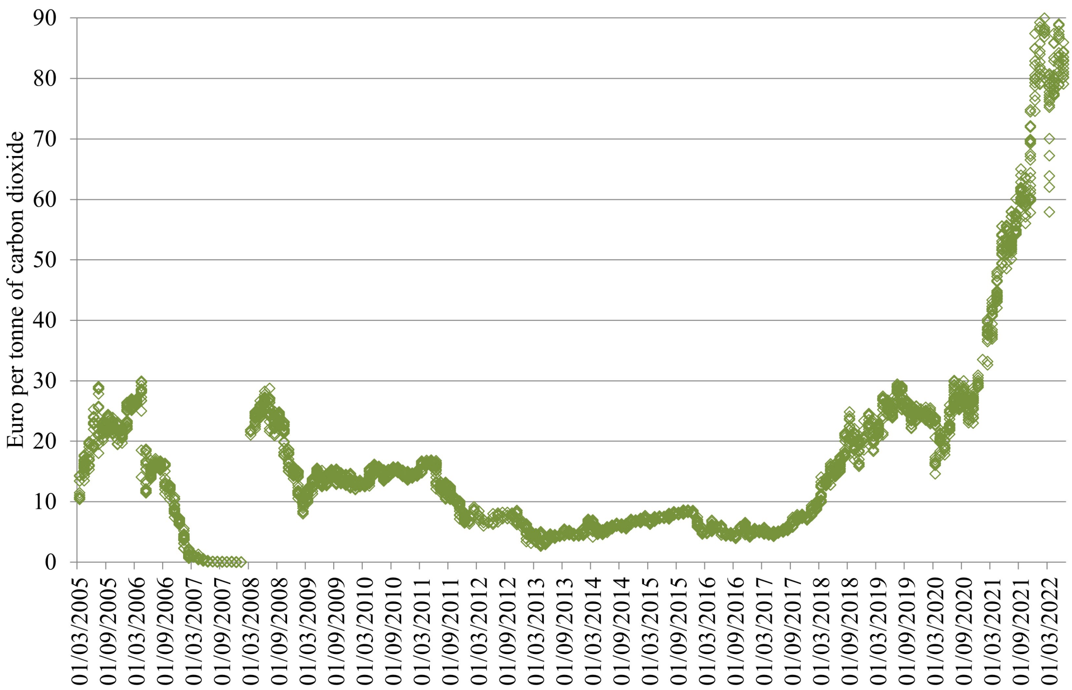
Liability for emission permits is seller beware. Under buyer beware liability, the buyer is liable for the product after the sale is completed. Fruit is an example. As soon as you have paid for a rotten orange, it is your problem. Seller beware liability is the opposite. It is rare, and typically only applies to situations where information asymmetries are strong. In many jurisdictions, if you buy a second-hand car, you can return it if problems emerge within a certain period after the sale. If you buy a new-build house, the builder is liable for structural defects for a number of years.

Liability for emission permits is seller beware. If a company emits carbon dioxide without holding a permit, a fine will be imposed. If a company sells fraudulent permits – that is, it sells its permits but does not cut its emissions correspondingly —then the companies that buy such permits are immune. The purchasing companies should report the incident to their national regulators, who in turn should contact the regulator of the company that committed the fraud (and notify the European Commission). The latter regulator should then impose a fine.

Although this seems acceptable in theory, practice is different. Law abiding companies in strictly regulated Member States do not need to worry about purchasing fake permits. Enforcement in the EU is as weak as enforcement in the weakest Member State. Three of the Member States have been suspended for monitoring irregularities by the UNFCCC. Organized crime has penetrated the government of two Member States. One Member State had a convicted fraudster as its prime minister. Another Member State falsified its National Accounts. Two Member States routinely falsified their milk and olive statistics to maximize EU subsidies. There is no reason to believe that regulated emissions equal the number of emission permits.

Initially, the price of emission permits was high. See Figure 4.8. It collapsed, however, when the extent of initial overallocation became known. Later, the price picked up again.

Since the start of the Great Recession, prices have gradually declined. The reason is twofold. First, lacklustre economic growth means that emissions are low (see Chapter 2.3). Second, people do not seem to believe that emissions will start growing again in the foreseeable future, or that emission targets will not be tightened.



Source: After EEX.

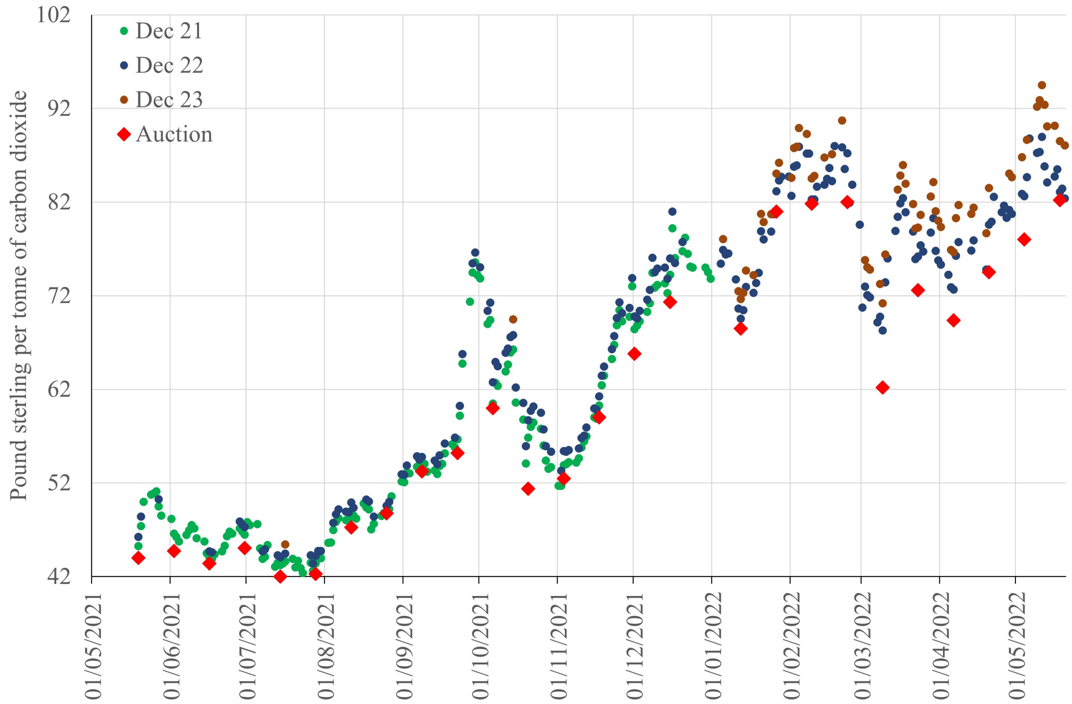
Figure 4.8: The price of greenhouse gas emission permits in the EU ETS

Box 4.5: Emissions trade in practice: The UK ETS

When the United Kingdom decided to leave the European Union, it also decided to leave the EU ETS. This was not necessary. Iceland, Liechtenstein and Norway are not part of the EU but they are part of the EU ETS. The UK decided to create its own market for tradable permits. The UK ETS is closely modelled on the EU ETS. The market regulations in the United Kingdom are for all intents and purposes a carbon copy of those in the European Union.

There is one exception. The UK ETS has a cost containment mechanism, which would be triggered if the monthly average permit price exceeds twice the average price of the two preceeding years for three months in a row. The cost containment mechanism was triggered twice in 2021, but the regulator used its discretion to ignore the trigger. In 2022, the trigger is higher, and from 2023 onwards it is higher still. While the UK and EU ETS regulations deviate in theory, they do not in practice.

The UK had been a net importer of emission permits. In the first year of the UK ETS, permit prices were slightly higher than in the EU, £62 rather than £60. See Figure 4.9. UK companies paid somewhat more for greenhouse gas emission reduction than they would have had, had they stayed in the EU.



Source: After ICE.

Figure 4.9: The price of greenhouse gas emission permits in the UK ETS

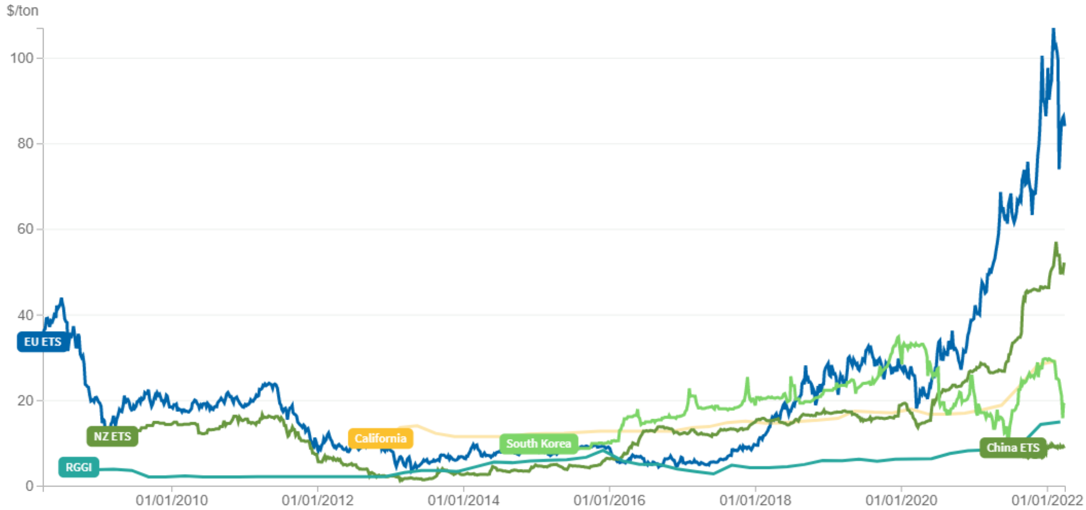
4.11 International trade in emission permits***

Long-distance trade precedes the formation of the nation state. Trade is the "natural" state of the economy. States erect artificial barriers to trade, but this typically slows down trade rather than end it.

The same holds for emission permits. If two countries each have a market in carbon dioxide emission permits, but with different prices, it would be mutually beneficial for one country to export permits and the other to import permits. Figure 4.10 shows that there is certainly room for arbitrage.

> Emission permits traded across borders require that importing countries recognize the permits of exporting countries.

Emission permits are not goods or services, however. Permits are government licenses. A license by a foreign government is worthless unless it is explicitly recognized by the home



Source: ICAP Allowance Price Explorer.

Figure 4.10: The price of greenhouse gas emission permits around the world

government. The same is not true for, say, a barrel of oil extracted in a foreign country or a haircut by a barber abroad. International trade in emission permits thus requires explicit acts of mutual recognition by all states involved, or at least unilateral recognition by importing countries.

If regulations are uniform, the international market in tradable permits would be seamless and have a single permit price. Regulations are not uniform, however. Emission permit markets differ in the way emissions are defined. Does the market include carbon dioxide emissions from land use change, or non-CO_2 greenhouse gases? Markets differ in the way emissions are monitored, and in the way rules are enforced. Regulators may impose different penalties for infractions, or have an explicit price floor or ceiling.

Enforcement in an international emission permits market is as weak as the weakest national enforcement. The international price ceiling is as low as the lowest national price ceiling (if the regulator releases more permits to keep the price below the ceiling). The international price floor is as low as the lowest national floor (if the regulator buys back permits to keep the price above the floor; any price floor above the minimum would invite a game of beggar-thy-neighbour).

National regulators are not powerless, however, against importing weak regulations from abroad. First of all, unwanted countries can be excluded. After all, licenses need to be mutually recognized. Countries can also impose import tariffs or quotas, and differentiate these by country of origin. Emission permits are government licenses and therefore not subject to WTO rules.

Countries can also impose conversion rates. For instance, an imported permit may be set equal to, say, 90% of a domestic permit. That is, 1 tonne of imported carbon dioxide may be deemed equal to 900 kg of domestic CO_2. This conversion rate may reflect different definitions of emissions, or different enforcement. Care should be taken that these conversion rates do not create opportunities for carry trade. As conversion rates are set by government fiat and therefore cannot be arbitraged away, an international body should set an internally consistent set of rates. Alternatively, if countries announce conversion rates after the end of the trading and enforcement period, conversion rates would emerge in the permit market much like exchange rates emerge in the currency market, reflecting the beliefs of traders in what the final decision will be.

In sum, while national emission permit markets could be merged to form an international market, to the benefit of all countries involved, market regulation should be considered more carefully in this case.

Box 4.6: Emissions trade in practice: The Clean Development Mechanism

The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) legislated for "where flexibility", three mechanisms that allow a country to reduce its costs of emission reduction by investing in abatement in another country. These mechanisms are trade in emission permits between countries of the OECD, Activities Implemented Jointly between OECD countries and countries of the former Soviet block, and the Clean Development Mechanism (CDM) between OECD countries and the rest of the world. Only the last instrument has been put to substantial use.

> The Clean Development Mechanism appears to have led to neither development not emission reduction.

A key characteristic of the CDM originates from the fact that most OECD countries have emission targets but other countries do not. It is therefore not possible to trade emission permits. Emission permits are derived from an emission allocation, and total emissions can readily be compared with total emission permits. Instead, in the CDM, there is trade in Certified emission reductions (CERs). CERs are defined on a project basis. CERs are the difference between what emissions would have been without the project, and actual emissions (with the project).

CERs are defined by a counterfactual. Therefore, CERs are bureaucratic constructs. The bureaucracy is quite elaborate, with many forms and many committees. This implies that the CDM is skewed towards larger projects (so as to justify the fixed cost of project approval) and towards middle-income countries (which have the necessary expertise to get the project approved). This also implies that the price of CERs has always been a few euros below the price of emission permits in the EU ETS, even though the two certificates are legally equivalent and fully fungible.

Because CERs are counterfactual and project-based, it is difficult to guarantee that the certificates represent real emission reduction. That is of course one reason why the bureaucracy is so elaborate. But current safeguards are insufficient. For instance, planting forests would permanently remove carbon dioxide from the atmosphere – if the trees remain. However, legal tenure of the land – and hence the integrity of the forest as a store of carbon – means little in countries with capricious courts or rulers, or in countries where contracts are badly enforced. Contracts can be annulled or ignored, leaving the holders of CERs empty-handed.

As another example, a project to close down a factory for motorcycles in Indonesia would qualify as emission reduction and be eligible for CERs—even if this project leaves the demand for motorcycles unchanged and hence emissions from motorcycle production. Such a project would be profitable if the revenue of the sale of CERs is greater than the cost of buying and winding down the business.

As a third example, some industrial gases, that are very potent greenhouse gases, can be made cheaply. Projects that closed the factories of such gases used to qualify for CERs.

This was discontinued when it became apparent that some factories were built with the sole purpose of closing them down and selling the resulting CERs—while selling on the manufacturing equipment to the next such scam.
Despite these problems, almost 8,000 CDM projects had been approved in September 2017. There clearly is a demand for certificates that can be held in lieu of emission reduction at home.

4.12 Technological change**

Technological progress in renewable energy, energy efficiency and agriculture drives the costs of climate policy.

The cost of greenhouse gas emission reduction is driven by the price difference between fossil fuel and carbon-neutral energy. Abatement costs would fall if technological change can be directed towards alternative energy sources. Similarly, abatement costs would fall if the rate of energy efficiency improvement can be accelerated. Furthermore, there is a large variation in energy efficiencies between similar activities in different companies, sectors, and countries. Emissions would fall if energy technology would diffuse faster.

Diverting R&D towards energy and agriculture would be expensive as these are small sectors in the economy.

Technological change should be treated with care. It would be great if technological change could be accelerated at zero cost. However, there may be large opportunity costs if technological progress is redirected towards energy. On a cost basis, energy is a few percent of the total economy. Costs would be substantial if we accelerate technological progress for energy at the expense of decelerating technological progress for the rest of the economy. In the short term, there is a fixed supply of smart and creative people. More people working on R&D in energy means fewer people working on R&D in ICT, medicine, and so on.

In the long term, the number of smart and creative people can be boosted, primarily by improving nutrition, health care, and education. The academic world is dominated by white men, not because they are smarter, but rather because they are privileged. Changing this is beyond the scope of climate policy, however.

Technological change is important. How can the government stimulate it? Technological progress comes in three stages: invention, innovation, and diffusion. Invention is a new idea or a new blueprint. Innovation takes an existing idea or blueprint and turns it into a product or service that can be sold, or a process that can be implemented. Diffusion takes the new product from its first sale to a substantial market penetration. All three stages are important, but they require a different set of skills and a different set of policy interventions (if any). Invention requires smart people being creative. It cannot be forced, but it can be stimulated. Invention is primarily done in universities, research institutes, and some corporate laboratories. Inventions rarely generate intellectual property rights. Inventions instead contribute to the global stock of knowledge. Inventors are motivated by glory and curiosity rather than by money. A country can best stimulate invention by rewarding its researchers for doing what they happen to be good at, and of course by supporting universities and research institutes.

As argued in Chapter 2, decarbonization of the economy does not require new inventions. We know how to supply the world's energy demand many times over without emitting carbon dioxide. The problem is that carbon-neutral energy sources are unproven, impractical, or expensive. Innovation and diffusion are therefore more important than invention.

Innovation is best done by corporate researchers. Innovation is not about creating something new, but rather about turning something that works in theory into something that works in practice, and sell it. There are a few successful government innovations, and many unsuccessful ones. Corporate innovation has a high failure rate too, of course, but not nearly as bad as the public sector. Innovators take risks and are motivated by the prospect of making it big. The role of the government is to incentivize large companies to put its smartest people on climate-friendly research and development; and start-ups to focus on alternative energy.

Diffusion is best done by entrepreneurs. It is about getting ever more customers to buy the new product. Diffusion is about turning something that works into something that people want. Diffusers are motivated by the prospect of a steady and growing stream of profits. Government can help through regulation, but it is not a core task of the public sector to supply the market. The policy instruments to incentivize diffusion are discussed above: taxes and tradable permits.

In sum, climate-specific technology policy should focus on innovation rather than invention or diffusion. The government has a number of instruments to stimulate innovation.

> R&D is best stimulated by patents, prizes, and taxes. Governments are bad at picking winners.

Patents are probably the key instrument. Innovations can be copied by other companies. If the embedded knowledge cannot be kept a secret—for instance, because the product can be reverse-engineered—patents provide legal protection against copycats. Essentially, patents give a temporary monopoly on a particular technology. The patent holder either exclusively makes the product, or licenses other companies to do so. The monopoly rents reward the innovator for the effort made in innovation and the risks taken. If patents are properly designed, the efficiency loss due to monopolistic supply is smaller than the welfare gain from accelerated innovation.

Patents are a generic instrument that serves all innovation, not just climate-friendly innovation. Other widely used instruments are R&D subsidies and tax breaks. There are two problems with this. First, it rewards effort rather than success – and perhaps not even that as creative accounting may be just as effective in reaping these subsidies. Second, R&D subsidies are often very specific. This is, politicians or civil servants decide which particular technology is worthy of support. It may be that politicians and civil servants have excellent foresight into what products are likely to succeed in the market place,[6] but more often than not government backs the wrong horse.

Economists refer to this as "picking winners". Governments are bad at picking winners. Politicians know a lot about politics, and civil servants know a lot about the civil service; they are less well-versed in the private sector. Besides, the public sector does not bet its own money and thus lacks a key device to discipline risk taking.

The government is a large consumer. It can use its buying power to back particular products that are not quite ready for the market. Again, the government is picking winners. This strategy of selective procurement also means that running the public sector is more expensive than need be, and may imply that civil servants are saddled with experimental products with teething problems. Selective procurement is a bonanza for lobbyists.

Government procurement only works with products that are already on the market. The government may also opt for conditional procurement. For instance, there used to be a proposal for a trust that would buy 100 million doses of a malaria vaccine from the first company that sells such vaccines for $1 or less. This guarantees a market for a yet-to-be-invented product. This is not picking winners, because the government specifies the outcome rather than the

[6] This begs the question why they did not opt to work in the private sector where such foresight is handsomely rewarded.

technology. It rewards success rather than effort. The same model can be applied for climate policy.

Instead of promising to buy particular goods, the government can also forbid its substitutes. The Montreal Protocol on Substances that Deplete the Ozone Layer (see Box 12.1), for instance, forbade CFCs, thus creating a market for HFCs. The chemical industry in the Netherlands voluntarily agreed that every new installation be in the global top five with regard to energy efficiency. The government could consider banning the sale of cars that are more than X% less fuel-efficient than the best car on the market (within a class and price range). This instrument creates an incentive to innovate: the ability to force out the competition. It lets innovators, rather than civil servants and politicians, set the pace of innovation. It rewards success not effort. And it does not pick winners.

Guaranteed procurement or a greater market share can be regarded as a "prize" for winning the technological race. The government can also grant actual prizes. This was a popular policy in the 18th and 19th centuries. More recently, the X Atari prizes have been reasonably successful. The prize for space flight, for instance, was $10 million but generated research worth $300 million; and may have kick-started a new market.

Innovation is best stimulated, however, by credible abatement policy. Innovation is an investment in the future. It is a bet that there will be a market for the product-to-be-created. In the case of greenhouse gas emission reduction, the demand is primarily driven by government policy. If companies do not believe that there will be climate policy in the future, they will not innovate. From this perspective, a carbon tax is preferred. Taxes are rarely abolished, and tend to go up. Subsidies, on the other hand, are often short-lived. Permit prices go up and down. direct regulation is also unpredictable, and there is no incentive to innovate beyond the target.

Further reading

There are many books on specific aspects of (international) climate policy, particularly on emissions trading. A good overview is Thomas Sterner and Jessica Coria's 2002 book *Policy Instruments for Environmental and Natural Resource Management*, but any environmental economics textbook covers the basics.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tdc.html.

Exercises

4.1. In Section 4.8, Weitzman's Theorem on prices versus quantities is illustrated with the case in which the regulator assumes that emission abatement is more expensive at the margin than it really is. Repeat the exercise assuming that the regulator believes that marginal abatement costs are lower than they really are. Repeat the exercise again assuming that the regulator believes that marginal damages costs are lower than they really are.

4.2. Consider I companies with emission reduction costs C_i=1/2$\alpha_i R_i^2$. Companies have baseline emissions E_i and an emissions target T_i. Without permit trade, companies have to cut emissions such that T_i= (1-R_i) E_i. What are emission cuts with permit trade? Hint: Assume that all companies are price-takers. What is the permit price? Assume that I=3, α_1=1, α_2=2, α_3=3, E_i=100 and T_i=90. What is the difference in costs with and without trade? What happens to the permit price and emission reductions if T_1=80 and T_3=100?

4.3. How did RGGI cope with states leaving and entering the programme?

4.4. Read and discuss:

- **D. Cameron, N. Clegg and N. Huhne (2011), *The Carbon Plan: Delivering our low carbon future*, London: HM Government.
- **P. Morell (2007), An evaluation of possible EU air transport emissions trading scheme allocation methods, *Energy Policy*, 35, 5562–5570.
- **A. Michaelowa and F. Jotzo (2006), Transaction costs, institutional rigidities and the size of the clean development mechanism, *Energy Policy*, 33, 511–523.
- **M. Wara (2007), Is the global carbon market working?, *Nature*, 455, 595–596.
- **M. Wara (2008), Measuring the Clean Development Mechanism's performance and potential, *UCLA Law Review*, 55, 1759–1803.
- ***C. Boehringer, H. Koschel and U. Moslener (2008), Efficiency losses from overlapping regulation of EU carbon emissions, *Journal of Regulatory Economics*, 33 (3), 299–317.
- ***P.L. Joskow, R. Schmalensee and E.M. Bailey (1998), The market for sulfur dioxide emissions, *American Economic Review*, 88, 669–685.
- ***A.B. Jaffe and R.N. Stavins (1995), Dynamic incentives of environmental regulations: The effects of alternative policy instruments on technology diffusion, *Journal of Environmental Economics and Management*, 29, S43–S63.
- ***A. Anger and J. Koehler (2010), Including aviation emissions in the EU ETS: Much ado about nothing? A review, *Transport Policy*, 17, 38–46.
- ****T. Requate and W. Unold (2003), Environmental policy incentives to adopt advanced technology: Will the true ranking please stand up?, *European Economic Review*, 47, 125–146.
- ****C. Fischer, I.W.H. Parry and W.A. Pizer (2003), Instrument choice for environmental protection when technological innovation is endogenous, *Journal of Environmental Economics and Management*, 45, 523–545.
- ****C. Fischer and R.G. Newell (2008), Environmental and technology policies for climate mitigation, *Journal of Environmental Economics and Management*, 55, 142–162.

4.5. Essay: What is your government's policy to improve the energy efficiency of residences and switch to cleaner sources of energy? (If none, consider the UK government's policy.) Is this a cost-effective policy? What would households have done without these subsidies?

Chapter 5

Impacts, adaptation and valuation

Thread

- Climate change affects managed and unmanaged ecosystems. Specialist and marginalized species will be hit hardest. #climateeconomics
- Global food production will first increase, mainly due to CO_2 fertilization, but decrease later in the century. #climateeconomics
- Climate change increases the demand for drinking, cooling and irrigation water. Both floods and droughts get worse. #climateeconomics
- Energy demand will go down in winter, up in summer. Labour productivity will decline, unless air-conditioned. #climateeconomics
- Cold-related deaths will go down, heat-related ones up. Infectious diseases, like malaria and diarrhoea, will increase. #climateeconomics
- Sea level rise will cause land loss, wetland loss, floods, saltwater intrusion; and require costly protection measures. #climateeconomics
- Adaptation substantially reduces the negative impacts of climate, and may even change their sign. #climateeconomics
- Most adaptation is private, e.g., clothing during a heatwave. Some adaptation is collective, e.g., siestas. #climateeconomics
- Some adaptation requires regulation, e.g., allowing people into air-conditioned shopping malls during heatwaves. #climateeconomics
- Some adaptation involves the public sector, e.g., health care during heatwaves, or agricultural extension services. #climateeconomics
- Little adaptation is public. Coastal protection and shared water resources are exceptions to the rule. #climateeconomics

- The public sector may hinder adaptation, e.g., agricultural subsidies that lock farmers into past behaviour. #climateeconomics
- Most systems change much faster than the climate, and adaptation will be one of many changes. #climateeconomics
- Uncertainty is a major issue for long-lived water infrastructure. Adaptation demands more robustness and flexibility. #climateeconomics
- The impacts of climate change are many and diverse. A superindicator is needed to assess its seriousness. #climateeconomics
- Money was invented to compare and add the value of diverse goods and services, and indeed income. #climateeconomics
- Behaviour in related markets (housing, recreation, labour) can be used to estimate the money value of environmental goods. #climateeconomics
- Revealed preference methods only reveal the direct consumption value of the environment. #climateeconomics
- Stated preference methods can reveal any value, but people do not necessarily speak the truth. #climateeconomics
- Measured values are multifaceted, difficult to generalize and thus hard to extrapolate to future climate change. #climateeconomics
- Willingness to accept compensation is (much) larger than willingness to pay because of loss aversion and imposed risk. #climateeconomics
- Do we buy a better climate for our grandchildren or do we compensate them for imposing a worse climate? #climateeconomics

5.1 Impacts of climate change**

The impacts of climate change are many and diverse.

Changes in temperature, rainfall, cloud cover, wind direction, wind speed, alkalinity, and so on, would directly affect plants and animals, and those effects would have further impacts through predation, competition and other ecological interactions. This is true for both managed and unmanaged ecosystems, as anyone who has ever travelled would have noted: As you travel south or north, vegetation changes with the climate. Some of these impacts will be positive, and others negative. Some impacts will be small, and others large.

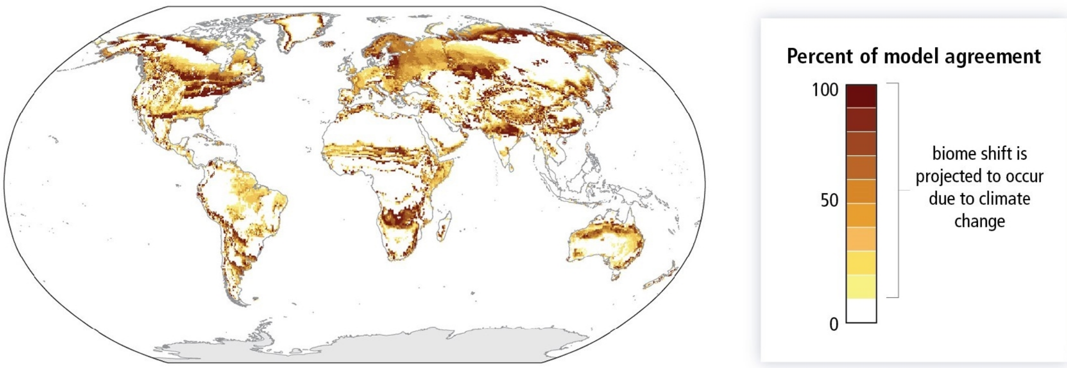
> Climate change affects managed and unmanaged ecosystems. Specialist and marginalized species will be hit hardest.

The biggest impacts will be seen for marginalized species and specialists. Marginalized species, by definition, are at the edge of survival. Any change, including climate change, could either push them over the edge to extinction or dramatically expand their ecological niche.

Specialists, by definition, thrive under very particular conditions. By contrast, generalists can live most anywhere. Often, specialists do not thrive—but rather survive where others cannot. If climate would change, their ecological niche could disappear. Although the right circumstances might well re-appear elsewhere, it is doubtful whether the new and the old niches are sufficiently connected to allow for migration. This is easily illustrated with Edelweiss, a pretty little plant that lives where few others can, high up in the Alps. If the world would warm, Edelweiss would have to move north—but it cannot jump from mountain top to mountain top, it cannot compete with the plants that live in the valleys, and there are no mountains immediately north of the Alps. In the wild, Edelweiss is in trouble.

Climate change would not mean that large parts of the planet would turn into a lifeless moonscape. Rather, nature would become duller, with fewer species covering larger areas.

Figure 5.1 illustrates the scale at which this might occur. Coloured areas denote a wholesale change in the composition of the ecosystem. The details depend on the model and the climate scenario, but the scale does not. For large parts of the Earth, future landscapes will be very different, with savannah where there used to be rainforest and forest where there used to be tundra.



Source: IPCC WG2 AR5 Chapter 4.

Figure 5.1: Model agreement on climate-change-driven biome shifts between 1990 and 2100

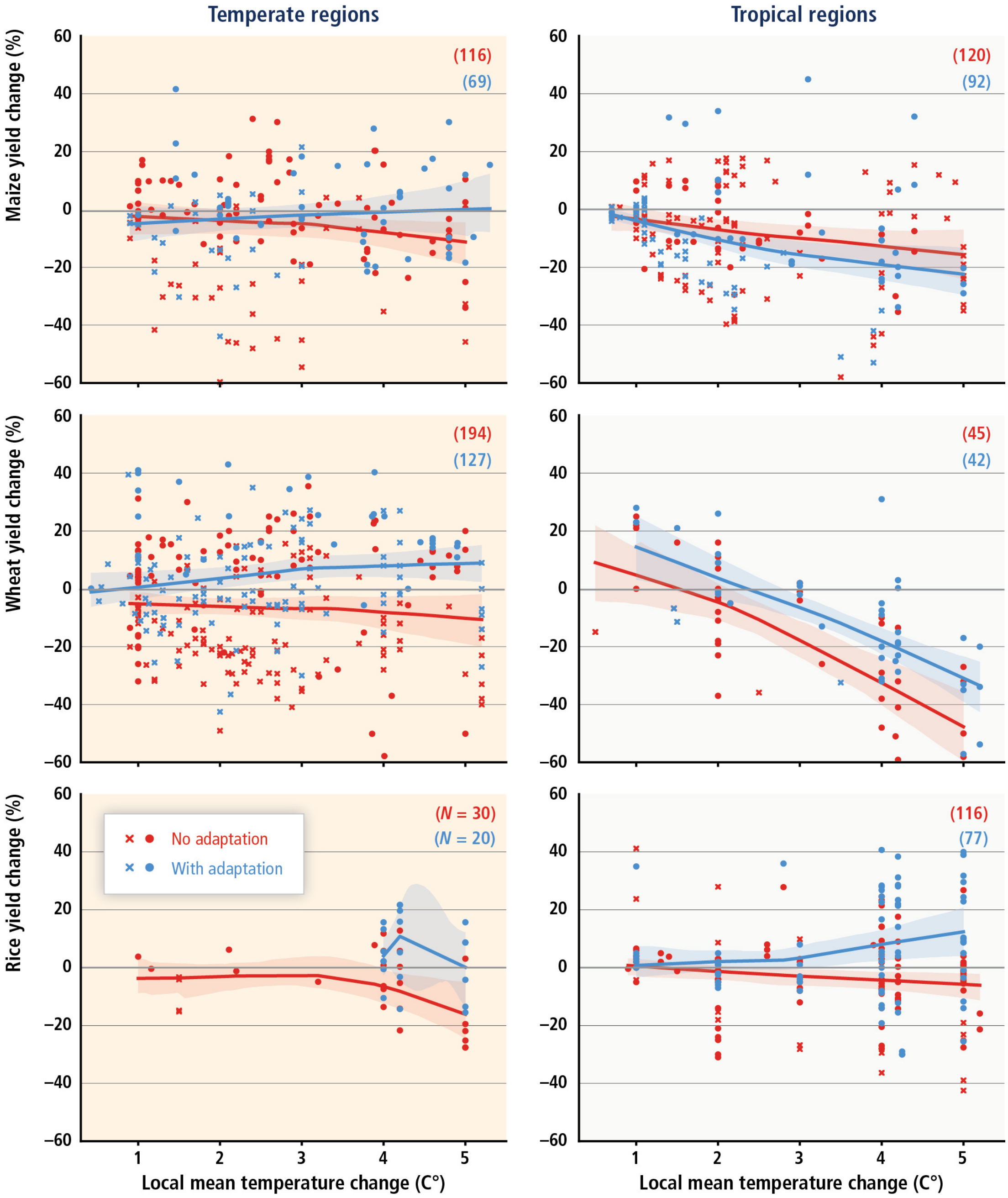
Agriculture and forestry would also be affected by climate change. Most crops, but weeds too, would grow faster because of the higher concentration of carbon dioxide in the atmosphere. This is a fertilizer, and allows plants to manage their water more efficiently. Some crops would benefit from warmer and wetter conditions. Other crops may suffer drier conditions or be less heat tolerant. The net impact depends on the crop and its location. This is illustrated in Figure 5.2, which shows published estimates of yield changes as a function of climate change for the three main crops for temperate and tropical regions with and without adaptation. The graphs show a wide variety of responses, big and small, positive and negative. The only clear message from Figure 5.2 is that adaptation increases crop yields.[1]

Global food production will first increase, mainly due to CO_2 fertilization, but decrease later in the century.

One way to cut through the confusing range of impact estimates shown in Figure 5.2, is to aggregate different crops in different places using a global model of agricultural markets. Figure 5.3 shows the aggregate impact according to five different models. The indicator is the

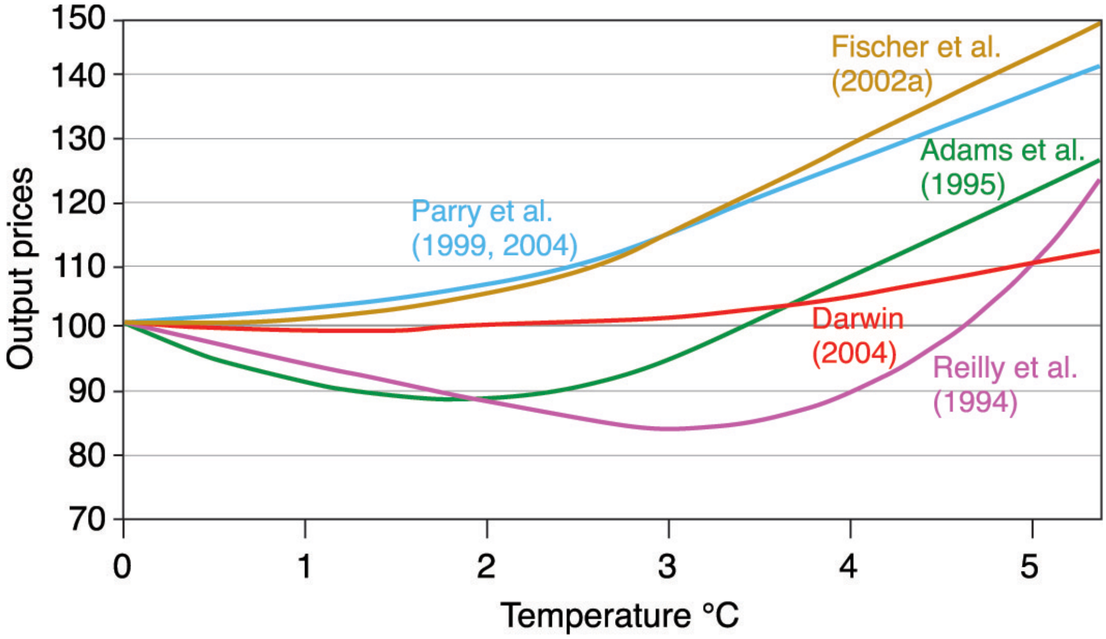
[1] That message is obscured by the results for tropical maize. Adaptation seems to reduce crop yields—farmers engage in self-harm. This is because the illustrious Intergovernmental Panel on Climate Change does not know how to deal with sample selection bias.

world market price for food. In the next few decades, world food production may well expand because of climate change, suppressing food prices. In the longer run, however, climate change is likely to reduce food production, pushing up food prices.



Source: IPCC WG2 AR5 Chapter 7.

Figure 5.2: The impact of climate change on crop yields



Source: IPCC WG2 AR4 Chapter 5. References in the figure are detailed in that chapter.

Figure 5.3: The impact of climate change on global food prices

> Climate change increases the demand for drinking, cooling and irrigation water. Both floods and droughts get worse.

Climate change affects water resources, directly through precipitation and evaporation and indirectly through changes in water use. This would have an impact on agriculture, nature, drinking water, and inland navigation. It would also affect power generation, which often uses water as a coolant. Less or hotter water would constrain that, as would regulations on the temperature of the discharge water.

> Energy demand will go down in winter, up in summer. Labour productivity will decline, unless air-conditioned.

There are further impacts on energy supply. Wind and wind power and cloud cover and solar power come immediately to mind, but thermal plants are less efficient when it is hot, and resistance increases with the temperature of transmission cables. Energy use would be affected too. Demand for cooling energy would increase, and demand for heating energy would fall. Construction and transport are interrupted by weather events such as cold spells, heat waves, floods, and fog. Every winter, tourists flock to mountains to ski while beaches are popular in summer. Climate change would affect the attractiveness of holidays in particular locations.

> Sea level rise will cause land loss, wetland loss, floods, saltwater intrusion; and require costly protection measures.

Sea level rise would have a number of effects. Coastal erosion would increase, and floods would be more frequent or intense. Saltwater would intrude into groundwater. Many fear that sea level rise would lead to the disappearance of atoll islands, which often do not reach more than a metre above the current high sea level. Saltwater intrusion is likely to make many of these islands inhabitable decades before they finally disappear beneath the waves. Coastal wetlands may drown, particularly if coastal defences prevent inland migration.

> Adaptation substantially reduces the negative impacts of climate, and may even change their sign.

Human adaptation is critically important in all impacts of climate change, but perhaps best illustrated for sea level rise. On a warm summer day, many people lie on the beach, their heads less than half a metre above the water. Sea level rise would drown them all—unless they adapt.[2] People rarely spend more than a few hours on the beach. When they come back the next day or the next year, they are not likely to lie down in the exact same spot. When their grandchildren visit the beach by the time sea level has risen by half a metre, they will not insist on sunbathing in the same location as granny used to do—particularly not when that spot is now under water. While this example seems ridiculous, many impact studies continue to assume that people do not adapt to climate change. This is sometimes referred to as the *Dumb Farmer Hypothesis*, assuming that farmers will plant and harvest the same crops at the same time as their fathers and grandfathers did, and apply the same pesticides and fertilizers. In fairness to the people who grow our food, this really is the *Dumb Analyst Hypothesis*[3]—farmers are a lot smarter than that.

Flood defences were known to the Sumerians and Ancient Chinese. As sea level rises, people will not sit on their hands while their buildings, roads and land are swept away. Dykes would be raised, groins built, beaches nourished, saltwater desalinated. In many places, the cost of adaptation would be the main impact of climate change, and residual impacts would be relatively small.

Climate change would also affect labour productivity. The human body is in a thermal equilibrium with its environment. As any warm-blooded animal, we need to keep our body at a particular temperature. Shivering to keep warm and sweating to keep cool cost energy. Work raises our body temperature. Sweating is less effective in humid conditions. So the human body is less able to do work when it is hot and humid. The productivity of outdoor, physical labour would fall if the climate warms, as would indoor work unless air-conditioned.

> Cold-related deaths will go down, heat-related ones up. Infectious diseases, like malaria and diarrhoea, will increase.

Through the same process, heatwaves affect human health. Healthy people tire when it is hot. The bodies of the very young, the very old, and people with cardiovascular or respiratory disorder may give up altogether. Cold kills too. Like heat, cold creates physiological stress. More importantly, during cold weather, people group together indoors, giving free reign to infectious diseases. Climate change would further affect human health through nutrition (see the discussion on agriculture above), through air pollution, and through vector-borne diseases such as diarrhoea, malaria and cholera.

5.2 The government's role in adaptation**

Is climate change a public good that merits government intervention?

[2]This is the *Gruenspecht Rule of Adaptation*, after Howard Gruenspecht.
[3]The Dumb Analyst Syndrome was coined by Colin Prentice.

The impacts of climate change are many and diverse. As adaptation is about altering those impacts, adaptation is diverse too. Instead of talking about generalities, a few examples are discussed below.

Climate change will make heatwaves more common. During hot weather, you should wear light clothes, not exert yourself, keep out of the sun, and drink lots (but little alcohol). This is adaptation, but private. People know this, and have the appropriate incentives to take these measures. There is no need for a government plan that will tell you not to put on your winter coat when it is hot outside. Parents should tell young children, though, and old people may need help.

> Most adaptation is private, e.g., clothing during a heatwave. Some adaptation is collective, e.g., siestas.

There are collective elements to this. It makes sense to have a siesta during the hottest hours of the day, and to have the main meal late in the evening. These things are more easily arranged when everyone in the neighbourhood does the same. There is no need, though, for the government to tell you when you should eat your dinner.

The government may run awareness campaigns to help unsuspecting populations cope with extreme heat (although such campaigns are not always effective), but there is no need for government intervention.

> Some adaptation requires regulation, e.g., allowing people into air-conditioned shopping malls during heatwaves.

There are public elements, however. Over 40,000 people died during the 2003 heatwave in France. Many medical professionals were on holiday then. There was no procedure to call them back. The people who could overrule procedure were on holiday too, and apparently did not follow the news back home. Shopping malls are air-conditioned, but during earlier heatwaves in the USA, security personnel removed people who came to seek relief from the heat rather than shop. In crime-infested neighbourhoods, people were afraid to open their windows, but there was no extra police on the street. Note that violent and sexual crime is more common during hot weather, so you would want to increase police presence anyway. Poor people could not afford the electricity to power theirs fans, but electricity bills were not waived during the heatwave. Clearly, the government has a role to play, as a facilitator of private adaptation, as a regulator, and as a service provider.

> Some adaptation involves the public sector, e.g., health care during heatwaves, or agricultural extension services.

Agriculture is our second example. Climate change would affect crop yields. Farmers could respond in a number of ways. Planting and harvest dates could be changed, as could the application of pesticide, fertilizer and irrigation. Different varieties or different crops could be planted, or farmers could seek alternative livelihoods. Seed companies and extension services could support farmers with advice. It is in the farmer's own interest to adapt as the alternative is a drop in income.

> The public sector may hinder adaptation, e.g., agricultural subsidies that lock farmers into past behaviour.

As with health and heat, the role of the government is limited. Extension services are often state-owned and -run (even though no public good is provided) and so is large-scale irrigation.

In other ways, the government hinders adaptation. Import tariffs distort international trade and discourage specialization in what is comparatively advantageous. Subsidies similarly distort the market, rewarding particular activities at the expense of others and shielding farmers from market signals. In the European Union, subsidies are particularly generous in disadvantaged areas. That is, farmers are encouraged to grow the wrong thing in the wrong place. Here, withdrawal is the best the government can do for adaptation.

> Little adaptation is public. Coastal protection and shared water resources are exceptions to the rule.

Sea level rise is the third example. There are private elements to adaptation. Tourists do not need to be told that they should not go sunbathing on a beach that has been eroded by sea level rise. Otherwise, coastal protection is a public good. Protection of a lot would be ineffective or exceedingly expensive unless it is coordinated with the projection of adjacent lots. Lots further inland benefit from the protection of the sea front, and should therefore contribute to the cost of coastal protection. Information asymmetries justify building codes (to help protect against wind and water) and land zoning. The government should take the lead in adaptation.

5.3 How to adapt**

> Most systems change much faster than the climate, and adaptation will be one of many changes.

A number of examples of how to adapt to climate change are given above. In most cases, adaptation to climate change is like adaptation to any change. In many systems, climate changes more slowly than other drivers, so adaptation to climate change would not post any particular challenge—recall the example of sunbathers on the beach and the risk of sea level rise.

There are two exceptions. Long-lived investments will have to withstand a wider range of weather. Future precipitation is particularly uncertain, with models disagreeing about the sign of change in many parts of the world. Investment in long-lived water infrastructure thus has to be prepared for a future in which anything can happen.

> Uncertainty is a major issue for long-lived water infrastructure. Adaptation demands more robustness and flexibility.

There are two ways of doing so: Make the investment more robust, or make the investment more flexible. Extra robustness entails that infrastructure can function under a wider range of weather conditions. This is relatively straightforward (but costly) if the sign of change is known. Sea walls, for instance, should be raised higher. The sign of future sea level rise is known, but the extent is uncertain. It would make sense to prepare for a high rate of sea level rise and raise the sea wall by more than is probably needed. This is because there is a large fixed cost in sea wall reinforcement (e.g., planning permission, project management, transport disruption) but a relative low variable cost (e.g., materials, labour).

Extra flexibility may be more appropriate if the sign of change is unknown. Extra flexibility entails that infrastructure can be scaled up or down as needed. This comes at a cost too, as both design and materials are more advanced. For instance, a number of small reservoirs are more flexible than one big one, as the total storage capacity can be increased or decreased by commissioning or decommissioning one of the reservoirs. Moveable dams and inflatable barriers can be used to stop water only when needed. Retention areas can be used to temporarily store extra water. Infrastructure designed with such features command a premium in the face of an uncertain future.

5.4 Purpose of valuation*

Monetary valuation seeks to estimate the value of environmental goods or services that are not traded on markets. Market goods and services are routinely valued and property is frequently valued too, typically in preparation for a sale. The purpose of environmental valuation is different.

> The impacts of climate change are many and diverse. A superindicator is needed to assess its seriousness.

There are many impacts of climate change, some positive, some negative, some big, some small. Impacts vary over space and over time. The question whether or not climate change is a problem, and whether it is a big problem or small problem cannot be answered without aggregating the impacts. Monetary valuation serves this purpose. It puts all impacts in a common metric, money in this case, which is a prerequisite for aggregation.

Expressing the total and marginal impact of climate change in monetary terms is handy because it allows for an immediate comparison with the impacts of greenhouse gas emission reduction. It also allows for a comparison with other issues, and to the Gross Domestic Product. Furthermore, if the victims of climate change are to be compensated, it will likely be in the form of money.

> Money was invented to compare and add the value of diverse goods and services, and indeed income.

Some people object to environmental valuation, or find it hard to understand how putting a price tag on something valuable is feasible or meaningful. Yet, money was invented exactly for this purpose. In a barter economy with N goods, there are $0.5 * N * (N-1)$ prices. In a money economy, there are only N prices. That is probably why money was invented:[4] To reduce the transaction and information costs of trade. And through the medium of money, some strange trade-offs are made. Working within a tight budget, students have to choose between a new pair of jeans, a night out, or a textbook. Professors can afford all those things, but have to make a choice between a boat, an extension to the house, or sending the kids to Harvard. Those things are incomparable at first glance, yet choices are made every day. Presumably, people can compare such things. Some things may be worth the money they cost, and other things not.

Monetary valuation of environmental goods and services is done for the purpose of improving decisions and making choices that are consistent with other choices we make. We would maximize environmental quality if that were costless. It is not. Sacrifices need to be made to reduce emissions. Some of these sacrifices are worth it, and others are not. Monetary valuation informs that decision.

5.5 Valuation methods: Revealed preferences*

> Behaviour in related markets (housing, recreation, labour) can be used to estimate the money value of environmental goods.

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.

[4] Besides the unit of accounting, money is also the means of exchange and a store of value.

The travel cost method is the oldest method, and perhaps the most intuitive one. 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 spent 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 expectation. You do not pay an entrance fee to get into your local park. However, you do spend time to get 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. 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 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.

The second 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. Expensive houses attract more well-to-do home owners, who tend to be better educated and socially more attractive as neighbours. Such neighbourhoods tend to have better schools and other facilities. At the larger scale, wages compensate both for the local cost of living and for the attractiveness of the environment, and house prices in turn reflect wages. In sum, the housing market is influenced by many things, and you need a large amount of observations and clever econometric methods to isolate the effect of the environment—but it can be done.

Defensive expenditure is a third class of revealed preference methods. 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 is 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. 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.

5.6 Valuation methods: Stated preferences*

> Revealed preference methods only reveal the direct consumption value of the environment.

Revealed preference methods have the advantage that actual decisions are analyzed. The disadvantage is that it considers only those values that are expressed, indirectly, in market transactions.

I care about whales. Nothing in my behaviour of the last 20 years has revealed that I do. I do not contribute to Greenpeace, the major NGO that campaigns for the preservation of whales, because I do not agree with their energy and climate policies. I do not go whale watching. I did that once. The whales did not show up. I will not do it again. You could have followed me around for 20 years, checked all my bank statements, and you would not have learned that I care about whales. Yet, I do. To find out, you need to attend my class or read my book. Or you could ask me.

Stated preference methods do exactly that. The contingent valuation method is the oldest and most widely used. It uses surveys (face-to-face, by phone, by mail, over the Internet) that include questions such as "how much would you be willing to contribute to help preserve the population of grey-blue humpback whales in the North Atlantic?" Researchers have now moved away from open-ended questions (as above) to single-bounded—"would you be willing to pay more than £50 per year"—or double-bounded—"would you be willing to pay between £50 and £75 per year"—questions plus randomization of interviewees. Dichotomous choice is another option. Would you pay £50? If not, would you pay £25? If so, would you pay £75?

More recently, contingent choice methods have become popular. Here, interviewees are asked to choose between sets of attributes—"would you rather contribute £50/year and have a population of 8,000 humpback whales or contribute £75/year and have a population of 10,000 humpback whales?" Contingent choice has gained acceptance because it resembles other purchase decisions more closely—think of the shelves with cornflakes in the supermarket—and because it reveals more about the environmental characteristics that interviewees care about.

> Stated preference methods can reveal any value, but people do not necessarily speak the truth.

The main advantage of stated preference methods is that you can value anything: consumption of environmental services (as in revealed preferences), option values (I am not using it now but I may want to use it later), bequest values (I do not care much but I would like my children to enjoy it), and existence values (I am happier because I know that there are whales out there).

The main disadvantage of stated preference methods is that interviewees do not put their money where their mouth is. Interviewees may therefore take less care in expressing their preferences, or they may try and mislead the interviewer.

Interviewees may be influenced by the interviewer; they may be repelled (and thus give a low value or none at all) or may try to impress (and thus give a high value). Interviewees may realize that they are not being asked to contribute, but rather that they are asked about spending government money, and that their answer will be averaged with other interviewees. Interviewees may care about the environmental service in question, but object to the suggested way of delivery (e.g., higher taxes for environmental protection).

Standard micro-economic theory assumes that people are rational and fully informed. In fact, experience is a better description. If people make routine decisions in a familiar environment—for example, the weekly trip to the supermarket—they buy the stuff that they want, and pay a reasonable price for an acceptable quality. If you let people make the same decisions in an unfamiliar environment—a foreign supermarket, say, in a country with a different language, other eating habits, and an unfamiliar currency—errors creep in. For decisions that are not routine—buying insurance or a car, say—people gather information by searching the Internet and talking to friends and family before making a choice.

Contingent valuation and contingent choice methods put interviewees in a situation that is unfamiliar and asks them to make a decision that is not routine. The results are therefore noisy.

Stated preference methods are now implemented with a standard battery of tests that check and correct for the many biases that may creep into the results. Although these methods are applied routinely in public policy making and litigation, it is a very active research field and results are less reliable than we would like them to be.

5.7 Issues for climate change**

There are two problems with valuation methods that are particularly relevant for the impact of climate change.

5.7.1 Benefit transfer

> Measured values are multifaceted, difficult to generalize and thus hard to extrapolate to future climate change.

Primary valuation is expensive. As suggested above, conceptually straightforward ideas are difficult to put into practice. An applied revealed preference study easily employs someone for a full year. Stated preference studies are considerably more time-consuming. Therefore, there are only a limited number of primary estimates. Because the methods are under continuous development, researchers often go back and re-value a good or service that was previously studied so that they can show that their new method makes a change.

Case studies are great for science and replication is better, but in order to inform public policy we need a comprehensive coverage of all goods and services affected in every location. Extrapolation is required. This is known as *benefit transfer*.

Two techniques are used to extrapolate primary estimates from one location to another, from one issue to another, and from one time to another. First, estimates are transfered without further ado. Second, existing estimates are subject to a meta-analysis, a set of statistical techniques to discover empirical regularities in previously published results. This may reveal, for instance, that richer people are willing to pay more for environmental protection; an income elasticity is estimated. Then, the estimated relationships are used to extrapolate from the observed sites to all sites of interest. This is known as benefit transfer by transfer function.

This is a reasonable approach. Unfortunately, meta-analytic regressions have low explanatory power, and tests of the validity of benefit transfer show large errors. The reason is twofold. The data are noisy, and values are highly context specific. Idiosyncrasy cannot be predicted.

This matters for climate change because the relevant impacts occur in the future, which cannot be observed. Furthermore, there have been few primary studies to value the impacts of climate change, so benefits are transferred from other issues, such as occupational health, air pollution, and eutrophication. Finally, valuation studies have disproportionally focused on rich countries, but the impacts of climate change are concentrated in poor countries. valuation of the impacts of climate change is thus a particularly uncertain business.

5.7.2 WTP versus WTAC**

The other problem with valuation that is especially important for climate change is as follows. Above, I conceptualize the question as the willingness to pay (WTP) to acquire an environmental good or improve an environmental service. You may also conceptualize the question as the willingness to accept compensation (WTAC) for a deterioration of environmental quality.

> Willingness to accept compensation is (much) larger than willingness to pay because of loss aversion and imposed risk.

Consider the following example. Someone knocks on your door, tells about the plans to convert the parking lot down the road into a park, and asks you for a financial contribution. Now contrast this to the situation where someone knocks on your door, tells about the plans to convert the park down the road into a parking lot, and offers you financial compensation.

Objectively, the comparison is the same: tarmac and cars versus trees and grass. There are differences, though. In one case, you are asked to contribute and are therefore constrained by your budget. In the other case, you are offered money and are therefore constrained by your perception of the other party's budget. Under standard micro-economic assumptions, the budget constraint makes a small difference. The difference between WTP and WTAC can be large, however, if income is a poor substitute for the good being valued.

There is another difference: You may be emotionally attached to the existing park because of the happy memories you have of the place. You may have often walked your dog there, or got your first kiss. You cannot be emotionally attached to a hypothetical park that was introduced to you a few minutes before. The amount you would be willing to accept as compensation for the loss of a park is thus greater than the amount you would be willing to pay to acquire a park.

Empirical studies indeed show this. See Figure 5.4. The willingness to accept compensation for the loss of a good or service is larger, often a lot larger, than the willingness to pay for the same good or service. Four explanations have been offered. The budget constraint and emotional attachment are two.

Studies have shown that people are loss averse. They attach a value to the status quo. Losing something is worse than gaining the same thing is good. Loss aversion has been shown to occur even for routine, low-worth goods (e.g., coffee mugs) that were acquired less than an hour ago. If you give students a mug and try to buy it back from them, they demand a price that is much higher than they would pay for the same mug in the shop next door. It is

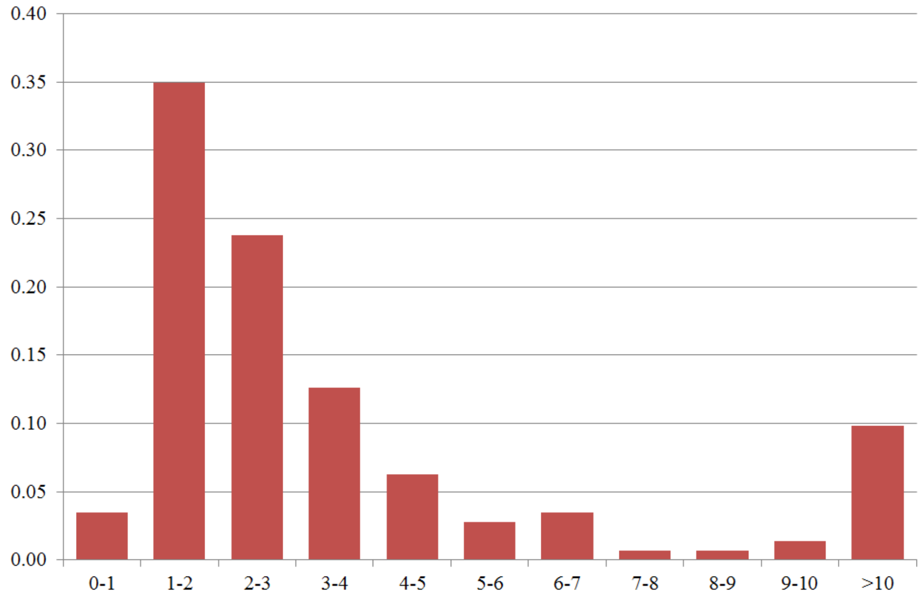


Figure 5.4: The histogram of the ratio of the mean WTP to the mean WTAC for 168 estimates from 37 studies

easy to describe such behaviour as irrational. It creates a dilemma for public policy. Do you educate people to be more rational, ignore this aspect of people's preference, or seek to reflect the strange will of the people in the government's decisions?

The fourth explanation of the difference between willingness to accept compensation and willingness to pay is that voluntary risks are viewed differently than involuntary risks. Suppose that you get drunk, go joy-riding, get into an accident, and lose a leg. That would feel bad. Now suppose I get drunk, go joy-riding, get you into an accident, and you lose a leg. That would feel worse—even though there is no objective difference: Your leg is gone. Context matters for valuation because people are social animals.

> Do we buy a better climate for our grandchildren or do we compensate them for imposing a worse climate?

This matters for climate change. Do we formulate climate policy as us buying a better climate for our children, or do we conceptualize the problem as us imposing a worse climate on our children and offering them compensation in return? Do we formulate climate policy as rich people buying a better climate for their richer children? Or as rich people imposing a worse climate on the children of the poor? Do we view carbon dioxide emissions as necessary for survival? Or as an indulgence of a luxurious life style? The value of climate change impacts would be different, depending on how the question is framed.

Further reading

Valuation methods are part of any good textbook on environmental economics. A good introduction is Garrod and Willes' 2000 book *Economic Valuation of the Environment: Methods and case studies* but Braden and Kolstad's 1991 book *Measuring the Demand for Environmental*

Quality continues to set the technical standard. Daniel Kahnemann's 2011 book *Thinking, Fast and Slow* is an easily accessible entry into some of the above material on survey methods.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tbb.html.

Exercises

5.1. Climate change would change landscapes as vegetation responds. How could you estimate the value of changes in the landscape?

5.2. Climate change would affect human health through changes in weather extremes and vector ecology. How could you estimate the value of changes in risk to human mortality and morbidity?

5.3. Climate change would affect species abundance and may lead to local and even global extinctions. How could you estimate the value of changes in biodiversity?

5.4. Estimates of the value of the impact of future climate change are necessarily based on data from the present and past. How could you estimate future values?

5.5. Would the valuation of the impact of climate change be different if we phrase the policy question as "buying a better climate for our grandchildren" or as "compensating our grandchildren for climate change"?

5.6. Section 4.10 discusses the Coase Theorem and its application to the initial allocation of emission permits. Does the Coase Theorem need to be reconsidered in the light of the discussion on the difference between willingness to pay and willingness to accept compensation?

5.7. Listen to Billy Bragg's "King Tide": https://www.youtube.com/watch?v=lWPZeQzN_Ws. What do you make of the lyrics?

5.8. Read and discuss:

- **S. Fankhauser, J.B. Smith and R.S.J. Tol (1999), Weathering climate change: Some simple rules to guide adaptation decisions, *Ecological Economics*, 30, 67–78.
- **K.A. Miller, S.L. Rhodes and L.J. MacDonnell (1997), Water allocation in a changing climate: Institutions and adaptation, *Climatic Change*, 35, 157–177.
- ***E.T. Mansur, R.O. Mendelsohn and W. Morrison (2008), Climate change adaptation: A study of fuel choice and consumption in the US energy sector, *Journal of Environmental Economics and Management*, 55, 175–193.
- ****D.L. Kelly, C.D. Kolstad and G.T. Mitchell (2005), Adjustment costs from environmental change, *Journal of Environmental Economics and Management*, 50, 468–495.
- **L.M. Brander, P. van Beukering and H.S.J. Cesar (2007), The recreational value of coral reefs: A meta-analysis, *Ecological Economics*, 63, 209–218.
- **W.K. Viscusi and J.E. Aldy (2003), The value of a statistical life: A critical review of market estimates throughout the world, *The Journal of Risk and Uncertainty*, 27, 5–76.
- ***J.K. Horowitz and K.E. McConnell (2002), A review of WTA/WTP studies, *Journal of Environmental Economics and Management*, 44, 427–447.

- ***R. Brouwer (2000), Environmental value transfer: State of the art and future prospects, *Ecological Economics*, 32, 137–152.
- ****R.O. Mendelsohn, W.D. Nordhaus and D. Shaw (1994), The impact of climate change on agriculture: A Ricardian analysis, *American Economic Review*, 84, 753–771.
- ****J.-M. Chevet, S. Lecocq and M. Visser (2011), Climate, grapevine phenology, wine production, and prices: Pauillac (1800-2009), *American Economic Review*, 101, 142–146.
- ****K. Rehdanz and D.J. Maddison (2005), Climate and happiness, *Ecological Economics*, 52, 111–125.
- ****O. Deschenes and M. Greenstone (2011), Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the US, *American Economic Journal: Applied Economics*, 3, 152–185.

Chapter 6

Economic impacts of climate change

Thread

- Our best estimate is that global warming of 2.5K would make the average person feels as if she had lost 1.7% of income. #climateeconomics
- There are 69 estimates of the total economic impact of climate change, showing a wide range of results. Our confidence is thus low. #climateeconomics
- Climate change may be beneficial at first but these are sunk gains. Future warming has net negative impacts. #climateeconomics
- The uncertainty about the economic impact of climate change is large and negative surprises are more likely than positive surprises. #climateeconomics
- Weather shocks have a larger impact than climate change because weather allows only for immediate adaptation. #climateeconomics
- Poor countries are more vulnerable because a larger share of their economic activity is exposed to the weather. #climateeconomics
- Poor countries are more vulnerable to climate change because they tend to be hotter and closer to biophysical limits. #climateeconomics
- Poor countries are more vulnerable because they lack the means, the wherewithal, and the political will to adapt. #climateeconomics
- As poverty implies vulnerability, economic growth is an, often superior, way to reduce the impact of climate change. #climateeconomics
- International involvement in adaptation is obsolete except for the bureaucrats and consultants involved. #climateeconomics
- International adaptation policy by and large ignores the lessons of decades of development policy. #climateeconomics

- The social cost of carbon is the benefit of reducing greenhouse gas emissions by a single tonne. #climateeconomics
- The social cost of carbon is an estimate of the desirable intensity of climate policy. #climateeconomics
- The social cost of carbon depends on many things, so there are many, widely different estimates. #climateeconomics
- The social cost of carbon is higher if the discount rate is lower, and its right tail is much fatter. #climateeconomics
- The social cost of carbon should rise by some 2% per year. #climateeconomics

6.1 Reasons for concern**

The impacts of climate change are many and diverse. The question whether climate change is beneficial or detrimental, big or large, depends on sector, location and time. Reading through Section 5.1, let alone the wider literature on which it is based, leaves you confused: Should you welcome climate change, be somewhat concerned, or worry a lot? Aggregate indicators are needed to assess whether climate change is, on balance, a good thing or a bad thing, and whether it is small or large relative to the many other problems that we have.

Figure 6.1 uses alternative high-level indicators and displays them against projected climate change. The indicators are alternatives in that they would appeal to people with different attitudes, with different values.

Some people worry about the unique and the vulnerable, such as atoll islands or butterflies. If you are so inclined, climate change is a big concern. Local extinctions of butterflies and global extinctions of rodents have been documented with climate change as the likely cause. Many butterflies have difficulty crossing open spaces and thus cannot migrate if climate change. Some rodents live on islands and cannot move. If the limited climate change of the past century already caused such problems, the more rapid climate change projected for this century must be disastrous (from this perspective). Stringent climate policy is thus justified.

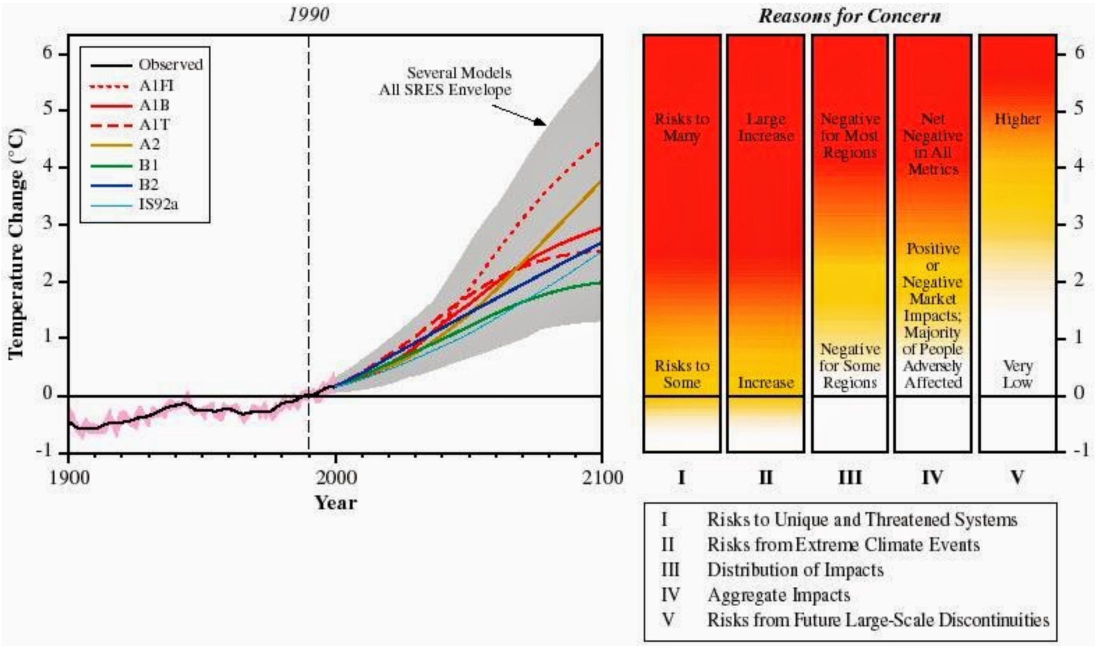
Other people only care about large, systemic impacts of climate change, such as changes in ocean currents and the melting of the polar ice caps. If you are so inclined, then climate policy can wait. The probability of these scenarios is minute, at least in the 21st century, and in some cases it is not known how greenhouse gas emission reduction would affect those probabilities—indeed whether they would go up or down.

Yet other people may care about the impact of climate change on total economic welfare, or about the distribution of that welfare. Those concerns are discussed below.

6.2 Total economic impacts**

Our best estimate is that global warming of 2.5°C would make the average person feels as if she had lost 1.7% of income.

Figure 6.2 shows the 69 published estimates of the total economic impact of climate change. The vertical axis is given in Hicksian equivalent variation, the maximum share of income that someone would be willing to give up, without being worse off, to avoid climate change. These numbers should be read as follows: A global warming of 2.5°C would make the average person feels as if she had lost 1.7% of her income—1.7% is the average of the 13 observations at 2.5°C.



Source: IPCC WG2 AR3 Chapter 19.

Figure 6.1: Projected climate change (left panel) and alternative reasons for concern about climate change (right panel)

6.2.1 Methods

The estimates in Figure 6.2 were derived as follows. Researchers used models—of every description: process models, optimization models, equilibrium models, statistical models, spatial or temporal analogues—to estimate the many impacts of climate change for all parts of the world in their natural units—changes in crop yields, acreage of land inundated, number of lifes lost, and so on—estimated the values of these impacts (using either market prices or the methods described in Chapter 5), multiplied the quantities and prices, and added everything up. This is the so-called *enumerative method*. The result is an estimate of the direct cost—price times quantity—of climate change. The direct cost is a poor approximation of the change in welfare, for instance because it ignores knock-on effects—such as forced migration affecting labour markets and elections—but it is an approximation nonetheless. The enumerative approach omits interactions between sectors—such as a change in water resources affecting agriculture or sea level rise affecting tourist facilities—and it ignores the price changes that would be induced by changes in demand or supply.

Other studies are based on the same physical impact estimates as in the enumerative studies above, but use these to shock a computable general equilibrium model. A computable general equilibrium model represents all markets of goods and services, as well as factors of production, within and between countries. These estimates thus include both partial equilibrium effects—the price of wheat goes up if its supply goes down—and general equilibrium effects in output, intermediate or input markets within and between economies —if wheat is more expensive, consumers have less money to spend on other commodities, and switch to other grains; farmers use more fertilizer and irrigation to compensate for adverse weather, and employ more labour; wheat imports increase. In this way, computable general equilibrium models include

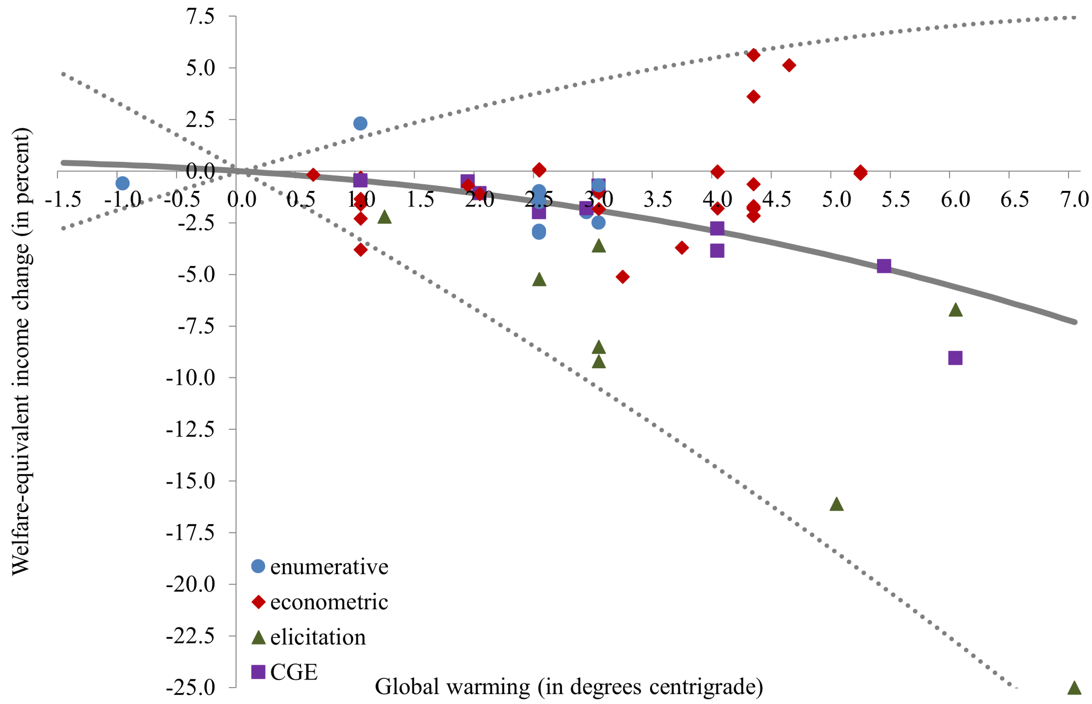


Figure 6.2: Alternative estimates of the global total annual impact of climate change. Symbols and colours denote different methods. The lines combine all estimates.

more adaptation than other methods. The welfare measure used in these studies is typically the Hicksian Equivalent Variation, a proper welfare measure that is, within the model, measured exactly. However, computable general equilibrium models are based on the national accounts and thus exclude all non-market effects. This mismeasures agriculture—subsistence agriculture is omitted—and health—lost work, medicine and medical services are included, but feeling miserable is not.

Some estimates elicit the views of (supposed) experts.[1] The question was about the impact of climate change on global output, which can alternatively be interpreted as a measure of economic activity (but not welfare) and a measure of income (and thus welfare).

Other estimates involve regressions of some sort of measure of economic welfare or activity on climate. Agricultural land prices, for instance, reflect the productivity of the land and hence the value of the climate that allows plants to grow. You do not just buy the land, but also the sun you expect to shine and the rain you expect to fall on it—this was first noted by David Ricardo in 1817. Price changes induced by climate change are used to estimate its direct cost, and thus approximate welfare changes. The estimated relationship between climate and household expenditure patterns has been used to approximate the change in total consumer surplus due to climate change. The estimated relationship between self-reported happiness on the one hand and climate and income on the other hand implies an estimate of the compensating variation, that is, the income change needed to compensate for a climate change while keeping welfare at its original level. The main advantage of the statistical method is that it is based on

[1]The first such studies were done at a time when no one could reasonably claim expertise on the economic impacts of climate change, later studies include people who never published on the topic but may reasonably be expected to have read some literature.

actual behaviour (rather than *assumed* behaviour as in the enumerative method). The main disadvantage is that climate variations over space are used to derive the impact of climate change over time. Space and time are different things, though. For instance, trade is much easier over space than over time. Looking at the Atlantic seaboard of the USA, wheat is grown in Maine and citrus fruit in Florida, with trucks going back and forth to ensure people in both states have a balanced diet. Using the cross-sectional relationship over time implicitly assumes a fleet of Tardises shipping wheat to the future and oranges to the past. Furthermore, technology and institutions differ much more strongly over space than over time, and their impact can thus not be detected in a cross-section. Technological progress in agriculture is skewed towards making marginal lands more productive. Farmer support is often biased towards the poorest. These effects flatten the relationship between climate and yield. Another disadvantage is that the Ricardian method, like the enumerative one, ignores the response of markets. Researchers have therefore begun to combine these statistical estimates with computable general equilibrium methods.

6.2.2 Weather and climate

There is another problem with the Ricardian method. Climate varies only slowly over time—it is, after all, the thirty-year average of weather—and it has not varied much over the period for which we have good economic data. The identification of the impact of climate therefore comes from cross-sectional variation, and as the climate varies only gradually over space, the cross-section needs to be large. This is problematic as so many other things vary over space too. The Ricardian method is therefore vulnerable to spurious associations because of confounding variables. This can be partly overcome with panel data, for confounders that vary over time as well as space—trade policy would be one example, if it has changed within sample, and if trade liberalization is preferentially between countries with similar climates. But panel data cannot help with confounders that do not change much over time—a cultural preference for pastoralism in dry areas would be one example.

In recent years, there have been a number of papers that estimate the impact of weather on a range of economic indicators. The key advantage of weather impacts is that weather is random, perhaps truly but certainly from an economic perspective. The impact of weather is therefore properly identified, or so people have argued. The problem with this argument is that by now many different economic activities have been found to be affected by the weather, and these activities of course impact one another.

> Weather shocks have a larger impact than climate change because weather allows only for immediate adaptation.

Although the rhetoric in some of these papers would have you believe otherwise, the impact of a weather shock is not the same as the impact of climate change. The impacts of weather shocks cannot readily be extrapolated to the impacts of climate change. Climate is what you expect, weather is what you get. Weather are draws from an probability distribution. Climate is that distribution. Climate change are shifts in the moments of the weather distribution. Weather is unpredictable for more than a few days ahead. Adaptation to weather shocks is therefore limited to immediate responses—put up an umbrella when it rains, close the flood doors when it pours. Adaptation to climate change extends to changes in the capital stock—buy an umbrella, invest in flood gates. Furthermore, adaptation to climate change depends on how people update their expectations for weather. In other words, weather studies estimate the short-run elasticity, whereas the interest is in the long-run elasticity. Extrapolating the impact of weather shocks to the impact of climate change is unlikely to lead to credible results.

However, although climate change is not marginal, its total impact is an integral of marginals. If you assume that (1) economic agents are rational and (2) their adaptation investments optimized; that (3) adaptation is private and (4) adaptation options continuous and smooth; and that (5) the economy is in a spatial equilibrium and (6) markets complete; then the impact of climate change can be derived from estimate of the impact of weather shocks. Adaptation investments are often long-lived, so both spot and future markets should be complete. Spatial zoning and transport hubs distort the spatial equilibrium. Adaptation is often lumpy, be it air conditioning or irrigation. Some adaptation options, such as coastal protection, are public goods. Infectious diseases are externalities. Agents are not always rational, and decisions sub-optimal. You really cannot use weather shocks to study the impact of climate change.

But, if we suspend our skepticism, there are now two handfuls of papers that estimate the impact of weather shocks on economic growth and extrapolate the results to the impact of climate change. The earlier studies assume that economic growth depends on temperature. The regressions obviously include country fixed effects, but these models assume that economic growth will be forever faster or slower because of climate change—this is the latest incarnation of climate determinism, a persistent theme in intellectual history that is remarkably resistant to evidence to the contrary. These studies fall in two groups. Some authors argue that *poorer* countries are more vulnerable to weather shocks, others that *hotter* countries are. Within sample, it is hard to distinguish between these two hypothesis: Most hot countries are poor, and most poor countries are hot. Out of sample, there is a large difference. We expect the future to be hotter and richer. If hot countries are more vulnerable, the impact of climate change escalates. But if rich countries are more vulnerable, the impact of climate change is muted. The former studies find rather large effects of climate change, with colder countries accelerating while economic growth reverses to shrink in hotter countries.

Later studies, with more credible econometrics, assume that economic growth depends on the change in temperature. This implies that, once climate change stops, it no longer affects the economy. These studies find more modest impacts, roughly in line with the estimates shown in Figure 6.2. The most recent studies extend the analysis to precipitation, without an overall change in conclusions.

6.2.3 Results

> There are 69 estimates of the total economic impact of climate change, showing a wide range of results. Our confidence is thus low.

Figure 6.2 contains many messages. There are 69 estimates, a thin basis for any conclusion. However, statements that climate change is the biggest (environmental) problem of humankind are simply unfounded—that is to say, we do not know whether it is true or not—although current estimates suggest that this is false: The 13 estimates for 2.5°C , which we may reach in 60–80 years time, show that researchers disagree on the sign of the net impact. Climate change may lead to a welfare gain or loss. At the same time, researchers agree on the order of magnitude. The welfare change caused by climate change is equivalent to the welfare change caused by an income change of a few percent. The average of the estimates is negative. That is, a century of climate change is about as bad as losing a year of economic growth.

> Climate change may be beneficial at first but these are sunk gains. Future warming has net negative impacts.

Some studies suggest that initial warming is positive on net. The initial benefits are due to reduce costs of heating in winter, reduced cold-related mortality and morbidity, and carbon dioxide fertilization, which makes plants grow faster and more drought resistant. This does not imply that greenhouse gas emissions should be subsidized. Figure 6.2 shows the impact of warming relative to pre-industrial times. Because of the slow workings of the climate system and the large inertia in the energy sector, a warming of 2°C can probably not be avoided and a warming of 1°C can certainly not be avoided—we are already past that point. That is, the initial net benefits of climate change are sunk benefits. We will reap these initial benefits no matter what we do to our emissions. For more pronounced warming, the negative impacts dominates, such as summer cooling costs, infectious diseases, and sea level rise.

That said, there are two studies that show positive impacts at substantial warming. One of these studies regresses economic growth rates on temperature levels. Richer, cooler countries have grown less fast. This study attributes this finding to *climate* rather than to *catch-up*, a more common interpretation. The other study assumes unfettered mobility of capital and labour, and relies on Siberia becoming a rather splendid place to live and work.

Most studies, however, show hat climate change has negative impacts on human welfare. Negative impacts include sea level rise, heat stress and its impacts on human health and labour productivity, higher demand of air conditioning, higher prevalence and virulence of tropical diseases, losses in agricultural production, and declining biodiversity. As you would expect, these impacts tend to become more negative for more pronounced warming, as shown by the solid line.

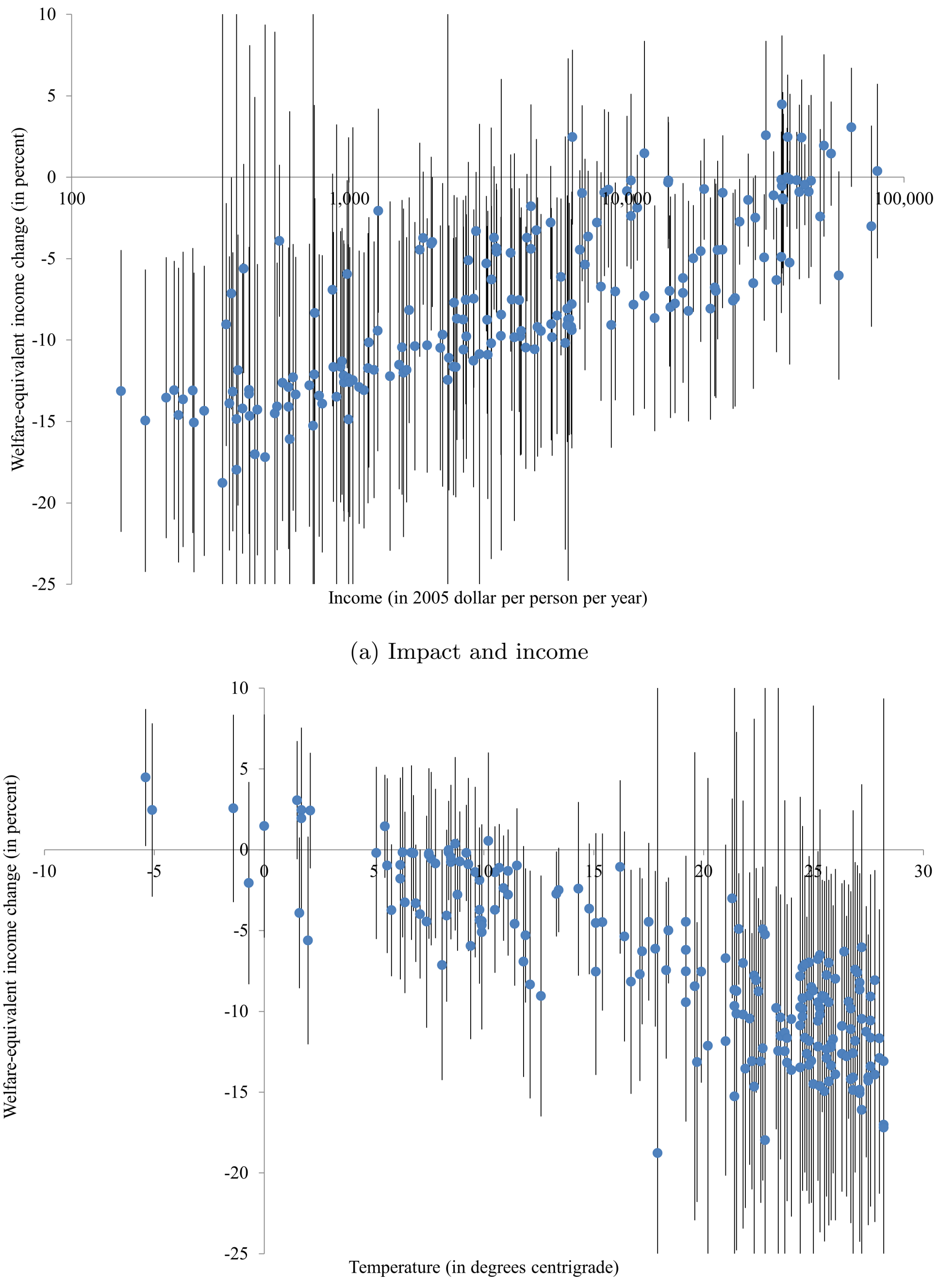
The uncertainty is rather large—indeed one may say that the estimates are all over the place. At 3.0°C warming, estimates vary between -0.7% and -9.2% of income. At 2.5°C warming, researchers cannot even agree on the sign of the impact. The error bars in Figure 6.2 depict the 90% confidence interval. This is probably an underestimate of the true uncertainty, as experts tend to be overconfident and as the 69 estimates were derived by a group of researchers who know each other and each other's work well—and sometimes reused estimates from previous studies.

The uncertainty is somewhat skewed to the right. Negative surprises are more likely than positive surprises of similar magnitude. This is true for the greenhouse gas emissions: It is easier to imagine a world that burns a lot of coal than a world that rapidly switches to wind and solar power. It is true for climate itself: Feedbacks that accelerate climate change are more likely than feedbacks that dampen warming. The best estimate for the climate sensitivity, the eventual warming due to a doubling of atmospheric carbon dioxide, is 2.5°C, with a range of 1.5°C to 4.5°C. The impacts of climate change are more than linear: If climate change doubles, its impacts more than double. Many have painted dismal scenarios of climate change, but no one has credibly suggested that climate change will make us all blissfully happy. In that light, the above conclusion needs to be rephrased: A century of climate change is no worse than losing a decade of economic growth.

> The uncertainty about the economic impact of climate change is large and negative surprises are more likely than positive surprises.

Figure 6.2 shows the world average impact for 69 studies. Figure 6.3 shows results from the same study as Figure 6.2 for 2.5°C warming. Countries are ranked from low to high per capita income and low to high temperature. In Figure 6.2, the world total impact is roughly zero. In Figure 6.3, the majority of countries show a negative impact. However, the world economy is concentrated in a few, rich countries. The world average in Figure 6.2 counts dollars, rather than countries, let alone people.

Figure 6.3 suggests that poorer countries are more vulnerable to climate change than are richer countries. There are a few exceptions to this—such as Mongolia, which is poor but so cold that warming would bring benefits, and Singapore, which is rich but a low-lying island on



(a) Impact and income

(b) Impact and temperature

Figure 6.3: The economic impact of climate change for a 2.5℃ warming for all countries as a function of their 2005 income (top panel) and temperature (bottom panel)

the equator—but by and large the negative impacts of climate change are concentrated in the developing economies.

> Poor countries are more vulnerable because a larger share of their economic activity is exposed to the weather.

There are three reasons for this. First, poorer countries are more exposed. Richer countries have a larger share of their economic activities in manufacturing and services, which are typically shielded (to a degree) against the vagaries of weather and hence climate change. Agriculture and water resources are far more important, relative to the size of the economy, in poorer countries.

> Poor countries are more vulnerable to climate change because they tend to be hotter and closer to biophysical limits.

Second, poorer countries tend to be in hotter places. This means that ecosystems are closer to their biophysical upper limits, and that there are no analogues for human behaviour and technology. Great Britain's future climate may become like Spain's current climate. The people of Britain would therefore adopt some of the habits of the people of Spain, and build their houses like the Spaniards do. Houses in Spain are designed to keep the heat out, whereas houses in the UK are build to keep the heat in. It makes sense to sleep through the heat of the day and, as digestion heats up the body, take the main meal in the cool of the night. If the hottest climate on the planet gets hotter still, there are no examples to copy from; new technologies will have to be invented, behaviour will have to be adjusted by trial and error.

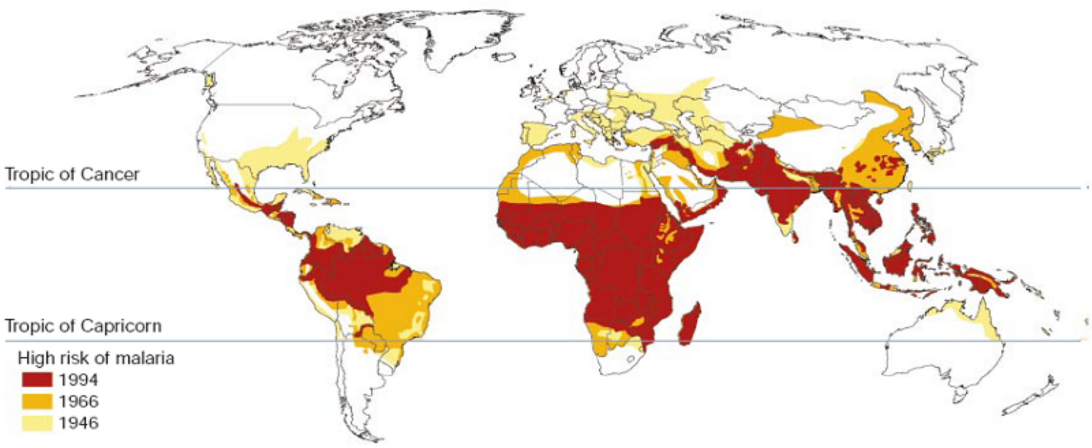
> Poor countries are more vulnerable because they lack the means, the wherewithal, and the political will to adapt.

Third, poorer countries tend to have a limited *adaptive capacity*. Adaptive capacity is the ability to adapt. It depends on a range of factors, such as the availability of technology and the ability to pay for those technologies. Sea level rise is a big problem if you do not know about dykes, or if you do but you cannot afford to build one. Flood protection has been known for millennia. Modern technology is at its summit in the Netherlands. Dutch engineers will happily share their expertise—for a rather steep fee. Adaptive capacity also depends on human and social capital. An ounce of prevention is worth a pound of cure, but prevention requires that you are able to recognize problems before they manifest themselves (i.e., predict the future) and that you are able to act on that knowledge (i.e., analytical capacity is connected to policy implementation). Furthermore, the powers that be need to care about the potential victims. A country's elite may be aware of the dangers of climate change and have the wherewithal to prevent the worst impacts, but if those impacts would fall on the politically and economically marginalized, or if the victims think that floods are due to the wrath of God rather than the incompetence of politicians, the elite may chose to ignore the impacts.

6.3 Impacts and development**

The impacts of climate change are to a large degree determined by adaptation to climate change. Adaptation is constrained by adaptive capacity. The components of adaptive capacity largely coincide with aspects of development. Therefore, future vulnerability to climate change will be very different from current vulnerability.

This is perhaps best illustrated with malaria. Figure 6.4 shows a map of projected changes in malaria due to climate change. A few areas see a decline. Most areas see an increase in the incidence of malaria, and the darker the colour, the greater the increase. Malaria is introduced in the darkest areas. The mechanisms are as follows. Mosquitoes carry the disease. Mosquitoes are more active during warm weather. Mosquitoes need warm, still standing water to breed. A warmer and wetter world would thus see more mosquitoes. The malaria parasite develops faster in warm conditions. A warmer world would thus see more malaria.

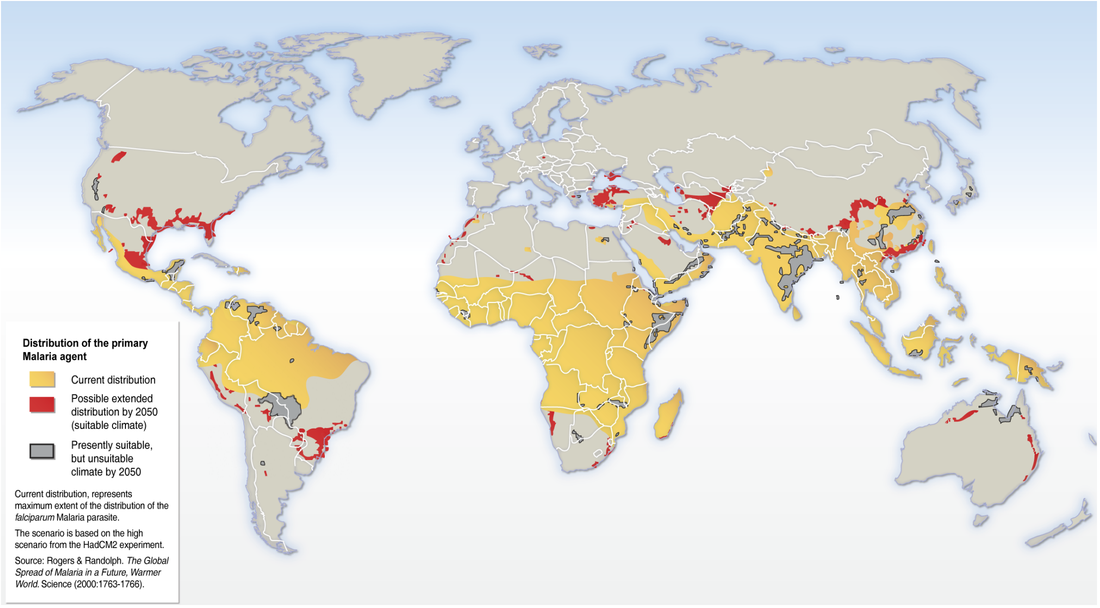


Source: Jeffrey Sachs and Pia Malaney (2002), The economic and social burden of malaria, *Nature*, 415, 680–685.

Figure 6.4: The impact of climate change on the malaria potential

Figure 6.5 shows the current and past distribution of malaria. In the lighter areas, all the natural conditions for malaria are met, but it does not occur. Malaria is now only present in the darkest areas. Affluence is the difference between the light and dark colours. Indeed, people in countries with an average income above $3,000/person/year do not die from malaria (contracted in their home country). The mechanisms are as follows. Mosquitoes need warm, still standing water to breed. First, draining of wetlands, surfacing of roads and yards, and roofing of buildings have led to a dramatic decline in the number of small puddles of water in the developed world. Second, the large-scale application of DDT in the 1950s killed many mosquitoes. Third, the life cycle of the malaria parasite requires both human and mosquito hosts. If a human is treated for malaria, she does not get sick. But she does not become infectious either. Herd immunity results if a sufficient number of people in a population take malaria medicine. A course of malaria medicine costs a few hundred dollars, a small fortune in poor countries and small change in rich countries. Malaria is thus a disease of both poverty and climate.

Figure 6.6 shows alternative projections of the future number of climate-change-induced malaria deaths. In blue, everything is kept constant except for the climate. The number of climate-change-induced malaria deaths increases from some 75,000 per year now to about 250,000 per year at the end of the century. Unfortunately, malaria records are not of sufficient quality to validate the model prediction of 75,000 climate deaths per year at present. The dotted lines indicate the uncertainty about the malaria model only (i.e., ignore the uncertainty about future greenhouse gas emissions or climate change). In the highest scenario, population growth is added and malaria numbers duly increase to about 750,000 deaths per year by 2100.



Source: David J. Rogers and Sarah E. Randolph (2000), The global spread of malaria in a future, warmer world, *Science*, 289 (5485), 1763–1766. Graphic by Hugo Ahlenius.

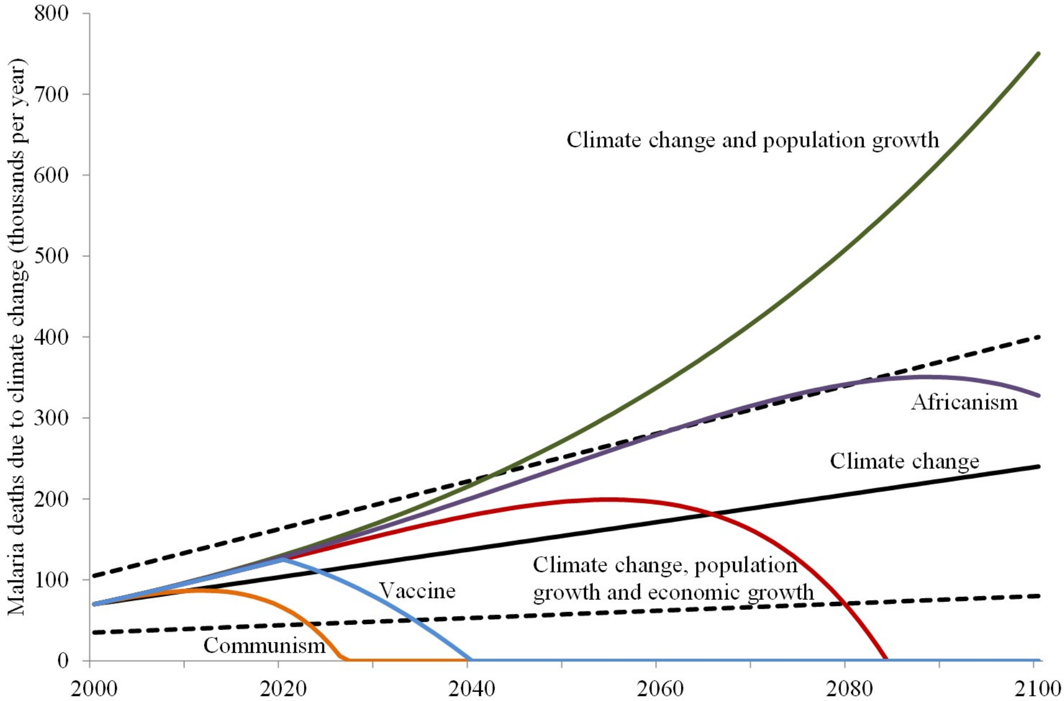
Figure 6.5: The current and past distribution of malaria

This scenario is much quoted by environmentalists. In the third scenario, per capita income also grows. Malaria numbers first rise but later fall and malaria is eradicated around 2085 (in this model, with this parameterization, under this scenario). This scenario assumes that the global pattern of the relationship between health care and development holds for malaria. In two alternative scenarios, the communist pattern and the African pattern are used. Qualitatively, the results are the same: Malaria first goes up with warming and population growth before it falls with economic growth; in the communist pattern, the decline is sooner and faster, in the African pattern, the decline is later and slower. This illustrates the large uncertainty. As malaria is concentrated in Africa, the third scenario may be too optimistic. The final scenario adds another complication. It assumes that a malaria vaccine will be developed by 2020 (the deadline set by the Bill and Melinda Gates Foundation; a first vaccine was announced at the end of 2011; final stage trials are ongoing in 2017). The vaccination campaigns against smallpox and polio took about 20 years. Using that number, malaria would be eradicated by 2040—not just climate-change-induced malaria, but all malaria.[2]

> As poverty implies vulnerability, economic growth is an, often superior, way to reduce the impact of climate change.

Figure 6.6 illustrates the relationships between the impacts of climate change and development, as well as the uncertainty about those relationships. It also begs a policy question.

[2]Figure 6.6 was developed in 1999, published in 2001. At that time, a malaria vaccine was considered unlikely if not impossible. The vaccine scenario was included as a development from leftfield. It is now real. Other things have happened too. A sustained effort, initiated by Gro Harlem Brundtland and George W. Bush, has halved malaria deaths, mostly through DDT, no longer banned, and bednets. Figure 6.6 is thus outdated. It is left standing as a warning against forecasters' hubris.



Notes: Scenarios: climate change only (with, in the dashed lines, the 67% confidence interval including only the uncertainty about the malaria model); climate change and population growth; climate change, population growth and economic growth; the latter with public health spending typical for African countries; the same with public health spending typical for Communist countries; and the same with invention of a malaria vaccine.

Figure 6.6: The impact of climate change on malaria for alternative scenarios

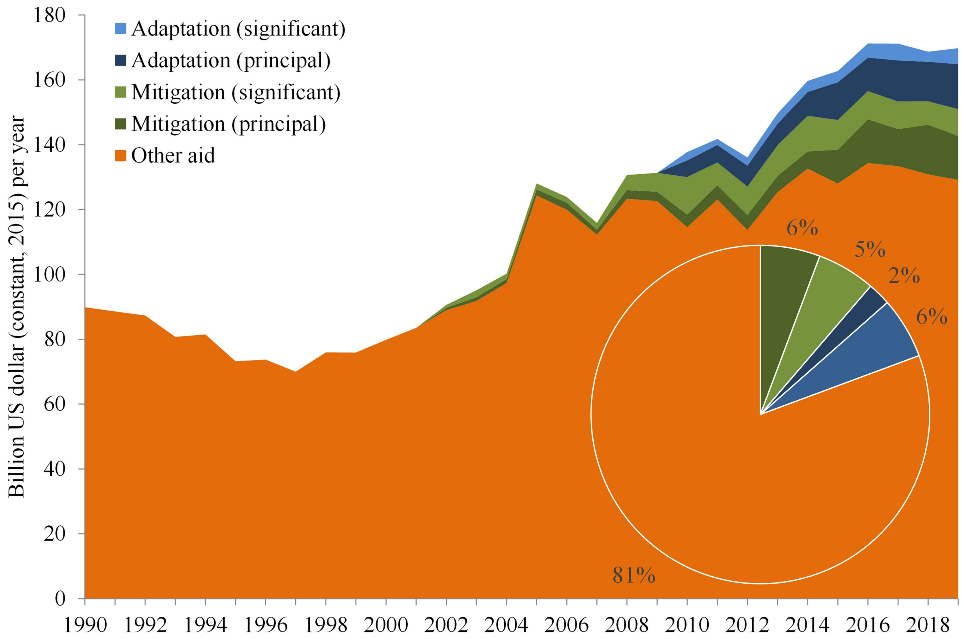
Malaria is one of the reasons for concern about climate change. Greenhouse gas emission reduction is not necessarily the best way to reduce the impact of climate change. Instead, money could be invested in medical technology or in public health care. This is the *Schelling Conjecture*.

6.4 Adaptation and development**

Poorer countries tend to be more vulnerable to climate change. The reasons include the structure of the economy and a lack of adaptive capacity. Economic development is therefore a key component of adaptation policy. Nobelist Thomas Schelling argued that climate change impacts may fall faster if we invest money in development aid rather than in emission reduction, the Schelling Conjecture.

> International involvement in adaptation is obsolete except for the bureaucrats and consultants involved.

As indicated above, rich countries and multilateral organizations are now funding adaptation in poor countries, using funds that would otherwise have been used as development aid. Mitigation has crowded out official development aid for longer. See Figure 6.7. There are two problems with this. First, adaptation is mostly a private good. External funding therefore crowds out internal funding. Outside money for adaptation really is an income transfer—but as the money is taken from development aid, the effect is zero.



Note: The inset shows the average shares for the period 2010–2019.

Figure 6.7: Total official development aid and aid for which adaptation and mitigation are the principal aim or a significant aim

Second, generic development aid is crowded out by specific development aid for adaptation to climate change. This may not be the first priority for development, and the adaptation money would be misallocated. The money for adaptation is partly controlled by people who understand climate change and its impacts, but who do not necessarily understand development.

> International adaptation policy by and large ignores the lessons of decades of development policy.

International funding for adaptation is earmarked for projects that are obviously adaptation, as the allocation of money needs to be approved by bureaucrats. Building dykes and digging irrigation canals are obvious forms of adaptation. It resembles, however, the paradigm that dominated development economics in the 1950s and 1960s. Then, underdevelopment was deemed to be identical to undercapitalization, and development aid focused on infrastructure projects. This view is now known to be wrong.

Providing information about future climate is another obvious form of adaptation. So, Western organizations operate satellites that keep an eye on the weather, Western scientists maintain databases and models to interpret the data, and Western consultants travel across Southern Africa to explain to farmers that the weather matters. One could argue, however, that secure title to land would do more to improve agriculture in Africa than better weather forecasts could—and that farmers with access to the capital market are better able to cope with climate change.

6.5 The social cost of carbon**

The focus above is on the total impact of climate change. From a policy perspective, the marginal impact is more relevant. This is because optimal climate policy (see Chapter 8) requires equating the marginal costs of greenhouse gas emission reduction (see Chapter 3) to its marginal benefits. Intuitively, climate change is a long-term, global problem. What matters to the climate are emissions aggregated over all countries and many decades. A single policy maker can only hope to change climate change by a little bit. The benefits of that are measured at the margin.

> The social cost of carbon is the benefit of reducing greenhouse gas emissions by a single tonne.

The marginal impact of greenhouse gas emissions is the damage done by emitting an additional tonne of, say, carbon dioxide. It is known as the marginal damage cost, and as the social cost of carbon. It is the change in the net present value of the monetized impacts due to a small change in emissions, normalized by those emissions. Because of symmetry, the marginal damage of a small increase in emissions equals the marginal benefits of a small reduction in emissions.

> The social cost of carbon is an estimate of the desirable intensity of climate policy.

If the emissions trajectory is optimal, then the social cost of carbon equals the Pigou tax: The price we should put on greenhouse gas emissions if we wish to optimize net present welfare. Estimates of the social cost of carbon thus tell us what to do, how intensive climate policy should be, how much energy rises should be raised. It is a normative concept.

> The social cost of carbon depends on many things, so there are many, widely different estimates.

There have been many estimates of the marginal damage cost of carbon dioxide, the latest count standing at 5905. At first sight, this is strange. Figure 6.2 shows only 69 estimates of the total impact of climate change. With 69 estimates of the total, how can there be 59053 estimates of its first partial derivative? The answer is that there are 69 comparative-static estimates of the total impact of climate change on the current economy and for a particular scenario. The static results in Figure 6.2 need to be turned into dynamic ones by assuming a particular scenario for emissions and climate change, by assuming a scenario for development and the evolution of adaptive capacity, and by assuming functional forms of the relationship between impacts on the one hand and climate and development on the other. Furthermore, impacts need to be aggregated over time, over space, and over states of the world (see Chapters 9, 10 and 11). This introduces many additional degrees of freedom, which explains the proliferation of estimates of the marginal damage cost of carbon dioxide. In fact, only a fraction of the 69 estimates of the total impact have been used to estimate the social cost of carbon.

Figure 6.8 summarizes the many estimates in a cumulative density function (CDF). The CDF shows that, if all published estimates are considered, there is 33% chance that the marginal damage cost is less that $200/tC and a 67% chance that it is greater.

> The social cost of carbon is higher if the discount rate is lower, and its right tail is much fatter.

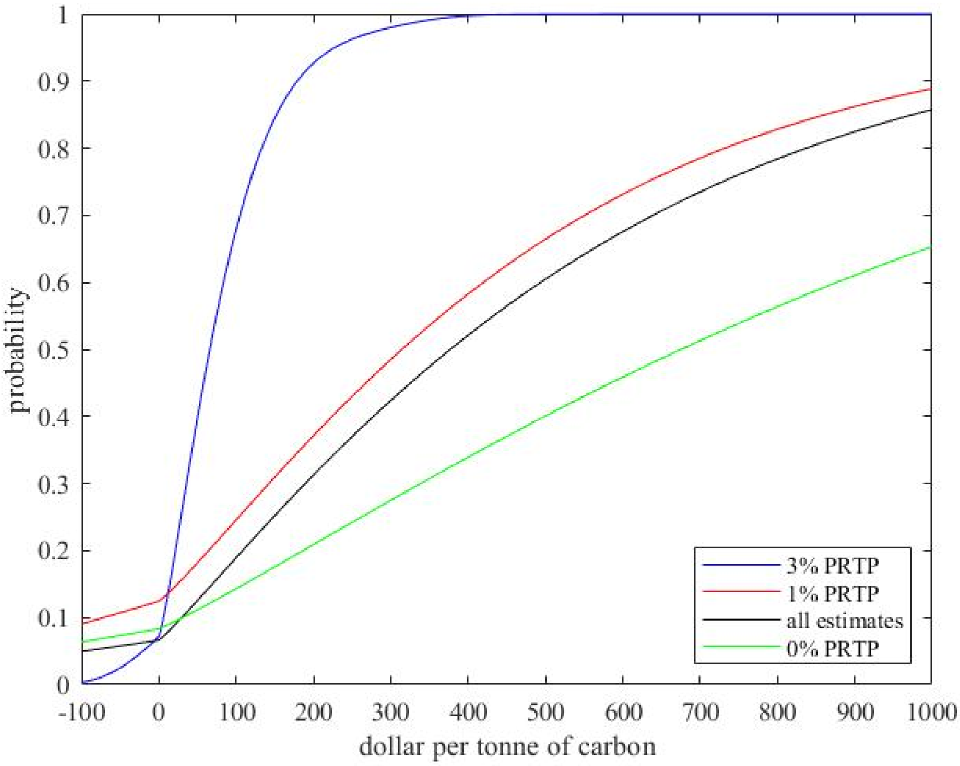


Figure 6.8: The cumulative distribution function of the social cost of carbon for all published studies and for all published studies that use a particular pure rate of time preference

Figure 6.8 also illustrates the power of one of the most important parameters: The pure rate of time preference (PRTP). The PRTP is the utility discount rate. It measures how much we care about the future for the sake of it being then not now (see Chapter 9). The sample is split into four: Estimates that use a PRTP of 0%, 1% or 3% are shown, while other estimates (a handful only) are ignored. The lower the discount rate you use, the more you care about the future, the more you care about climate change, and the higher the marginal damage cost. The median estimate, for instance, is around \$50/tC for a 3% pure rate of time preference, almost \$300/tC for 1% rate, and \$650/tC or so for 0% rate.

Table 6.1 shows some of the characteristics. With a PRTP of 3%, a carbon price of \$40/tC can be justified. With a rate of 1%, a carbon price of \$364/tC passes the benefit–cost test.

The discount rate has another effect. The CDF for all estimates does not really converge

Table 6.1: The marginal damage costs of carbon dioxide emissions in \$/tC

	all	3%	1%	0%	Pigou	SCC
mean	179	43	163	407	154	195
std. err.	16	54	301	539	19	23

Note: Pigou and SCC are the marginal damage costs with and without optimal emission reduction, respectively. Numbers shown are for a 1% PRTP.

to one, that is, there is a chance that the carbon tax should be greater than $1,000/tC. This is entirely driven by the estimates that use a PRTP of 0%. For a higher rate, the CDF rapidly converges to one. This means that the discount rate not only discounts the impacts of climate change, but also the uncertainty about the impacts. This is intuitive. As we look further into the future, the uncertainty becomes ever larger. We have a clear idea of what next year will be like, and a rough idea of the next decade, but only a foggy idea of the next century. The discount rate curtails how far we look into the future, and thus how much uncertainty we have to contend with.[3]

Figure 6.9 shows the same information as Figure 6.8 (for a pure rate of time preference of 3%), but now as a probability distribution function, the first partial derivative of the cumulative density function. Figure 6.9 splits the 3% PRTP sample into those studies that estimate the marginal damage cost along a no climate policy scenario, and those studies that impose a carbon tax equal to the marginal damage cost estimate. If the carbon tax equals the marginal damage cost, it is known as the Pigou tax (see Section 4.1). If a carbon tax is imposed, emissions fall and climate change is less of a problem. Therefore, the Pigou tax is less than the social cost of carbon: $154/tC versus $195/tC. Figure 6.9 and Table 6.1 also show that a carbon tax sharply reduces the uncertainty about the marginal damage cost of carbon dioxide emissions.

6.6 The growth rate of the social cost of carbon***

The social cost of carbon should rise by some 1.5% per year.

There are a number of studies of the evolution over time of the marginal damage costs of greenhouse gas emissions. The mean growth rate of the marginal damage cost is 2.2% per year, with a standard deviation of 1.0%. If we take all studies that use a no-policy scenario, the mean growth rate of the social cost of carbon is 2.3% with a standard deviation of 1.0%. If we take all studies that use an optimal scenario, the mean growth rate of the Pigou tax is 2.1% with a standard deviation of 1.0%.

The difference in growth between the social cost of carbon and the Pigou tax is because climate policy affects climate change in the long run, but not in the short run. The Pigou tax is therefore not only lower than the social cost of carbon (cf. Figure 6.9), it also rises more slowly.

There is a sharp contrast between dynamic efficiency and dynamic cost-efficacy. In the latter case, the price of carbon should rise at a rate that is about 0.6% higher than the rate of discount (see Section 4.6). In the former case, the price of carbon should rise at some 2.2% per year.

Further reading

Every six years, Working Group II of the Intergovernmental Panel on Climate Change publishes a major assessment of the impacts of climate change. The information is layered, with a Summary for Policy Makers with high-level information, Technical Summaries with more detail, and multiple chapters with a lot of detail and references to the underlying literature. See its

[3] The marginal damage cost is the net present value of marginal damages in the future. The marginal damage is thus a summation of a series, and you would want it to converge, that is, its value should not change if you add an extra year at the end. If you use the low utility discount rate of 0.1% per year advocated by Lord Stern of Brentford, welfare impacts 12,000 years from today may still affect the net present value. Forecasting that far into the future is hard. *I've been to year 3000. Nothing has changed but they live underwater.* 12,000 years ago, humans were hunter-gatherers. Agriculture had yet to be invented.

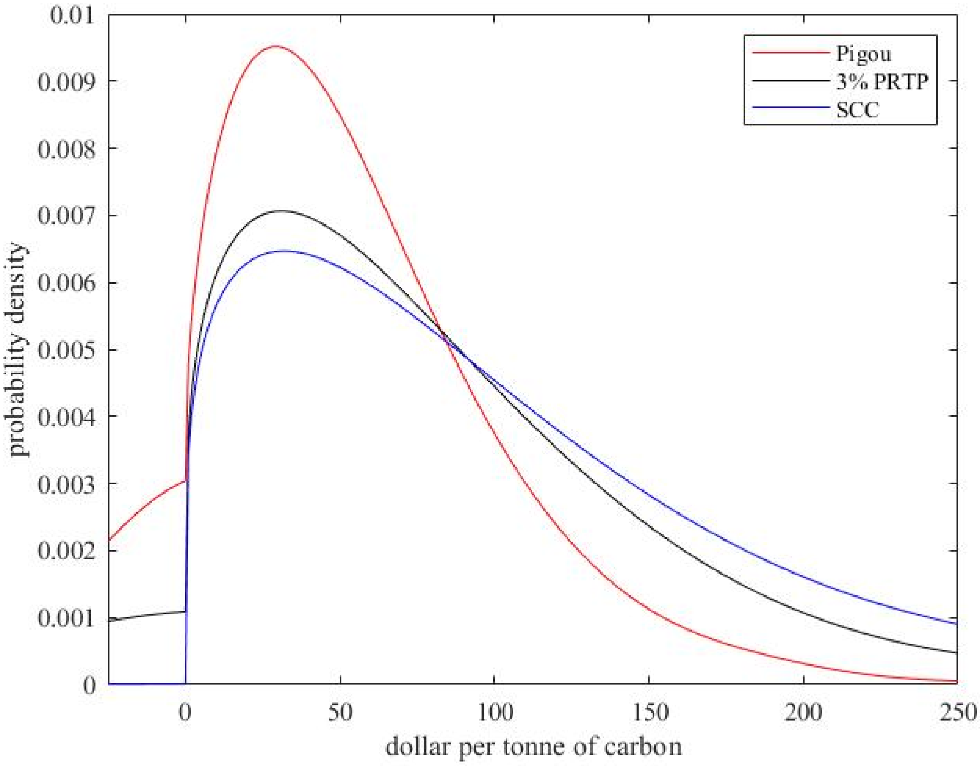


Figure 6.9: The probability density function of the social cost of carbon for all published studies that use a 3% pure rate of time preference, for all studies that estimate the social costs of carbon and for all studies that estimate the Pigou tax

website: . Samuel Fankhauser's 1995 book *Valuing Climate Change: The Economics of the Greenhouse* remains the best introduction to the economic impact of climate change. Matthew E. Kahn's 2010 book *Climatopolis* is a light-hearted introduction into how people adapt to climate change. His 2021 *Adapting to Climate Change* is a non-technical follow-up.

IDEAS/RePEc has a bibliography on impacts: http://biblio.repec.org/entry/tdd.html and one on adaptation: http://biblio.repec.org/entry/tdj.html.

Exercises

6.1. The statistical method to estimate the impacts of climate change uses the so-called ergodic assumption: It assumes that the relationship between welfare and climate that was estimated over space also holds over time. Formulate three objections to the ergodic assumption.

6.2. How will the marginal damage cost of carbon dioxide respond to:

- An increase in greenhouse gas emissions?
- An improvement in health care for infectious diseases?

- An improvement in health care for cardiovascular diseases?
- An increase in economic growth?

6.3. Suppose you have a budget of $100 million. You want to use this money to reduce the impacts of climate change on poor countries. How would you allocate the money over mitigation and adaptation?

6.4. Read and discuss:

- **G.W. Yohe and R.S.J. Tol (2002), Indicators for social and economic coping capacity —moving toward a working definition of adaptive capacity, *Global Environmental Change*, 12, 25–40.
- **T.C. Schelling (2000), Intergenerational and international discounting, *Risk Analysis*, 20, 833–837.
- ***W.N. Adger (2006), Vulnerability, *Global Environmental Change*, 16, 268–281.
- ***R.S.J. Tol (2005), Emission abatement versus development as strategies to reduce vulnerability to climate change: An application of FUND, *Environment and Development Economics*, 10, 615–629.
- ***M. Greenstone, E. Kopits and A. Wolverton (2013), Developing a social cost of carbon for US regulatory analysis: A methodology and interpretation, *Review of Environmental Economics and Policy*, 7, 23–46.
- ***M. Dell, B.F. Jones and B.F. Olken (2014), What do we learn from the weather? The new climate-economy literature, *Journal of Economic Literature*, 52, 740–798.
- ****J.P. Berrens et al. (2006), Information and effort in contingent valuation surveys: Application to global climate change using national Internet samples, *Journal of Environmental Economics and Management*, 47, 331–363.
- ****W.K. Viscusi and R.J. Zeckhauser (2006), The perception and valuation of the risks of climate change: A rational and behavioral blend, *Climatic Change*, 77, 151–177.

Chapter 7

Climate and development

Thread

- Climate change affects economic growth through its impact on productivity, labour force, and depreciation. #climateeconomics

- Negative impacts would decelerate growth. These indirect impacts are of the same size as the direct impacts. #climateeconomics

- The rational response to these impacts is to consume more, invest less and further decelerate growth. #climateeconomics

- Poor countries grow more slowly in hot years. Slow growth in Africa may have been caused by a secular decline in precipitation. #climateeconomics

- Some say climate and geography are economic destiny, others that climate and geography are not important. #climateeconomics

- Climate may contribute to trapping people in poverty, e.g., through infant mortality or via volatility and insecurity. #climateeconomics

- Natural disasters have a negative effect on welfare and economic growth, particularly in developing countries. #climateeconomics

7.1 Introduction

Chapter 6 discusses the static impacts of climate change and its distribution. These impact estimates are conditional on a given level of economic development, typically that of the recent past. Chapter 6 shows that poor societies are more vulnerable to climate change for three reasons, one of which—location—is an association but the other two—economic structure, adaptive capacity—are causal. These static impact estimates overlook one thing: Climate change would also affect economic growth and development. If climate change reduces economic growth, societies would be more vulnerable to climate change than they otherwise would have been, further reducing economic growth. This chapter explores these issues.

7.2 Exponential growth**

Climate change affects welfare in four different ways—utility, labour supply, productivity, depreciation—the latter three of which have ramifications for growth. Climate change may affect utility directly. For instance, climate change may drive a species to extinction. If this species has an existence value, and an existence value only, utility will fall—but the economy is not affected. It is hard to think of a concrete example. Existence values are well-documented, but most charismatic species generate tourism revenue too. But if we assume that tourists are attracted to whales in general, rather than to specific species of whale, then the extinction of a one species would not affect tourist numbers, particularly if it is one of the smaller, less spectacular whales.

> Climate change affects economic growth through its impact on productivity, labour force, and depreciation.

Climate change may affect the size of the labour force, through changes in mortality, or its productivity, through changes in morbidity. Furthermore, manual labour is harder in hot and humid climates. This would have an impact on total output, and thus on investment and future output. Climate change may also affect the productivity of other inputs. These effects can be direct. For instance, crops may grow less well if it is hotter and drier. Traffic and transport may be disrupted by extreme weather. This affects total output and hence investment and future output.

Cognition, too, may be negatively affected by heat. People may make more mistakes during hot weather, and students perform worse at exams. This also reduces productivity, output and investment. It may direct funds towards less profitable projects. There are indirect effects on productivity too. Climate change would increase the demand for air conditioning: This allows office work to continue, unaffected by the heat outside, but would of course increase costs without increasing output—the definition of a productivity loss. This changes the composition of supply too, in this case shifting towards a relatively unproductive sector (power generation). As productivity changes, so do output and investment.

Finally, climate change may affect capital deprecation. More frequent floods, for instance, would wash away bridges, roads, and buildings. This implies that there is less capital and thus less output and investment. It also implies that more investment goes towards replacing capital and less towards expanding the capital stock.

> Negative impacts would decelerate growth. These indirect impacts are of the same size as the direct impacts.

If the static impacts of climate change are negative, so are the impacts on economic growth: Lower output reduces investment, so that future capital and hence future output are lower too. Calibrated models show that the indirect effect of climate change on welfare—lower income due to slower economic growth—is of similar size as the direct effect of climate change over the course of the 21st century.

> The rational response to these impacts is to consume more, invest less and further decelerate growth.

The above assumes that people and companies do not adjust their savings and investment in response to climate change. Lower output does not necessarily mean lower investment if the savings' rate goes up. However, if anything, the savings' rate goes down in response to reduced output. First, for a fixed savings' rate, reduced output means reduced consumption. A higher savings' rate means lower consumption still, a sacrifice many households would be reluctant to make. Second, if climate change reduces output, then so it reduces the returns to investment. The optimal savings' rate thus falls, further reducing investment and growth. Calibrated models indeed show that, with an endogenous savings' rate, economic growth decelerates further—if only slightly.

Calibrated models also show that if more of economic growth is endogenous (to the model), the impact of climate change on growth is larger. In the canonical Solow model, 25% of economic growth is explained by capital accumulation (which is in the model) and 75% by technological progress (which is not in the model). If technological progress is included in the model—making it a so-called new growth model—then investments in R&D or human capital would fall just like investments in physical capital would. As a result, economic growth decelerates even further.

7.2.1 Empirical evidence

> Poor countries grow more slowly in hot years. Slow growth in Africa may have been caused by a secular decline in precipitation.

There is empirical evidence that economic growth slows down in extraordinarily hot years, particularly in poor countries, with the effects concentrated in agriculture and industry. Most studies show that this effect is small, but there is some support for larger impacts. The main problem with these studies is that they relate *weather shocks* to changes in economic output. Unusually hot weather is unusual. It therefore does not pay to fully prepare for such a rare event, and we suffer if it does occur. A weather shock is therefore a poor analogue for climate change: As hot weather becomes less unusual, we will be better prepared. In other words, the empirical studies of the impact of weather on economic activity estimate a short-term elasticity; a study of the impact of climate change requires a long-term elasticity. In this case, the short-term elasticity is likely to be larger than the long-term elasticity, so that the generally small effects found are likely to be upper bounds of the real impact.

One study found that the decline in rainfall in the 20th century partly explains why the economies of sub-Saharan Africa have grown more slowly than those of other developing regions. This evidence is more convincing as it relates a secular change in the weather—i.e., climate change—to a secular trend in economic development. There is another study that found that hot and wet conditions and large variability in rainfall reduce long-term growth in poor countries (but not in hot ones) and increase the probability of being poor.

7.3 Poverty traps**

Poverty is concentrated in the tropics and subtropics. Figure 7.1 shows the standard of living—per capita income measured in purchasing parity dollar—for a large number of countries at twelve different points in time. Until 1750, cold countries appear to be at a disadvantage. After that, hot countries are poorer. Over time, the point of gravity of the world economy shifted from the Middle East and Mediterranean to Western Europe and North America.

> Some say climate and geography are economic destiny, others that climate and geography are not important.

Although the correlation is clear, causation is disputed. Some argue that climate and geography are destiny. Environmental determinism was a popular theory in centuries past. The then dominant people argued that they were on top because some deity had bestowed them

Source: After Angus Maddison.

Figure 7.1: Standard of living as a function of the annual mean temperature

with the best of all climates. Jared Diamond is the main current proponent of this hypothesis, albeit without the dodgy theology. He argues that the current distribution of income across the world can be explained by a few factors of geography. The orientation of the axis of the Eurasian continent is East-West. That implies that areas with similar climates are connected. An innovation in one place—say, a newly domestic animal or a newly bred crop—can be used in a large area. This is not the case on continents with a North–South orientation, that is, Africa and the Americas. The distribution of domesticable plants and animals is also supposed to have been more favourable in Eurasia. Europe got ahead of China because its geography was conducive to many small kingdoms, competing for supremacy and thus innovative; China's geography, instead, invited a uniform emire. Diamond's grasp of history is not without blemish, and his notion that human history is shaped by geographic factors beyond our control is in contrast with the facts. Diamond's hypothesis is easily dismissed when comparing the two halves of Hispaniola and Korea.

> Climate may contribute to trapping people in poverty, e.g., through infant mortality or via volatility and insecurity.

Others, including Jeffrey Sachs, argue that climate and geography are contributing factors to (under)development, influential but not predominant. Diseases such as malaria and diarrhoea impair children's cognitive and physical development. This leads to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children, and risk-averse parents to have more children than they really want. As a result, investment in the children's health and education is spread thin and the children are likely to grow up to a life of poverty. Infectious diseases are more virulent and prevalent in warmer and wetter climates. Climate change may increase infant and child mortality and morbidity and thus trap more people in poverty.

Infrastructure also affects economic development. Travel and transport allow for trade (Ricardian growth) and specialization (Smithian growth). Infrastructure is more expensive in some climates than in others, for example because of repairs after frequent floods. Disasters have other effects on development too. Households and companies trade-off returns to investment against its safety. In a high-risk environment, safe assets with a low return would be preferred, particularly if insurance or asset diversification is expensive or unavailable—as is often the case in poor countries. Slow growth is the result. The jury is still out, though, on the relationship between climate change and weather-related disasters, and between climate change and human-made disasters (such as violent conflict).

Yet others, including Daron Acemoglu, argue that climate and geography were important in the past in shaping institutions (education, rule of law, etc.) but that institutions explain the current pattern of development. Tropical diseases determined the pattern of European colonization. Some parts of the world were hospitable to Europeans, who settled there (often after removing or killing the natives) and established universities, courts and representative government. Europeans could not cope with the diseases prevalent in other parts of the world, and therefore raided rather than settled. The plunder, pillage and rape that followed destroyed native societies. This historical divide, which is due to climate through the spread of tropical diseases, explains the current income distribution rather well. However, climate affected only past, not current development.

Others still, including William Easterly and Dani Rodrik, argue that institutions are the only thing that matters: Climate and geography have no power to explain the distribution of income across the world once the effects of education, the rule of law, the quality of governance have been accounted for. This extreme position—that the only thing that matters to humans are other humans—cannot seriously be maintained. Climate indisputably affects agriculture, energy, health, and tourism. Geography incontrovertibly affects transport.

The question is not whether but to what extent climate determines the pattern of development. Could it be that climate is a contributing factor to the probability that people are trapped in poverty? If so, the impacts of climate change may be (much) larger than commonly believed. The welfare impacts of growing at a small rate versus not growing at all are large when accumulated over a century or more.

7.3.1 Empirical evidence

All four schools of thought—climate is destiny, climate is important, climate was important but is no longer, and climate is irrelevant—have empirical support. This reflects the difficulty of establishing causality in a cross-section when there are many confounding factors—including, to confuse the institutional determinists, evidence that climate shapes culture. One recent paper argues that the tse-tse fly, which is confined to certain climates, plays an important role in Africa's poverty, as it prevents the use of animals for milk, meat, transport and traction. Another recent paper argues that it is not climate, but rather UV-radiation that explains incomes, through its impact on the probability of going blind and hence the incentive to learn a craft or trade. Unfortunately, the current state of knowledge is that we do not know. I think we can safely exclude the two extreme positions, but it is too early to say whether climate played in minor or major role in determining why some people are poor and others rich—and hence under what circumstances climate change would prevent certain economies from growing.

7.4 Climate and culture****

Although there is evidence that climate affects development, the received wisdom in economics is that institutions matter more, indeed dominate the climate signal—allowing for the possibility that climate and geography may have shaped those institutions.

Besides formal institutions, such as the rule of law and higher education, culture also matters. Some have argued that highly volatile environments induce a feast-and-famine culture. A rational response to the risk of losing it all, whether to a drought or a warlord, could indeed be to enjoy the good times while they last and hope to make it through the bad times. Legitimate concerns about investment in tangible assets such as cattle may spill over into investment in intangible assets such as education. If such an investment-is-pointless attitude becomes engrained, people may be slow to escape poverty even if volatility falls. The psychologist Evert van der Vliert has documented that many cultural traits *associate* with climate, including proneness to depression, aggression, creativity, xenophobia, and individualism.

The economist Oded Galor takes this research a step further, claiming *causality*. He argues that people from areas with higher crop yields are more oriented towards the long-term—agriculture requires planning and patience—and that people from more volative climates are more loss-averse—they would have been wiped out if not. Loss aversion and long-term orientation drive human behaviour and so economic development. Galor emphasizes, however, that these human traits are an adaptation to the climate of the deep past and change only very slowly. The impact of future climate change would therefore be limited.

Table 7.1: Empirical evidence of the impact of climate on economic development and growth

Study	Data	Dependent variable	Findings
Gallup, Sachs and Mellinger (1999) IRSR	Cross-section	Per capita income, growth	A climate suitable for malaria affects development and growth; controlled for institutions.
Acemoglu, Johnson and Robinson (2001) AER	Cross-section	Per capita income	Protection against the risk of expropriation is the key predictor of development. Expropriation risk is best explained by the mortality of European settles at the onset of colonialization.
Bloom, Canning and Sevilla (2003) JEG	Cross-section	Per capita income	Development in poor countries, and the chance of being poor are affected by temperature and precipitation.
Easterly and Levine (2003) JME	Cross-section	Per capita income	Geography and climate explain a broad range of institutions. Institutions in turn explain development.
Rodrik, Subramanian and Trebbi (2004) JEG	Cross-section	Per capita income	Geography and climate explain a broad range of institutions. Institutions in turn explain development.
Olsson and Hibbs (2005) EER	Cross-section	Per capita income	Climate, latitude, continental size and orientation, and domesticable plants and animals significantly influence development; controlled for institutions.
Nordhaus (2006) PNAS	Cross-section	Income	The relationship between temperature and output is negative when measured per capita and positive per area.
Barrios, Bertinelli and Strobl (2010) REStat	Panel	Growth	The secular decline in rainfall in sub-Saharan Africa explains slow economic growth.
Dell, Jones and Olken (2012) AEJ Macro	Panel	Growth	Temperature shocks affect economic growth, but only in poor countries.
Alsan (2015) AER	Cross-section	Night lights, number of cattle	Climate limits the spread of the tse-tse fly, which affected pre-colonial agriculture and political centralization, and hence current development.
Anderson, Dalgaard and Selaya (2016) REStud	Cross-section	Per capita income	Not climate but ultraviolet radiation explains disease ecology and hence development.
Henderson, Squires, Storeygard and Weil (2018) QJE	Cross-section	Night lights	Temperature, rainfall, growing days and malaria suitability all affect development.

7.5 Natural disasters***

Natural disasters have a number of effects on the economy. When disaster strikes, economic activity is disrupted and input factors are destroyed. Some disasters, such as floods and storms, particularly affect physical capital, such as buildings, roads and bridges. Other disasters, such as epidemics, primarily affect people and thus the labour force. Disruption of economic activity shows up in Gross Domestic Product. Destruction of capital, on the other hand, does not; it shows up in Net Domestic Product.

After the disaster, there is recovery. The deaths are buried, debris cleared away. Savings are mobilized, and insurance payouts and charity received to rebuild houses and roads. These are economic activities, and thus contribute to GDP.

Natural disasters have a negative effect on welfare and economic growth, particularly in developing countries.

Natural disasters thus neatly illustrate Bastiat's *broken window fallacy*: Destruction of the capital stock is not measured by GDP. Repair of the capital stock is. A naive look at GDP growth rates may thus lead one to conclude that natural disasters are good for short-term economic growth. This is not the case. Natural disasters stimulate economic activity. Natural disasters do not improve welfare. GDP is a measure of economic activity. It is not a welfare indicator. In cases like these, we should focus on NDP growth rates, but data availability is limited.

Natural disasters have different impacts at different phases of the business cycle. During a recession, the loss of input factors is less problematic as there is overcapacity anyway. The recovery phase is a Keynesian economic stimulus. During a boom, capacity is tight and lost inputs cannot readily be replaced. The demand stimulus from recovery may drive up inflation rather than output.

Natural disasters also have different impacts on different economies. Recovery requires resources. In developed economies, recovery is paid for by insurance, from household and company reserves, by the government, or by new loans from commercial lenders. In developing economies, contributions from these sources are limited, and recovery depends on support from informal networks and charity. Recovery from natural disasters is therefore slower, and sometimes much slower in developing countries than in developed economies. There may be hysteresis if customers switch to new suppliers.

Recovery replaces destroyed capital goods with new ones. Although the initial response is to restore things “exactly as they were”, in fact replacements are often superior: New machinery would be state-of-the-art, new buildings better designed, new roads without previous bottlenecks, and so on. This does not accelerate economic growth in the long run: The capital stock would be replaced anyway. Natural disasters force the hand of economic agents with regard to the timing of replacement investment. Discretionary timing would be preferred.

The impact of natural disasters on the economy in the short term is therefore mixed, but probably negative on net. The same is true in the long term. If there is a risk of natural disasters, resources are diverted to protective measures, be they financial (e.g., insurance) or physical (e.g., dykes). Insurance premiums are invested in liquid assets with a low return. The return on dykes is zero. If the disaster risk were zero, those resources could be used for consumption or for investment in productive assets.

7.5.1 Empirical evidence

The empirical evidence on the impact of natural disasters has grown rapidly. Earlier studies suffered from measurement errors—GDP is a poor indicator but most widely reported, and natural disasters are only reported when they cause substantial damage to humans—and endogeneity issues—richer societies are better able to shield themselves from natural disasters. There is now a substantial body of literature that shows that natural disasters indeed slow down economic growth, that this negative effect is stronger in poorer countries, probably because of financial underdevelopment. There is also some evidence that natural disasters weaken the financial sector, suggesting a potential poverty trap: Bad weather has a negative effect on insurers and banks, which leaves the exposed people more vulnerable to bad weather.

Further reading

Oded Galor's *The Journey of Humanity* (2022) is a non-technical introduction to growth and development with a particular emphasis on the role of climate and geography. Hubert Lamb's *Climate, History and the Modern World* (1995) is old but good. Lucien Febvre's *A Geographical Introduction to History* (1924) demolishes environmental determinism.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tde.html.

Exercises

7.1. Construct a Solow growth model of a one-sector, closed economy, assuming a Cobb–Douglas production function in labour and capital. Assume that the capital stock is in its steady-state value (either by running the model for 100 years without changing anything, or by solving the steady-state analytically). Assume, in turn, that climate change

- reduces total factor productivity by 10%
- increases depreciation by 10%
- reduces labour supply by 10%

What are the implications for per capita consumption after 1 year, 10 years, 100 years?

7.2. Read and discuss:

- **W. Easterly and R. Levine (2003), Tropics, germs and crops: How endowments influence economic development, *Journal of Monetary Economics*, 50, 3–39.
- **S. Barrios, L. Bertinelli and E. Strobl (2011), Trends in rainfall and economic growth in Africa: A neglected cause of the African growth tragedy, *Review of Economics and Statistics*, 92, 350–366.
- ***S. Fankhauser and R.S.J. Tol (2005), On climate change and growth, *Resource and Energy Economics*, 27, 1–17.
- ***M.E. Kahn (2005), The death toll from natural disasters: The role of income, geography, and institutions, *Review of Economics and Statistics*, 87, 271–284.
- ***L.A. Bakkensen and R.O. Mendelsohn (2015), Risk and adaptation: Evidence from global hurricane damages and fatalities, *Journal of the American Association of Environmental and Resource Economists*, 3, 555–587.

- ***T. Deryugina, L. Kawano and S. Levitt (2018), The economic impact of hurricane Katrina on its victims: Evidence from individual tax returns, *American Economic Journal: Applied Economics*, 10, 202–233.
- ****O. Galor and D.N. Weil (1996), The gender gap, fertility and growth, *American Economic Review*, 86, 374–387.

7.3. Essay: Read the studies in Table 7.1. Who has the strongest evidence?

Chapter 8

Optimal climate policy

Thread

- Article 2 of the UN Framework Convention on Climate Change calls for stabilization of the atmospheric concentration of CO_2. #climateeconomics
- Part of CO_2 emissions stay in the atmosphere forever—or rather, is removed at the rate at which rocks grow. #climateeconomics
- Thus, stabilization of the atmospheric concentration of CO_2 implies that CO_2 emissions have to go to zero. #climateeconomics
- Two degrees is an arbitrary target, set by 11 German professors, adopted internationally for want of an alternative. #climateeconomics
- In the social optimum, the marginal net present costs of a policy equal its marginal net present benefits. #climateeconomics
- The marginal costs of complete emission reduction are high. Eliminating all emissions is very difficult. #climateeconomics
- The incremental benefits of complete emission reduction are small. A little bit of climate change does little damage. #climateeconomics
- It cannot be optimal to reduce greenhouse gas emissions to zero, so it cannot be optimal to stabilize CO_2 concentrations. #climateeconomics
- Estimates of the abatement costs and benefits point to an optimal emission reduction effort that is modest. #climateeconomics
- Whereas all credible studies agree that emission reduction should start slow and stop short of 100% in the long-term ... #climateeconomics
- ... the magnitude of the "modest" effort in the medium term is very sensitive to a large number of assumptions. #climateeconomics
- 100% emission reduction is justified if there is a perfect and permanent substitute for fossil fuels at a reasonable price. #climateeconomics

- Secondary benefits are a good reason to cut other pollutants but not carbon dioxide. #climateeconomics
- The relative prices of greenhouse gases should equal their relative social costs of carbon or their relative shadow prices. #climateeconomics
- The global warming potential is a poor approximation of the relative social cost of carbon, incorrectly applied in a constrained optimization. #climateeconomics

8.1 The ultimate target**

Article 2 of the UN Framework Convention on Climate Change calls for stabilization of the atmospheric concentration of CO_2.

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), ratified by almost all countries, states that its

> ultimate objective [...] is to achieve [...] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Anyone can read anything into the second sentence. It is waffle. What is meant by "ecosystems" —all ecosystems, the majority of ecosystems? What is "natural adaptation" of ecosystems? Is the impact of the Younger Dryas an example of such "natural adaptation"? Does unthreatened "food production" refer to local food security, national food security, or global food security? Is food production only "threatened" by climate change, or does the large-scale production of bioenergy also count as a threat to food production? Could the impacts of greenhouse gas emission reduction be seen to disable "economic development to proceed"? Appealing but vapid language makes great diplomacy—everyone can sign up.

The first sentence seems to be of a similar nature. How can anyone object to avoiding (otherwise unspecified) danger? The word "stabilization", however, is not innocuous. Let us consider a simple stock model:

$$L_t = (1 - \delta)L_{t-1} + M_{t-1} \tag{8.1}$$

where L_t is the stock at time t, M is emissions, and δ is the rate of degradation. Equation (8.1) is a first-order linear difference equation. It describes a geometric process.

Stabilization requires that the stock does not change: $L_t = L_{t-1}$. Then

$$L = (1 - \delta)L + M \Leftrightarrow \delta L = M \Leftrightarrow L = \frac{M}{\delta} \tag{8.2}$$

That is, if emissions are stabilized —$M_t = M_{t-1}$—then concentrations stabilize too at a level that is inversely proportional to the rate of degradation of emissions in the atmosphere. In this case, stabilization of concentrations implies that emissions be stabilized at any level. Article 2 appears void—at least, until a temperature target was adopted in the Paris Agreement of 2015.

Figure 1.6 shows a stylized representation of the carbon cycle. Carbon dioxide is removed from the atmosphere by a number of processes. One of these is the weathering of rock, which is a very slow process. Mathematically, it is best to think about carbon dioxide in the atmosphere as five separate stocks

$$L_t = \sum_{i=1}^{5} L_{i,t} \tag{8.3}$$

each governed by its own first-order linear difference equation

$$L_{i,t} = (1 - \delta_i)L_{i,t-1} + \vartheta_i M_{t-1}; \sum_{i=1}^{5} \vartheta_i = 1 \tag{8.4}$$

> Part of CO_2 emissions stay in the atmosphere forever—or rather, is removed at the rate at which rocks grow.

Atmospheric stabilization then requires stabilization of each of the five sub-concentrations. However, atmospheric degradation in one of the five components is by a geological process (rock weathering) at a geological time scale. At a human time scale, there is no degradation at all: $\delta_i = 0$ for i=5; $\vartheta_5 = 0.13$. That is, about 13% of anthropogenic carbon dioxide emissions stay in the atmosphere practically forever.

Figure 8.1 illustrates this for past emissions of carbon dioxide. The darkest colour represents the background concentration. In slightly lighter grey are the "permanent" additions to the atmosphere. The lighter tones represent those parts of the carbon dioxide concentration that will eventually disappear. Figure 8.2 repeats this for scenarios of future emissions. The solid lines are the actual concentrations, the dashed lines the "permanent" parts.

> Thus, stabilization of the atmospheric concentration of CO_2 implies that CO_2 emissions have to go to zero.

The permanence of emissions poses a problem. In Equation 8.2, the stable concentration is inversely proportional to the rate of degradation. Dividing by zero is not possible. However, there is a solution for $\delta = 0$: If $M = 0$, concentrations stabilize.

The first sentence of Article 2 of the UN Framework Convention on Climate Change is therefore not vacuous. In fact, it is radical. Stabilization of the atmospheric concentration of carbon dioxide requires that emissions are reduced to zero. Almost all countries are under a legal obligation to reduce their emissions by 100%.

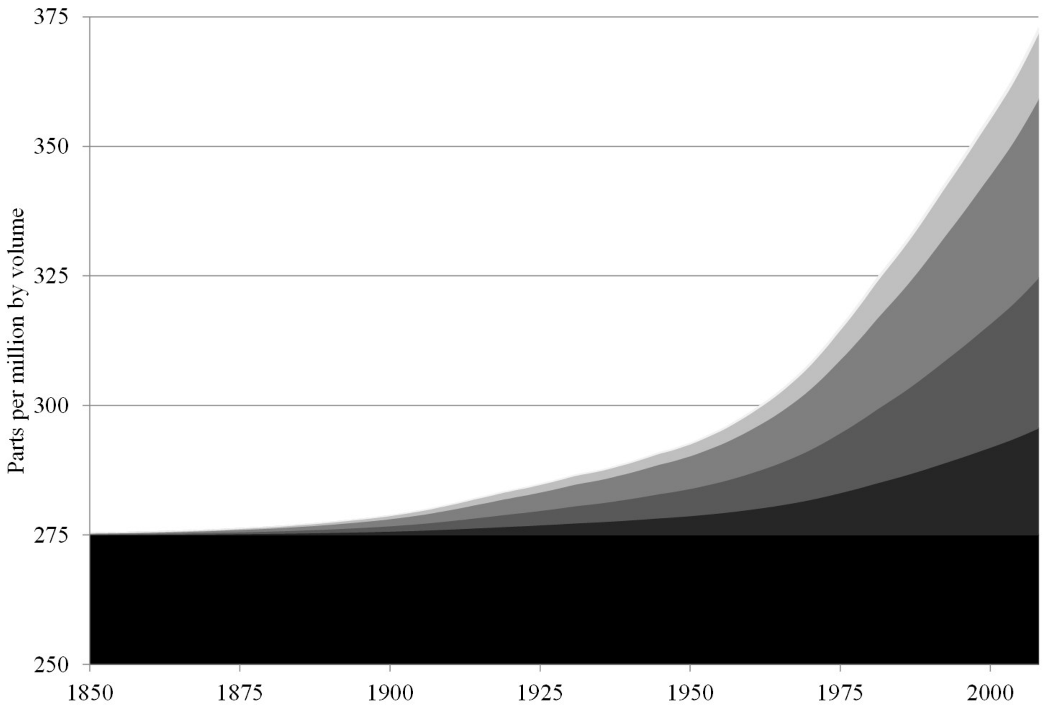
There is no evidence to suggest that the people who drafted Article 2 were aware of this. The people who ratified the UNFCCC probably did not realize the implications either. Indeed, politicians regularly refer to an 80% emission reduction goal in the long run, with the greener ones opting for 90%. International law says it is 100%, and it had said so since 1992.

Box 8.1: The Two Degrees target

Nobelist William Nordhaus was the first to suggest that the global mean surface air temperature should not exceed 2°C above pre-industrial. He did so in a 1975 *Cowles Foundation Discussion Paper*, claiming that

> if the global temperature were more than about 2°C above the current value, this would the climate outside of the range of observations which have been made over the [last] hundred thousand years.

Nordhaus did not repeat this claim in his 1977 paper in the *American Economic Review*. Influenced by Ralph d'Arge, Nordhaus soon abandoned arbitary targets in favour of



Note: The darker the colour, the more permanent the concentration. The bottom panel enlarges aspects of the top panel.

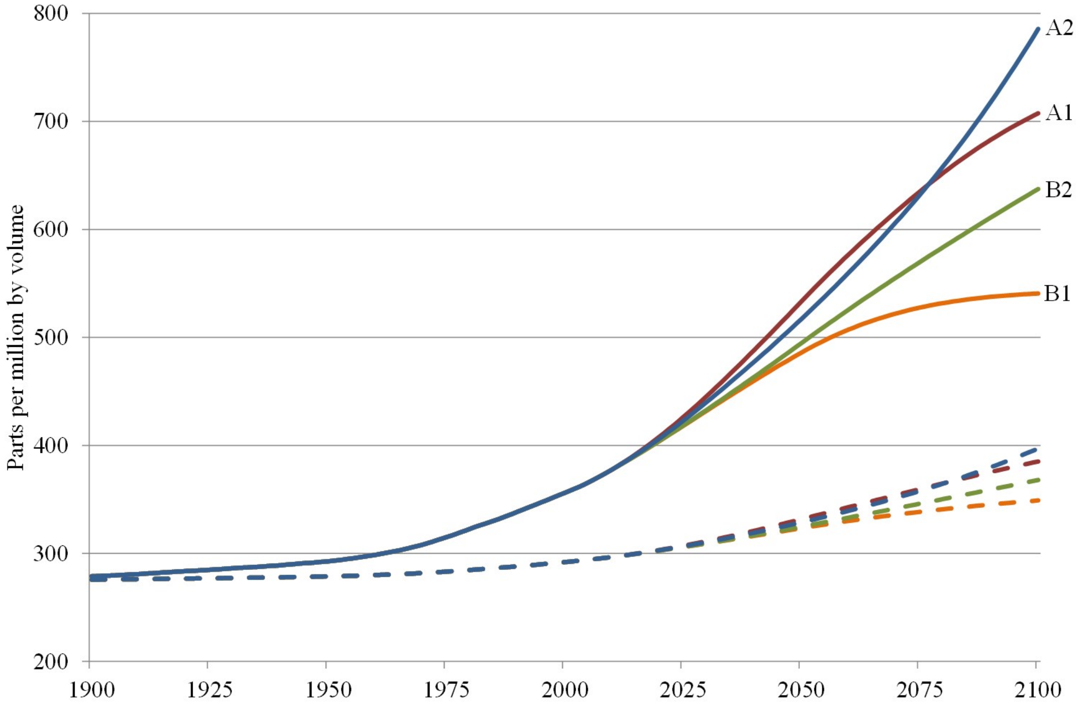
Figure 8.1: The atmospheric concentration of carbon dioxide

benefit–cost analysis. Nordhaus' 1975 remarks were largely forgotten until they were lifted from obscurity in 2011 by Carlo and Julia Jaeger.

Early attempts to set an upper limit to climate change focused on the rate of global warming. Research by the Netherlands National Institute for Public Health and the Environment and the Stockholm Environment Institute suggested that the world should not warm faster than 0.1°C per decade. This, however, is roughly equal to the natural variability of the global climate.

> Two degrees is an arbitrary target, set by 11 German professors, adopted internationally for want of an alternative.

The two degrees target was adopted in 1995 by the Scientific Advisory Council Global Environmental Change of the (German) Federal Government (WBGU), a committee of 11 German professors. It rests on three arguments. First, it aims to safeguard creation, a peculiar reason for a scientific council of a secular government. Like Nordhaus, the WBGU refers to the range of global temperatures since the emergence of modern humans. This is Hume's *is-ought fallacy.* By the same reasoning, we should be concerned about life expectancy, literacy and women's rights, all of which are decidedly above their historical ranges. It also ignores the generally accepted view of paleontologists and paleoanthropologists that humans evolved in the subtropics and later migrated to temperate climates.



Note: The dotted lines give the permanent part of the concentration.

Figure 8.2: The atmospheric concentration of carbon dioxide according to four SRES scenarios

The second argument by the WBGU is that 2°C warming would cause economic damages of 5% of GDP, a view that is not supported by the literature (see Chapter 6) and was not at the time. WBGU further claims that drastic ecological impacts could be expected if more warming were to happen, a claim that was far beyond the state of ecological research at the time.

The two degrees target was adopted by the German government in the same year, and a year later without much discussion by the Council of the European Union. This was a largely futile gesture. The European Union is not in charge of the global climate. The international negotiations at the time were focused on emission reduction targets for the year 2012 (see Box 12.4).

The two degrees target was reaffirmed by the Council of the European Union in 2004, as preparations for a successor treaty to the Kyoto Protocol began. From then on, the two degrees target, dreamed up by a committee of 8 middle-aged German men and 3 middle-aged German women, begins to gain traction. It was the only long-term, global target, and thus became a focal point for the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

After that, the two degrees target was the only game in town at the international climate negotiations under the United Nations Framework Convention on Climate Change (see Box 12.3). It was agreed in 2010 in Cancun to

> establish clear objectives for reducing human-generated greenhouse gas emis-

sions over time to keep the global average temperature rise below two degrees

This target was formally adopted in the 2015 Paris Agreement (see Box 12.5).

8.2 Benefit–cost analysis*

Benefit–cost 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 benefit–cost ratio. You should fund the projects with the highest benefit–cost 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.

Benefit–cost analysis works differently if there is a continuum of actions. A carbon tax, for example, can take any value (even if politicians tend to think in rounded numbers). In this case, benefit–cost 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 be equal to zero. Rearranging, marginal benefits should equal marginal costs.

Figures 8.3, 8.4 and 8.5 derive this graphically. Figure 8.3 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 greenhouse gases. 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 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 8.3.

Figure 8.4 introduces the gross damages from emissions. The more is emitted, the greater the damage. Figure 8.4 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 8.5 shows the slopes of the curves of Figure 8.4, 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.

In terms of calculus, consider

$$\max_M W = B(M) - D(M) \tag{8.5}$$

where W denotes net gains or welfare, M are emissions, D are the damages of emissions and B are the benefits of emissions. The emissions are the control variable. That is, emissions are chosen so as to maximize net gains. Then the first-order conditions are

$$\frac{\partial W}{\partial M} = 0 \Leftrightarrow \frac{\partial D}{\partial M} - \frac{\partial B}{\partial M} = 0 \Leftrightarrow \frac{\partial D}{\partial M} = \frac{\partial B}{\partial M} \tag{8.6}$$

That is, the marginal benefits of emissions should equal the marginal damages of emissions.

In the social optimum, the marginal net present costs of a policy equal its marginal net present benefits.

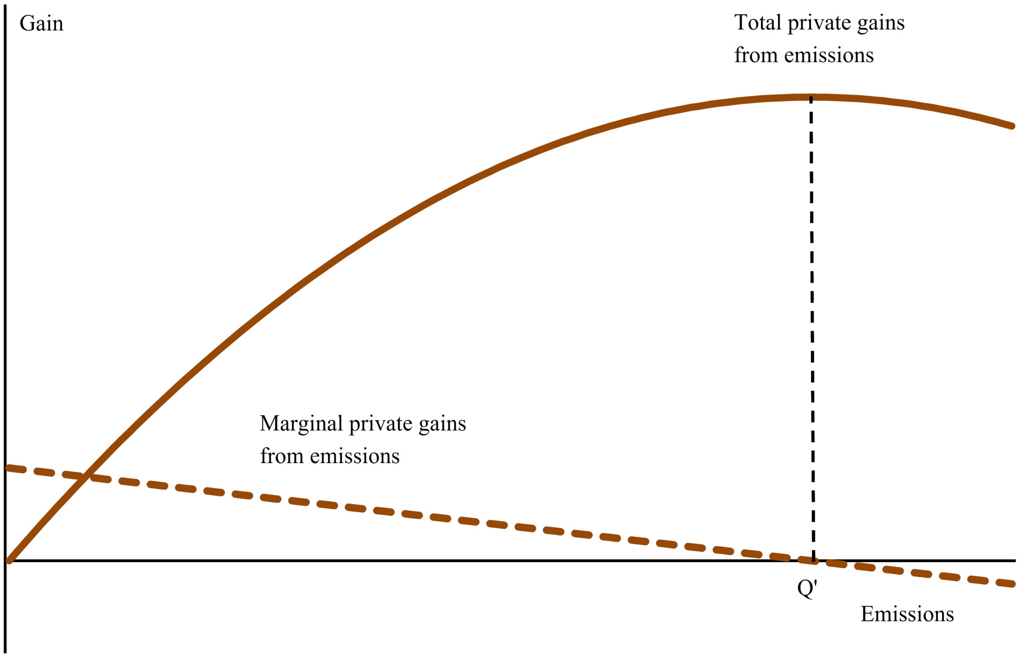


Figure 8.3: Optimal emissions if there are no external costs

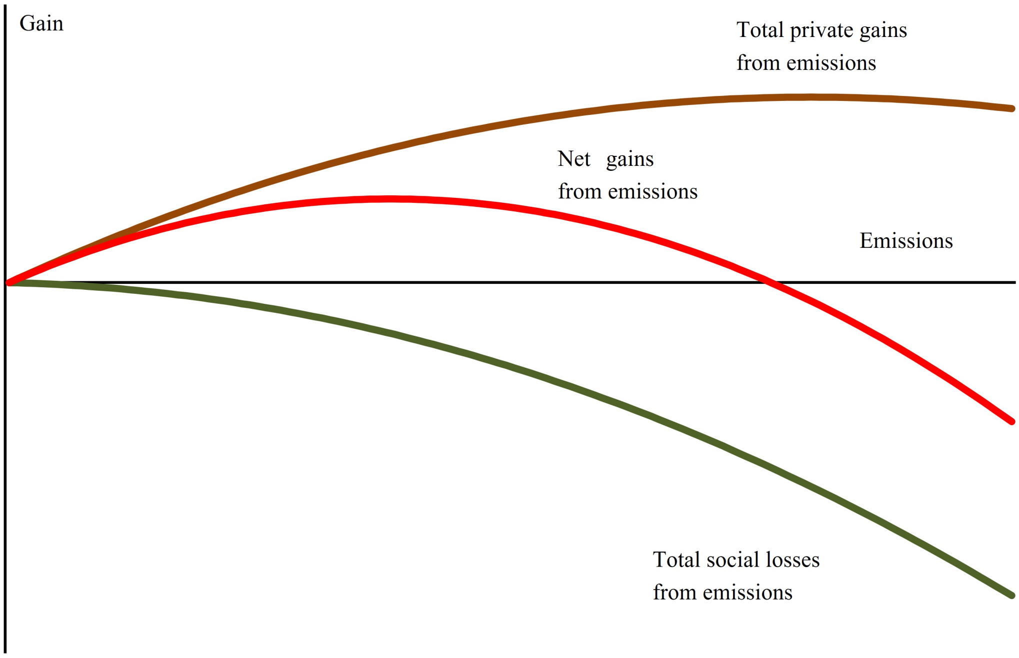


Figure 8.4: Costs and benefits of emissions

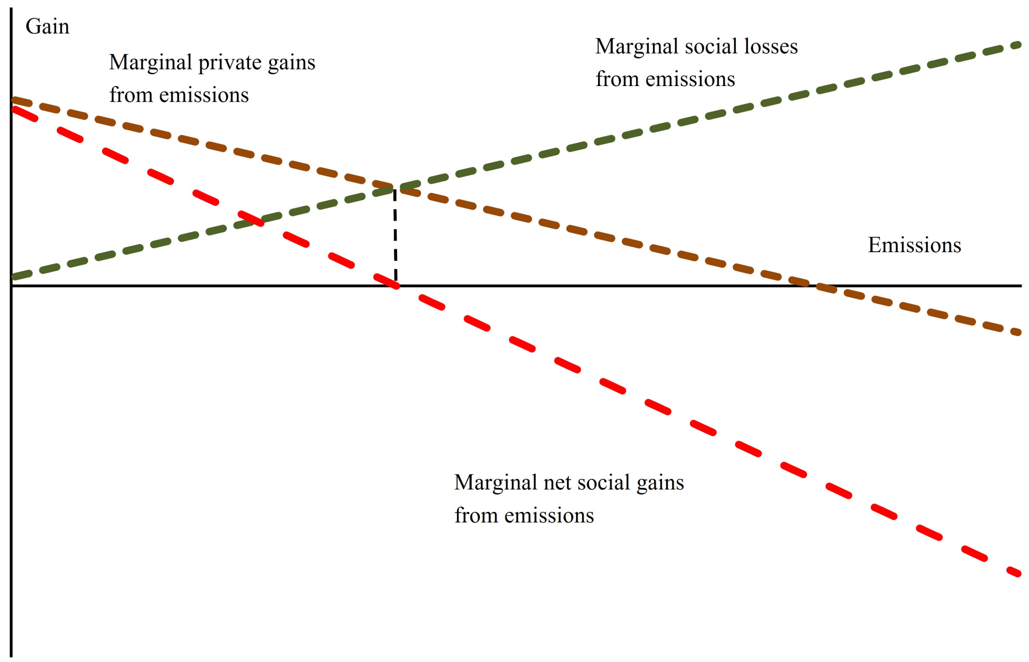


Figure 8.5: Optimal emissions with external costs

Climate change is a dynamic problem, however. Therefore, we need to rewrite Equation (8.5)

$$\max_{M_0,M_1,...} \sum_t \frac{W_t}{(1+r)^t} = \sum_t \frac{B_t(M_t) - D_t(M_t, M_{t-1}, ..., M_0)}{(1+r)^t} \tag{8.7}$$

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 too 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 (8.6), the level of emissions needs to be chosen simultaneously at every point in time. There are therefore many first order conditions:

$$\frac{1}{(1+r)^t} \sum_s \frac{1}{(1+r)^s} \frac{\partial D_{t+s}}{\partial M_t} = \frac{1}{(1+r)^t} \frac{\partial B_t}{\partial M_t} \forall t \tag{8.8}$$

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 8.5 illustrates Equation (8.8) as well as Equation (8.6): Costs and (net present) benefits should be equal at the margin (simultaneously at every point in time).

Figure 8.5 also illustrates two fundamental insights from benefit–cost 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, benefit–cost 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, benefit–cost analysis rarely calls for a complete elimination of emissions.

8.2.1 Application to climate change**

The marginal costs of complete emission reduction are high. Eliminating all emissions is very difficult.

Applied to climate change, greenhouse gas emissions can be reduced by a little bit without much of a bother. Energy use is often wasteful or the result of perverse incentives. On the other hand, eliminating all emissions is disruptive. While technical but costly alternatives have been identified for most applications of carbon dioxide, this is not (yet) the case for every niche application (e.g., in space travel and the military). Alternative energy sources are relatively cheap when applied at a small scale, but much more expensive at a large scale. Photovoltaic panels can be mounted on roofs (that is, with a zero opportunity cost for space) but roof space is finite. A little wind power can be easily integrated into an electricity network, but grid reinforcement, back up capacity, and frequency regulators are necessary when wind penetration is more than a few percent.

The incremental benefits of complete emission reduction are small. A little bit of climate change does little damage.

Vice versa, uncontrolled climate change can do a lot of damage and the initial emission reductions thus bring substantial benefits. Reducing climate change from 6℃ to 5℃ is probably a big benefit to human welfare. However, as climate change is reduced further and further, those benefits fall: The benefit of warming by 4℃ rather than 5℃ is smaller, the benefit of warming by 3℃ rather than 4℃ smaller still. The benefits from reducing global warming from 0.1℃ per century to 0.01℃ are tiny.

Therefore, a benefit–cost analysis will not recommend a 100% emission reduction. Yet, a 100% emission reduction is required by international law.

It cannot be optimal to reduce greenhouse gas emissions to zero, so it cannot be optimal to stabilize CO_2 concentrations.

8.2.2 Tipping points***

The popular discourse on climate change often refers to *tipping points*. These are non-linearities in the climate system or in its impacts. Crossing a certain threshold in global warming would lead to either a rapid acceleration of climate change or a sudden worsening of its impacts. One example is the disappearance of the arctic sea ice. Ice is light in colour; it has a high albedo, reflecting a lot of sunlight. Water is dark. If sea ice melts, the albedo falls, and warming accelerates. Another example is melting permafrost. This would release methane, a potent greenhouse gas, accelerating warming. On the impact side, a tipping point would occur if a dike or dam failure would lead to a catastrophic flood and the subsequent abandonment of Bangkok, Holland, London, or Shanghai.

Figure 8.6 shows the impact of a tipping point on cost-benefit analysis. There is a sudden jump in the social losses of emissions and hence in the net gains. There are now two local optima, one coinciding with the optimum in Figure 8.4. The local optimum just before the tipping point is the global optimum. You can see why environmentalists like to talk about tipping points.

Figure 8.7 shows the corresponding marginal cost and benefit curves. The tipping point introduces a discontinuity in the marginal benefit curve. The benefit function is no longer smooth.[1] As a result, marginal benefits equal marginal costs at two points, corresponding to the two local optima seen in Figure 8.6. You can see why cost-benefit analysts are not fond of tipping points.

The top left graph in Figure 8.8 repeats Figure 8.7, but without the marginal net gains. The top right graph introduces uncertainty. A tipping point is a discontinuity that causes havoc in a cost-benefit analysis. But everything about climate change is uncertain. How could we possibly know for certain when we would tip over the point? The top right graph of Figure 8.8 illustrates this. I pretend that the severity of the tipping point is known with certainty, but that there are two equally likely possibilities when it would occur. The result is two discontinuities in the marginal benefit curve, but these are half as big as they occur with a change of 0.5.

The bottom left graph in Figure 8.8 continues down this path. There are now four possible locations of the tipping point, each with a chance of 0.25, and four smaller discontinuities. The bottom right graph shows the logical conclusion. It shows the marginal benefit curve with a tipping point. The location of the tipping point is uncertain, but follows a known distribution function, in this case a normal one. The marginal benefit curve is now continuous again.

Tipping points therefore do not fundamentally alter the cost-benefit analysis,[2] unless there is unwarranted certainty about their location. That said, the possibility of tipping points and the associated large damages do increase the benefits of reducing emissions, and so increase the optimal amount of emission reduction.

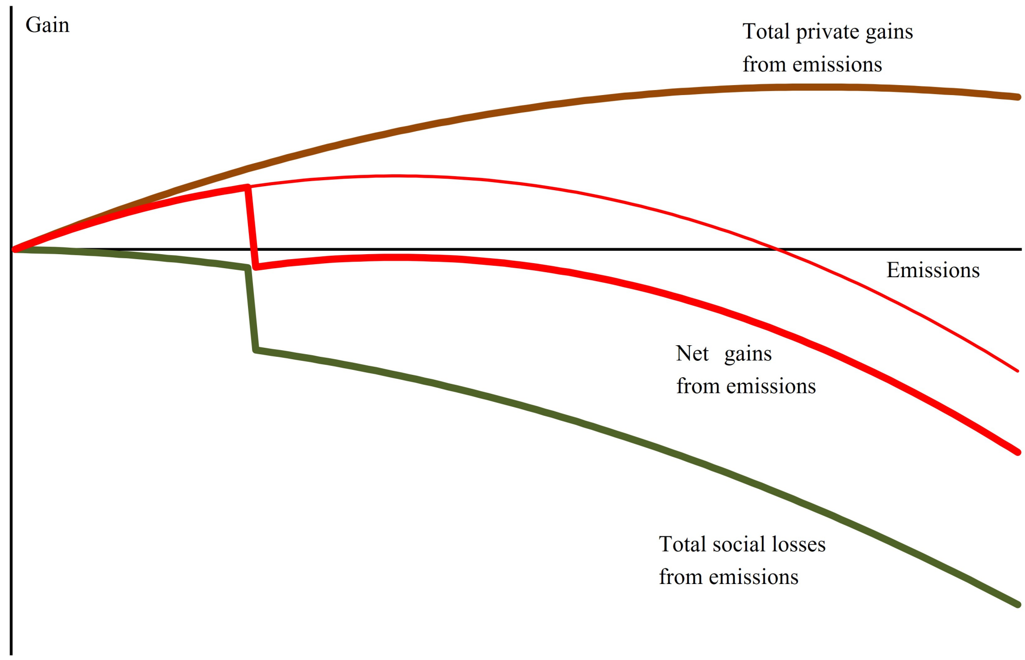


Figure 8.6: Costs and benefits of emissions with a tipping point

[1] A mathematician would say that the function belongs to C^0 but not C^1.

[2] The marginal benefit curve is no longer monotone. It increases with emissions for the most part, but not everywhere. The net benefit function is therefore no longer convex, and there may be multiple optima.

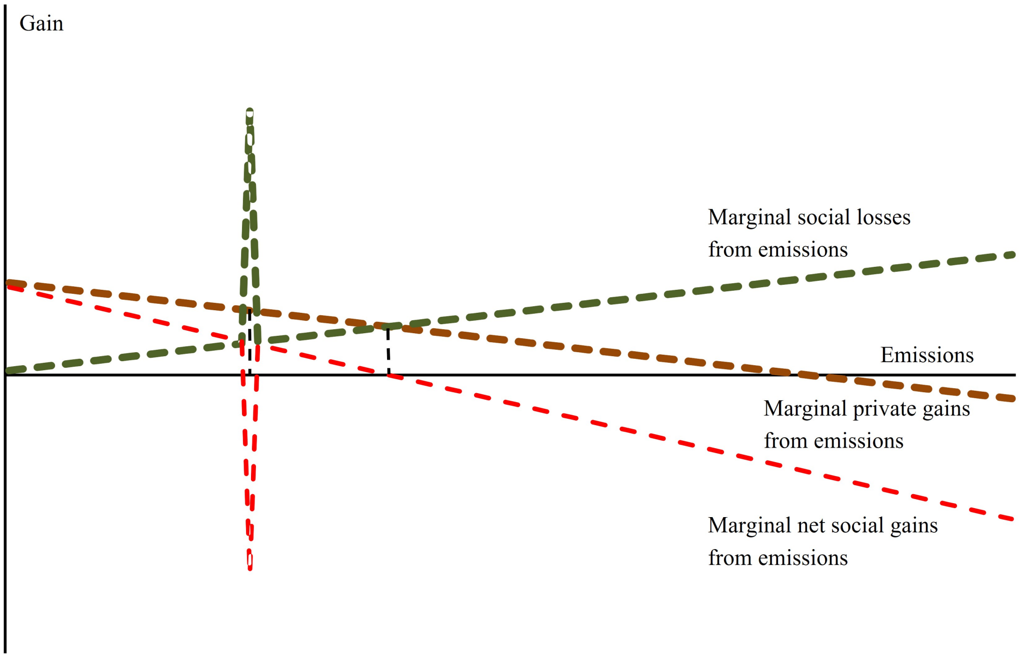


Figure 8.7: Marginal costs and benefits of emissions with a tipping point

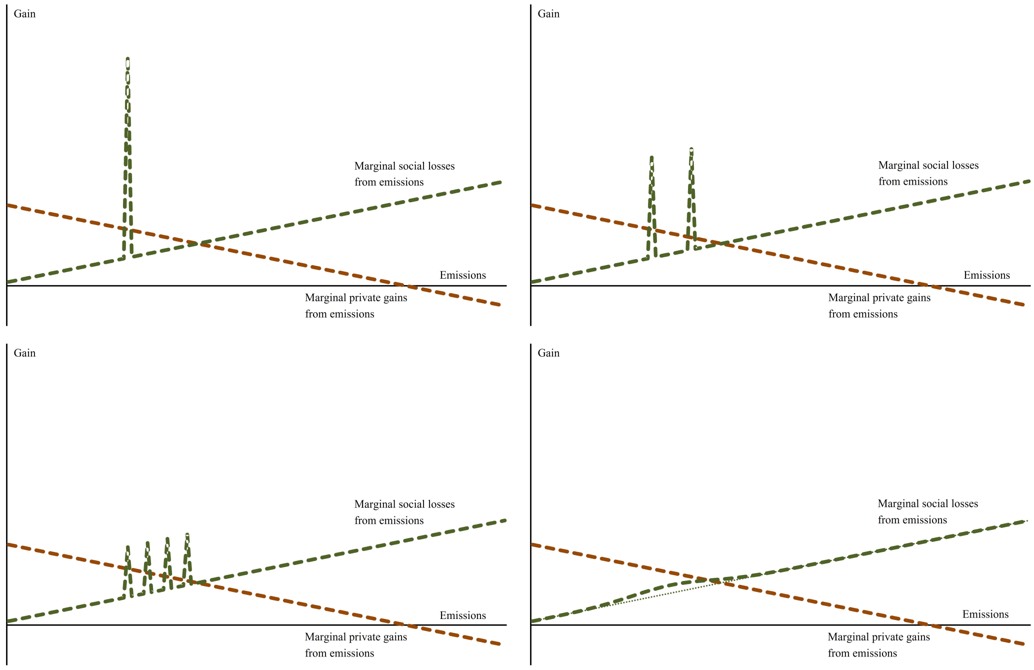


Figure 8.8: Marginal costs and benefits of emissions with uncertainty about the location of a tipping point

8.3 Estimates of optimal emission reduction**

Estimates of the abatement costs and benefits point to an optimal emission reduction effort that is modest.

Estimates of the marginal costs of greenhouse gas emission reduction were shown in Chapter 3. Estimates of the marginal benefits were shown in Chapter 6. A cursory comparison reveals that while emission reduction can be justified, deep cuts cannot.

This is confirmed by Figure 8.9 and Figure 8.10. It shows results of the DICE model, developed by William Nordhaus of Yale University, work for which he was awarded the 2018 Nobel Prize in Economics. Figure 8.9 shows the carbon tax that maximizes global welfare, and the corresponding emission control rate. Figure 8.10 shows the corresponding atmospheric concentrations of carbon dioxide.

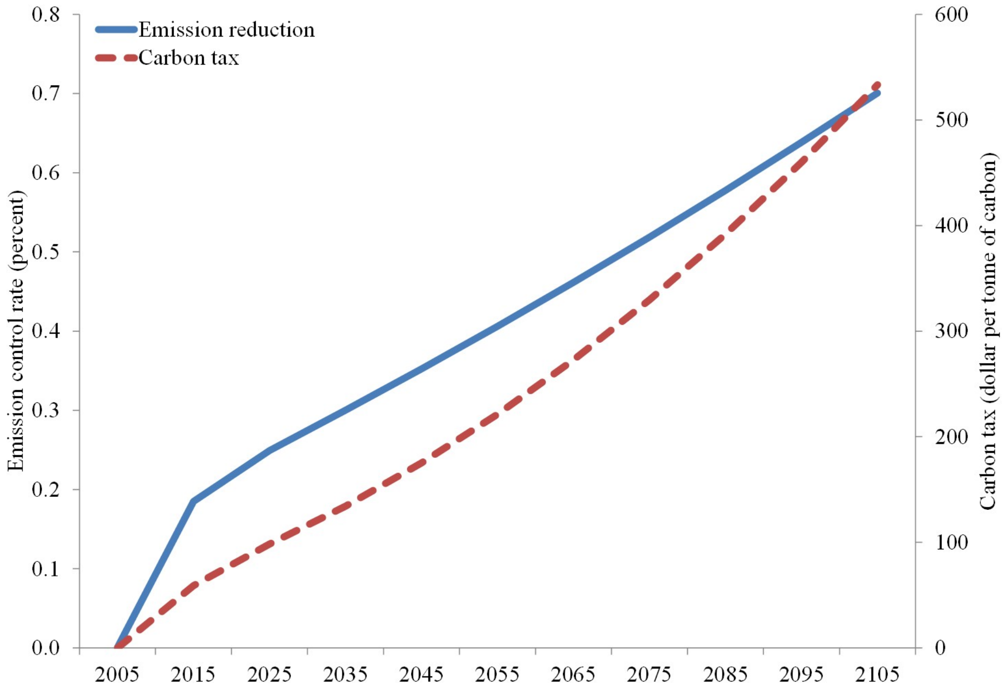


Figure 8.9: Optimal emission control and carbon tax

Essentially, the DICE model answers the question "if the world were ruled by a benevolent dictator, a philosopher-queen, what would she do about greenhouse gas emissions?" The answer is a little bit of emission reduction at first, more later, but not enough to stabilize the carbon dioxide concentration.

The details of this result depend, of course, on the many assumptions made in the DICE model. These assumptions are uncertain, and some are controversial. Nordhaus first published the bottom-line conclusion in 1991. Many researchers have since tried to overturn the result, which came as a shock then and continues to annoy people to this day.

Whereas all credible studies agree that emission reduction should start slow and stop short of 100% in the long-term, the magnitude of the "modest" effort in the medium term is very sensitive to a large number of assumptions.

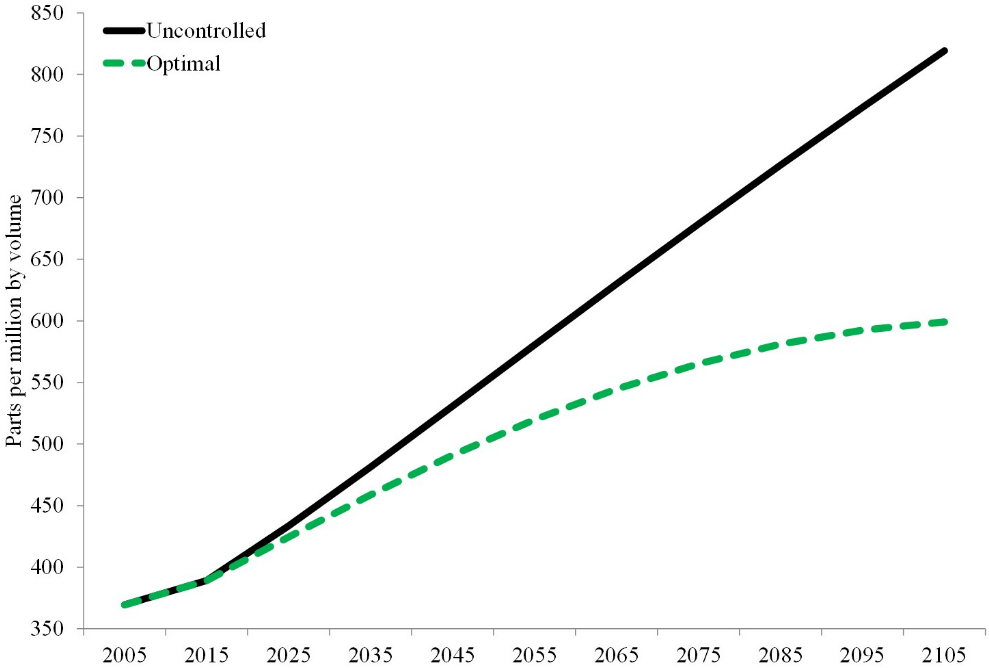


Figure 8.10: Optimal and uncontrolled carbon dioxide concentrations

The following results have emerged since 1991. The first part of the conclusion is robust. In the short run, emission reduction should be modest regardless of the assumptions that you make or the way in which you structure the model or the problem. Let us assume that a carbon tax is the instrument of choice for climate policy. A carbon tax is there to change behaviour. However, a substantial part of our behaviour with regard to energy use is fixed. For households, energy use depends on the houses we will live in, the cars we drive, and where we go to school or work. A carbon tax may induce us to buy a different car or move closer to work—but only when we had planned to replace our car or move anyway. In the meantime, a carbon tax imposes a cost without any gain. Similarly, corporate energy use is determined to a large degree by machinery, buildings, and locations—things that change slowly. Rapid emission reduction would require that we discard perfectly good durable and production goods. Capital destruction would entail a large cost.

The second part of the conclusion is very sensitive to assumptions. The rate of acceleration of climate policy can take a wide range of values, depending on the model parameter and the structure of the model. That said, emission reduction always intensifies over time, at least until such time that we approach complete decarbonization of the economy, many decades in the future.

However, the third part of the conclusion is again robust. As argued in Section 8.2, it is hard to imagine that a benefit–cost analysis would ever lead to a 100% emission reduction, and a 100% emission reduction is needed to stabilize the atmospheric concentration of carbon dioxide.

100% emission reduction is justified if there is a perfect and permanent substitute for fossil fuels at a reasonable price.

8.3.1 A backstop

There is one exception to this: a backstop technology. A backstop technology has five key characteristics. First, it is an energy source that does not emit carbon dioxide. This is a reasonable assumption. Second, a backstop is so abundant that it can meet all energy demand. This is another reasonable assumption, certainly in time. Third, a backstop is so abundant that its supply curve is flat. Its marginal cost is constant. This is a more peculiar assumption. Although wind turbines do not vary much in cost, building wind power in windy places first and less-windy places later would lead to an increase in costs per kilowatthour. The effect of these three assumptions is shown in Figure 8.11. If the backstop is expensive, it does not have an effect on optimal emissions $Q*$. If the backstop is cheap, optimal emissions are substantially lower at $Q**$. If the carbon tax is high enough, that is, higher than the marginal cost of the backstop, emissions fall precipitously.

The last two assumptions are key. Fourth, the energy sector is lumpy. Once the backstop is competitive at the margin, it will outcompete other energy sources. This is not unreasonable for particular applications—for instance, all new power plants tend to be the same—it is less so for all energy use everywhere. Fifth, the economy is hysteretic, that is, the economy would not leave its carbon-neutral state without active policy intervention. In Figure 8.11, the marginal cost of emission reduction would drop to zero.

If these five conditions are met, a sufficiently high carbon tax would trigger the deployment of the backstop technology. The economy would decarbonize and never look back. A benefit–cost analysis would justify complete emission reduction. These are big ifs, though. Substantial fossil fuel resources will be left in the ground if anthropogenic climate change is stopped at a reasonable warming. We will know where the coal, oil and gas are, and we will know how to use it. With climate change no longer a concern, will we resist the temptation to start burning fossil fuels again?

8.4 Secondary benefits***

A famous cartoon by Joel Pett argues that, even if climate change were a hoax, as mistakenly claimed by some, then we would still want to reduce carbon dioxide emissions because that would lead to clean water and air, energy independence, green jobs, livable cities, etc. These are the so-called *secondary benefits* of climate policy—its primary benefit is decelerated climate change. Secondary benefits are also referred to as ancillary benefits or co-benefits. Energy use, agriculture and transport are the key sources of greenhouse gas emissions and many other environmental problems. Climate policy will thus have an impact on other issues as well. But the recent scandal around Volkswagen reveals two things. First, greenhouse gas emission reduction can lead, and did lead in this case, to higher emissions of air pollutants. Second, the secondary disbenefit arose because of poorly designed air quality monitoring. This chapter argues that the co-benefits of climate policy may be positive as well as negative, and reiterates that it is better to have a portfolio of policies than to try and solve non-climate problems through greenhouse gas emission reduction.

There are many interactions between climate policy and other domains of public policy:

- Switching from petrol to diesel reduces carbon dioxide emissions, increases emissions of nitrogen oxides and particulates.
- Scrubbers on smokestacks reduce sulphur emissions, but increase carbon dioxide emissions.
- Switching from coal to gas, or from fossil fuels to renewables reduces both carbon dioxide and air pollutant emissions.

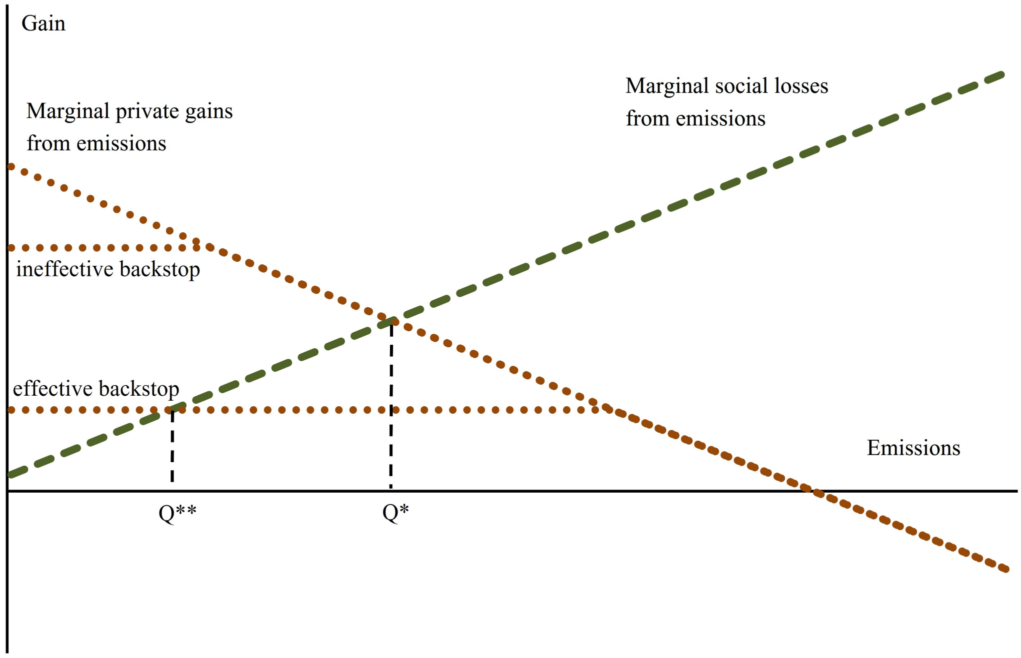


Figure 8.11: Optimal emissions with a backstop technology

- Energy efficiency improvement reduces both carbon dioxide and air pollutant emissions.

These four examples are surely not the only ways in which climate policy affects other issues. Other examples include the use of fertilizers and pesticides in bioenergy cultivation and their impact on hypoxia and biodiversity; the impact of wind turbines on health, recreation, and wildlife; the effect of a switch from private to public transport on congestion, road safety, air quality and noise; and the impact of deforestation and afforestation on nature conservation.

While it is true that energy, agriculture and transport causes many other (environmental) problems besides climate change, it is not true that these so-called ancillary or secondary benefits are a major reason to reduce greenhouse gas emissions. To see why, consider two criterion pollutants A—for conventional air pollution—and G—for the enhanced greenhouse effect. The total benefits D equal

$$D = \psi_A M_A + \psi_G M_G \tag{8.9}$$

Emission controls R_G and R_A affect both M_A and M_G

$$M_G = \chi_{AG} R_A + \chi_{GG} R_G \tag{8.10}$$

$$M_A = \chi_{AA} R_A + \chi_{GA} R_G \tag{8.11}$$

The costs of emission reduction B are given by

$$B = 0.5\beta_A R_A^2 + 0.5\beta_G R_G^2 \tag{8.12}$$

Rework Equation (8.9)

$$\begin{aligned} D = \psi_A(\chi_{AA} R_A + \chi_{GA} R_G) + \psi_G(\chi_{AG} R_A + \chi_{GG} R_G) = \\ = (\psi_A \chi_{AA} + \psi_G \chi_{AG}) R_A + (\psi_G \chi_{GG} + \psi_A \chi_{GA}) R_G \end{aligned} \tag{8.13}$$

The optimal control rate for greenhouse gas emissions then equals

$$\frac{\partial D}{\partial R_G} = \psi_G \chi_{GG} + \psi_A \chi_{GA} = \beta_G R_G = \frac{\partial B}{\partial R_G} \Rightarrow R'_G = \frac{\psi_G \chi_{GG} + \psi_A \chi_{GA}}{\beta_G} \tag{8.14}$$

and for air pollutants

$$\frac{\partial D}{\partial R_A} = \psi_A \chi_{AA} + \psi_G \chi_{AG} = \beta_A R_A = \frac{\partial B}{\partial R_A} \Rightarrow R'_A = \frac{\psi_A \chi_{AA} + \psi_G \chi_{AG}}{\beta_A} \tag{8.15}$$

Simple as this model may be, it illustrates a number of things. First, secondary benefits increase greenhouse gas emission reduction if $\chi_{GA} > 0$. Because greenhouse gas emission abatement also reduces conventional air pollution, we should do more of it. There is, however, no guarantee that $\chi_{GA} > 0$. For instance, diesel emits less carbon dioxide per kilometre travelled than petrol, but more particulate matter. That is, $\chi_{GA} < 0$ and air pollution worsens if greenhouse gas emissions are reduced by switching from petrol to diesel cars. Particulate matter is a secondary *cost* rather than a secondary *benefit*. Similarly, χ_{AG} may be positive or negative. If acid rain is reduced by a switch from coal-fired power generation to gas-fired power, then carbon dioxide emissions fall too and $\chi_{AG} > 0$. If, on the other hand, sulphur emissions are avoided by putting a scrubber on the smoke stack, then a carbon tax would increase the costs of scrubbing and $\chi_{AG} < 0$.

The second insight is as follows. If climate change is a hoax, $\psi_G = 0$, greenhouse gas emission reduction is not zero. Air pollution is a justification for greenhouse gas emission reduction regardless of the reality of climate change.

> Secondary benefits are a good reason to cut other pollutants but not carbon dioxide.

The second insight rests on the assumption of linearity in the benefits above. To see that, replace Equation (8.11) by

$$M_A = \chi_{AA} R_A + \chi_{GA} R_G + \chi R_A R_G = \chi_{AA} R_A + (\chi_{GA} + \chi R_A) R_G \tag{8.16}$$

This can be interpreted as follows. If $\chi < 0$, the positive effect of greenhouse gas emission reduction R_G on air pollution M_A falls at the margin as air pollution falls. This is a reasonable assumption for a local, short-lived environmental problem. The first-order conditions (8.14) and (8.15) are replaced by

$$\frac{\partial D}{\partial R_G} = \psi_G \chi_{GG} + \psi_A \chi_{GA} + \psi_A \chi R_S = \beta_G R_G = \frac{\partial B}{\partial R_G} \Rightarrow$$
$$\Rightarrow R'_G = \frac{\psi_G \chi_{GG} + \psi_A \chi_{GA}}{\beta_G} + \frac{\psi_A \chi R_S}{\beta_G} \tag{8.17}$$

and

$$\frac{\partial D}{\partial R_A} = \psi_A \chi_{AA} + \psi_G \chi_{AG} + \psi_G \chi R_G = \beta_A R_A = \frac{\partial B}{\partial R_A} \Rightarrow$$
$$\Rightarrow R'_A = \frac{\psi_A \chi_{AA} + \psi_G \chi_{AG}}{\beta_A} + \frac{\psi_G \chi R_G}{\beta_A} \tag{8.18}$$

Equation (8.17) shows that there is secondary benefit $\psi_A \chi_{GA}$ of greenhouse gas emission reduction, but that this falls as χ gets more negative and as air pollution control R_A gets stricter.

Equations (8.17) and (8.18) form a system of two equations and two unknowns, but it is linear so by substituting (8.18) into (8.17) we find

$$R'_G = \frac{(\psi_A \chi_{GA} + \psi_G \chi_{GG})\beta_A + (\psi_A \chi_{AA} + \psi_G \chi_{AG})\psi_A \chi}{\beta_G \beta_A - \psi_A^2 \chi^2} \tag{8.19}$$

and

$$R'_A = \frac{(\psi_A \chi_{AA} + \psi_G \chi_{AG})\beta_G + (\psi_A \chi_{GA} + \psi_G \chi_{GG})\psi_A \chi}{\beta_G \beta_A - \psi_A^2 \chi^2} \tag{8.20}$$

The optimal solution (8.19) and (8.20) reduces to (8.14) and (8.15) for $\chi = 0$.

For $\chi < 0$, both the numerator and the denominator are smaller than for $\chi = 0$, so the effect on R'_G appears ambiguous. However, if we impose conditions on the parameters such that $R_G \geq 0$, $R_A \geq 0$ and $\chi_{GA} + \chi R_A \geq 0$ then $\chi < 0$ unambiguously causes a fall in R'_G. This is more easily seen from (8.17) where the impact of χ depends on the sign of R_A.

If climate change is a hoax, $\psi_G = 0$, optimal greenhouse gas emission reduction is

$$R'_G = \frac{\psi_A}{\beta_G}(\chi_{GA} + \chi R_A) \tag{8.21}$$

The impact of $\chi < 0$ is to weaken the secondary reason to reduce greenhouse gas emissions.

The marginal benefit of greenhouse gas emission reduction is

$$\frac{\partial D}{\partial R_G} = \psi_G \chi_{GG} + \psi_A(\chi_{AG} + \chi R_S) \tag{8.22}$$

The first component $\psi_G \chi_{GG}$ is the *primary benefit*, the impact of greenhouse gas emission reduction on the problems caused by greenhouse gas emissions. The second component $\psi_A(\chi_{AG} + \chi R_S)$ is the *secondary benefit*, the impact of greenhouse gas emission reduction on the problems caused by air pollution. The secondary benefit depends on air pollution policy R_A. The secondary benefit is maximized if there is no air pollution policy $R_A = 0$.

8.5 The green paradox****

In the standard model of the exploitation of an exhaustible resource, a carbon price would increase greenhouse gas emissions. This is the *green paradox*, a term coined by Hans-Werner Sinn. The reason is as follows. A carbon price makes fossil fuels less attractive, alternative fuels more attractive. This means that climate policy shortens the remaining life-time of fossil fuels, as renewables will outcompete them sooner than without climate policy. It would, however, be wasteful to leave fossil fuels in the ground. Therefore, the rational response to a carbon price is to exploit fossil fuel reserves faster—that is the only option if an exhaustible resource is to be exhausted in a shorter time.

To see this, let us consider an optimal stock depletion model. Energy E is the only source of welfare. We seek to maximise its net present value:

$$W = \int_0^{\bar{t}} U(E(t))e^{-\rho t}\mathrm{d}t \tag{8.23}$$

under the constraint

$$\dot{\Theta} = -E(t) \tag{8.24}$$

where $\Theta(t)$ is the remaining stock of fossil energy. Form the Hamiltonian

$$\mathcal{H} = U + \pi\dot{\Theta} \tag{8.25}$$

where π is the shadow price of energy. The first order condition for static efficiency is

$$\frac{\partial \mathcal{H}}{\partial E} = U_E - \pi = 0 \Rightarrow U_E = \pi \tag{8.26}$$

that is, the marginal value of energy equals its price. The first order condition for dynamic efficiency is

$$\dot{\pi} - \rho\pi = \frac{\partial \mathcal{H}}{\partial \Theta} = 0 \Rightarrow \frac{\dot{\pi}}{\pi} = \rho \tag{8.27}$$

which is the Hotelling rule: The price of a non-renewable resource should rise with the interest rate.

Let us assume that demand for energy goes to zero at choke price $\bar{\pi}$. It make no sense to leave energy unused, so $\bar{t}$ is defined by

$$\int_0^{\bar{t}} R\mathrm{d}t = \Theta(0) \tag{8.28}$$

That is, the cumulative total of energy use equals the total resource stock. The supply goes to zero when demand goes to zero, $\pi(\bar{t}) = \bar{\pi}$.

Climate policy can be interpreted in two different ways. First, you can see climate policy as hastening the end of fossil fuels, that is, $\bar{t}$ falls. Alternatively, the switch to alternative energy happens at a lower price, that is, $\bar{\pi}$ falls. In our model, these two interpretations are equivalent.

However, the Hotelling rule still holds. If the choke price falls, then so do all preceding prices. Lower prices mean that supply is larger. A larger supply means that the stock is exhausted sooner. The optimal response to the announcement of an earlier end to a finite resource is to use more of it sooner. This is the green paradox: Long-term climate policy increases emissions in the short-term.

The logic of the green paradox is inexorable and its mathematics impeccable. However, the Hotelling model applies to reserves. Once the fixed costs of developing a coal mine, oil well, or gas field have been incurred, it does make sense to exhaust the reserve as long as the selling price exceeds the variable costs. The green paradox does not apply to resources. A carbon price does discourage exploration and development of new mines, wells and fields. Figure 2.4 reveals that future climate change is driven more by resources than reserves, so the green paradox may not be as problematic as it seems at first sight.

8.6 Trade-offs between greenhouse gases****

The first-order condition for optimal emission reduction is that the marginal costs of greenhouse gas emission reduction equals its marginal benefits. If carbon dioxide were the only greenhouse gas, the first-order condition establishes a price for its emission. There are many greenhouse gases, in fact, each with its own first-order conditions and its own price.

Instead of looking at the *absolute* prices of all greenhouse gases, it is more instructive to consider the absolute price of carbon dioxide (see Sections 3.1 and 6.5) and the *relative* prices of all other greenhouse gases.

> The relative prices of greenhouse gases shoudl equal their relative social costs of carbon or their relative shadow prices.

The marginal damage of carbon dioxide emissions is given by

$$\frac{\partial D}{\partial M_c} = \sum_t \frac{1}{(1+r)^t}\frac{\partial D_t}{\partial M_c} = \sum_t \frac{1}{(1+r)^t}\frac{\partial D_t}{\partial T_t}\frac{\partial T_t}{\partial M_c} =$$
$$= \sum_t \frac{1}{(1+r)^t}\frac{\partial D_t}{\partial T_t}\sum_s \frac{\partial T_t}{\partial F_{t-s}}\frac{\partial F_{t-s}}{\partial L_{c,t-s}}\frac{\partial L_{c,t-s}}{\partial M_c} \quad (8.29)$$

The first term on the right-hand side is as above—compare with Equation 8.8. The second term recognizes that the impact of climate change does not directly depend on emissions M, but rather via climate change T. The third and final term has that climate change T at time t depends on radiative forcing F in previous periods, which in turn depends on concentrations L and emissions M.

The relative price of greenhouse gas i is then

$$\frac{\frac{\partial D}{\partial M_i}}{\frac{\partial D}{\partial M_c}} = \frac{\sum_t \frac{1}{(1+r)^t}\frac{\partial D_t}{\partial T_t}\sum_s \frac{\partial T_t}{\partial F_{t-s}}\frac{\partial F_{t-s}}{\partial L_{i,t-s}}\frac{\partial L_{i,t-s}}{\partial M_i}}{\sum_t \frac{1}{(1+r)^t}\frac{\partial D_t}{\partial T_t}\sum_s \frac{\partial T_t}{\partial F_{t-s}}\frac{\partial F_{t-s}}{\partial L_{c,t-s}}\frac{\partial L_{c,t-s}}{\partial M_c}} \quad (8.30)$$

This is the ratio of the social cost of greenhouse gas i to the social cost of carbon dioxide. The nominator and the denominator of Equation (8.30) have elements in common—particularly, the discount rate and the damage function—suggesting that the uncertainty about the relative price of greenhouse gas i is smaller than the uncertainty about its absolute price.

The global warming potential is a poor approximation of the relative social cost of carbon, incorrectly applied in a constrained optimization.

There are a large number of assumptions in Equation (8.30). One can set the discount rate to zero $r = 0$. One can assume that impacts of climate change are proportional to temperature: $\frac{\partial D_t}{\partial T_t} = \psi_1$. Then

$$\frac{\frac{\partial D}{\partial M_i}}{\frac{\partial D}{\partial M_c}} = \frac{\sum_t \sum_s \frac{\partial T_t}{\partial F_{t-s}}\frac{\partial F_{t-s}}{\partial L_{i,t-s}}\frac{\partial L_{i,t-s}}{\partial M_i}}{\sum_t \sum_s \frac{\partial T_t}{\partial F_{t-s}}\frac{\partial F_{t-s}}{\partial L_{c,t-s}}\frac{\partial L_{c,t-s}}{\partial M_c}} \quad (8.31)$$

One can assume that global warming is proportional to radiative forcing: $\frac{\partial T_t}{\partial F_s} = \varphi_2$. One can further assume that concentrations are unchanged. Finally, one can ignore impacts after $t = \bar{t}$. Then

$$\frac{\frac{\partial D}{\partial M_i}}{\frac{\partial D}{\partial M_c}} = \frac{\sum_{t=0}^{\bar{t}} \frac{\partial F}{\partial L_i}\frac{\partial L_i}{\partial M_i}}{\sum_{t=0}^{\bar{t}} \frac{\partial F}{\partial L_c}\frac{\partial L_c}{\partial M_c}} \quad (8.32)$$

The assumptions leading from (8.30) to (8.32) seem restrictive: No discounting; linear impacts; linear climate change; constant concentrations; finite time horizon. Equation (8.32) is known as the *Global Warming Potential*. The Kyoto Protocol of the United Nations Framework Convention for Climate Change specifies that the relative prices of greenhouse gas be based on Equation (8.32) with $\bar{t} = 100$. The Kyoto Protocol thus introduces a distortion in the relative prices of greenhouse gases.

The parameter values needed to make Equation (8.32) work are set by the Subsidiary Body for Scientific and Technical Advice, a committee under the United Nations Framework Convention of Climate Change. This has the disadvantage that the parameter value lag behind the latest scientific insights, but the advantage that all countries use the same accounting standard.

The Kyoto Protocol also introduces an internal inconsistency. Equation (8.30) gives the relative price in the optimum. Equation (8.32) is a special case of that equation, and therefore still based on benefit–cost reasoning. The UNFCCC and its Kyoto Protocol—and Paris Agreement for that matter—explicitly reject such reasoning. Instead, a target is set that should be met at the lowest possible cost. This calls for a cost-effectiveness analysis, rather than a benefit–cost analysis.

For a single gas, a cost-effective emission trajectory solves

$$\min_{M_{c,0},M_{c,1},\ldots} \sum_t B_t(1+r)^{-t} \text{ s.t. } T_{\bar{t}} \leq \bar{t} \tag{8.33}$$

For simplicity, I assume that the temperature constraint holds for one period, $\bar{t}$, only. A more realistic constraint complicates notation without additional insight.

The first-order conditions are

$$\frac{\partial B_t}{\partial M_{c,t}}(1+r)^{-t} = \lambda \frac{\partial T_{\bar{t}}}{\partial M_{c,t}} \forall t \tag{8.34}$$

That is, the marginal present emission reduction cost (on the left hand side) equal the shadow price of the intertemporal constraint λ times the marginal contribution to meeting that constraint.

For multiple gases, the first-order conditions are similar. There is an extra index to denote the various gases. The constraint is shared over time and between gases. The relative price of greenhouse gas emissions then becomes

$$\frac{\frac{\partial B_t}{\partial M_{i,t}}}{\frac{\partial B_t}{\partial M_{c,t}}} = \frac{\lambda \frac{\partial T_{\bar{t}}}{\partial M_{i,t}}(1+r)^t}{\lambda \frac{\partial T_{\bar{t}}}{\partial M_{c,t}}(1+r)^t} = \frac{\frac{\partial T_{\bar{t}}}{\partial M_{i,t}}}{\frac{\partial T_{\bar{t}}}{\partial M_{c,t}}} \forall t \tag{8.35}$$

That is, the cost-effective ratio of marginal emission reduction costs equals the ratio of marginal contributions to the constraint.

Equation (8.35) is very different from Equations (8.30) and (8.32). The latter two are integrals over time whereas the former is instantaneous at the time the constraint bites. The difference is most pronounced for short-lived gases. Methane, for instance, has an atmospheric half-life of a decade or so, compared with carbon dioxide which stays in the atmosphere for decades and centuries. methane emission reduction therefore contributes to reduced climate change in the short run—which may count as a substantial benefit with a high discount rate—but not in the long run. A benefit–cost analysis thus favours methane emission reduction now, whereas a cost-effectiveness analysis does not.

Further reading

William Nordhaus' 1994 book *Managing the Global Commons: Economics of Climate Change*, Nordhaus and Joseph Boyer's 2000 book *Warming and the World: Economic Models of Global Warming* and Nordhaus' 2008 book *A Question of Balance: Weighing the Options on Global Warming Policies* set the standard for analyses of optimal climate policy. Nordhaus' 2021 *The Spirit of Green* casts a wider net.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tdf.html.

Exercises

8.1. The European Union argues that the carbon dioxide concentration should not exceed 450 ppm. Work out the global emissions budget. Work out the global emissions budget if the constraint holds only in the very long run. Hint: Past emissions and a simple carbon cycle model are under MLIAM01 on the resource site.

8.2. In the DICE model, Nordhaus assumes that the impact of climate change is proportional to $0.28T^2$, where T is the global mean surface air temperature (in degrees Celsius, in deviation from pre-industrial times). What happens to optimal climate policy if the impact function is $-4.33T+1.92T^2$ instead (as suggested by Tol) or $-0.348T^2+0.0109T^6$ (as suggested by Weitzman)? Hint: The model code is on the resource site under DICE2007.

8.3. In the DICE model, Nordhaus assumes that there is a backstop technology that can provide carbon-free energy at a fixed cost. In the standard model, the cost is set at \$1260/tC in 2005 (and falling over time). What happens to optimal climate policy if this is set at \$630/tC and \$2520/tC? Hint: The model code is on the resource site under DICE2007.

8.4. Consider an economic agent who seeks to maximize her consumption

$$\max_{A,R} Y - \alpha(1-A)(1-R) - 0.5\beta A^2 - 0.5\gamma R^2 \tag{8.36}$$

where Y is income, I monetized impact, A is adaptation and R is emission reduction; α, β and γ are parameters. What is the optimal level of adaptation? What is the optimal level of emission reduction? If emission reduction were zero, how would that affect optimal adaptation? If adaptation were zero, how would that affect optimal emission reduction?

8.5. Suppose that the agent in the above exercise receives a donation D to finance adaptation. How does that affect her decisions?

8.6. Read and discuss:

- **T.C. Schelling (1995), Intergenerational discounting, *Energy Policy*, 23, 395–401.
- **T.C. Schelling (2000), Intergenerational and international discounting, *Risk Analysis*, 20, 833–837.
- **T.M.L. Wigley, R.G. Richels and J.A. Edmonds (1996), Economic and environmental choices in the stabilization of atmospheric CO_2, *Nature*, 379, 240–243.
- ***J.E. Aldy, M.J. Kottchen and A.A. Leiserowitz (2012), Willingness to pay and political support for a US national clean energy standard, *Nature Climate Change*, 2, 596–599.
- ***K.C. de Bruin, R.B. Dellink and R.S.J. Tol (2009), AD-DICE: An implementation of adaptation in the DICE model, *Climatic Change*, 95, 63–81.
- ****R.O. Mendelsohn (2000), Efficient adaptation to climate change, *Climatic Change*, 45, 583–600.
- ***R.S.J. Tol (2005), Emission abatement versus development as strategies to reduce vulnerability to climate change: an application of FUND, *Environment and Development Economics*, 10, 615–629.
- ***L.H. Goulder and K. Mathai (2000), Optimal CO_2 abatement in the presence of induced technological change, *Journal of Environmental Economics and Management*, 39, 1–18.
- ****D. Burtraw et al. (2003), Ancillary benefits of reduced air pollution in the US from moderate greenhouse gas mitigation policies in the electricity sector, *Journal of Environmental Economics and Management*, 45, 650-673.

- ****N.H. Stern (2008), The economics of climate change, *American Economic Review*, 98, 1–37.
- ****T.C. Schelling (1992), Some economics of global warming, *American Economic Review*, 82, 1–14.

Chapter 9

Discounting

Thread

- You'd only care about climate change if you care about the distant future, far-away lands, remote probabilities. #climateeconomics
- We discount the future because we are impatient and because we expect to become richer and happier. #climateeconomics
- The Ramsey rule has these three components: pure time preference and consumption growth transformed to utility growth. #climateeconomics
- The Ramsey rule describes the discount rate of consumers. In equilibrium it equals the interest rate paid on the capital market. #climateeconomics
- The total and marginal net present impact of climate change rise sharply with a falling discount rate. #climateeconomics
- If the discount rate is uncertain, it is as if it falls as we peer further into the future. #climateeconomics
- If the discount rate falls, we can use a high (low) one for short (long) projects. #climateeconomics
- Time discounting violates anonymity: Different generations are treated differently. #climateeconomics
- No time discounting implies that we violate Pareto: Welfare can increase if we hurt someone. #climateeconomics
- Welfare functions can be based on ethical reasons or on empirical evidence, but should be consistent across policies. #climateeconomics
- Ethical welfare functions are undemocratic. Empirical evidence is contradictory and difficult to interpret. #climateeconomics

9.1 Introduction

You'd only care about climate change if you care about the distant future, far-away lands, remote probabilities.

Climate change is a long-term, uncertain, global problem. If you do not care about the distant future, remote probabilities, and far-away lands, then climate change is of little concern.

The first statement is a positive statement, and an uncontroversial one. The second statement is a normative statement, and a controversial one. It is also vague. In this chapter and the next two, the relationships between attitudes towards the future, towards risks, and towards others are made more precise. This chapter is about time.

9.2 The Ramsey rule**

Climate change is a long-term problem. If you do not care about the distant future, then climate change is of little concern. This is clear from Section 6.5. Table 6.1 shows that the social cost of carbon is higher if the discount rate is lower. If the discount rate is higher, you care less about the future. If you care less about the future, you care less about climate change. If you care less about climate change, you would impose a lower carbon tax.

The Ramsey rule has these three components: pure time preference and consumption growth transformed to utility growth.

The Ramsey rule says that the consumption rate of discount r consists of three components:

$$r = \rho + \eta g \tag{9.1}$$

First, we discount the future because we expect to be richer (g). Indeed, it would not make sense to transfer money from your relatively poor current self to a relatively rich future self. The faster the expected growth, the higher the discount rate. Second, the evaluation of "relatively poor" versus "relatively rich" depends on the curvature of the utility function, commonly referred to as the rate of relative risk aversion (η). Together η and g constitute the growth rate of utility, the rate at which we grow happier. This part of the Ramsey rule is largely uncontroversial.[1]

We discount the future because we are impatient and because we expect to become richer and happier.

The third part is controversial. People discount the future for the sake of it being the future. This is captured by the pure rate of time preference (ρ),[2] also referred to as the utility rate of discount. Philosophers and religious leaders have long maintained that we should not treat the future differently than the present, that is, $\rho = 0$. Yet people do. All empirical evidence suggests that people are impatient. The observed consumption discount rate typically exceeds the growth rate of consumption, corrected for the rate of risk aversion.

The Ramsey rule describes discount rate of consumers, in equilibrium equal to the interest rate paid on the capital market.

[1] There is the slight matter of the measurement of consumption growth. In theory, this is the growth rate of all the things we care about. In practice, it is the growth rate of material consumption as captured by the national accounts. The rate of relative risk aversion is hard to measure too.

[2] It is, in fact, the rate of pure time preference, but no one calls it that.

The Ramsey rule describes the consumption rate of discount from an individual perspective. If the economy is in a dynamic equilibrium, the consumption rate of discount equals the interest rate, the price of money on the capital market. If the interest rate were higher than the consumption rate of discount, the bank would pay more for your savings than you think they are worth. Savings would increase, and the price of capital (i.e., the interest rate) would fall as the supply of investment increases. Vice versa, if the interest rate were lower, savings would fall and the interest rate would rise.

9.3 Derivation of the Ramsey rule***

The consumption rate of discount r measures trade-offs over time. The consumption rate of discount is defined as that rate that leaves you indifferent between a reduction in consumption now in return for an increase in consumption later; or between an increase in consumption now in return for a later decrease.

The consumption rate of discount is thus a rate of change between now, $t = 0$, and some later time, t. It is a rate of change, not of consumption C, but of a change in consumption, dC. Thus the consumption rate of discount is defined as

$$e^{rt} := \frac{\mathrm{d}C_t}{\mathrm{d}C_0} \Leftrightarrow e^{rt}\mathrm{d}C_0 = \mathrm{d}C_t \Leftrightarrow \mathrm{d}C_0 = e^{-rt}\mathrm{d}C_t \tag{9.2}$$

If we set $\mathrm{d}C_t$=1 then it is obvious that e^{-rt} is the discount factor: the present value of money received in the future. That is, receiving \$1 at future time t is worth \$dC today.

"Worth" implies an indifference condition. That is, the net present welfare W is unaffected by the shift in consumption from now to then. Or (roughly) $W(C_0, C_1, \ldots, C_{t-1}, C_t, C_{t+1}, \ldots) = W(C_0 + \mathrm{d}C_0, C_1, \ldots, C_{t-1}, C_t - \mathrm{d}C_t, C_{t+1}, \ldots)$. Actually, this condition should hold at the margin. That is, the total derivative of net present welfare to the income transfer from now to then equal zero. If we assume that net present welfare function is as follows

$$W = \int_t U(C_t)e^{-rt}\mathrm{d}t \tag{9.3}$$

where U is instantaneous utility and ρ the utility rate of discount, then the condition is:

$$\mathrm{d}W = U_{C_0}\mathrm{d}C_0 - e^{-\rho t}U_{C_t}\mathrm{d}C_t = 0 \Leftrightarrow \frac{\mathrm{d}C_t}{\mathrm{d}C_0} = e^{\rho t}\frac{U_{C_0}}{U_{C_t}} \tag{9.4}$$

Assuming a CRRA utility function:

$$U_i(C_i) = \begin{cases} \frac{C_i^{1-\eta}}{1-\eta} & \eta \neq 1 \\ \ln C_i & \eta = 1 \end{cases} \tag{9.5}$$

we have that

$$U_C = C^{-\eta} \tag{9.6}$$

As $C_t = e^{gt}C_0$, we have that

$$U_{C_t} = C_t^{-\eta} = e^{-\eta gt}C_0^{-\eta} \tag{9.7}$$

Substituting (9.6) and (9.7) into (9.4):

$$\frac{\mathrm{d}C_t}{\mathrm{d}C_0} = e^{\rho t}\frac{C_0^{-\eta}}{e^{-\eta gt}C_0^{-\eta}} = e^{\rho t + \eta gt} \tag{9.8}$$

Combining this with (9.2), we have that

$$e^{rt} = e^{\rho t + \eta g t} \Leftrightarrow r = \rho + \eta g \tag{9.9}$$

This is the Ramsey rule, after Professor Frank Ramsey of Cambridge University, who published a variant of the above derivation in 1928. He also showed that, in equilibrium, the consumption rate of discount equals the rate of return on investment.

9.4 The Gollier–Ramsey rule****

Section 9.3 derives the Ramsey rule. We assumed that the future rate of growth in consumption, g, is known with certainty. It rarely is. Let us instead assume that g is normally distributed with mean μ and standard deviation σ. If $g \sim \mathrm{N}(\mu, \sigma^2)$ then $-\eta g \sim \mathrm{N}(-\eta\mu, \eta^2\sigma^2)$.

By definition, a variable is lognormally distributed if its log is normally distributed: $X \sim \mathrm{LN}(\mu, \sigma^2)$ if $\ln X \sim \mathrm{N}(\mu, \sigma^2)$. So, $e^{-\eta g} \sim \mathrm{LN}(-\eta\mu, \eta^2\sigma^2)$. Its expected value $\mathrm{E}e^{-\eta g} = e^{-\eta\mu + 0.5\eta^2\sigma^2}$. The Ramsey rule thus becomes

$$r = \rho + \eta\mu - 0.5\eta^2\sigma^2 \tag{9.10}$$

where μ is the *expected* growth rate of consumption. We commonly express the Ramsey rule in the *modal* growth rate g. Since $g = \mu - 0.5\sigma^2$, Equation (9.10) can be rewritten as

$$r = \rho + \eta\left(g - 0.5\sigma^2\right) - 0.5\eta^2\sigma^2 = \rho + \eta g - 0.5\eta(\eta + 1)\sigma^2 \tag{9.11}$$

This is the Gollier-Ramsey rule. It says that if we are uncertain about how rich we will be in the future, then we should lower our discount rate and, hence, save more. This is because the curvature of the utility function implies that we should care more about, and thus put greater emphasis on those possible futures in which we are poor than on those futures in which we are rich. This is known as the *prudence effect*.[3] Note that the prudence effect lowers the discount rate by a fixed amount.

9.5 Endogenous population****

In the derivation of the Ramsey rule, we assume that the intertemporal welfare function depends on individual utility. Assume instead that

$$W = \int_t N_t U(C_t) e^{-rt} \mathrm{d}t \tag{9.12}$$

where N is the number of people. Then the indifference condition is:

$$\mathrm{d}W = N_0 U_{C_0} \mathrm{d}C_0 - e^{-\rho t} N_t U_{C_t} \mathrm{d}C_t = 0 \Leftrightarrow \frac{\mathrm{d}C_t}{\mathrm{d}C_0} = e^{\rho t} \frac{N_0}{N_t} \frac{U_{C_0}}{U_{C_t}} \tag{9.13}$$

If $\aleph$ denotes the growth rate of the population, $N_t = e^{\aleph t} N_0$, so that

$$e^{rt} = e^{\rho t + \aleph t + \eta g t} \Leftrightarrow r = \rho + \aleph + \eta g \tag{9.14}$$

[3] *Relative prudence* is defined as $-CU'''/U''$. If we assume a CRRA utility function then relative prudence equals $\eta + 1$.

The consumption discount rate has increased (if ρ, η and g are unchanged). We care less about the future, and thus about climate change, if we account for population growth—if the population grows, that is.

This raises the question which intertemporal welfare function to use, Equation (9.3) or (9.12)—*average* or *total* utilitarianism? Neither is satisfactory. The difference becomes clear if we consider endogenous population growth. Climate change and climate policy directly affect mortality and, if not directly then indirectly, fertility. A different carbon tax means a different number of future people. Climate change and policy also affect migration, that is, the number of people in a country.

Average utilitarianism, Equation (9.3), means that we should seek to prevent a child being conceived if that child would have a below-average expected income, as she would drag the average down and reduce social welfare. Similarly, we should only allow wealthy immigrants into our country. A high negative value on premature mortality would prevent a recommendation to kill the poor but it is clear that average utilitarianism raises many ethical problems.

Total utilitarianism, Equation (9.12), is just as problematic. Every child born, every immigrant admitted raises welfare as long as their utility is positive. Indeed, as welfare is linear in the number of people but less-than-linear in their income, total utilitarianism prefers more miserable people to fewer happy ones. We do not want that either.

As the impact of climate change and policy on population is not that large, we cannot use a carbon tax, say, to drive either average or total utilitarianism to its repugnant extreme. However, in climate models with endogenous population, the choice between average and total utilitarianism does affect policy recommendations.

Although economists have long been aware of the problems of average and total utilitarianism, practical alternatives have yet to be proposed. One contender is *critical-level utilitarianism*

$$W = \int_t N_t^* [U(C_t) - \underline{U}] e^{-rt} \mathrm{d}t \tag{9.15}$$

where N^* is the number of people for whom $U(C) > \underline{U}$. If $\underline{U} = 0$, this is total utilitarianism. For $\underline{U} > 0$, we only add people to the population if they would live a life worth living, a figure that is difficult to ascertain.

The Ramsey rule changes again. The growth rate of utility ηg is attenuated, as it is now the growth rate of the utility in excess of its minimum threshold. The growth rate of the population is now the growth rate of the number of people with a worthwhile life. The discount rate falls if climate change pushes people under the $\underline{U}$ threshold, giving extra weight to this eventuality, and increasing the social cost of carbon.

9.6 Declining discount rates***

9.6.1 Hyperbolic discounting

The standard discount factor, reflected in Equation (9.3), is exponential. This is because *exponential* or *geometric* discounting guarantees *time consistency*: The mere passage of time does not alter our decisions. This is easily seen. Suppose time s passes. Re-examining the decisions based on maximizing the welfare function in Equation (9.3), we multiply net present welfare by $e^{-\rho s}$. The first-order conditions for intertemporal trade-offs then become

$$U_{C_s} e^{-\rho s} = U_{C_{s+t}} e^{-\rho(s+t)} = U_{C_{s+t}} e^{-\rho s} e^{-\rho t} \Leftrightarrow U_{C_s} = U_{C_{s+t}} e^{-\rho t} \tag{9.16}$$

That is, $e^{-\rho s}$ drops out of the equation. It is not in the first-order condition so it does not influence behaviour. All prices are multiplied by the same factor, and relative prices are unchanged.

Time has passed, but nothing else has changed, so we have no reason to change our mind and revise our decision. In other words, time consistency implies that intertemporal trade-offs are driven by the time passed between benefits and costs, rather than by the time at which benefits and costs are realized.

Equation (9.16) shows that exponential discounting implies time consistency. The reverse is not true. What we need for time consistency is that $\mathbb{D}(t+s) = \mathbb{D}(t)\mathbb{D}(s)$, where $\mathbb{D}$ is the discount factor. This holds for the exponential function, and for any other power function.[4]

Time consistency is a desirable characteristic. You should change your mind if circumstances change, not if time passes. Exponential discounting has counterintuitive implications though. The relative difference between year 10 and year 11 is the same as the relative difference between year 100 and year 101 and between year 1000 and year 1001. As in Equation (9.16), s (the year of origin) is irrelevant; only t (the time passed) matters. This is strange. You can tell the difference between now and a year from now. Can you tell the difference between 10 years from now and 11? Between 1000 years from now and 1001?

Intuitively, you may argue that the relative difference between year 10 and year 11 is more like the relative difference between year 100 and year 110, and between year 1000 and year 1100. That intuition is supported by behavioural data, experimental data and survey data. Observed discount factors are *hyperbolic* rather than geometric. That is, as the time horizon expands, the discount rate appears to fall.

An *ad hoc* way to reflect this is to replace t by $\ln t$:

$$W = \int_t U(C_t) e^{-\rho \ln t} \mathrm{d}t \tag{9.17}$$

The indifference condition between time s and $s+t$ then depends on both s and t:

$$U_{C_s} e^{-\rho \ln s} = U_{C_{s+t}} e^{-\rho \ln(s+t)} \tag{9.18}$$

However, the indifference condition between time s and time st only depends on t, where t is not the *absolute* time passed, but the *relative* time:

$$U_{C_s} e^{-\rho \ln s} = U_{C_{st}} e^{-\rho \ln st} = U_{C_{st}} e^{-\rho(\ln s + \ln t)} \Leftrightarrow U_{C_s} = U_{C_{st}} e^{-\rho \ln t} \tag{9.19}$$

The *declining* discount rate becomes apparent if we consider the growth rate of present utility, for exponential discounting:

$$\frac{\partial U(C_t)e^{-\rho t}/\partial t}{U(C_t)e^{-\rho t}} = \frac{\partial U/\partial C_t \, \partial C_t/\partial t \, e^{-\rho t} - \rho U(C_t)e^{-\rho t}}{U(C_t)e^{-\rho t}} = \frac{\dot{U}_t}{U_t} - \rho \tag{9.20}$$

This is in fact another indifference condition. For $\rho = 0$, marginal utility should be the same at every point of time. This is arbitrage. In a static optimum, the marginal utility of all agents should be the same. In a dynamic optimum without discounting, agents are at different points in time but, as time does not matter, their marginal utility should be equal. If marginal utility is the same over time, its growth rate is zero.

In a dynamic optimum with discounting, the arbitrage condition, better known as the Euler equation, implies $\dot{U}_t/U_t = \rho$. This is because utility discounting over time is analogous to given different agents different weights in a static optimum. That is exactly what time discounting does: Lower weight is attached to future utility.

[4]Time consistency also requires time seperability. That is, the utility U of consumption C at time t is the product of a function in C and a function in t: $U(C,t) = \mathbb{D}(t)U(C)$.

Table 9.1: Discount factors and the certainty equivalent discount rate

time	Value of \$1000 after t years				certainty equivalent
	1%	4%	7%	1 or 7%	discount rate
1	\$990	\$961	\$932	\$961	3.9%
10	\$905	\$670	\$497	\$701	3.1%
100	\$368	\$18	\$91	\$184	1.0%

For hyperbolic discounting:

$$\frac{{}^{(\partial U(C_t)e^{-\rho \ln t})}/_{\partial t}}{U(C_t)e^{-\rho \ln t}} = \frac{{}^{\partial U}/_{\partial C_t}{}^{\partial C_t}/_{\partial t}e^{-\rho \ln t} - {}^{\rho}/_{t}U(C_t)e^{-\rho t}}{U(C_t)e^{-\rho \ln t}} = \frac{\dot{U}_t}{U_t} - \frac{\rho}{t} \tag{9.21}$$

This implies that ${}^{\dot{U}_t}/_{U_t} = {}^{\rho}/_{t}$. That is, the effective discount rate *falls* as time goes by.

The replacement of time by its natural logarithm in the discount factor is entirely *ad hoc*. It is inspired by observations, but the data suggest that people do something like this rather than exactly this.

9.6.2 Uncertainty and disagreement about the discount rate

If the discount rate is uncertain, it is as if it falls as we peer further into the future.

The discount rate also falls as we peer further into the future if we are uncertain about what discount rate to use, or if we disagree. This again follows from Equation (9.16) and is illustrated in Table 9.1. The first-order conditions are determined by the discount factor rather than the discount rate. Suppose we are uncertain about the discount rate. There is a 50% chance that it should be 1%, and a 50% chance that it should be 7%. Table 9.1 shows the corresponding discount factors. Obviously, benefits in the far future are worth little with a high discount rate; distant benefits are worth more with a low discount rate.

Table 9.1 also shows the discount factor for a discount rate of 4%, the average of 1% and 7%, and the average discount factor for a discount rate of 1% and 7%. The former is always smaller than the latter (by Jensen's inequality) and the gap widens as we look further into the future. This is further illustrated by inverting the average discount factor, which yields the certainty-equivalent discount rate. The certainty-equivalent discount rate is always smaller than the average discount rate and the gap widens as we look further into the future.

Table 9.1 gives a numerical illustration. But the certainty-equivalent discount rate always falls over time. The intuition is as follows. Suppose that the 1% and 7% reflect disagreement, with one person arguing for the low discount rate and the other for a high one. We can split the difference on the discount rate and set it to $0.5 \times 1\% + 0.5 \times 7\% = 4\%$, or we can split the difference on the discount factor and set it to $0.5 \times 1.01^{-t} + 0.5 \times 1.07^{-t}$. The latter option is better. Both of our subjects have an opinion about intertemporal trade-offs in the short-run, and the average reflects both opinions: $0.5 \times 1.01^{-1} + 0.5 \times 1.07^{-1} \approx 1.04^{-1}$. In the long-run, however, the person with the high discount rate is indifferent $1.07^{-100} \approx 0$, but the person with the low discount rate is not $1.01^{-100} > 0$; the latter's opinion therefore dominates $0.5 \times 1.01^{-100} + 0.5 \times 1.07^{-100} \approx 0.5 \times 1.01^{-100}$.[5] If we split the difference between two people

[5] As $0.5 \times 1.01^{-101} + 0.5 \times 1.07^{-101} \approx 0.5 \times 1.01^{-101}$ the discount factor falls by approximately 1% between year 100 and 101. That is, the 0.5 drops out.

who care, we should split the difference. If we split the difference between someone who cares and someone who does not, we should listen to the one who cares.[6]

The same reasoning holds for uncertainty about the discount rate. In one state of the world, you are indifferent about the long run; in another state of the world, you are not. The latter dominates. Therefore, the discount rate falls as we look further into the future.

If the discount rate falls, we can use a high (low) one for short (long) projects.

This allows us to square a circle. We do not want to ignore the far future. But using a low discount rate would imply that we have to reconsider our priorities for short-term investments too. If the discount rate falls over time, we can use a high discount rate to evaluate investments that pay off in the short run and a low discount rate for investments in the long run.

None of this implies time inconsistency. Returning to the Ramsey rule, Equation (9.1), the money discount rate may fall because we are uncertain about future economic growth. Time consistency requires that utility is discounted at a constant rate. Similarly, observed time preferences are not for utility; hyperbolic discounting for *money* is not inconsistent with exponential discounting for *utility*.

We establish above that the discount rate is a key determinant of the social cost of carbon. The same is true for declining discount rates. For example, one estimate has that the social cost of carbon is \$2/tC for a constant money discount rate of 4% per year. If the discount rate starts at 4% but falls as outlined above, for the same model parameterization and scenario, the social cost of carbon is \$88/tC.

9.7 Axiomatic approaches to intertemporal welfare****

Equation (9.3) posits an intertemporal welfare function. This is a common approach: Let us assume that, in this case, the discount factor declines exponentially. Often, such assumptions are justified with some reference to the plausible properties of the assumed function. The correct approach, however, is to first posit desirable properties (called axioms) and then derive the welfare function from those.

If the welfare function is used to assess welfare over an infinitely long time, it cannot simultaneously satisfy the axioms of *Anonymity* and *Strong Pareto*. Both axioms are desirable. The Strong Pareto axiom is similar to Pareto superiority: Situation A is preferred to situation B if no one is worse off and at least one agent is better off. The difference is that Pareto superiority applies to different people at the same time, whereas Strong Pareto refers to people living at different times. Strong Pareto is obviously a desirable property.[7]

Anonymity means that a welfare function should be indifferent to the question whether one agent or another gains an equivalent amount. This is obviously a desirable property, but it cannot be satisfied if Strong Pareto is imposed too.

Intertemporal decisions are typically conceptualized as trade-offs between a sequence of generations. Generations arrive in a particular order. Anonymity is then a peculiar requirement. To see this, drop exponential discounting, and consider a more general intertemporal welfare function

$$W = \int_t U(C_t)\mathbb{D}(t)\mathrm{d}t \text{ with } \frac{\partial \mathbb{D}}{\partial t} < 0 \tag{9.22}$$

Note that the discount factor $\mathbb{D}$ is some declining function of time, rather than the exponentially declining function used in Equation (9.3).

[6] This is an argument akin to the Pareto principle: We can make someone better off by taking their advice without making someone else worse off as they have no opinion either way.

[7] In *Weak Pareto*, all need to be better off.

Time discounting violates anonymity: Different generations are treated differently.

Equations (9.3) and (9.22) violate anonymity. Consider the following series of instantaneous welfare {1,2,1,1,1,. . . } and {1,1,2,1,1,. . . }. Anonymity would imply indifference between the two situations, which is fair enough if you were distributing 6 chocolate bars between 5 students in a class. Discounted welfare would prefer the former over the latter, because the 2 occurs earlier. We can only have Anonymity if $\partial\mathbb{D}/\partial t = 0$, that is, if every generation is given the same weight—which we might as well set equal to one.

No time discounting implies that we violate Pareto: Welfare can increase if we hurt someone.

Equations (9.3) and (9.22) do satisfy Strong Pareto:

$$\frac{\partial W}{\partial U_{C_t}} > 0 \forall t \tag{9.23}$$

The axiomatic approach to intertemporal welfare goes back to the work of Tjalling Koopmans, a Nobel laureate in economics, in the 1960s. Although Koopmans was uneasy about discounting the future for the mere sake of it being the future—he clearly preferred $\rho = 0$ in Equation (9.1) on religious grounds—his analysis shows that discounting is unavoidable.

Koopmans' result follows inescapably from his axioms. Other axioms would lead to different intertemporal welfare functions. Graciela Chichilnisky replaced the axiom of Anonymity with axioms of *Independence* and *Non-dictatorship*. Francisco Alvarez-Cuadrado and Ngo Van Long dropped independence,[8] and replaced it with a second non-dictatorship axiom.

A net present welfare criterion violates the axiom of non-dictatorship of the present. Essentially, if we use Equation (9.22) to chart an optimal course for the entire future, then we let the preferences of the current generation dictate the policy choices of future generations. This is the way the world is, but perhaps not how it should be. That is, we would prefer non-dictatorship.

There is a welfare criterion that satisfies strong Pareto as well as axioms of non-dictatorship of the present and the poorest:

$$W = \vartheta \int_t U(C_t)\mathbb{D}(t)\mathrm{d}t + (1-\vartheta)U(\underline{C}) \tag{9.24}$$

That is, the welfare criterion—dubbed the Bentham–Rawls welfare criterion—is the weighted sum of standard net present welfare—the Bentham component[9]—and the utility of the least-well-off generation—the Rawls component. If $\vartheta = 1$, welfare is dictated by the concerns of the current generation; if $\vartheta = 0$, the poorest generation dictates the outcome (up to the point where it no longer is the poorest). For $0 < \vartheta < 1$, neither the current nor the poorest generation dictate the result—unless the current generation is the poorest. This formulation puts a price on the current generation getting rich at the expense of future generations.

The implications for climate policy are as follows. The social cost of carbon is the first partial derivative of Equation (9.24) to emissions today M_0. The equation is a linear combination, and so are its derivatives. The first component is standard net present welfare, and its first partial derivative is the standard social cost of carbon. This is multiplied by $\vartheta < 1$, and therefore

[8] This is fortunate. Axioms supposed to have intuitive appeal and you should be able to explain them in a sentence or two. Not so the axiom of independence.

[9] Actually, Paul Samuelson was the first to write down an intertemporal welfare function.

smaller. The question is thus whether the first partial derivative can make up the difference. This would require that

$$(1-\vartheta)\frac{\partial \int_t U(C_t)D(t)\mathrm{d}t}{\partial M_0} > (1-\vartheta)\frac{\partial U(\underline{C})}{\partial M_0} \tag{9.25}$$

This is unlikely. The utility of the poorest generation is included in standard net present welfare, albeit discounted. Therefore, if the poorest generation is in a distant future, and if nearer generations face positive impacts at the margin, the condition (9.25) may be met.

Under conventional assumptions, the Bentham–Rawls social cost of carbon is smaller than the conventional (Bentham) social cost of carbon. Indeed, most scenarios of climate change assume steady economic growth. See Chapter 2. That means the current generation is the poorest, and the Bentham-Rawls social cost of carbon is strictly smaller than the Bentham social cost of carbon.

However, if climate change *reverses* economic growth—see Chapter 7—then the social cost of carbon increase discontinuously. This would be a sharp drop indeed, as consumption of some future generation falls from richer than today to subsistence levels or below. This would induce more emission reduction, perhaps enough to prevent such catastrophic climate change.

9.8 Measuring time preferences***

9.8.1 Preliminaries

In Section 9.6 we argue that the discount rate may decline as we look further into the future, for instance if discounting is hyperbolic. This would happen if we are uncertain about the discount rate, perhaps because we cannot accurately predict future growth. Declining discount rates are also consistent with experimental and observational evidence, showing that people regard the long- and short-term differently. There is an alternative interpretation, however, known as *present bias*.[10] Algebraically, the discount factor

$$\mathbb{D}(t) = \begin{cases} \xi e^{-\rho t} & t > 0 \\ 1 & t = 1 \end{cases} \tag{9.26}$$

with $0 < \xi < 1$. In words, there is a discount factor ξ between "now" and the "future", but trade-offs between different points in the future are governed by conventional exponential discounting. Of course, if we compare a trade-off between times 0 and t and between times 0 and s, then present-bias will appear as if the discount rate is not constant over the time horizon. This hampers the interpretation of data on intertemporal trade-offs.

If we seek to measure time preferences, we cannot *assume* that people have geometric or hyperbolic discount functions, or are present-biased. We need to let the data decide. Benhabib, Bisin and Schotter proposed the following discount factor

$$\mathbb{D}(t) = \begin{cases} \xi e^{-\rho t} & \nu = 1 \\ \xi(1-(1-\nu)\rho t)^{\frac{1}{1-\nu}} & \nu \neq 1 \end{cases} \tag{9.27}$$

If $\xi = 1$, there is no present bias. If $\xi = \nu = 1$, discounting is exponential. If $\xi = 1$ and $\nu = 2$, discounting is hyperbolic

$$\mathbb{D}(t) = \frac{1}{1+\rho t} \tag{9.28}$$

[10] Discounting with present bias is also referred to as *quasi-hyperbolic* discounting, an ugly and imprecise term.

For other parameter values, discounting is somewhere in between these three special cases. We can use this function, or a generalization like this, to analyze the data and estimate the parameters so as to determine who of our subjects' preferences are time-consistent, present-biased or hyperbolic.

9.8.2 Natural experiments

The Ramsey rule and its extensions can be used to infer time preference ρ, but only up to a point. Interest rates not only reflect the price of time but also the risk of default, so we could focus on virtually risk-free securities such as US treasuries to obtain an estimate of r. We may study the housing market, in which some properties are held in perpetuity (freeholds) and other properties revert to the previous owner (leaseholds). The growth rate of consumption g is readily observable—at least if we choose to believe that the national accounts are complete and accurate. We know, of course, that the national accounts have difficulty capturing quality changes in consumer goods, and only partially reflect consumption that does not involve a market transaction.

But even if we know g and r, the Ramsey rule will tell us the linear relationship between time preference ρ and the curvature of the utility function η, rather than the value of either parameter. And even so, we made two jumps of faith, first, that capital markets (which set r) reflect social preferences and, second, that product markets (which set g) reflect social preferences. If markets are imperfect—say because of market power, public goods, or externalities—it is more difficult to deduce preferences from observed behaviour.

Alternatively, we could use the internal rate of return of public investment as our estimate of r, although we then implicitly assume that government actions reflects the will of the people and that government agencies, their consultants and their suppliers do not systematically try to deceive the budgetary authorities about the expected returns to their investments.

9.8.3 Controlled experiments

Given the difficulties in using natural experiments in revealing time preferences, economists have turned to the controlled environments of surveys and experiments. This has the advantage of precise measurements—assuming that respondents faithfully follow instructions and answer questions. The disadvantages are, first, that stakes are low (in experiments) or zero (in surveys), providing little incentive for respondents to discover and reveal their true preferences, and, second, that samples are often unrepresentative (particularly in experiments). Experiments on time preferences use deferred payments and so also reflect the extent to which subjects *trust* the experimenter. Payments can only be deferred for a short while—weeks, maybe months—while often, and certainly for climate policy our interest lies in discount rates over years and decades.

People do not know their time preferences, as "time preference" and "utility" are academic constructs to help understand, describe and predict behaviour. So, we cannot ask someone "what is your pure rate of time preference?". We can ask, however, "would you rather have \$100 now or \$110 in a year from now?". If the respondent opts for the latter, then we know her discount rate is less than 10% per year—and by asking a sequence of such questions, we can narrow down our estimate of her discount rate.

The estimate thus obtained is a consumption discount rate, and we would need to estimate the curvature of her utility function and expected income growth to discern the pure rate of time preference using the Ramsey rule.

And as discounting need not be exponential, we need to add more questions. We need to present the respondents with choices between now and later, and between two later points in time to distinguish hyperbolic discounting from present-bias. If we want to estimate the degree of hyperbolicity, as in Equation (9.27), we need to add yet more choices. And we need to account for noise in the data: Only a rich menu of intertemporal choice will inform us about the discount factor of the respondents. At the same time, we need to worry about fatigue. Subjects can only stomach so many questions, and fewer repetitive ones.

9.9 The choice of parameters**

Table 6.1 and Figures 6.8 and 6.9 show just how important the discount rate is for the social cost of carbon and hence for optimal climate policy. Further examples are given throughout this chapter.

> Welfare functions can be based on ethical reasons or on empirical evidence, but should be consistent across policies.

The pure rate of time preference, together with the rates of risk aversion and inequity aversion discussed below, is often referred to as an "ethical parameter". For individuals, ethical parameters reflect the attitude towards the future, towards risk, and towards others. Such attitudes may be based on moral reasoning or may result from social norms and upbringing. To an analyst, these parameters reflect the preferences of economic agents, and are measurable.

For society, these parameters also reflect attitudes, towards the future, towards risk, towards inequity within society, and towards inequity between societies. The parameters are measurable in the sense that decisions made can be interpreted as to their implied rates of time preference, risk aversion and inequity aversion. However, what is and what ought to be are different things. Besides, analyses of the preferences revealed by government decisions show inconsistent behaviour. It is the role of decision analysts to improve policy making by removing inconsistencies and weeding out decisions that please no one. It is the role of moral leaders to improve preferences so that decisions are better, too, in the ethical sense of the word.

> Ethical welfare functions are undemocratic. Empirical evidence is contradictory and difficult to interpret.

This is a deep issue. Reasonable people can and should disagree. The two polar positions are as follows. You can take a philosophical approach, and reason from first principles what the pure rate of time preference should be. If you find that difficult, you can take guidance from a thought leader such as Aristotle, Laozi, Jesus Christ, St Augustine, Mohammed, Adolf Hitler, Johnny Rotten, Lord Stern, or Lady Gaga. Alternatively, you can argue that government decisions should reflect the will of the people and try to measure that will.

Almost all thought leaders who have expressed an opinion on time preference—Aristotle, St Augustine, Mohammed, Thomas Aquinas, John Broome, and Lord Stern—have argued that it is unethical to discount the future just because it is the future.[11] But who are they to dictate how you should behave? Aristotle was racist, sexist, pro-slavery. Maybe he was wrong on usury too.

Lady Gaga argues that we should accept people as they are, including their impatience, ugly and diseased as it may be. Studies of revealed and stated preferences almost unanimously reveal that the vast majority of people in most circumstances discount the future. We want the good things, and we want them now.

[11] Johnny Rotten disagrees, singing that it is better to burn out than to fade away. Unlike his mate Sid Vicious, Rotten did not follow this advice, hawks butter instead. Lemmy sang that he did not want to live forever and was, indeed, killed by death.

Both approaches are deeply flawed. Public policy by philosophical or religious principles is paternalistic and at risk of intolerance, authoritarianism and totalitarianism. Regimes that are deemed evil by history justified themselves by lofty principles and worthy aims.

But the will of the people is not unproblematic either. Besides the potential errors and biases of measuring time preferences, democracy is not the same as mob rule. A democratic government is supposed to safeguard minorities and use due process. A government is also supposed to provide public goods exactly because individuals cannot—some go as far as saying that that is why governments were invented in the first place. Protecting the future is the sort of thing that the state can do but individuals cannot. In these cases, the collective will of the people deviates from the will of individual people. My preferences as a consumer are not the same as my preferences as a voter. It is a political question how much an elected government can and should deviate from the majority opinion.

There is agreement too. Public policy should be internally consistent. If there is good reason to adopt a low pure rate of time preference for public investment in climate policy, then those reasons also apply to public investments in education, health care, and pensions. If there is a good reason to worry about the tail risks of climate change, then we should also be concerned about pandemics and meteorites. If there is good reason to worry about the impacts of climate change on people in other countries, then this should also affect aid, trade and migration policy.

Further reading

Christian Gollier's *The Economics of Risk and Time* (2004) and *Pricing the Planet's Future: The Economics of Discounting in an Uncertain Future* (2012) are excellent books on discounting, uncertainty, and the interactions between the two. Paul Portney and John Weyant's *Discounting and Intergenerational Equity* (1999) and Joel Scheraga's *Discounting and Environmental Policy* are fine collections on discounting.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tdg.html.

Exercises

9.1. Assume that the global mean surface air temperature (in deviation from pre-industrial times) rises from 0.8℃ in 2000 to 3.8℃. Assume that the impact function is $-4.33T + 1.92T^2$. Compute the stream of impacts for the 21st century. Discount these impacts back to 2000 using a 0%, 1%, 3%, 5%, and 10% consumption discount rate.

9.2. Design an online survey or experiment to estimate the discount rate. Implement this using Google Forms, Survey Monkey, a Twitter Poll or whatever means you think best. Gather data and estimate the discount rate.

9.3. Help your fellow students by taking their surveys and experiments. Which one do you think works best?

9.4. Take the survey: https://www.surveygizmo.com/s3/4219168/Time. Which question do you think is best? Which questions are suitable for estimating the rate of time preference? Look at the results and do just that.How would you elicit attitudes towards time? Are the estimated parameters relevant for climate policy?

9.5. Read and discuss:

- ***S. Giglio, M. Maggiori and J. Stroebel (2015), Very long-run discount rates, *Quarterly Journal of Economics*, 130, 1–53.
- ***M.L. Cropper, S.K. Adeyde and P.R. Portney (1994), Preferences for life saving programs: how the public discounts time and age, *Journal of Risk and Uncertainty*, 8, 243–265.
- ***N. Henderson and I.J. Bateman (1995), Empirical and public choice evidence for hyperbolic social discount rates and the implications for intergenerational discounting, *Environmental and Resource Economics*, 5, 413–423.
- ****S. Frederick, G. Loewenstein and T. O'Donoghue (2002), Time discounting and time preference: A critical review, *Journal of Economic Literature*, 40, 351–401.
- ****S. Dietz and G.B. Asheim (2012), Climate policy under sustainable discounted utilitarianism, *Journal of Environmental Economics and Management*, 63, 321–335.
- ****R.S.J. Tol (2013), Climate policy with Bentham-Rawls preferences, *Economics Letters*, 118, 424–428.
- ****M. Ha Duong and N. Treich (2004), Risk aversion, intergenerational equity and climate change, *Environmental and Resource Economics*, 28, 195–207.

Chapter 10

Uncertainty

Thread

- Climate policy is more stringent under uncertainty because negative surprises are more likely than positive surprises. #climateeconomics
- It is wrong to use the average monetized impact because the more severe scenarios have a larger effect on utility. #climateeconomics
- The risk premium corrects for asymmetric impacts, putting more weight on low probability, high impact scenarios. #climateeconomics
- The risk premium is positive, and climate policy more stringent under uncertainty because people are risk averse. #climateeconomics
- Experts disagree on the probabilities of climate change. As most people are averse to ambiguity, this calls for deeper emission cuts. #climateeconomics
- The uncertainty about climate change may be too large to apply expected utility maximization to guide climate policy. #climateeconomics
- Alternative decision criteria point to similar rates of desirable emission reduction. #climateeconomics
- Irreversibility with uncertainty calls for yet more caution: Mistakes cannot be undone. #climateeconomics
- Greenhouse gas emissions stay in the atmosphere for a long time and lock us into climate change. #climateeconomics
- Energy and transport capital are long-lived and lock us into levels and patterns of energy use. #climateeconomics
- The risk of being locked into undesirable climate change is greater than the risk of being locked into expensive energy. #climateeconomics
- Irreversibility thus calls for more stringent climate policy. #climateeconomics
- Optimal emission reduction today depends on expected climate policy in the future. #climateeconomics

- Future climate policy depends on future knowledge. The prospect of learning thus affects current climate policy. #climateeconomics
- Future learning implies that current climate policy needs to hedge less against future policy mistakes. #climateeconomics
- Therefore, the prospect of learning in the future implies that optimal climate policy is less stringent today. #climateeconomics

10.1 Uncertainty**

You'd only care about climate change if you care about the distant future, remote probabilities, far-away lands. This chapter focuses on the remote probabilities, specifically the impact of uncertainty on optimal climate policy.

Chapter 9 shows that care should be taken when aggregating dollar impacts over time, and Chapter 11 argues the same for aggregation over people with different incomes. Similar care should be taken when aggregating dollar impacts over different states of the world, each representing a possible but uncertain scenario of how the future might unfold.

Confronted with uncertainty about the impacts of climate change—itself due to uncertainty about emissions, about climate change, about vulnerability to climate change, about the impacts of climate change, and about the value of those impacts—it is tempting to calculate the expected impacts as follows:

$$\mathbb{E}D = \sum_s p_s D_s \tag{10.1}$$

where $\mathbb{E}$ is the expectation operator, and p_s is the probability of the (discrete) state of the world s. If the uncertainty is continuous, Equation 10.1 is replaced by

$$\mathbb{E}D = \int_D Df(D)\mathrm{d}D \tag{10.2}$$

> Climate policy is more stringent under uncertainty because negative surprises are more likely than positive surprises.

These equations, straightforward as they may be, tell us something fundamental about the role of uncertainty in climate policy. Our best guess is that the world will warm by 2.5℃ if ambient carbon dioxide doubles. But the uncertainty is asymmetric. The IPCC gives a range of 1.5–4.5℃. If we give the two extremes a change of 20%, and the central value a chance of 60%, the *expected* warming is 2.7℃. That is 0.2℃ higher than the best guess. This is because the expection is $0.2 \times (2.5 - 1.5)$℃ below the best guess, and $0.2 \times (4.5 - 2.5)$℃ above. The asymmetry drives a wedge between the best guess and the expectation. As in this case the bad surprise is larger than the good surprise, the expectation is more worrisome than the best guess.

If we assume that warming is 2.5℃ with a 60% chance, 3.5℃ with a 30% chance, and 1.5℃ with a 10% chance, then the best guess is 2.5℃ and the expectation 2.7℃. The difference with the previous example is that asymmetry is now in the probability rather than in the effect size. The impact is the same.

If we assume that the impact of climate change is proportional to the temperature change, then the proportional difference between the best guess impact and the expected impact is the same as the proportional difference between the best guess warming and the expected warming. If instead we assume that the impact of climate change is proportional to warming squared, then the best guess impact is 6.25 and the expected impact is 7.65. The gap widens because the bad surprise gets disproportionally worse.

Table 6.1 in Section 6.5 illustrates this for the social cost of carbon. The mean is always substantial higher than the mode. In other words, if we include uncertainty, we would impose a higher carbon tax than if we ignore it.

10.2 The risk premium**

It is wrong to use the average monetized impact because the more severe scenarios have a larger effect on utility.

Equations (10.1) and (10.2) are intuitive but wrong. The expected damage violates the *St Petersburg Paradox* in that it assumes that large gains offset equally large losses of equal probability. In other words, the prospect of winning a million pounds with a 1% probability cancels the prospect of losing a million pounds with a 1% probability. Few people would accept such a bet.

We should instead use the full welfare calculation:

$$\mathbb{E}U(C,D) = \int_D U(C,D)f(D)\mathrm{d}D \tag{10.3}$$

The expected welfare loss is then

$$\mathbb{E}\Delta U = U(C,D=0) - \mathbb{E}U(C,D) \tag{10.4}$$

The certainty equivalent damage $\mathbb{C}D$ is defined by

$$U(C,D=0) - U(C,D=\mathbb{C}D) = U(C,D=0) - \mathbb{E}U(C,D) \tag{10.5}$$

which can be reworked as

$$\mathbb{C}D = U^{-1}\left[C, \mathbb{E}U(C,D)\right] = U^{-1}\left[C, \int_D U(C,D)f(D)\mathrm{d}D\right] \tag{10.6}$$

That is, we compute the expected welfare loss and then invert the welfare function to obtain an impact measure in money. In Equation (10.2), we first converted to money and then computed the expectation. The difference may seem trivial and in many cases it is—but not in all.

The risk premium corrects for asymmetric impacts, putting more weight on low probability, high impact scenarios.

The risk premium $\mathbb{R}$ is defined as

$$\mathbb{R}D = \mathbb{C}D - \mathbb{E}D \geq 0 \tag{10.7}$$

The risk premium is positive, and climate policy is therefore more stringent. It is strictly positive for risk-averse actors, if the impacts of climate change are harmful. We argue in Chapter 6 that the net impacts of climate change are negative. Empirical evidence has that most people are risk averse.

The risk premium is positive, and climate policy more stringent under uncertainty because people are risk averse.

Table 10.1: Expected damage, certainty equivalent damage, and risk premium

	impact	income		impact	income	
		100	1000		100	1000
0%	0	*4.61*	*6.91*	0	*4.61*	*6.91*
50%	10	*4.50*	*6.90*	10	*4.50*	*6.90*
50%	20	*4.38*	*6.89*	98	*0.69*	*6.80*
expectation	15	*4.44*	*6.89*	54	*2.60*	*6.85*
certainty equivalent		15.15	15.01		86.58	55.02
risk premium		0.15	0.01		32.58	1.02

Note: Italicised numbers are in utils, other numbers in dollars.

Table 10.1 shows the difference between the expected damage and the certainty-equivalent damage. The third column is constructed as follows. Base income is 100, and base utility is 4.61. There is a 50% chance that income falls to 90 and uility to 4.50; and a 50% chance that income falls to 80 and utility to 4.38. Expected utility is thus 4.44. This corresponds to an income of 84.85. The certainty equivalent loss is thus 15.15. The expected loss is 15.00, so that the risk premium is 0.15. This is small, hardly worth the complicated computations.

Table 10.1 illustrates that the risk premium is small if damages are small relative to income, but the risk premium rapidly grows if not. If there is a chance of losing all or most, then the utility loss grows rapidly, much more rapidly than the income loss. This drives a wedge between the expected welfare loss and the expected income loss, and so between the certainty-equivalent damage and the expected damage.

10.3 Ambiguity****

Experts disagree on the probabilities of climate change. As most people are averse to ambiguity, this calls for deeper emission cuts.

Often, we are uncertain about what probability density function to use to describe the uncertainty about the parameter of interest. That is definitely the case in climate change. Different experts will give different opinions, not only about the most likely outcome, but also about the range of possible outcomes. You may be tempted to treat this as higher-order uncertainty, and define

$$\mathbb{E}U(C,D) = \sum_s p_s \int_D U(C,D) f_s(D) \mathrm{d}D \tag{10.8}$$

where essentially we add another integration to the expected impacts, this time over all possible probability density functions f_s, weighted by their probability p_s.

However, Equation (10.8) violates the *Allais Paradox*: People prefer to enter a lottery with known probabilities over a lottery with unknown probabilities—even if the convoluted probabilities are identical. Assuming *smooth ambiguity*,[1] this can be accommodated as follows:

$$\mathbb{E}U_A(C,D) = \sum_s p_s U_A \left[C, \int_D U(C,D) f_s(D) \mathrm{d}D \right] \tag{10.9}$$

[1]This is also known as *KMM ambiguity*; KMM stands for Klibanoff, Marinacci and Mukerji (2005), *Econometrica*, 73, 1849–1892. I here use the subscript A, which stands for either ambiguity or Allais.

The lucidity equivalent damage is then defined as

$$\mathbb{L}D = U^{-1}\left(U_A^{-1}\left(C, \mathbb{E}U_A(C, D)\right)\right) \tag{10.10}$$

Inverse utility U^{-1} is needed to express the lucidity equivalent in money; the term between brackets is defined in the same way at the certainty equivalent. The ambiguity premium is defined as

$$\mathbb{A}D = \mathbb{L}D - \mathbb{C}D \tag{10.11}$$

If U_A is a linear function, $U_A(U) = U$, the ambiguity premium is zero. In other words, there is no ambiguity aversion and the lucidity equivalent damage equals the certainty equivalent damage. The Allais Paradox has that U_A is not linear. A typical parameterization is $U_A(U) = U^{1-\eta_A}$, where η_A is the rate of relative ambiguity aversion. Ambiguity aversion thus further raises the concern about climate change and increases the social cost of carbon.

10.4 Deep uncertainty***

The expected value of the impact of climate is the integral over the impact times its probability; see Equation (10.2). In the tail of the distribution, the impact escalates but its chance falls precipitously. If the tail of the distribution is thin—and this is true in most cases—the probability falls faster than the damage grows. The product—chance times impact—thus falls to zero. The integral converges. The expectation exists and is bounded.

However, if the tail is fat, the probability does not fall as fast as we move out into the tail. Indeed, the damage grows faster than its chance falls. The product thus rises, and the integral does not converge. The expectation does not exist, or is infinitely large.

> The uncertainty about climate change may be too large to apply expected utility maximization to guide climate policy.

The Dismal Theorem, first published by the late Martin Weitzman of Harvard University in 2009, shows that the uncertainty about climate change and its impacts is such that tails are indeed fat. Weitzman showed that the probability of ever more extreme climate change falls only very slowly. In Section 10.2 we saw that the disutility of climate change may rise very fast. This would have the same effect: The expected value is unbounded.

Fat tails pose a problem. The expectation of welfare must exist if the aim is to maximize expected welfare. Essentially, the Dismal Theorem has that expected utility maximization cannot be applied to climate policy—nor can benefit–cost analysis, as that is its monetized approximation.

Different people have interpreted the Dismal Theorem in different ways. One interpretation is that the Dismal Theorem formalizes the Precautionary Principle.[2] A related interpretation is that very stringent climate policy is justified. If the expected welfare loss is unbounded, then the social cost of carbon—its first partial derivative—is arbitrarily large. Therefore, optimal climate policy is *arbitrarily* stringent.

[2]There are two interpretations of the Precautionary Principle:

- It is better to be safe than sorry: Risk aversion implies that it is typically better to overregulate than underregulate.
- Uncertainty is no excuse: It is rarely optimal to wait for all uncertainties to be resolved before taking action.

The Dismal Theorem would replate to the first interpretation, but you do not need fat-tailed uncertainty for the impact of risk aversion to take hold.

This cannot be right. Arbitrarily stringent climate policy means an arbitrarily high carbon tax. That means an end to the use of fossil fuels now. Your mobile phone cannot be recharged, and its battery will run out in hours. But that is not the worst of it. We cannot grow enough food without fertilizers. We cannot transport food from the countryside to the cities without trucks. We cannot store food without refridgeration. An arbitrarily high carbon tax would mean that millions if not billions will starve to death in a matter of weeks. But even that is not likely. We cannot purify drinking water and pipe it to our homes without electricity. People will die of drinking dirty water before they starve. An arbitrarily high carbon tax would kill billions of people. That cannot be the optimum.

The interpretation that climate policy should be arbitrarily stringent is categorically incorrect too. If expected utility does not exist, you cannot apply expected utility maximization to climate policy—but you cannot derive policy conclusions from its non-existence either. The only valid conclusion is that you need to find an alternative decision criterion than expected utility.

Alternative decision criteria point to similar rates of desirable emission reduction.

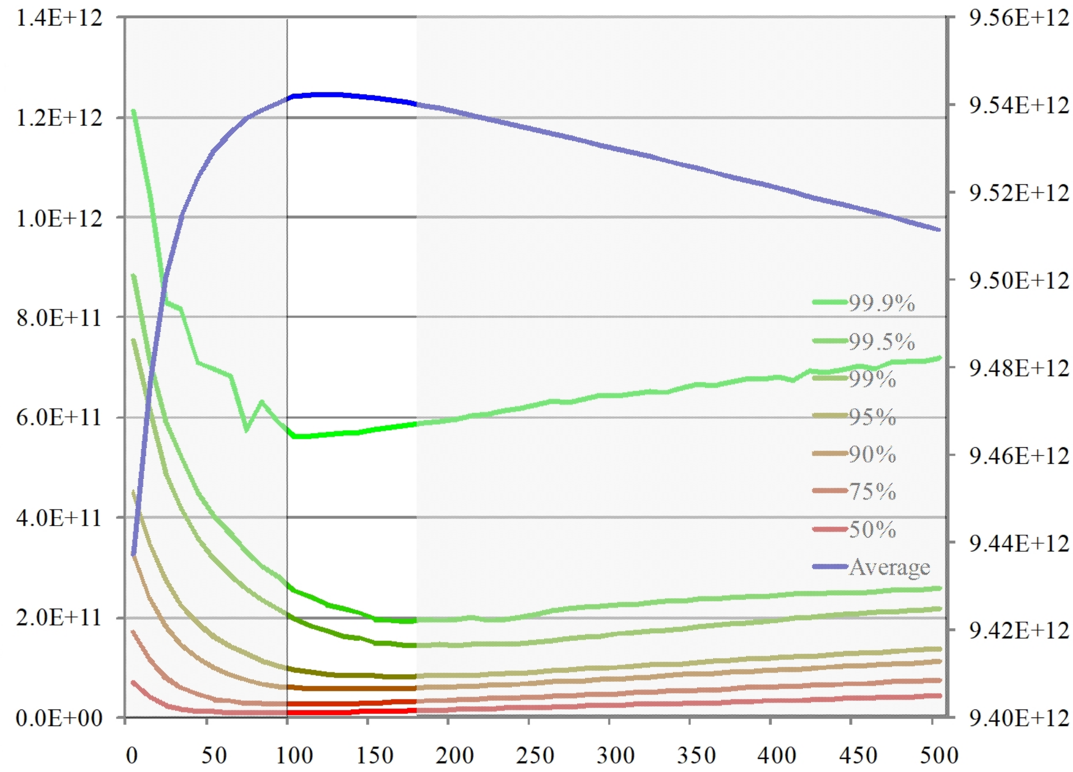
Such alternatives are available, notably minimax regret. It works as follows. For each state of the world, find the optimal course of action—say, the carbon tax that maximizes welfare. Note that we do this for each state of the world, so that there is no uncertainty and fat tails are irrelevant. Define regret as the difference between the optimal welfare and actual welfare; in the optimum, regret is thus zero. Regret is defined for each state of the world. Then, across states of the world, find the maximum regret. Finally, across policies, find the intervention that minimizes maximum regret. Minimax regret does not find an optimum. Instead, it avoids the worst.

The main advantage of minimax regret is that, unlike expected welfare maximization, it can handle situations in which some policies have really bad consequences, perhaps only with a small change, and other policies do not. If all options lead to dreadful outcomes, minimax regret will select the least dreadful one.

Figure 10.1 shows an application. The figure first shows the expected net present welfare as a function of the carbon tax. Static efficiency has that the carbon tax is the same for emissions from all sectors in all countries—see Section 4.4—and that there is a fixed ratio between the prices for different gases—see Section 8.6. Dynamic efficiency has that the carbon tax rises with something akin to the discount rate—see Section 4.6. This implies that the optimal climate policy can be characterized by a single number, say the carbon tax on power generation in the USA in 2020, as all other carbon prices follow immediately from this single price. Therefore, Figure 10.1 shows expected net present welfare as a function of the 2015 tax on carbon dioxide. The result is taken from a Monte Carlo analysis with a finite number of runs. The expectation thus exists by definition.

The welfare function has an interesting shape. Welfare rapidly improves as we move from a zero carbon tax to the optimum. As the carbon exceeds the optimum, welfare falls only gradually. This implies that, if we would introduce a higher form of risk aversion, we would rather have a carbon tax that is larger than the optimum than one that is smaller.

Figure 10.1 also shows regret, again as a function of the initial carbon tax. Minimax regret was developed as a decision criterion to select between a countable set of alternatives and discrete uncertainty. Here, we chose from a continuous carbon tax under unbounded uncertainty. We therefore cannot define maximum regret. We can, however, consider percentiles of the probability distribution of regret. The figure shows various regret percentiles. The shape is similar to that of expected welfare, but upside down as we want to minimize regret and maximize welfare. As we move away from a zero carbon tax, regret rapidly falls until it reaches its minimum, beyond which it gradually rises. Again, we would rather err with a carbon tax that is too high than with one that is too low. The carbon tax recommended by minipercentile regret is comparable to the optimal carbon tax. This is in sharp contrast to the Dismal Theorem.



Source: D. Anthoff and R.S.J. Tol (2014), Climate policy under fat-tailed risk, *Annals of Operations Research*, 220 (1), 223–237.

Figure 10.1: Expected welfare and minipercentile regret as a function of the initial carbon tax

Other objections to the Dismal Theorem have been raised too. In the original formulation, Weitzman only considers the impacts of climate change, which indeed may be very negative. Climate policy is a two-sided problem, however. The impact of emission abatement may be very negative too. Gradual emission reduction would not pose a serious problem to the economy (see Chapter 3), but in the short-run, fossil fuels are an essential input to the economy. In the long-run, we can improve energy efficiency and switch to alternative energy sources; in the short-run, reduced economic activity is the only option available to reduce emissions. Overly stringent climate policy thus bears a very substantial cost and this must be weighed against the risks of climate change.

Furthermore, the Dismal Theorem hangs on the welfare impact of very substantial climate change. In a logarithmic utility function (or any other CRRA one), welfare losses rapidly escalate if consumption falls below one (in whatever unit consumption happens to be measured). Other utility functions do not show this behaviour; utility falls with falling consumption, but not precipitously so at low levels of consumption. The Dismal Theorem therefore stands or falls with CRRA being a valid description of the behaviour of people on the edge of disaster, who are typically too busy surviving to participate in economists' data gathering.

10.5 Irreversibility and learning***

10.5.1 Introduction

Section 8.2 introduced benefit–cost analysis for both static and dynamic problems. Section 10.1 discussed benefit–cost analysis under risk. In a risk context, parameters are not known with certainty but their probability density functions are. For instance, we do not know the social cost of carbon, but we do have estimates of its PDF. Here, we take both issues a step further, introducing irreversibilities and learning.

The impact of irreversibility on decisions is intuitive:

- If I could do something fun today that will not do any damage later, then I should do it.
- If I could do something fun today that will cause a disaster the day after tomorrow, then I should not do it.
- If I could do something fun today that might cause a disaster the day after tomorrow, then I should wonder whether it is worth the risk.
- If I could do something fun today that might cause a disaster the day after tomorrow, but I can undo my actions without cost tomorrow when I will know more, then I should do it.
- If I could do something fun today that might cause a disaster the day after tomorrow, but I can undo my actions at a cost tomorrow when I will know more, then I should wonder whether it is worth the cost.

In other words, actions with irreversible consequences should be considered more carefully than actions with reversible consequences.

> Irreversibility with uncertainty calls for yet more caution: Mistakes cannot be undone.

The impact of learning is not trivial. It is obvious that as we learn more about the climate problem, we can refine our actions. We do not know, however, what we will learn—if we would, we would have learned it already. The fact that we know that we will learn affects current optimal policy, even if we do not know what we will learn. This is counterintuitive. The rest of the section explains how.

10.5.2 A stylized example

Consider a three period problem. Greenhouse gases are emitted in periods 1 and 2, accumulate in the atmosphere, and do damage in period 3. We seek to minimize the net present value of the sum of the abatement costs and the damage costs, by setting emission reduction targets in periods 1 and 2.

We will consider four variants of this problem. In every variant, uncontrolled emissions M_t are 100 units in period 1 and 2. The atmospheric concentration equals 90% of the concentration in the previous period plus the emissions in the previous period. Without emission control, the atmospheric concentration is therefore 190 units. emission reduction costs B are quadratic in emission reduction effort R, with unit marginal costs, that is:

$$B_t = 0.5R_t^2 \Rightarrow \frac{\partial B_t}{\partial R_t} = R_t \text{ for } t = 1, 2 \tag{10.12}$$

Controlled emissions equal $M_t - R_t$. The discount rate is 10%. All parameters in the model are known with certainty, except for the damages of climate change: Damages are either high or low, with a 50% chance. In the second and fourth variant of the model, it is revealed in the second period whether damages are high or low. In the first and third variant, there is no learning. In the first two variants, impacts are linear in concentration. In the last two variants, impacts are quadratic:

	No learning	Learning
Linear impacts	Variant 1	Variant 2
Quadratic impacts	Variant 3	Variant 4

In the first two variants, damage D is 10 times the atmospheric concentration in period 3 with a 50% probability, and 20 times that with a 50% chance. Without learning, the problem is then

$$\min_{R_1,R_2} W = 0.5R_1^2 + \frac{0.5R_2^2}{1+0.1} + (0.5 \cdot 10 + 0.5 \cdot 20)\frac{0.9(100 - R_1) + 100 - R_2}{(1+0.1)^2} \tag{10.13}$$

This is an unconstrained maximization—because we substituted the stock function into the objective function—so the first-order conditions for optimality are

$$\frac{\partial W}{\partial R_1} = 0 \Rightarrow R_1 = \frac{(0.5 \cdot 10 + 0.5 \cdot 20)0.9}{(1+0.1)^2} = 10.9 \tag{10.14}$$

$$\frac{\partial W}{\partial R_2} = 0 \Rightarrow R_2 = \frac{0.5 \cdot 10 + 0.5 \cdot 20}{1+0.1} = 13.5 \tag{10.15}$$

Crucially, the first-order conditions for optimal emission reduction in period 1 are independent of emission reduction in period 2—the problem is a sequence of static optimizations, rather than a truly dynamic one. With learning, we cannot use Equation (10.13) because decisions are made conditional on different information. It is common to solve problems like these by backward induction, first solving the optimization problem of the final period and then working towards the present. That is, for period 2

$$\min_{R_2} W_2 = 0.5R_2^2 + \psi\frac{0.9(100 - R_1) + 100 - R_2}{1+0.1} \text{ for } \psi = 10, 20 \tag{10.16}$$

The first-order conditions are

$$\frac{\partial W_2}{\partial R_2} = 0 \Rightarrow R_{2,i} = \frac{\psi}{1+0.1} = 9, 18 \tag{10.17}$$

Without learning, the optimal decision is to reduce emissions in period 2 by 13.5 units. With learning, the optimal decision is to reduce emissions by either 9 or 18 units. On average, in anticipation, the decision is the same —for $\frac{9+18}{2} = \frac{27}{2} = 13.5$ —but in actuality it is not.

For period 1, the problem is

$$\min_{R_1} W_1 = 0.5R_1^2 + (0.5 \cdot 10 + 0.5 \cdot 20)\frac{0.9(100 - R_1) + 100 - (0.5R_{2,1} + 0.5R_{2,2})}{(1+0.1)^2} \quad (10.18)$$

That is, the optimal action in the first period depends on the expected action in the second period. The first-order conditions are

$$\frac{\partial W_1}{\partial R_1} = 0 \Rightarrow R_1 = \frac{(0.5 \cdot 10 + 0.5 \cdot 20)0.9}{(1+0.1)^2} = 10.9 \quad (10.19)$$

Learning does not affect the optimal decision in the first period. There is no difference between (10.14) and (10.19): Because optimal emission reduction in period 2 is proportional to impacts, the average emission reduction equals the emission reduction at the average impact. More formally, the expectation of the maximum (exp max) equals the maximum of the expectation (max exp).

In general, exp max $\neq$ max exp. Both the expectation (exp) and the maximization (max) are so-called operators. You can only switch the order of operators if all are linear. The expectation is a linear operator: the mean is a weighted sum. Maximization is not a linear operator, unless the first-order conditions are linear. They are in this case.

> Optimal emission reduction today depends on expected climate policy in the future.

In the third and fourth variant, damage D is proportional to the atmospheric concentration squared; the parameter is 0.026 with a 50% probability, and 0.053 with 50% chance; these parameters are chosen such that the social cost of carbon in each scenario is equal in the no-control case to the ones above. Without learning, the problem is then

$$\min_{R_1,R_2} W = 0.5R_1^2 + \frac{0.5R_2^2}{1+0.1} + (0.5 \cdot 10 + 0.5 \cdot 20)\frac{(0.9(100 - R_1) + 100 - R_2)^2}{(1+0.1)^2} \quad (10.20)$$

The first-order conditions are

$$\frac{\partial W}{\partial R_1} = R_1 - (0.5 \cdot 10 + 0.5 \cdot 20)\frac{2 \cdot 0.9(0.9(100 - R_1) + 100 - R_2)}{(1+0.1)^2} = 0 \Leftrightarrow$$
$$R_1 = \frac{(0.5 \cdot 10 + 0.5 \cdot 20)2 \cdot 0.9(0.9 \cdot 100 + 100 - R_2)}{(1+0.1)^2 + 2 \cdot 0.9 \cdot 0.9(0.5 \cdot 10 + 0.5 \cdot 20)} \quad (10.21)$$

$$\frac{\partial W}{\partial R_2} = \frac{R_2}{1+0.1} - (0.5 \cdot 10 + 0.5 \cdot 20)\frac{2(0.9(100 - R_1) + 100 - R_2)}{(1+0.1)^2} = 0 \Leftrightarrow$$
$$R_2 = \frac{(0.5 \cdot 10 + 0.5 \cdot 20)2(0.9(100 - R_1) + 100)}{(1+0.1) + 2(0.5 \cdot 10 + 0.5 \cdot 20)} \quad (10.22)$$

This is a system of two linear equations with two unknowns. It solves as $R_1 = 9.92$ and $R_2 = 12.13$. The crucial difference with the first variant is that the optimal decisions in the two periods interact: R_1 depends on R_2 and R_2 depends on R_1.

Future climate policy depends on future knowledge. The prospect of learning thus affects current climate policy.

With learning, the first order condition for period two equals

$$\frac{\partial W_2}{\partial R_2} = \frac{R_2}{1+0.1} - \psi\frac{2(0.9(100-R_1)+100-R_2}{(1+0.1)^2} = 0 \Leftrightarrow$$
$$R_2 = \frac{2\psi(0.9(100-R_1)+100)}{(1+0.1)+2\psi} \tag{10.23}$$

For period one, this is

$$\frac{\partial W_1}{\partial R_1} = R_1 - (0.5\cdot 10+0.5\cdot 20)\frac{2\cdot 0.9(0.9(100-R_1)+100-0.5R_{2,1}-0.5R_{2,2})}{(1+0.1)^2} = 0 \Leftrightarrow$$
$$R_1 = \frac{(0.5\cdot 10+0.5\cdot 20)2\cdot 0.9(0.9\cdot 100+100-0.5R_{2,1}-0.5R_{2,2})}{(1+0.1)^2+2\cdot 0.9\cdot 0.9(0.5\cdot 10+0.5\cdot 20)} \tag{10.24}$$

The difference between (10.21) and (10.24) is that the former (without learning) has the emission reduction in the second period based on the average damage, whereas the latter (with learning) has the average emission reduction in the second period.

With learning, the solution is R_2=8.72, 15.82 with an average of 12.05. This compares to R_2=12.13 without learning. The reason is intuitive. Although the problem has been set-up with linear utility (or zero risk aversion), the damage function is curved. This acts like risk aversion. Therefore, if the damages are unknown, a rational decision maker would err on the safe side, and be closer to the high damage scenarios.

Future learning implies that current climate policy needs to hedge less against future policy mistakes.

With learning, R_1=9.86 compared to R_1=9.92 without learning. The intuition is as follows. With learning, underinvestment in emission reduction will be recognized and can be corrected in period 2. Without learning, a rational decision maker is more cautious. She needs to contend not only with uncertainty about the state of the world, but also with an imperfectly informed successor. Without learning, today's decision maker hedges against bad decisions in the future. With learning, bad decisions in the future are less likely, so the need to hedge against them is less pronounced.

10.5.3 Applications to climate change

The previous section argued, using a stylized example, that in an imperfectly known, dynamic, non-linear system with irreversibilities, the prospect of future learning affects current optimal behaviour—even if it is not known what will be learned. The intuition is as follows. Net present welfare depends on future choices. Therefore, current choices are influenced by future choices. If there is learning, future choices will be different than if there is no learning. Therefore, future learning affects current choices. Specifically, because of learning, future choices will be better tailored to the actual threat of climate change. As future choices will be better, we can be less worried now.

Greenhouse gas emissions stay in the atmosphere for a long time and lock us into climate change.

The climate problem obviously meets the criteria: uncertainty, dynamics, non-linearity and irreversibility characterize the costs and benefits of greenhouse gas emission reduction. Greenhouse gases stay in the atmosphere for a long time, hundreds of years in the case of carbon dioxide and nitrous oxide, and thousands of years in the case of some halocarbons. It will take decades and centuries for the deep ocean to find a new equilibrium with the changes in the atmosphere. The time horizon is long enough that learning is inevitable—and there is a large-scale research programme on climate change, its impacts and its countermeasures. Therefore, from the analysis above, we would expect that the prospect of future learning affects optimal greenhouse gas emission reduction.

Energy and transport capital are long-lived and lock us into levels and patterns of energy use.

Climate policy is far more complicated than the stylized model above. A crucial difference is that there are irreversibilities on both sides of the equation. Carbon dioxide remains in the atmosphere for a long time. On the other hand, capital is long-lived. An investment in renewable energy cannot be reversed without accepting the cost of capital destruction. Optimal emission reduction thus balances two irreversibilities.

The risk of being locked into undesirable climate change is greater than the risk of being locked into expensive energy.

However, the risk of being locked into expensive energy is limited. The economic impact is not that large in the first place, and the time-scale is measured in decades. Climate change lasts for centuries, and its economic impact may be much larger. It is safe to say that the balance of irreversibility argues for emission reduction that is more ambitious.

Irreversibility thus calls for more stringent climate policy.

Figure 10.2 shows the impact of future learning on optimal emission reduction in the near-term, measured as the percentage change from optimal emission reduction without learning.

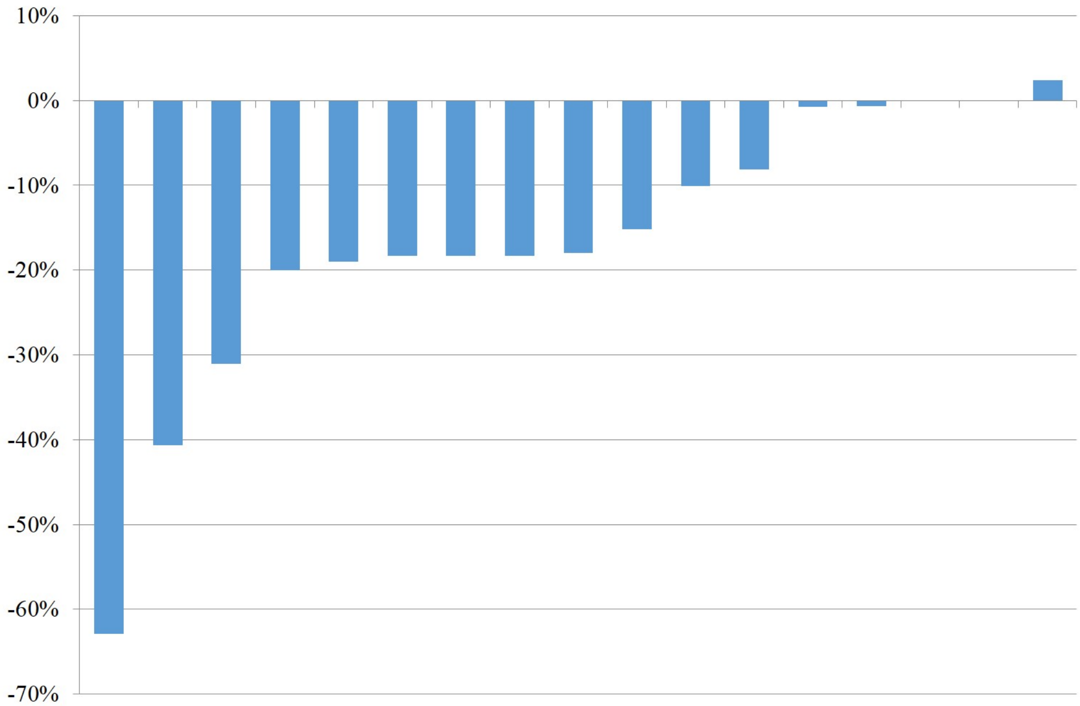
Therefore, the prospect of learning in the future implies that optimal climate policy is less stringent today.

There are 17 estimates in Figure 10.2, taken from five studies, each reporting results for a few sensitivity analyses. One estimate has that the irreversibility of emission abatement outweighs the irreversibility of emissions; optimal emissions are thus lower (or optimal abatement more stringent) due to learning. Two estimates are indistinguishable from zero. Fourteen estimates have that learning increases optimal emissions (or makes optimal abatement less lenient). The estimated effect spans two orders of magnitude, from 0.6% to 63%, with most estimates in the high teens. That is, learning is more than an intellectual curiosity. Learning appears to have a substantial effect on optimal emission abatement. Table 10.2 confirms this message, showing the optimal rate of greenhouse gas emission control as a function of the rate of learning and the degree of irreversibility. Specifically, because we can reasonably expect to know more in the future, we can afford a more lenient climate policy today.

10.6 Measuring risk preferences***

10.6.1 Preliminaries

The discussion of risk in decision analysis goes back to Daniel Bernoulli's observation, in 1738, about the following lottery. Suppose you are offered the chance to win \$2 with probability 1/2,



Note: Emission reduction is relative to emission reduction without learning.

Source: After A. Ingham, J. Ma and A. Ulph (1996), Climate change, mitigation and adaptation with uncertainty and learning, *Energy Policy*, 35 (11), 5354–5369.

Figure 10.2: The effect of future learning on near-term optimal emission reduction according to different studies and model parameterizations

$4 with probability 1/4, $8 with probability 1/8, and so on ... The expected pay-off is infinite. Yet, no one would be willing to pay an infinite amount—or even their annual income—to enter into this lottery. This is known as the St Petersburg Paradox, as that is where Bernoulli was at the time. Standard economic theory offers a reason for this: The utility function is curved. We are almost indifferent between winning a very large amount of money and winning even more.

A general form of a curved utility function is

$$U_i\left(C_i\right) = \frac{1-\eta_H}{\eta_H}\left(\frac{\upsilon C_i}{1-\eta_H} + \underline{\mathrm{U}}\right)^{\eta_H} \tag{10.25}$$

Absolute risk aversion is defined as

$$ARA := -\frac{U''}{U'} = \frac{\upsilon^2\left(\frac{\upsilon C_i}{1-\eta_H} + \underline{\mathrm{U}}\right)^{\eta_H - 2}}{\upsilon\left(\frac{\upsilon C_i}{1-\eta_H} + \underline{\mathrm{U}}\right)^{\eta_H - 1}} = \left(\frac{C_i}{1-\eta_H} + \frac{\underline{\mathrm{U}}}{\upsilon}\right)^{-1} \tag{10.26}$$

Absolute risk aversion falls hyperbolically with consumption, which is why the utility function in Equation (10.25) is known as HARA, which is short for Hyperbolic Absolute Risk Aversion. Risk tolerance, the inverse of absolute risk aversion, is a linear function in consumption.

Table 10.2: The optimal control rate of carbon dioxide emissions as a function of the rate of learning for different degrees of irreversibility

learning	reversible	part reversible	irreversible
0.00	15.5%	15.5%	15.5%
0.25	15.5%	15.4%	14.0%
0.50	15.5%	15.3%	12.5%
0.75	15.5%	15.2%	9.5%
1.00	15.5%	15.1%	8.0%

Source: After C.D. Kolstad (1994), George Bush v Al Gore, *Energy Policy*, 22 (9), 771–778.

Restrictions need to be placed on the parameters: $\upsilon > 0$ and

$$\left(\frac{C_i}{1-\eta_H} + \frac{\underline{\mathrm{U}}}{\upsilon}\right)^{-1} > 0 \tag{10.27}$$

This puts a lower bound on utility for $\eta_H \leq 1$ and an upper bound for $\eta_H > 1$. As an upper bound on utility seems inconsistent, we have effectively that $\eta_H \leq 1$. Note that Weitzman's Dismal Theorem then no longer holds: As utility cannot go to minus infinity, its expectation exists.

There are two limiting cases. For $\eta_H = 0$, utility is logarithmic: $U(C) = \ln(\upsilon C + \underline{\mathrm{U}})$. For $\eta_H \to 1$, utility becomes linear in consumption: $U = \upsilon C + \underline{\mathrm{U}}$.

Relative risk aversion is defined as

$$RRA := -C_i \frac{U''}{U'} = C_i \cdot ARA = C_i \left(\frac{C_i}{1-\eta_H} + \frac{\underline{\mathrm{U}}}{\upsilon}\right)^{-1} = \left(\frac{1}{1-\eta_H} + \frac{\underline{\mathrm{U}}}{\upsilon C_i}\right)^{-1} \tag{10.28}$$

This implies that relative risk aversion is constant (in C_i) if $\underline{\mathrm{U}} = 0$. The utility function is then

$$U_i(C_i) = \frac{1-\eta_H}{\eta_H}\left(\frac{\alpha C_i}{1-\eta_H}\right)^{\eta}_{H} \overset{\eta_H = 1-\eta}{=} \frac{\eta(1-\eta)}{1-\eta}\frac{\upsilon^{1-\eta}}{\eta^{1-\eta}}\frac{C_i^{1-\eta}}{1-\eta} \tag{10.29}$$

which is proportional to the CRRA utility function (9.5) and, for the right choice of η_H, identical.

The HARA utility function and its special cases predict how economic agents evaluate lotteries with pay-offs that are large relative to their income, and how risk behaviour changes with income. Such lotteries are rare, and data are therefore scarce. The predictions about how risk aversion changes with income are equally hard to test, because income tends to change only slowly over time. Empirical studies compare risk aversion for people with different incomes, but rich and poor differ in many ways.

Empirical and experimental studies of risk behaviour therefore tend to rely on a different approach. *Prospect theory*, proposed by Daniel Kahneman and Amos Tversky, is now the accepted way to evaluate lotteries. Here, the worth U of a lottery equals

$$U_P = \sum_s p_s f(D_s) = \sum_s p_s D_s^{\eta} \tag{10.30}$$

where D_s is the pay-off in state-of-the-world s and p_s is chance of this happening. The general form in the middle of Equation (10.30) is often replace by the specific form to the right, where η is a parameter akin to risk aversion.

This can be compared to the standard form

$$U = \sum_s p_s \left(U(C_i + D_s) - U(C_i) \right) = \sum_s p_s \frac{(C_i + D_s)^{1-\eta} - C_i^{1-\eta}}{1-\eta} \tag{10.31}$$

The main difference between (10.30) and (10.31) is that the latter depends on base income C whereas the former does not. However, in applications, researchers often find that risk parameter η varies systemically with observable characteristics such as income.

Loss aversion is a more serious challenge to the old micro-economics. With loss aversion, Equation (10.30) would be:

$$U_L = \sum_s p_s D_s^\eta I_{D_s>0} - p_s \iota (-D_s)^\eta I_{D_s<0} \tag{10.32}$$

That is, people would evaluate losses and gains differently; and $\iota > 1$ is much larger than suggested by the St Petersburg Paradox.

People often have trouble estimating probabilities. This may be systematic, in that some will always think that small probabilities are larger than they really are, or smaller. Figure 10.3 illustrates this with data from the USA. Respondents tend to overestimate the number of deaths due to rare causes, and underestimate the number of deaths due to common causes. This can be included in (10.32) following Drazen Prelec:

$$U_R = \sum_s e^{-\left[\ln\left(\frac{1}{p_s}\right)\right]^\gamma} D_s^\eta I_{D_s>0} - e^{-\left[\ln\left(\frac{1}{p_s}\right)\right]^\gamma} \iota (-D_s)^\eta I_{D_s<0} \tag{10.33}$$

If $\gamma < 1$, people put too much emphasis on small probabilities (as suggested by the empirical evidence). If $\gamma > 1$, put too little emphasis on small probabilities.

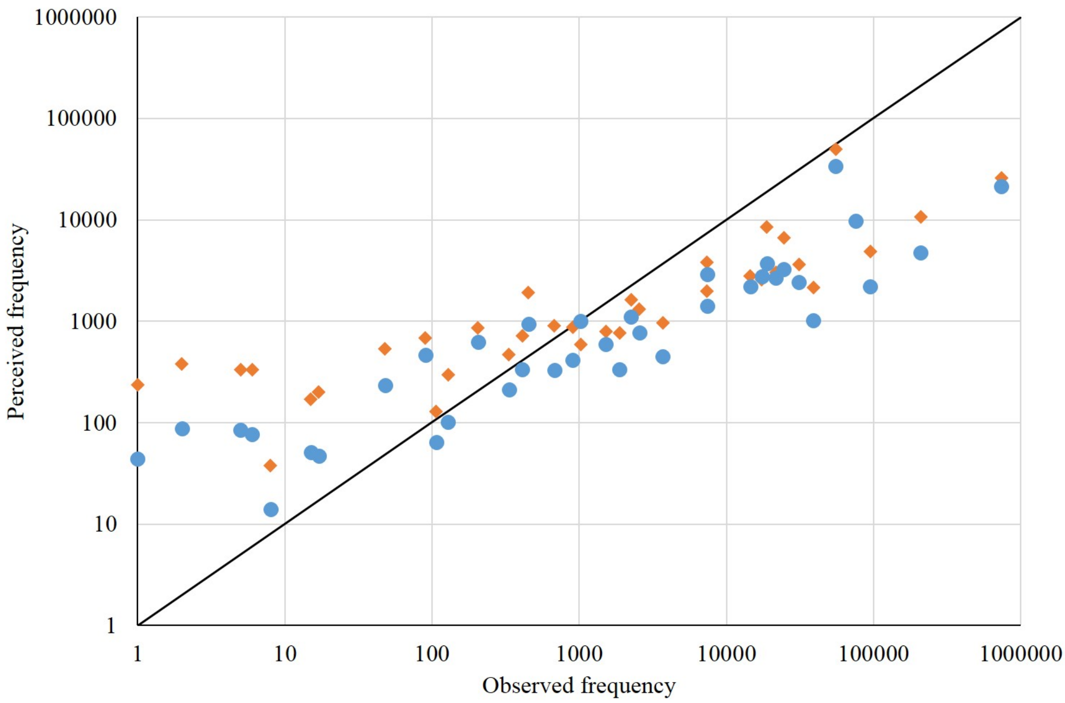
As with time preference, attitudes towards risk are more complicated than suggested by standard micro-economics. This implies that an observation that seems to imply risk aversion may in fact be a manifestation of loss aversion, risk amplification, or ambiguity aversion. It also implies the data need to be carefully constructed, with repeated observations of the same individuals, to distinguish between the different aspects of risk attitudes.

10.6.2 Natural experiments

People make risky decisions on a daily basis. Some play the lottery or bet on the horses. But the results of hardly any decision can be predicted with certainty, be it crossing the road, picking a movie to watch, selecting a diet, joining a sports club, buying a stock, choosing what to study, or getting married. While life is full of risk, inferring risk preferences is not trivial. Risk is rarely the only consideration in making a decision. We observe the choices people made, but not the alternatives they did not choose let alone the utility they would have obtained had they chosen those. We know the objective probabilities of outcomes from population statistics, but do not know the subjective probabilities for the individual. These things need to be kept in mind when interpreting the data.

10.6.3 Controlled experiments

Laboratory experiments, field experiments, and surveys create the impression of contol. Unlike observations that you happened upon, you can determine the environmental parameters and the situation that people respond to—or so you hope, as interviewees and experimental subjects bring baggage that you do not know about. In experiments and surveys, we can elicit choices



Source: After S. Lichtenstein et al. (1978), Judged frequency of lethal events, *Journal of Experimental Psychology: Human Learning and Memory*, 4 (6), 551–578.

Figure 10.3: Estimated and actual number of deaths by cause for two samples of respondents

under risk. We can do so without consequences for the respondent—stated preferences—or with consequences—revealed preferences. The ethics board is unlikely to give permission for an experiment with negative consequences for the subject, so measuring loss aversion is difficult. Budget constraints dictate that payouts are small, so experiments are preferably done on the poor, be it students or people in developing countries.

Table 10.3 illustrates the basic approach taken in many experiments and surveys. Respondents are asked to chose between two lotteries, one with a higher expected return but a greater spread and one with a lower expected payoff but a lower risk. In the first choice, the low-risk lottery dominates. Probablities are gradually changed until, in the final choice, the high-risk lottery dominates. More risk-averse respondents switch later from low- to high-risk lottery. There are a number of design choices. If you ask people to chose between two lotteries, the responses are not biased by a general aversion to gambling. If you give people more choices, you get a more precise estimate of their risk aversion, but at the risk of fatigue. You can make the arithmetic easy, and lose precision, or hard, and lose respondents. A rational respondent would switch once; you can impose this condition, or allow people to make mistakes so as to identify those who did not understand or care. In the example in Table 10.3, the payouts are the same and the probabilities differ. In this experimental set-up, it is therefore not possible to distinguish between risk aversion (which operates on probability times payoff) and risk amplification (which operates on probability).

Table 10.3: Which lottery do you prefer?

0/10 chance to win \$2.00 10/10 chance to win \$1.60		0/10 chance to win \$3.85 10/10 chance to win \$0.10	
1/10 chance to win \$2.00 9/10 chance to win \$1.60		1/10 chance to win \$3.85 9/10 chance to win \$0.10	
2/10 chance to win \$2.00 8/10 chance to win \$1.60		2/10 chance to win \$3.85 8/10 chance to win \$0.10	
3/10 chance to win \$2.00 7/10 chance to win \$1.60		3/10 chance to win \$3.85 7/10 chance to win \$0.10	
4/10 chance to win \$2.00 6/10 chance to win \$1.60		4/10 chance to win \$3.85 6/10 chance to win \$0.10	
5/10 chance to win \$2.00 5/10 chance to win \$1.60		5/10 chance to win \$3.85 5/10 chance to win \$0.10	
6/10 chance to win \$2.00 4/10 chance to win \$1.60		6/10 chance to win \$3.85 4/10 chance to win \$0.10	
7/10 chance to win \$2.00 3/10 chance to win \$1.60		7/10 chance to win \$3.85 3/10 chance to win \$0.10	
8/10 chance to win \$2.00 2/10 chance to win \$1.60		8/10 chance to win \$3.85 2/10 chance to win \$0.10	
9/10 chance to win \$2.00 1/10 chance to win \$1.60		9/10 chance to win \$3.85 1/10 chance to win \$0.10	
0/10 chance to win \$2.00 10/10 chance to win \$1.60		10/10 chance to win \$3.85 0/10 chance to win \$0.10	

Source: After Holt and Laury (2002), *American Economic Review*, 92, 1644–1655.

Further reading

The best introduction to uncertainty, irreversibility and learning is *Buying Greenhouse Insurance* (1991) by Alan Manne and Richard Richels. Highlights were published in 1991 in *Energy Policy* under the same title. Christian Gollier's 2004 *The Economics of Risk and Time* is more advanced but tough-going.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tdh.html.

Exercises

10.1. Assume that the global mean surface air temperature (in deviation from pre-industrial times) rises from 0.8℃ in 2000 to 3.8℃ with a 50% probability, to 2.8℃ with a 25% probability, and to 4.8℃ with a 25% probability. Assume that the impact function is $-4.33T + 1.92T^2$. Compute the stream of average impacts for the 21st century. How does this compare with the impact of a 3.8℃ warming? Assume that per capita income rises from $6,400/person/year in 2000 to $86,000/person/year in 2100. Compute the certainty equivalent impact. How does this compare with the average impact? Assume that per capita income does not grow. How does this change the certainty equivalent impact?

10.2. Derive Equations (10.21–10.22) for a 50% probability of an impact of 9 and a 50% probability of an impact of 21. Repeat again for a 50% probability of an impact of 11 and a 50% probability of an impact of 21. What is the relative impact of a mean-preserving increase in spread (first exercise) versus a spread-preserving increase in mean (second exercise)?

10.3. Derive Equations (10.24–10.23) if 100% of the carbon dioxide stays in the atmosphere for the next period, and if 0% does. What is the impact on the effect of learning on optimal control?

10.4. Show that utility functions $U(C)$ and $\kappa U(C) + \iota$ give the same predicted behaviour.

10.5. Show that the HARA utility function (10.25) is logarithmic for $\eta_H = 0$. Hint: use l'Hôpital's rule, twice. Show that it is linear for $\eta_H \to 1$.

10.6. Design an online survey or experiment to estimate the rate of risk aversion. Implement this using Google Forms, Survey Monkey, a Twitter Poll or whatever means you think best. Gather data and estimate the rate of risk aversion.

10.7. Help your fellow students by taking their surveys and experiments. Which one do you think works best?

10.8. Take the survey: http://www.surveygizmo.com/s3/3249587/Risk. Which question do you think is best? Which questions are suitable for estimating the rate of risk aversion? Look at the results and do just that. How would you elicit attitudes towards risk? Are the estimated parameters relevant for climate policy?

10.9. Read and discuss:

- **C.D. Kolstad (1994), George Bush versus Al Gore: Irreversibilities in greenhouse gas accumulation and emission control investment, *Energy Policy*, 22, 771–778.
- **A.S. Manne and R.G. Richels (1995), Greenhouse debate: Economic efficiency, burden sharing, and hedging strategies, *Energy Journal*, 16, 1–37.

- ***W.K. Viscusi and H. Chesson (1999), Hopes and fears: The conflicting effects of risk ambiguity, *Theory and Decision*, 47, 157–184.
- ***M.L. Weitzman (2009), On modeling and interpretation the economics of catastrophic climate change, *Review of Economics and Statistics*, 91, 1–19.
- ***W.D. Nordhaus (2011), The economics of tail events with an application to climate change, *Review of Environmental Economics and Policy*, 5, 240–257.
- ****A. Millner (2013), On welfare frameworks and catastrophic climate risks, *Journal of Environmental Economics and Management*, 65, 310–325.
- ****A. Millner, S. Dietz and G.M. Heal (2013), Scientific ambiguity and climate policy, *Environmental and Resource Economics*, 55, 21–46.
- ***R.S. Pindyck (2007), Uncertainty in environmental economics, *Review of Environmental Economics and Policy*, 1, 45–65.
- ***K. Keller, B.M. Bolker and D.F. Bradford (2004), Uncertain climate thresholds and optimal economic growth, *Journal of Environmental Economics and Management*, 48 (1), 723–741.
- ****A. Ingham, J. Ma and A.M. Ulph (2007), Climate change, mitigation and adaptation with uncertainty and learning, *Energy Policy*, 35, 5354–5369.
- ****A. Lange and N. Treich (2008), Uncertainty, learning and ambiguity in economic models on climate policy: Some classical results and new directions, *Climatic Change*, 89, 7–21.
- ****E. Baker (2005), Uncertainty and learning in a strategic environment: Global climate change, *Resource and Energy Economics*, 27, 19–40.

Chapter 11

Equity

Thread

- It is wrong to add up monetized impacts because a dollar to a poor woman is not a dollar to a rich woman. #climateeconomics
- Equity weights correct for this, putting more weight on the impacts in poorer countries but keeping their values as is. #climateeconomics
- Equity weights tend to increase the global impact, as poorer countries tend to be more vulnerable to climate change. #climateeconomics
- Climate policy advice is based on a mix of positive and normative statements. #climateeconomics
- Analysts should distinguish between facts and values when presenting their recommendations. #climateeconomics
- Analysts should not seek to impose their will, or assume that others agree with their politics. #climateeconomics

11.1 Equity**

You'd only care about climate change if you care about the distant future, remote probabilities, far-away lands. This chapter is about far-away lands, or rather about our concern for distant others.

> It is wrong to add up monetized impacts because a dollar to a poor woman is not a dollar to a rich woman.

The impact of climate change varies greatly between countries. Particularly, poor countries tend to be most vulnerable. See Chapter 6. The studies referred to in that chapter estimate the impacts per country or region, and add up the results, in dollars, to the global total. This is wrong. Particularly, health risks are valued according to the national average willingness to pay. As the willingness to pay to reduce health risks is bound by the ability to pay (see Chapter 5), health risks in poor countries are deemed to be less severe than health risks in rich countries. In a rich country like the United Kingdom, the willingness to pay to avoid a statistical death may amount to \$7,000,000. In a poor country like Bangladesh, the value of a statistical life may only be \$70,000. In other words, we care more, in monetary terms, about the death of someone who is rich than about the death of someone who is poor. This is hard to stomach, and unwise to say out loud in a UN meeting (as became clear in 1995 during the final stage of the preparation of the Second Assessment Report of Working Group 3 of the Intergovernmental Panel on Climate Change).

Two solutions have been proposed to this moral conundrum. First, for a global problem such as climate change, global average values should be used, say \$700,000. This does not work, however. If the Bangladeshi government would use the global average willingness to pay to reduced health risks for its climate policy, and the national average for its flood management, then it should shift its resources from flood defence to greenhouse gas emission reduction—because lifes saved by climate policy are ten times as valuable. If the UK government would use the global average for climate policy and the national average for flood management, then it should shift its resources from climate to floods—because lifes saved by flood policy are ten times as worthy. This cannot be the solution.

> Equity weights correct for this, putting more weight on the impacts in poorer countries but keeping their values as is.

The other solution is to use *equity weights*. The problem with aggregating dollars is that a dollar to a poor woman is not the same as a dollar to a rich woman. Equity weights correct for this. Formally,

$$D_W = \sum_c \frac{1}{W_M} \frac{\partial W}{\partial U_c} \frac{\partial U_c}{\partial D_c} D_c \tag{11.1}$$

The global damage D_W is a weighted sum of the country damages D_c. The weights have three components. First, the monetized damages D_c are transformed into utility by multiplying them with the marginal utility. Technically, marginal utility is the *Jacobian* that transforms variables from money space to utility space. The first partial derivative is like a ratio with utility as the unit in the nominator and money as the unit of the denominator. The unit of marginal utility is thus utils per dollar.

The second component of the equity weight is another Jacobian, transforming national utility into global welfare. The third component is a normalization. We transformed damages from money into utility, and utility into welfare. The global damages are expressed in money, however. The normalization thus has to be expressed in dollars per welfare. The term W_M in Equation (11.1) does exactly that. It considers the situation in which the global budget constraint is slight loosened—say, a Martian comes along and gives us a dollar—and the windfall gain is optimally distributed over the world population. This normalization is appropriate in the sense that it is equity neutral.

If we assume that the utility function exhibits a constant relative rate of risk aversion, and that global welfare is the simple sum of national utilities—that is, a utilitarian welfare function in which we do not care about the distribution of utility, although we do care, through the curvature of the utility function, about the distribution of income—then Equation (11.1) becomes

$$D_W = \sum_c \left(\frac{y_W}{y_c}\right)^\eta D_c \tag{11.2}$$

where y_c is the national average per capita income, y_W is the global average per capita income and η is the rate of risk aversion. Equation (11.2) is more intuitive. Damages in countries with a below average income receive a greater weight. The weight increases as the utility function is more curved. If utility is linear in income, $\eta = 0$, global damage is the simple sum of country damage. That is, the studies in Chapter 6 make the peculiar assumption of risk neutrality.

Equity weights matter. According to one estimate, the social cost of carbon equals \$16/tC without equity weights, but \$28/tC with, for a relatively small $\eta = 1$.

Returning to the justification, equity weights can imply global average values, for

$$D_W = \sum_c \left(\frac{y_W}{y_c}\right)^\eta D_c = \sum_c \left(\frac{y_W}{y_c}\right)^\eta \pi_c H_c = \\ = \sum_c \left(\frac{y_W}{y_c}\right)^\eta \left(\frac{y_c}{y_W}\right)^\varepsilon \pi_W H_c \overset{\eta=\varepsilon}{=} \sum_c \pi_W H_c \quad (11.3)$$

where H_c is the physical impact (say, the number of premature deaths), π_c is the national unit value (say, the willingness to pay to reduce health risks), π_W is the global average unit value, and ε is the income elasticity of that value. If $\eta = \varepsilon$, all impacts are valued at the global average. There is, of course, no reason why the rate of risk aversion would be equal to the income elasticity of willingness to pay.

11.2 Derivation of equity weights***

Above, equity weights are posited. The derivation is as follows. Assume a global, intertemporal welfare function

$$W = \sum_c \int_t U(C_c(t)) e^{-\rho t} \mathrm{d}t \quad (11.4)$$

where the global welfare W is the sum of the present welfare of a finite number of countries c. The present welfare of country c is the integral over the stream of utility U, derived from consumption C at time t, discounted at rate ρ.

The utility function is assumed to exhibit a constant relative rate of risk aversion, so

$$U = \frac{C^{1-\eta}}{1-\eta} \quad (11.5)$$

where η is the rate of risk aversion.

The social cost of carbon is the effect of an infinitesimally small change in emissions on welfare

$$scc_W := \frac{\partial W}{\partial M(0)} = \sum_c \int_t \frac{\partial U(C_c(t))}{\partial C_c(t)} \frac{\partial C_c(t)}{\partial M(0)} e^{-\rho t} \mathrm{d}t = \\ = \sum_c \int_t C_c(t)^{-\eta} \frac{\partial C_c(t)}{\partial M(0)} e^{-\rho t} \mathrm{d}t = \\ = \sum_c \int_t C_c(0)^{-\eta} e^{-\eta g t} \frac{\partial C_c(t)}{\partial E(0)} e^{-\rho t} \mathrm{d}t = \\ = \sum_c C_c(0)^{-\eta} \int_t \frac{\partial C_c(t)}{\partial M(0)} e^{-(\rho+\eta g)t} \mathrm{d}t = \\ = \sum_c C_c(0)^{-\eta} SCC_c \quad (11.6)$$

That is, the global social cost of carbon scc_W is the weighted sum of the national social costs of carbon scc_c.

Equation (11.6) does not specify the social cost of carbon as we normally think about it. Its unit is utils per tonne of carbon, rather than dollars per tonne of carbon. We therefore need to normalize it with something that is measured in utils per dollar. For a single agent, or a country with a representative agent, we would normalize by marginal utility with respect to consumption. Normalization for a global planner requires a bit more thought.

Consider the instantaneous global welfare function

$$W = \sum_c U(C_c) \tag{11.7}$$

Maximize this, subject to the budget constraint that total consumption cannot exceed total income Y. Assuming CRRA, the first-order conditions are

$$C_c^{-\eta} = \lambda \tag{11.8}$$

$$\sum_c C_c = Y \tag{11.9}$$

The budget constraint is shared, so marginal utilities are equalized. The rate of risk aversion is assumed to be equal for all, so consumption is equalized. The solution is thus

$$\bar{C}^{-\eta} = \lambda \tag{11.10}$$

The shadow price of the budget constraint λ equals the increase in welfare if the budget constraint is slightly slackened. This is therefore an appropriate measure of marginal welfare with respect to consumption for a global planner.

Therefore, using (11.10) to normalize (11.6) we find

$$SCC_W = \frac{scc_W}{\bar{C}^{-\eta}} = \sum_c \left(\frac{\bar{C}}{C_c}\right)^{-\eta} SCC_c \tag{11.11}$$

which is Equation (11.2).

Equation (11.10) is peculiar. The derivation of equity weights depends on the optimal allocation of consumption, and the optimal allocation is that everyone consumes the same. Actual consumption is not equal. We may argue that the current income distribution is suboptimal, or we may argue that we should have used a different welfare function:

$$W = \sum_c \vartheta_c U(C_c) \tag{11.12}$$

which implies that $C_c^{-\eta} = {}^{\lambda}\!/_{\vartheta_c}$. If we set $\vartheta_c = C_c^{-\eta}$, the current income distribution is optimal! These weights are known as Negishi weights. Negishi weights cancel equity weights. A dollar to a poor woman is a dollar to a rich woman, because a poor women is worth less than a rich woman.[1]

Negishi weights are strange but they do highlight an issue with equity weights. Equity weights increase the social cost of carbon. This would mean a higher carbon tax. Rich people would see an increase in the price of energy. This increase would be on behalf of the less

[1] Negishi weights are frequently used in economics to solve a market equilibrium as a "social optimum", because the latter is numerically easier rather than optimal in any conventional sense of that word.

fortunate. This is suboptimal. An income transfer from rich to poor would do less damage to the rich and more good to the poor, exactly because a dollar to a poor woman is worth more than a dollar to a rich woman. It is for this reason that the use of equity weights fell out of fashion for policy evaluation *within* countries. We should not use climate policy to solve issues of unequal income of people living in the same country. Those problems are better solved by fiscal policy, that is, progressive taxation and income support. However, income transfers are small *between* countries. This justifies the use of equity weights.

11.3 Measuring equity preferences***

11.3.1 Preliminaries

Consider a Bergson–Samuelson welfare function as specified by Atkinson:

$$W(U_1, U_2, \ldots, U_n) = \begin{cases} \sum_{i=1}^n \frac{U_i^{1-\omega}}{1-\omega} & \omega \neq 1 \\ \prod_{i=1}^n U_i & \omega = 1 \end{cases} \tag{11.13}$$

where W is social welfare, U_i is the utility of individual i, and ω is a parameter, that can be interpreted as the pure rate of inequity aversion, or the rate of aversion to inequity in utility. Consider a small change in the utility of a miserable person m versus a blissful person b:

$$\frac{\frac{\partial W}{\partial U_m}}{\frac{\partial W}{\partial U_b}} = \left(\frac{U_m}{U_b}\right)^{\omega} \begin{cases} > 1 & & \omega > 0 \\ = 1 & \text{for} & \omega = 0 \\ < 1 & & \omega < 0 \end{cases} \tag{11.14}$$

That is, if $\omega = 0$, the social planner is indifferent between extra utility flowing to the miserable or blissful person. If $\omega > 0$, the social planner would rather make the miserable person happier than the blissful one. And if $\omega < 0$, the social planner favours the blissful person.

This is further emphasized if we take the limits

$$\lim_{\omega \uparrow \infty} W = \min_i U_i; \; \lim_{\omega \downarrow -\infty} W = \max_i U_i \tag{11.15}$$

That is, as the rate of inequity aversion increases, the Bergson–Samuelson–Atkinson welfare function approaches (what some would call) a Rawlsian welfare function, according to which we should seek to maximize the utility of the worst-off person. And if the rate of inequity aversion falls towards minus infinity, Bergson–Samuelson–Atkinson approaches a Nietzschean function, according to which we should seek to maximize the utility of the best-off person.

The above is about the distribution of utility, which is unobserved. Let us assume an iso-elastic utility function, see Equation (11.5). Then the trade-off between giving more income to a poor person p versus a rich person r is governed by:

$$\frac{\frac{\partial W}{\partial U_p}}{\frac{\partial W}{\partial U_r}} = \left(\frac{C_p}{C_r}\right)^{\eta + \omega(1-\eta)} := \left(\frac{C_p}{C_r}\right)^{\epsilon} \tag{11.16}$$

where ϵ is the consumption rate of inequity aversion, or the rate of aversion to inequity in consumption.

There is a problem with Equation (11.16): If we observe decisions about how to allocate income across people (e.g., by the system of taxes and benefits), we can deduce information about the *consumption* rate of inequity aversion ϵ, but not about the *pure* rate of inequity aversion ω or the rate of risk aversion η. This is intuitive: If someone is risk averse but equity neutral, then a small monetary gain is worth more to a poor woman than to a rich one. Ditto if someone is risk neutral and inequity averse.

The above framework has another problem: If income can be re-allocated without cost, then the optimal distribution is an egalitarian one (provided that $\eta + \omega(1-\eta) > 0$). Therefore, inequity preferences are typically inferred under the assumption that income transfers are not costless. Transferring money may be by way of Okun's leaky bucket, so that more money is taken away from the rich than given to the poor. This can be explained by the overhead costs of charity and taxation. Alternatively, the bucket may leak because income transfers discourage work and education.

There is a key prediction: If everyone's consumption is multiplied by λ, then social welfare is multiplied by $\lambda^{(1-\eta)(1-\omega)}$. However, λ drops out 11.16, so that social policy is unaffected: Concern about inequality is not affected by the average income level. Sen and Foster proposed alternative social welfare functions, multiplying average income by one minus the Gini coefficient (Sen) or by the Theil-L or Theil-T index (Foster). These indices are invariant under unit changes in income measurements. Therefore, as with Bergson–Samuelson–Atkinson, if everyone's consumption is multiplied by λ, then social welfare is multiplied by λ and social policy is again unaffected. This property is testable.

If, however, we keep (11.13) but change (11.5) to a Stone-Geary function

$$U_i(C_i) = \begin{cases} \frac{(C_i - \underline{C})^{1-\eta}}{1-\eta} & \eta \neq 1 \\ \ln(C_i - \underline{C}) & \eta = 1 \end{cases} \tag{11.17}$$

where $\underline{C}$ is the minimally acceptable or survivable level of income, then a uniform change in income does change optimal social policy.

11.3.2 Natural experiments

Equal absolute sacrifice

The public attitude to inequity within a jurisdiction can be derived from the system of taxes and benefits, which typically disproportionally take from the rich and disproportionally give to the poor. The principle of equal absolute sacrifice has that all suffer in the same way. Assuming that taxes are set on the basis of this principle, the curvature of the utility function is implied. Consider

$$\Delta U_i = U_i(Y_i) - U_i(Y_i - \tau_i) = c \tag{11.18}$$

where Y_i is the income of individual i, τ are her taxes, and A is a constant—that is, all suffer the same utility loss due to taxation.

Taking derivatives to Y_i, we have

$$U_i'(Y_i) - U_i'(Y_i - \tau_i)\left(1 - \frac{\partial \tau_i}{\partial Y_i}\right) = 0 \tag{11.19}$$

Assuming an iso-elastic utility function (11.5) and rearranging

$$\left(\frac{Y_i}{Y_i - \tau_i}\right)^{-\eta} = 1 - \frac{\partial \tau_i}{\partial Y_i} \tag{11.20}$$

Taking logs

$$-\eta \ln\left(\frac{Y_i}{Y_i - \tau_i}\right) = \ln\left(1 - \frac{\partial \tau_i}{\partial Y_i}\right) \tag{11.21}$$

We can thus estimate η by regressing the log of one minus the marginal tax on the log of the ratio of income before and after tax.

Figures 11.1 and 11.2 illustrate the procedure with income tax data for the United Kingdom in the fiscal year 2011–2. Income taxation is mildly progressive for incomes below £45,000, with average tax rates gradually rising to 15%, and strongly progressive above that, with average tax rates rapidly rising to 30% and more (Figure 11.1). The elements of Equation (11.21) are shown in Figure 11.2. While there is a clear negative correlation, there is a lot of noise too. The implied inequity aversion is 1.74 (with a standard deviation of 0.15).

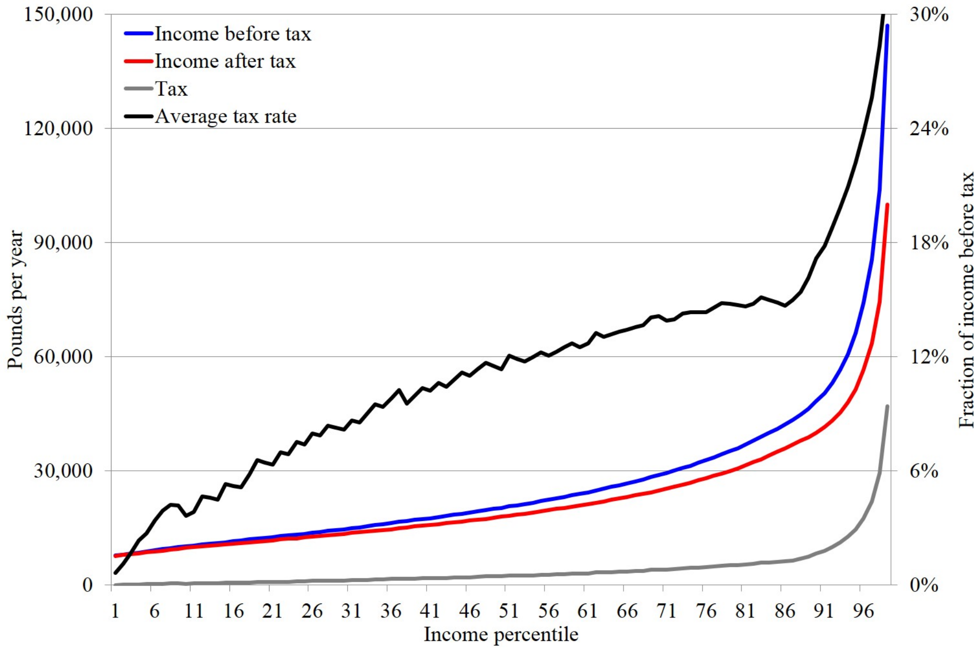


Figure 11.1: The income distribution in the UK, before and after tax, the absolute tax and the average tax rate, in 2012

Optimal taxation

The above analysis leads to a simple regression, but rests on the assumptions that public policy is set on the principle of equal absolute sacrifice in utility, that taxes are lump-sum and that taxes do not affect behaviour. There is a large literature in public economics that considers optimal taxation, based on more realistic assumptions. The optimal tax depends on the assumed social preferences, which determine what is better and best. In principle, these results can be inverted, assuming that the observed tax system is optimal, to reveal social preferences. Practice is more complicated.

Let us consider a simple model (following Atkinson and Stiglitz). An individual maximizes her utility, which is a function of total consumption C and leisure time $1 - S$

$$U = \vartheta \ln C + (1 - \vartheta) \ln(1 - S) \tag{11.22}$$

Consumption equals after-tax income

$$C = (1 - \tau)wL + Q \tag{11.23}$$

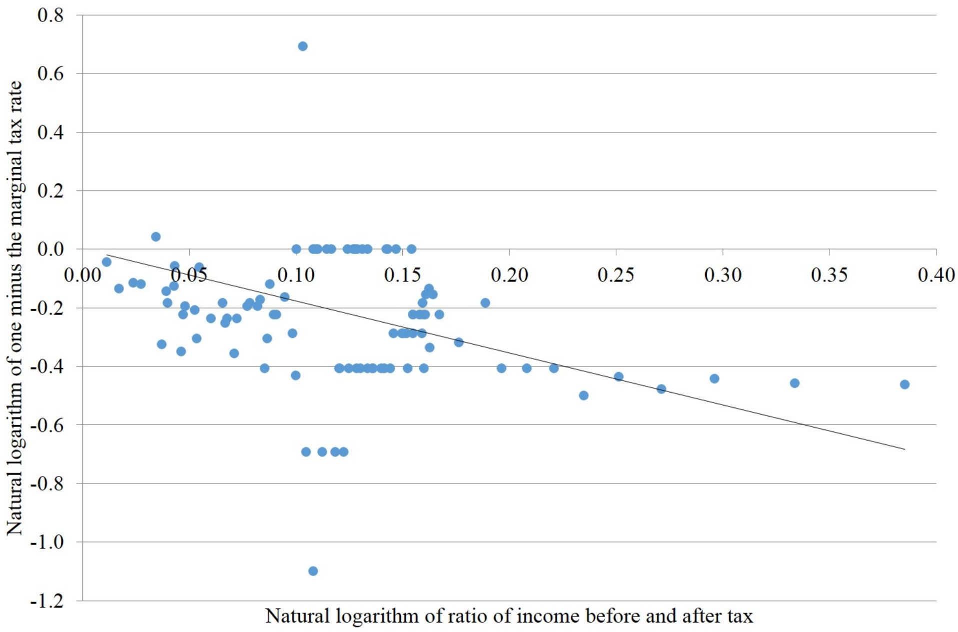


Figure 11.2: The principle of equal absolute sacrifice as used to estimate the rate of aversion to inequality in income

where w is the wage rate, and wL is pre-tax income. The government levies a linear income tax τ and gives everyone a lump sum payment Q (which may be in cash, or in kind in the form of the provision of public goods).

Substituting (11.23) in (11.22) and maximizing with respect to the number of hours worked, we find the first-order condition

$$\frac{\partial U}{\partial S} = \frac{\vartheta(1-\tau)w}{(1-\tau)wS+Q} - \frac{1-\vartheta}{1-S} = 0 \tag{11.24}$$

Rearranging

$$S^* = \vartheta - \frac{(1-\vartheta)Q}{(1-\tau)w} \tag{11.25}$$

Note that $0 < \tau < 1$ so that labour supply falls as the tax increases. Therefore, any increase in transfers, financed by a tax increase, leads to a reduction in total income. In other words, the bucket is leaky. A higher tax discourages work so that there is less revenue for distribution.

The indirect utility function is

$$V = \vartheta \ln[(1-\tau)wS^* + Q] + (1-\vartheta)\ln[1-S^*] \tag{11.26}$$

The social planner seeks to optimize (11.13)—but with indirect utility rather than utility, to account for individuals reoptimizing their behaviour—by choosing tax and transfers, subject to the constraint

$$\sum \tau w_i S_i^* = \sum Q = NQ \tag{11.27}$$

where N is the number of individuals. The first-order conditions are

$$\frac{\partial W}{\partial \tau} = \sum V_i^{-\omega} \frac{\partial V_i}{\partial \tau} - \lambda \sum w_i S_i^* \frac{\partial S_i^*}{\partial \tau} = 0 \tag{11.28}$$

$$\frac{\partial W}{\partial Q} = \sum V_i^{-\omega} \frac{\partial V_i}{\partial Q} - \lambda \sum w_i S_i^* \frac{\partial S_i^*}{\partial Q} + \lambda N = 0 \tag{11.29}$$

and (11.27).

This is a system with three equations and three unknowns, τ, Q and λ. We know that

$$\frac{\partial V_i}{\partial \tau} = \frac{\vartheta}{C^*}\frac{\partial C^*}{\partial \tau} - \frac{1-\vartheta}{(1-S^*)}\frac{\partial S^*}{\partial \tau} \tag{11.30}$$

$$\frac{\partial V}{\partial Q} = \frac{\vartheta}{C^*}\frac{\partial C^*}{\partial Q} - \frac{1-\vartheta}{(1-S^*)}\frac{\partial S^*}{\partial Q} \tag{11.31}$$

$$\frac{\partial C^*}{\partial \tau} = (1-\tau)w\frac{\partial S^*}{\partial \tau} - wS^* \tag{11.32}$$

$$\frac{\partial C^*}{\partial Q} = (1-\tau)w\frac{\partial S^*}{\partial Q} + 1 \tag{11.33}$$

$$\frac{\partial S^*}{\partial \tau} = -\frac{(1-\vartheta)Q}{(1-\tau)^2 w} \tag{11.34}$$

$$\frac{\partial S^*}{\partial Q} = -\frac{(1-\vartheta)Q}{(1-\tau)w} \tag{11.35}$$

Inspection shows that these equations are non-linear. For instance, we see τ, τ^{-1} and τ^{-2}. There is no closed form solution. We have to use numerical methods to find a solution.

Note that the above equations are the simplest and most tractable version of the argument. This goes to show that interpreting actual fiscal policy as an expression of equity preferences is really rather involved, and that the interpretation rests on a number of assumptions that may be more or less realistic.

Solving the social planning problem for the 2012 pre-tax income distribution, we find that the optimal flat tax ranges from 53% for $\omega = 0.1$ to 57% for $\omega = 1.5$. See Figure 11.3.

In other words, there is a weak relationship between the rate of inequity aversion and the optimal rate of the flat tax. Inverting the argument, we find that very different rates of inequity aversion imply very similar tax rates.

Of course, the analysis is overly simple, but it nonetheless depends on a fair number of explicit assumptions. Anyone expressing an opinion about the system of taxes and benefits implicitly reveals her rate of inequity aversion, but also her beliefs about the income distribution, the income elasticity of labour supply, and all other parameters that make a model like this tick. As an empirical strategy to estimate the rate of inequity aversion, this appears to be a dead end.

11.3.3 Controlled experiments

Inequity aversion can be estimated using choice experiments. Table 11.1 shows an example (after Ernst Fehr). The question posed to the interviewees is simple: Which situation do you prefer? A, B or C? The situations are different. Situation A describes a rich but unequal situation. In situation B, person 1 sacrifices \$4,000 so that person 3 gains \$1,000. The bucket is rather leaky. The bottom half of Table 11.1 shows that the implications for total welfare for alternative values of η (assuming $\omega = 0$).

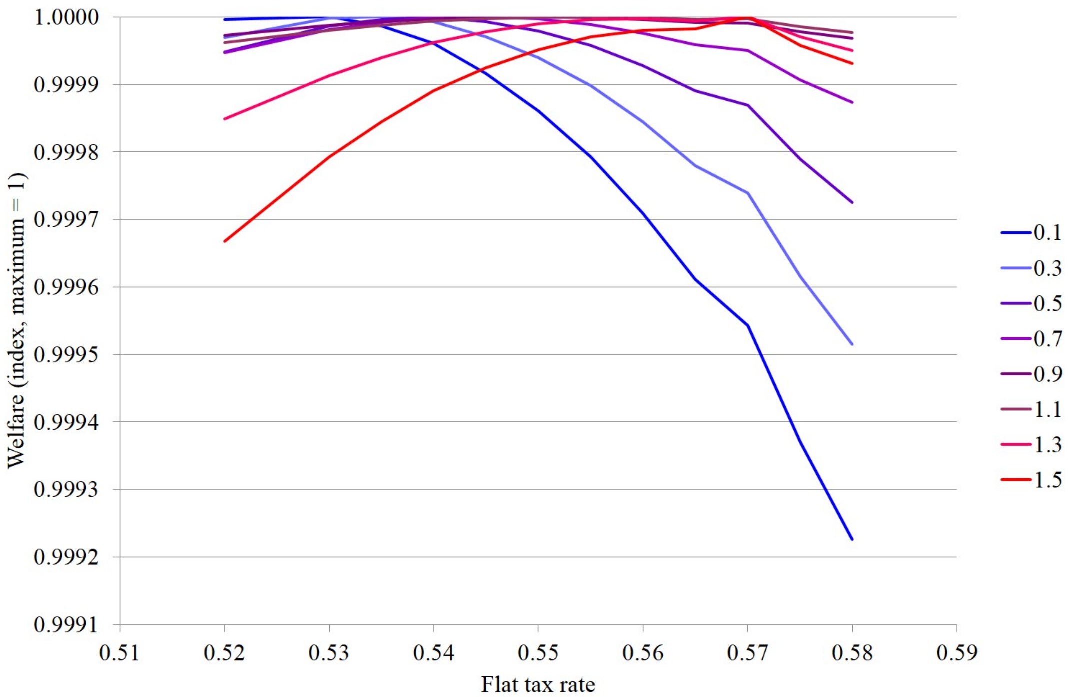


Figure 11.3: Welfare as a function of the rate of the flat tax and the rate of aversion to inequality in utility

An inequity neutral person, with $\eta = 0$, would prefer the situation where income is highest, regardless of its distribution. As η increases, sacrificing total income for a more egalitarian allocation becomes more attractive. If $\eta = 0.82$, the social planner is indifferent between situations A and B. If $\eta = 1.15$, the social planner is indifferent between situations B and C.

A choice experiment as shown in Table 11.1 thus puts bounds on the rate of inequity aversion of the interviewee. Repeated experiments (with different values) would narrow these bounds.

11.4 Implications for climate policy**

Figure 11.4 illustrates the implication for climate, focusing on the social cost of carbon.

> The total and marginal net present impact of climate change rise sharply with a falling discount rate.

In Panel (a), equity and uncertainty are ignored. The social cost of carbon is shown as a function of two parameters, viz. the pure rate of time preference and the rate of risk aversion. The relationships are simple. The higher the pure rate of time preference, the less you care about the future, and the lower the social cost of carbon. The rate of risk aversion only affects the discount rate (see the Ramsey rule, Equation 9.1). The lower the rate of risk aversion, the lower the discount rate, the more you care about the future, and the higher the social cost of carbon.

> Equity weights tend to increase the global impact, as poorer countries tend to be more vulnerable to climate change.

Table 11.1: A choice experiment on the income distribution

	Situation A	Situation B	Situation C
Person 1	\$21,000	\$17,000	\$13,000
Person 2	\$9,000	\$9,000	\$9,000
Person 3	\$3,000	\$4,000	\$5,000
Inequity aversion		Total welfare	
0.00	**33,000**	30,000	27,000
0.50	**589.11**	577.00	559.19
0.75	**116.72**	116.45	115.31
0.82	**85.994**	**85.994**	85.484
1.00	27.064	**27.140**	27.095
1.15	-4.9436	**-4.9079**	**-4.9079**
1.25	-1.2834	-1.2640	**-1.2610**
2.00	-0.00049206	-0.00041993	**-0.00038803**

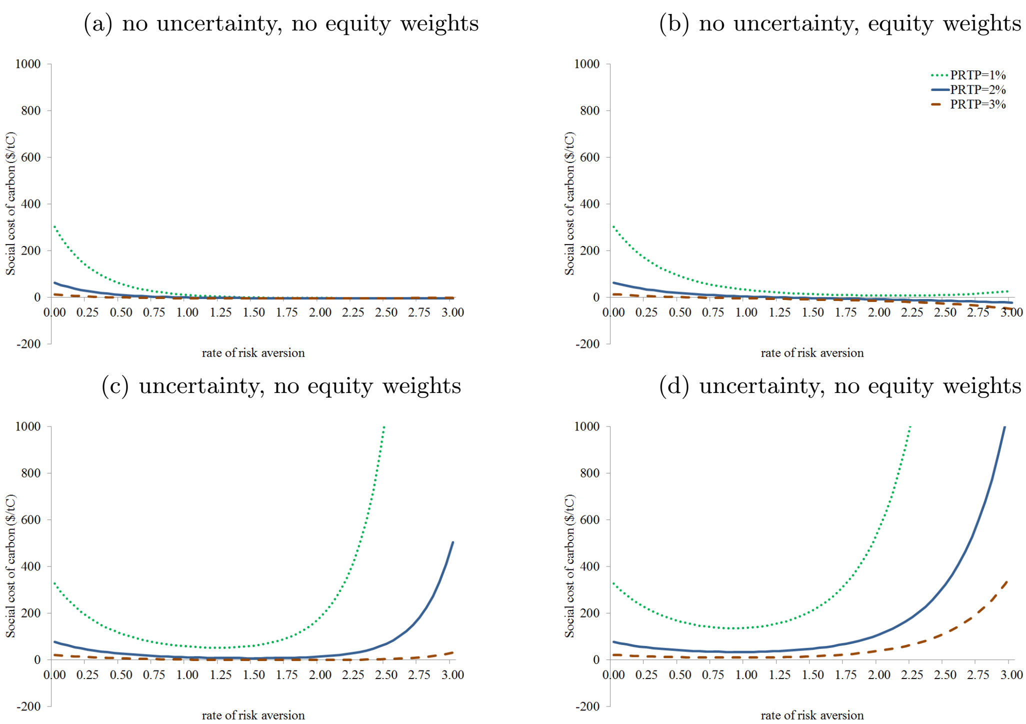


Figure 11.4: The social cost of carbon as a function of the parameters of the Ramsey rule

Panel (b) introduces equity (but ignores uncertainty). For a pure rate of time preference of 1%, the results are intuitive albeit ambiguous. The lower the rate of risk aversion, the lower the discount rate, the more you care about the future, and the higher the social cost of carbon. At the same time, the lower the rate of risk aversion, the less you care about poor countries, and the lower the social cost of carbon. For higher pure rates of time preference, the relationship is more complex still. Because of carbon dioxide fertilization, the impacts of climate change on poor countries are positive in the short run (but negative in the long run). As the negative impacts in the long run are discounted away, the social cost of carbon becomes more negative as the rate of risk aversion increases.

> The risk premium tends to be positive because climate change risks are skewed towards bad outcomes.

Panel (c) introduces uncertainty (but ignores equity). It shows the certainty equivalent social cost of carbon as a function of the pure rate of time preference and the rate of risk aversion. The result is as expected. Because negative surprises are more likely than positive surprises of equal size, the expectation of the social cost of carbon is larger than its mode. The certainty equivalent of the social cost of carbon is larger still because it further emphasizes the negatives; this would also be true if the uncertainty is symmetric. The difference between the certainty equivalent and the expectation grows as the rate of risk aversion increases.

Panel (d) uses both equity and uncertainty. The pattern is roughly the same as in Panel (c), except that the uncertainty is such that the positive impacts in the best guess are more than offset by the negative impacts in the tails of the distribution. Most strikingly, the results span an enormous range. Depending on the choice of parameters, almost any carbon tax can be defended. This, of course, begs the question what parameters should be used.

11.5 The curvature of the utility function****

In the discussion of Figure 11.4, the curvature of the utility function η plays a triple role: It measures the monetary trade-offs between the current self and a richer, future self; between a fortunate self and a less fortunate self; and between rich and poor people. These are conceptually different things, yet we assumed them to be numerically the same. It does not have to be that way. Let us first separate time and risk.

11.5.1 Epstein-Zin preferences****

In discrete time, expected net present welfare at time s is defined as

$$\mathbb{E}W(s) = \mathbb{E}\left(\sum_{t=s}^{\infty} \frac{1}{(1+\rho)^{t-s}} U(t+s)\right) = \mathbb{E}\left(U(s) + \frac{1}{1+\rho}\sum_{t=s+1}^{\infty} \frac{1}{(1+\rho)^{t-s-1}} U(t+s)\right) \tag{11.36}$$

Recall that the expectation is an integral or summation, so that by the fundamental theorem of calculus

$$\mathbb{E}W(s) = \mathbb{E}U(s) + \mathbb{E}\left(\frac{1}{1+\rho}\sum_{t=s+1}^{\infty} \frac{1}{(1+\rho)^{t-s-1}} U(t+s)\right) = U(s) + \frac{1}{1+\rho}\mathbb{E}W(s+1) \tag{11.37}$$

where we make the additional assumption that there is no uncertainty about the utility at time s when decisions are made. Utility is knowable to an affine transformation so we can rewrite this as

$$\mathbb{E}W(s) = (1-\vartheta)U(s) + \vartheta\mathbb{E}W(s+1) \tag{11.38}$$

We have recast the expected net present welfare as a recursive function, a linear combination of current utility and the expected net present welfare in the next period.

Epstein-Zin preferences generalize this as

$$W_{EZ}(s) = \left((1-\vartheta)C(s)^{1-\zeta} + \vartheta\left(\mathbb{E}\left(W_{EZ}(s+1)^{1-\eta}\right)\right)^{\frac{1-\zeta}{1-\eta}}\right)^{\frac{1}{1-\zeta}} \tag{11.39}$$

Three things happened here. We replaced the sum in Equation (11.38) by a CES-aggregate. The expectation in Equation (11.38), another sum, is also replaced by a CES-aggregate.[2] Finally, in the first period, utility is replaced by a power function of consumption, which is pretty much utility.

Equation (11.39) is an intimidating expression. It is not immediately obvious what all the parameters do. Let us first assume that we know the future for certain. Then

$$W_{EZ}(s) = \left((1-\vartheta)C(s)^{1-\zeta} + \vartheta W_{EZ}(s+1)^{1-\zeta}\right)^{\frac{1}{1-\zeta}} \tag{11.40}$$

If we set $W = W_{EZ}^{1-\zeta}$, we have

$$W(s) = (1-\vartheta)C(s)^{1-\zeta} + \vartheta W(s+1) = (1-\vartheta)\sum_{t=0}^{\infty}\vartheta^t C(s+t)^{1-\zeta} \tag{11.41}$$

We are back to net present welfare. ϑ is the discount factor of utility, $\vartheta = (1+\rho)^{-1}$. $1-\zeta$ is the curvature of the utility function that enters into the Ramsey Rule; see Equation (9.1). While above we refer to this parameter as the Arrow-Pratt rate of relative risk aversion, we can here give it its proper interpretation: ζ is a measure of the substitution between consumption now and consumption later.

If we set $\zeta = \eta$ then

$$W_{EZ}(s)^{1-\eta} = (1-\vartheta)C_s^{1-\eta} + \vartheta\mathbb{E}\left(W_{EZ}(s+1)^{1-\eta}\right) \tag{11.42}$$

For $W(s) = W_{EZ}(s)^{1-\eta}$, we have

$$W(s) = (1-\vartheta)C(s)^{1-\eta} + \vartheta\mathbb{E}W_s(s+1) \tag{11.43}$$

that is, expected net present welfare with η as the curvature of the utility function.

We now have an interpretation for the parameters. η is the rate of relative risk aversion for static gambles. ζ is the inverse of the intertemporal elasticity of substitution for deterministic variations. Epstein-Zin preferences[3] thus allow us to make a distinction between the curvature of the utility function in risk space—trade-offs between a fortunate and unfortunate self are governed by η —and the curvature of the utility function in time—trade-offs between an earlier and later self are governed by ζ. Generally $\zeta \neq \eta$.

[2]Mathematicians refer to CES-aggregates as generalized summations.

[3]Larry Epstein and Stanley Zin could not have done this without David Kreps and Evan Porteus.

11.5.2 Inequity aversion

The derivations above are all for a single decision maker. Inequity aversion is readily introduced by subscripting Equation (11.39) with an r for region and substituting this into Equation (11.13)

$$W_{EZ'}(s) = \sum_r \frac{W_{EZ}(s,r)^{1-\omega}}{1-\omega} \tag{11.44}$$

This adds an additional curvature to the utility function, one that is specific to inequality.

Note that the nesting matters for the interpretation. η is the rate of relative risk aversion, where the risks are measured in money. ζ measures aversion to intertemporal inequality—but this is intertemporal inequality in expected *utility*, not intertemporal inequality in expected *consumption*. Aversion of intertemporal inequality in expected consumption depends on both η and ζ. ω is the rate of aversion to interpersonal inequality, where inequality is inequality in expected net present welfare. Aversion to interpersonal inequality in consumption today depends on ω and η, and to inequality tomorrow on ω, η, and ζ.

It does not stop here. We ignored ambiguity aversion. We assumed that inequality aversion is the same within and between groups—although one might argue that income transfers render within-group inequality aversion obsolete. Instead of the triple nest of CES functions in Equation (11.44), we would have a quintuple nest. Notation would be tiresome. Additional insight would be almost nil.

11.6 Advice and advocacy****

Climate policy advice is based on a mix of positive and normative statements.

It should be clear to the reader by now that there is no such thing as best climate policy. Although the optimum is unambiguous and objective—it is mathematics—the best policy is best conditional on a number of subjective choices, some of which are hotly disputed, while some other positions are widely but not universally supported. Any argument for a particular carbon tax is thus an argument for a particular social welfare function with a particular set of parameters. In fact, as shown in Chapter 4, any argument in favour of a carbon tax, of whatever level, rests on the assumption that concerns about economic efficiency can be traded off against concerns about climate efficacy.

Analysts should distinguish between facts and values when presenting their recommendations.

In this sense, climate policy is no different from other policies that economists get involved in. Education, health, labour, and a range of other policies are based on a mix of positive and normative elements. For an individual researcher, it is important to distinguish between those parts of the analysis that are based on impartial interpretations of the available evidence, for example on price elasticities, and those parts that are partial reflections on what society ought to do or be, for example on inequity aversion. This is doubly important when speaking to lay people, who may not have the knowledge to draw the dividing line between *what is* and *what ought to be* as accurately as other experts would. An individual researcher must develop the understanding that her world views are not self-evidently true, probably not shared by everyone else and perhaps even repugnant to some. In fact, academics are unrepresentative of the population in every respect.[4] For a policy maker seeking advice, it is important to seek input from a number of experts with different perspectives.

> Analysts should not seek to impose their will, or assume that others agree with their politics.

To economists (and other social scientists) this comes almost naturally. The great economists of history—Ibn Khaldun, Smith, Ricardo, Mills, Marx, Keynes, Tinbergen, Friedman, Schelling, Baumol—were all deeply involved in the controversial policy issues of their times. The same is true for contemporary economists, great and small. It is made clear to young economists that they will not just *study* the economy, but help *shape* it. The example that was used during my induction was that one day, perhaps, one of us freshers would become governor of the central bank.[5] Indeed, Ben Bernanke, one the greatest students of monetary policy, became Chairperson of the Federal Reserve, one of the most powerful makers of monetary policy. Raghuram Rajan and Janet Yellen are not bad scholars either.

Natural scientists do not generally share these sensitivities. Of the three core questions—what if, so what, what to do—natural scientists focus almost exclusively on "what if?" That is, they seek to develop an understanding of a particular aspect of the real world in the hope of gaining predictive skills. They aim to do so objectively, although they can only achieve replication. A group of culturally homogenous people would share the same blind spots; and the choice what to research and what not is of course a subjective one.

Social scientists tend to be more comfortable with the other two core questions, "so what?" —who would be hurt or helped if the predicted impacts come true and how big are these effects?—and "what to do?"—what is the appropriate course of action and its intensity to prevent, alleviate or stimulate the predicted impact? Natural scientists are often less comfortable with such questions.

Silvio Funtowicz and Jerry Ravetz even coined a new term—post-normal science—to describe research in areas where the policy stakes are high, the science is uncertain, and values are disputed.[6] Post-normal science makes clear that the conventional rules of natural science do not apply to a problem like climatic change. Post-normal science calls for extended peer-review, involving non-experts in research from the design stage onwards. Unfortunately, lay voices are sometimes used to overrule expert concerns about quality.

The most important thing to remember is that low-quality research is irrelevant—or rather, that it should be. Flimsy results are often used to support a political position—policy-based evidence making. That should not be. Policy should be informed by the best available knowledge.

Roger Pielke Jr provides a classification of the behaviour of experts in advising policy. The "pure scientist" may do policy-relevant research, but does not get involved in policy or policy advice, and her research agenda is set independently of policy concerns. The "science arbiter" restricts her role to predicting the impact of alternative policies under discussion; she does not judge these impacts on their merits. The "issue advocate" seeks to restrict the number of policy options under consideration to the ones that adhere to her political convictions. The "honest broker", like the "science arbiter" assesses impacts of policy options, but also seeks to add

[4] Academics are smarter and better educated than most but also tend to have values and ideas that find little support outside academia.

[5] Actually, a guy one year below me did.

[6] "Normal" refers to Thomas Kuhn, who was adamant that his description of the normal practice of research only refers to the natural sciences. "Post" suggests a chronological order in time, as if earlier debates about the solar system, the abolition of slavery, eugenics, and public pensions were not hugely controversial, both academically and politically.

new options to those already considered. Finally, the "stealth advocate" is actually an "issue advocate" but pretends to be a "science arbiter" or an "honest broker". Pielke's classification is incomplete. The "plausible denier" phrases negative advice so that the unsuspecting client hears the opposite, maintaining both scientific credibility and funding.

Obviously, one should strive to be an "honest broker". In the context of the discussion above, that means showing the sensitivity of key policy variables to parameters; and to discuss why some argue for one parameter value and others for a different number. I find it helps to state my personal opinion, but always make clear that I speak as a citizen rather than an expert, and add that others would disagree with me.

Further reading

Ferenc Toth's *Fair Weather: Equity Concerns in Climate Change* (2009) is one of the best treatises on equity and climate policy. Stephen Gardiner's *Climate Ethics* (2010), John Broome's *Climate Matters* (2012) and Dominic Roser's *Climate Justice* (2016) are worth a read. Jeremy Williams' *Climate Change is Racist* (2021) covers an aspect this chapter overlooks.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tdg.html.

Exercises

11.1. Aggregate the national impacts of climate change using equity weights with inequity aversion 0, 1, 2 and 3; data: https://sites.google.com/site/climateeconomics/data/06-economic-impacts.

11.2. The derivation of equity weights assumes a utilitarian welfare function. What would the equity weights be if welfare is given by

$$W = \sum_c \frac{U_c^{1-\gamma}}{1-\gamma} \tag{11.45}$$

11.3. Rework Equation (11.25) assuming CES utility

$$U = [\delta^{1-\rho} C^\rho + (1-\delta)^{1-\rho} (1-L)^\rho]^{\frac{1}{\rho}} \tag{11.46}$$

11.4. Rework Equation (11.25) assuming a quadratic tax

$$\tau = \phi + \psi w L \tag{11.47}$$

11.5. Send a picture of an oleander to your instructor. What have oleanders to do with climate advice and advocacy?

11.6. Design an online survey or experiment to estimate the rate of inequity aversion. Implement this using Google Forms, Survey Monkey, a Twitter Poll or whatever means you think best. Gather data and estimate the rate of inequity aversion.

11.7. Help your fellow students by taking their surveys and experiments. Which one do you think works best?

11.8. Take the survey: https://www.surveygizmo.com/s3/4219259/Equity. Which question do you think is best? Which questions are suitable for estimating the rate of inequity aversion? Look at the results and do just that. How would you elicit attitudes towards equity? Are the estimated parameters relevant for climate policy?

11.9. Read and discuss:

- **D. Anthoff, C. Hepburn and R.S.J. Tol (2009), Equity weighing and the marginal, damage costs of climate change, *Ecological Economics*, 68, 836–849.
- **D. Anthoff and R.S.J. Tol (2010), On international equity weights and national decision making on climate change, *Journal of Environmental Economics and Management*, 60, 14–20.
- ***A. Lange, C. Vogt and A. Ziegler (2007), On the importance of equity in international climate policy: An empirical analysis, *Energy Economics*, 29, 545–562.
- ***A. Lang, A. Loeschel, C. Vogt and A. Ziegler (2010), On the self-interested use of equity in international climate negotiations, *European Economic Review*, 54, 359–375.
- ***A. Dannenberg, B. Sturm and C. Vogt (2010), Do equity preferences matter for climate negotiators? An experimental investigation, *Environmental and Resource Economics*, 47, 91–109.

Chapter 12

International environmental agreements

Thread

- International climate policy has a long history of good intentions but little to show for 25 years of negotiations. #climateeconomics
- The UNFCCC sets the rules for international climate negotiations, says that rich countries should cut emissions first. #climateeconomics
- The Kyoto Protocol put obligations on a few countries only and there were no meaningful sanctions for missed targets. #climateeconomics
- The targets of the Kyoto Protocol ended in 2012, but its international flexibility mechanisms did not expire. #climateeconomics
- Hopes were high for Copenhagen, but the final attempt at legally binding targets failed. #climateeconomics
- In Paris, international climate policy switched to pledge-and-review. Countries are obliged to do whatever they want. #climateeconomics
- The Kigali treaty phases out HFCs, particularly powerful greenhouse gases for which there is a substitute. #climateeconomics
- Greenhouse gas emission reduction is a global public good. Countries would not cooperate on providing public goods … #climateeconomics
- … because the cost savings from lower emission abatement would be private while the additional impacts would be shared. #climateeconomics
- As the national cost of carbon is a fraction of the global cost, abatement falls if international cooperation falters. #climateeconomics
- People adapt to climate change, reducing the negative impacts and increasing the positive impacts. #climateeconomics

- Adaptation reduces the need to mitigate climate change, and mitigation reduces the need to adapt. #climateeconomics
- Mitigation requires some international cooperation. Adaptation does not. In fact, most adaptation is local and private. #climateeconomics
- Countries with a smaller share of the total impact of climate change have a stronger incentive to free-ride. #climateeconomics
- A coalition is stable if no one wants to join, if no one wants to leave, and if all are better off than in Nash. #climateeconomics
- Coalition formation is like barter: You promise to abate more, and in return the others do more too. #climateeconomics
- You plan to promise little, and hope the others will promise lots. And they plan and hope the same things. #climateeconomics
- Game theory predicts that environmental agreements either have many signatories who do little, or a few who do lots. #climateeconomics
- Either way, the impact on emissions is small. The Kyoto Protocol and Paris Agreement are as predicted by game theory. #climateeconomics
- The hole in the ozone layer and acid rain had simple, cheap technical solutions within industry. #climateeconomics
- Ozone policy was supported by export restrictions not applicable to climate policy. #climateeconomics
- Acid emissions fell for reasons other than environmental policy. This does not (yet) apply to greenhouse gas emissions. #climateeconomics

12.1 Cooperative and non-cooperative abatement**

Chapter 8 discusses climate policy from the perspective of a global social planner, a benevolent dictator or philosopher-queen. This is a useful yardstick. A global social planner can maximize global welfare. This is the best climate policy. It cannot be improved upon. At the same time, this is an unrealistic perspective. There is nothing that remotely resembles a global social planner, in that no institution can force emission reduction policies on sovereign countries let alone mobilize the transfers needed to turn a potential Pareto improvement into an actual one. More realistic representations of climate policy therefore must lead to lower welfare than in global optimum.

> As the national cost of carbon is a fraction of the global cost, abatement falls if international cooperation falters.

Figure 12.1 shows a regional breakdown of the social cost of carbon. In this particular example, the global social cost of carbon is $16/tC. The global social cost of carbon is the sum of the regional social costs of carbon, which are by definition a fraction of the global cost. If the world were run by 16 regional social planners who ignore their impact on the rest of the world, then each would impose a carbon tax that equals the regional social cost of carbon. If

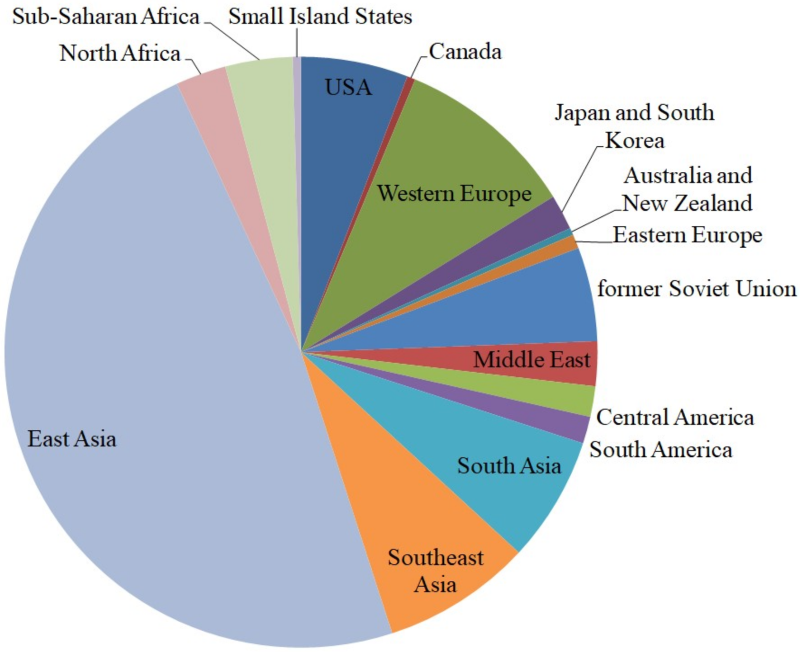


Figure 12.1: Regional breakdown of the social cost of carbon

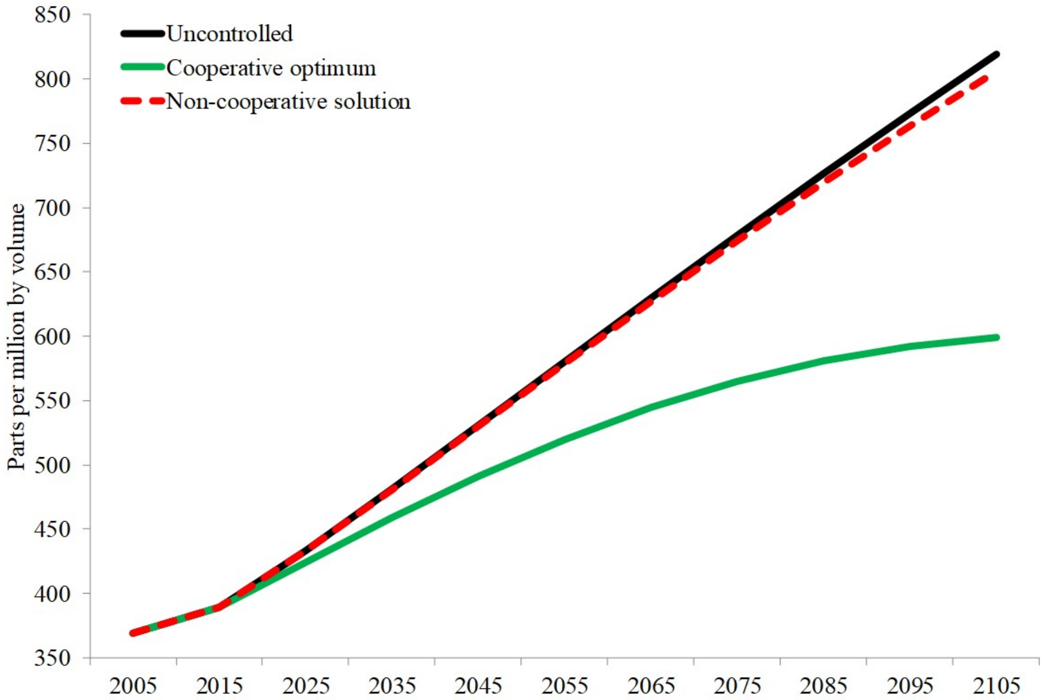
the numbers of Figure 12.1 are correct, the global social planner would impose a carbon tax of \$16/tC. The European social planner would impose a carbon tax of almost 10% of \$16/tC, that is, \$1.50/tC.

Figure 12.2 shows the implications. In Figure 12.2, there are 190 countries (rather than 16 regions as in Figure 12.1). In the non-cooperative scenario, each of the national social planners equates the national social cost of carbon to the national marginal abatement cost. The result is some emission reduction, but much less than in the cooperative case, in which the global social cost of carbon is used. (The cooperative case was discussed in Chapter 8.)

> Greenhouse gas emission reduction is a global public good. Countries would not cooperate on providing public goods because the cost savings from lower emission abatement would be private while the additional impacts would be shared.

The above discussion highligths that greenhouse gas emission reduction is a public good. Other people cannot be excluded from the impacts of your emission reduction, and you can enjoy the fruits of emission reduction without affecting anyone else's enjoyment. In other words, emission reduction is non-rival and non-excludable. It is a public good. That implies that, while the costs of your emission reduction are fully borne by you, the benefits of your emission reduction are spread across the world, with you receiving only a small share. We would normally expect the government to step in, either directly providing the public or incentivizing its private provision. However, greenhouse gas emission reduction is a *global* public good. There is no global government to provide this public good, or get countries to provide it.

The difference between cooperative and non-cooperative climate policy is thus intuitive and large. These are polar cases, however. Obviously, the world is not run cooperatively. At the



Source: After W.D. Nordhaus and Z. Yang (1996), A regional dynamic general-equilibrium model of alternative climate-change strategies, *American Economic Review*, 86 (4), 741–765.

Figure 12.2: The cooperative and non-cooperative atmospheric concentration of carbon dioxide

same time, countries do not operate in isolation either. The question is how much cooperation on climate policy can be sustained by sovereign, self-interested nations. We first look at free-riding, and then at partial coalition formation.

12.2 Adaptation versus mitigation**

> People adapt to climate change, reducing the negative impacts and increasing the positive impacts.

Adaptation includes any action to make the negative impacts of climate change less bad, positive impacts better, or even turn negative impacts into positive ones. Adaptation occurs on all levels of decision making, from individuals to the United Nations. Adaptation occurs on all time-scales from seconds to millennia. Some adaptation is in response to past climate change. Other adaptation is in anticipation of future climate change.

> Adaptation reduces the need to mitigate climate change, and mitigation reduces the need to adapt.

Adaptation aims to make climate change less bad. Therefore, adaptation reduces the need for emission abatement. Vice versa, emission reduction leads to less climate change. Therefore, mitigation reduces the need for adaptation. Thus adaptation and mitigation are policy substitutes. The more you do of the one, the less you do of the other.

Note that there are people who confuse *substitutes* versus *complements* with *corner solutions* versus *interior solutions*. Because climate change cannot be fully avoided, the policy mix includes both adaptation and mitigation. That does not make adaptation and mitigation complements, though.

> Mitigation requires some international cooperation. Adaptation does not. In fact, most adaptation is local and private.

Adaptation was low on the policy agenda for a long time. This was primarily because policy makers were focused on greenhouse gas emission reduction, and thought that discussing adaptation would be tantamount to admitting defeat. This has now changed. It is now widely accepted in policy circles that climate change cannot be fully avoided. (There was never any doubt about this in academic circles.) Whereas effective mitigation depends on the actions of other countries, effective adaptation rarely does. As the difficulties with reaching an international agreement on emission targets became increasingly apparent, attention has shifted to adaptation.

Many governments have formulated national adaptation plans. Indeed, they are obliged to do so under the UNFCCC. There is financial and technical support for poor countries to help develop their national adaptation plans. And there is a nascent multilateral adaptation fund to co-finance adaptation in poor countries, on top of the adaptation financed through the system of development banks. This has been a bonanza for consultants.

12.3 Free-riding**

Free-riding is a customary if somewhat peculiar way to study the provision of public goods. Full cooperation is the starting point of the analysis. Then, each country considers whether it wants to continue to cooperate. Countries do not take other countries' incentives to cooperate into account. This is the best response in the Nash sense of the word, and therefore this disregard for the plans of others is often called Nash behaviour. Nash is not the originator of this assumption,[1] however, and a more accurate description would be to call this myopic behaviour. That is, a country considers whether it wants to continue to cooperate, assuming that the other countries do continue to cooperate. The trade-off then is between the cost savings due to lower emission reduction made versus the additional damages incurred.

Let us investigate this a bit more using a linear-quadratic game. The costs B of emission reduction R for country i are

$$B_i = \beta_i R_i^2 \tag{12.1}$$

where β is a parameter, denoting the unit cost of emission reduction. By assumption, the costs of emission reduction of country i only depend on emission reduction in country i. The sole effect of emission reduction in other countries is on climate change and its damages.

The benefits D of emission reduction are

$$D_i = \psi_i \sum_j R_j M_j \tag{12.2}$$

where ψ is a parameter, denoting the social cost of carbon, and M are emissions in the absence of climate policy. That is, the benefits of the emission reduction depend on the actions of all countries, weighted by their emission reduction effort R and their initial emissions M.

[1] John Forbes Nash Jr, whose beautiful mind won the 1994 Nobel Prize in Economics and the 2015 Abel Prize, showed that you can ignore the response of other players if you are in an equilibrium and there are infinitely many players in the game, so that your influence on them is infinitesimally small. The starting point here is not necessarily an equilibrium, and countries do respond to each other's inaction.

In the non-cooperative solution, each country maximizes its own net benefits by equating the marginal cost and benefits:

$$\frac{\partial D_i}{\partial R_i} = \psi_i M_i = 2\beta_i R_i = \frac{\partial B_i}{\partial R_i} \forall i \Rightarrow R_i^* = \frac{\psi_i M_i}{2\beta_i} \forall i \tag{12.3}$$

In the cooperative solution, all countries jointly maximize their collective net benefits by equating the marginal costs and benefits:

$$\frac{\partial \sum_j D_j}{\partial R_i} = M_i \sum_j \psi_j = 2\beta_i R_i = \frac{\partial B_i}{\partial R_i} \forall i \Rightarrow R_i' = \frac{\sum_j \psi_j M_i}{2\beta_i} =: \frac{\psi M_i}{2\beta_i} \forall i \tag{12.4}$$

At first sight, the cooperative and non-cooperative solutions look very similar. In both cases, optimal emission reduction equals the marginal benefits times own emissions over two times the unit abatement cost. There is one crucial difference, however. In the non-cooperative solution, only the marginal benefits to the own country are considered, whereas in the cooperative solution the marginal benefits to all countries are considered.

The difference in costs follows from substituting (12.3) and (12.20) into (12.1):

$$B_i' - B_i^* = \beta_i \left(\frac{\psi M_i}{2\beta_i}\right)^2 - \beta_i \left(\frac{\psi_i M_i}{2\beta_i}\right)^2 = (\psi^2 - \psi_i^2)\frac{M_i^2}{4\beta_i} \forall i \tag{12.5}$$

As we are considering free-riding, the difference in benefits follows from the change in emission reduction by the own country only:

$$D_i' - D_i^* = \psi_i \left(\frac{\psi M_i}{2\beta_i} - \frac{\psi_i M_i}{2\beta_i}\right) M_i = \frac{(\psi\psi_i - \psi_i^2)M_i^2}{2\beta_i} \forall i \tag{12.6}$$

It would be in a country's best interest to free-ride if the cost savings of Equation (12.5) exceed the additional damages of Equation (12.6).

Countries with a smaller share of the total impact of climate change have a stronger incentive to free-ride.

This is almost always the case. Table 12.1 illustrates this. For convenience, emissions are set equal to one, and unit costs to one-half. In the first row, the national social cost of carbon is one-quarter of the global social cost. Then, the cost-savings are 7.5 and the additional damages are 3. It is better to free-ride. In the second row, the national social cost of carbon is one-tenth of the global social cost. Then, the cost-savings are higher: 49.5. They are much higher as a smaller country would need to do much more for the rest of world. The additional benefits are higher too: 9. But, since the emission reduction costs are quadratic and the emission reduction benefits linear, also in this case it is better to free-ride. In the third row, the national social cost of carbon is one-half of the global social cost. The cost-savings fall to 1.5. The additional damages fall too, to 1. It is still better to free-ride.

In this set-up, every country has an incentive to free-ride. In a more general set-up, almost every country would have. As a result, cooperation collapses.

12.4 Cartel formation**

Above, we contrast full cooperation and non-cooperation. There are intermediate cases too, in which some countries cooperate with one another and others do not. This is usually studied with the help of cartel formation games (which originated with Claude d'Aspremont's work in industrial organization).

Table 12.1: Free-riding illustrated

ψ	ψ_i	β	M	ΔB	ΔD	$\Delta D - \Delta B$
4	1	0.5	1	7.5	3	-4.5
10	1	0.5	1	49.5	9	-40.5
2	1	0.5	1	1.5	1	-0.5

A coalition is stable if no one wants to join, if no one wants to leave, and if all are better off than in Nash.

A coalition is said to be stable if and only if it is internally stable, externally stable, and profitable. A coalition is said to be internally stable if none of its members is better off outside the coalition. A coalition is said to be externally stable if none of its non-members is better off inside the coalition. This is intuitive: A coalition is stable if no one wants to leave and no one wants to join. A coalition is said to be profitable if all of its members are at least as well off as in the fully non-cooperative case. This final condition partly overcomes the myopic nature of the first two conditions (which only consider a single move by a single agent). An alternative interpretation is that cartel theory takes the non-cooperative solution as its starting point.

The grand coalition (which contains all agents) is always externally stable (as there are no non-members). For a coalition of two, internal stability and profitability are the same (as we consider only one coalition).

Coalition formation is like barter: You promise to abate more, and in return the others do more too.

Cartel formation can be illustrated with the linear-quadratic game of Section 12.3. For simplicity, assume that there are two agents only. The costs of emission reduction are then

$$B_1 = \beta_1 R_1^2; B_2 = \beta_2 R_2^2 \tag{12.7}$$

The benefits of emission reduction are

$$D_1 = \psi_1(R_1 M_1 + R_2 M_2); D_2 = \psi_2(R_1 M_1 + R_2 M_2) \tag{12.8}$$

The non-cooperative solution is

$$R_1^* = \frac{\psi_1 M_1}{2\beta_1}; R_2^* \frac{\psi_2 M_2}{2\beta_2} \tag{12.9}$$

The cooperative solution is

$$R_1' = \frac{(\psi_1 + \psi_2) M_1}{2\beta_1}; R_2' = \frac{(\psi_1 + \psi_2) M_2}{2\beta_2} \tag{12.10}$$

Subtracting (12.9) from (12.10), we find that the extra emission reduction in the cooperative case equals

$$\Delta R_1 = \frac{\psi_2 M_1}{2\beta_1}; \Delta R_2 = \frac{\psi_1 M_2}{2\beta_2} \tag{12.11}$$

You plan to promise little, and hope the others will promise lots. And they plan and hope the same things.

Cooperation can thus be interpreted as barter trade. Player 1 reduces his emissions further (at a cost to player 1) and in return player 2 further reduces her emissions as well (which benefits player 1). Cooperation is in player 1's interest if the benefits exceed the costs. Player 1 would like to increase his abatement by a little bit and get a lot of additional abatement by player 2 in return. However, player 2 wants the same: Do a little more herself, and hope that the other offers a lot in return. A deal can only be made if both parties are better off. A stable cooperation thus meets the criterion

$$\Delta B_1 < \Delta D_1 \wedge \Delta B_2 < \Delta D_2 \tag{12.12}$$

For a coalition of N players, this becomes

$$\Delta B_1 < \Delta D_1 \wedge \Delta B_2 < \Delta D_2 \wedge ... \wedge \Delta B_N < \Delta D_N \tag{12.13}$$

This is a stringent set of conditions. As more players are added to the coalition, each coalition member is asked to do more at accelerating cost. The benefits increase too, but the benefits are reaped by members and non-members alike. Equation (12.13) thus implies one solution to the cartel formation game: Stable international environmental agreements have few signatories.

> Game theory predicts that environmental agreements either have many signatories who do little, or a few who do lots. Either way, the impact on emissions is small. The Kyoto Protocol and Paris Agreement are as predicted by game theory.

Scott Barrett showed that there is, in fact, another solution. There may be many signatories, each committing to little over and above what they would have done anyway. That is, international environmental agreements are either wide and shallow (many signatories not doing much) or deep and narrow (few signatories doing a lot). In either case, the impact on global emissions is limited.

Box 12.1: The Montreal Protocol

The Vienna Convention for the Protection of the Ozone Layer was negotiated in 1985 in Vienna. It is a framework convention, setting the parameters for later, substantive negotiations. In 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer was negotiated under the Vienna Convention. The Montreal Protocol foresees a phase-out of chlorofluorocarbons (CFCs) from a small number of countries at a leisurely pace. The ambitions of the Montreal Protocol have been strengthened and its scope extended in 1990 (London), 1991 (Nairobi), 1992 (Copenhagen), 1993 (Bangkok), 1995 (Vienna), 1997 (Montreal), 1998 (Australia), and 1999 (Beijing). Since 2001, the production, use and sale of CFCs has been banned worldwide.

This is a surprise. CFCs are long-lived chemicals used as refrigerants, propellants and solvents. CFCs are inert, which explains their popularity. However, high in the atmosphere, UV radiation breaks down CFCs. The chlorine thus released destroys ozone in a catalytic reaction. The ozone layer blocks UV-B radiation. As the ozone layer thins due to CFC emissions, more UV-B radiation reaches the surface, harming animal and bacterial life everywhere. CFC emission reduction is therefore a global public good, and its success thus requires explanation.

The hole in the ozone layer is a long-term, global environmental problem with negative consequences for humans and nature. In that sense, it is similar to climate change. There are structural differences, though, and incidental ones too.

To start with the latter, while the Vienna Convention is a United Nations treaty, the negotiations that led to the Montreal Protocol involved only two dozen countries, all rich, and all keen to protect their people against the cancers caused by UV radiation. Negotiations are much easier with fewer, like-minded countries. The strategy for ozone was to start small and expand later, whereas all countries were involved in the climate negotiations from the start.
Another key difference is that the Montreal Protocol includes sanctions for non-compliance. The Kyoto Protocol and the Paris Agreement do not — see Box 12.4 and Box 12.5. These sanctions, while never used, arguably did change behaviour.

> The hole in the ozone layer and acid rain had simple, cheap technical solutions within industry.

There are two structural differences. Greenhouse gases are ubiquitous and intrinsic to energy and agriculture. CFCs are industrial gases with nice applications. CFCs were produced in countries that worried most about its consequences. Fossil fuels come, to a large extent, from countries with concerns other than climate change.
Despite all that, hopes were low for the negotiations in Montreal. Every country present wanted to see CFCs emissions reduced, but argued that other countries should go first. That changed during the final days of the convention, when the USA changed position overnight, taking the Europeans and Japanese by surprise, and a ban on CFCs was agreed. This was because a US company with strong political connections had commercialized an alternative to CFCs. Effectively, the Montreal Protocol handed DuPont a competitive advantage over its international rivals.
The breakthrough were hydrofluorocarbons (HFCs), almost as good as CFCs and slightly more expensive. That is the third structural difference with climate policy: There is no simple, technical fix for greenhouse gas emissions.

> Ozone policy was supported by export restrictions not applicable to climate policy.

The Montreal Protocol not only bans the use of CFCs in the countries that signed up. It also bans the export of CFCs to countries that did not. Non-signatories thus had to choose between importing the substitute HFCs — which makes signing the Montreal Protocol costless — or producing CFCs domestically. Because there are large economies of scale in CFC production, smaller countries opted for the former.
India signed the Montreal Protocol after substantial technological support was promised. China's signature on the Montreal Protocol was a pre-condition for its entry into the World Trade Organization.
The full text of the Montreal Protocol can be read here:
http://ozone.unep.org/montreal-protocol-substances-deplete-ozone-layer/32506
The Vienna Convention was amended again in 2016 (Kigali)—see Box 12.6.

12.5 Multiple coalitions****

Above, we use cartel theory to study the formation of a single coalition. A coalition is d'Aspremont stable if it is profitable, if no one wants to leave, and if no one wants to join. We can use a similar set-up for multiple coalitions: A set of coalitions is stable if each coalition is profitable, if no coalition member wants to leave to play non-cooperatively, if no non-cooperative players want to join a coalition, and if no coalition member wants to switch to a different coalition.

On the one hand, multiple coalitions allow for more choice. You would therefore expect welfare to improve. On the other hand, multiple coalitions impose an additional constraint on the equilibrium, namely *inter-coalition stability*. There is no such condition for one coalition, two for two coalitions, six for three coalitions, and $N(N-1)$ for N coalitions. This implies the solution space rapidly shrinks as more coalitions are added. In other words, multiple coalitions cannot reduce emissions by much more than can a single coalition, for the simple reason that there cannot be many coalitions.

What about two coalitions? Coalitions are formed simultaneously, but intuition is clearer for sequential coalition formation. Suppose there are a large number of players. The first coalition forms. Stability dictates that the coalition is small. There are therefore a large number of non-cooperative players left. A second coalition would thus form under conditions that are very similar as when the first coalition formed. The second coalition is therefore small too.

The same would be true for the third coalition, and the number of inter-coalition conditions is six (three times two) so that the space of feasible solutions is small if not empty. With four coalitions, there are twelve inter-coalition conditions (on top of four internal stability, four external stability, and four profitability conditions), so that solutions are likely to be infeasible.

Now suppose there are a small number of players. The first coalition forms. The impact of the formation of that first coalition on the remaining, non-cooperative players is relatively large. A second coalition can thus make a difference. If there are few players to begin with, two coalitions can have a large fraction playing cooperatively.

This is a paradoxical result: Multiple coalitions matter more for negotiations with few players than for many players.

Box 12.2: The Sofia Protocol

Acid rain adversely affects fish and trees, and damages limestone buildings and marble statues. Acidification is caused by emissions of sulphur dioxide and nitrogen oxide, mostly from the burning of fossil fuels. Once emitted, these substances can stay in the atmosphere for weeks and cross continents in that time. Acid rain is therefore an international environmental problem, albeit at a continentental rather than a global scale. In Europe and North America, acid rain is a problem of the past. It has largely been solved. In the USA, the federal government stepped in. But how and why was this done in Europe?

In 1979, the Convention on Long-Range Transboundary Air Pollution (LRTAP) was negotiated, a framework convention like the UNFCCC (see Box 12.3) and the Vienna Convention (see Box 12.1). The LRTAP Convention was negotiated under the United Nations Economic Commission for Europe (UNECE), a relict of the early years after World War II. The UNECE has far fewer members than the UN, and negotiations are correspondingly simpler.

The 1985 Helsinki Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 per cent does as it says. Its ambition was sharpened by the 1994 Oslo Protocol on Further Reduction of Sulphur Emissions. The 1988 Sofia Protocol concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes confirms that LRTAP protocols do what they say on the tin. This trend was broken by the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, which set strict caps on sulphur and nitrogen emissions for 2010 and 2020.

At first sight, it seems that these protocols were successful. Emissions have fallen sharply. Predictions from game theory are proven wrong that the voluntary provision of a continental public good is not possible.

> Acid emissions fell for reasons other than environmental policy. This does not (yet) apply to greenhouse gas emissions.

That would be the wrong interpretation. Some of the drivers of acid rain, particularly transport, also cause local air pollution—and cleaning up the latter also cleans up the former. Another major source of acidifying emissions, coal-fired power generation, fell out of favour as the price of natural gas dropped and newly competitive electricity markets sought a better deal for their customers. The heavy industry in Eastern Europe collapsed after the Berlin Wall fell.

Emission reduction was therefore at least in part circumstantial rather than due to acid rain policy. But policy intervention did have a role to play. Particularly, scrubbers were put on smokestacks. Scrubbers cost money and energy, and regulation is the only reason to use this end-of-pipe technology. Scrubbers are applied by the same companies that cause the problem. In this sense, acidification is more like the hole in the ozone layer—see Box 12.1—than like climate change: Emissions were concentrated in a few applications, controlled by a small number of companies, and there was a technical solution at reasonable cost. It is feasible to have an international environmental treaty in which each signatory binds itself to do little. Against acid rain, doing a little was enough.

The LRTAP convention and its protocols can be found here:
http://www.unece.org/environmental-policy/conventions/envlrtapwelcome/the-air-convention-and-its-protocols/the-convention-and-its-achievements.html.

12.6 Lindahl equilibrium****

The *Lindahl equilibrium* is one theoretical solution to providing a public good. In the Lindahl equilibrium, countries contribute to the total provision of the public good according to their willingness to pay. The total willingness to pay thus equals the sum of individual willingnesses to pay. This is the *Samuelson condition*.

Let's return to the linear-quadratic model above. The benefit of country i of emission reduction equals $\psi_i \sum_j R_j M_j$. Its marginal benefit is thus ψ_i and the global benefit is $\sum_i \psi_i =: \psi$. The sum total paid for emission reduction is then $\psi \sum_j R_j M_j$.

The public good is cost-effectively provided. If the costs of emission reduction equals $\beta_i R_i^2$ then the marginal costs are $2\beta R_i$. Cost-effectiveness implies that costs are equated at the margin so that $2\beta R_i = 2\beta R_j$ or, taking country 1 as the standard, $R_j = \frac{\beta_1}{\beta_j} R_1$.

The Lindahl equilibrium is found where the total sum paid for emission reduction is equals its total cost. That is,

$$\psi \sum_i \frac{\beta_1}{\beta_i} R_1 M_i = \psi \sum_i R_i M_i = \sum_i \beta_i R_i^2 = \sum_i \beta_i \frac{\beta_1^2}{\beta_i^2} R_1^2 \tag{12.14}$$

or

$$\psi \beta_1 R_1 \sum_i \frac{M_i}{\beta_i} = \beta_1^2 R_1^2 \sum_i \frac{1}{\beta_i} \tag{12.15}$$

This implies that

$$R_i = \frac{\psi}{\beta_i} \frac{\sum_j \frac{M_j}{\beta_j}}{\sum_j \frac{1}{\beta_j}} \tag{12.16}$$

One way to think about the Lindahl equilibrium is that each country contributes to a global fund, which then uses the collected monies to buy emission reduction where that is cheapest. This is David Bradford's no-cap-but-trade proposal, but Bradford did not assume that countries would know their marginal benefit of emission reduction, instead let them contribute what is politically feasible.

The Lindahl equilibrium is efficient and individually rational. The grand coalition is stabilized by side payments. If a country stops contributing to the global fund, the global fund stops compensating its climate policy costs.

The Lindahl equilibrium is often dismissed because it requires individually priced contributions to a public good, which is then provided by a third party. It is individually rational to free-ride on that arrrangement. That objection does not hold in this case because each country is both a contributor and a provider. Another objection is to the individual prices. This requires a lot of information and would run afoul of anti-discrimination laws when applied in a national context. It is much less of an issue between countries.

That said, the Lindahl equilibrium assumes zero transaction costs. If the global fund charges substantial overheads, it would not work. Transaction costs would be small if there is a global emissions trading system and the global fund would have the authority to set the overall cap and the national allocations; or if the global fund would have the authority to set carbon taxes in every country; or if the global fund would buy carbon tax levels in a reverse auction. In these cases, there would effectively be a supranational climate authority and we would not need Lindahl to provide the global public good in the first place. Realistically, the global fund would have a hard time purchasing emission reduction at the lowest possible cost.

12.7 Linked games***

The game considered in Section 12.3 is about a single issue. Few real-life negotiations ever are. Let us introduce a second issue, a club good. We stick with a linear-quadratic game because that gives closed-form solutions. The costs B^C of emission reduction R^C for country i are

$$B_i^C = \beta_i^C {R_i^C}^2 \tag{12.17}$$

where β^C is a parameter. As above, the costs of emission reduction of country i are assumed to be independent from emission reduction in countries $j \neq i$.

The benefits D^C of emission reduction are different:

$$D_i^C = \begin{cases} \psi_i^C R_i^C M_i^C & \text{if non-cooperative} \\ \psi_i^C \sum_j R_j^C M_j^C & \text{cooperative} \end{cases} \tag{12.18}$$

where ψ^C is a parameter. There is a key difference between Equation (12.2) and Equation (12.18). In the public good game above, agent i reaps the benefits from the actions of all other agents, regardless of cooperation. In the club good game, agent i does not. As the names suggest, in the club good game, benefits are *excludable*; in the public good game, benefits are *non-excludable*. In both cases, benefits are *non-rival*.

The non-cooperative solution is as above:

$$\frac{\partial D_i^C}{\partial R_i^C} = \psi_i^C M_i^C = 2\beta_i^C R_i^C = \frac{\partial B_i^C}{\partial R_i^C} \forall i \Rightarrow {R_i^C}^* = \frac{\psi_i^C M_i^C}{2\beta_i} \forall i \tag{12.19}$$

The cooperative solution is too:

$$\frac{\partial \sum_j D_j^C}{\partial R_i^C} = M_i^C \sum_j \psi_j^C = 2\beta_i^C R_i^C = \frac{\partial B_i^C}{\partial R_i^C} \forall i \Rightarrow R_i^{C'} = \frac{\sum_j \psi_j^C M_i^C}{2\beta_i} =: \frac{\psi^C M_i^C}{2\beta_i} \forall i \tag{12.20}$$

At first sight, nothing has changed. However, the incentives to free-ride have.

The difference in costs are as above:

$$B_i^{C'} - B_i^{C^*} = \beta_i^C \left(\frac{\psi^C M_i^C}{2\beta_i^C}\right)^2 - \beta_i^C \left(\frac{\psi_i^C M_i^C}{2\beta_i^C}\right)^2 = (\psi^{C^2} - \psi_i^{C^2}) \frac{M_i^{C^2}}{4\beta_i^C} \forall i \tag{12.21}$$

The difference in benefits are not:

$$D_i^{C'} - D_i^{C^*} = \frac{(\psi^C \psi_i^C - \psi_i^{C^2}) M_i^{C^2}}{2\beta_i^C} + \psi^C \psi_i^C \sum_{j \neq i} \frac{M_j^C}{2\beta_j^C} \forall i \tag{12.22}$$

The first term on the right-hand side is as in the public good game. The second term is new. Non-cooperation implies exclusion and is therefore more expensive. The incentive to free-ride is therefore smaller for a club good than for the public good.

It is tempting, therefore, to argue that public goods should be linked to club goods. If the game are played together, there is less reason to free-ride on the provision of the public good. You would lose your access to the club and all the benefits that come with that. This is true. One popular suggestion is to tie greenhouse gas emission reduction with access to advanced renewables, a desirable technology regardless of climate policy. However, things are different from the perspective of the club. The link to the public good dilutes the attractiveness of the club. Cooperation on the provision of the club good is less rewarding if the admission price includes cooperation on the provision of the public good. If you have a patent on advanced solar power, you would want to license it to all potential clients, not just to those who have stringent climate policies. Climate clubs work for the climate, but not for the club.

A different sort of linkage is feasible. As argued above, the incentive to free-ride on the provision of a public good is stronger for agents with a smaller stake. You could therefore try to link two public good games, where players are big in one game but small in the other and *vice versa*. This works in theory, but there is a risk that all agents are mid-sized in the coupled game and all free-ride. In practice, it is difficult to find two issues whose asymmetries are each other's polar opposites. In fact, some countries are big players regardless of the issue at hand—China and the USA—while other countries' stakes are always small.

12.8 Repeated games***

The games discussed above are static. Agents make one decision. Climate change is a long-term problem, however, and governments, companies and households continually refine and revise their climate policies. Repeated or dynamic games are more complicated than static games, and they come in many varieties depending on how agents are assumed to learn about other agents' actions and on how they respond.

12.8.1 Open-loop games

Open-loop games are the simplest of repeated or dynamic games. Agents in an open-loop game cannot observe the actions of other agents—and therefore do not respond to what others

Table 12.2: Free-riding in an open-loop game

	r	g_B	g_D	ΔB	ΔD	$\Delta D - \Delta B$
Static	-	-	-	7.5	3	-4.5
Open-loop	5%	0	0	142.5	57	-85.5
	5%	0	4%	142.5	297	154.5

are doing or change course. The model is therefore easily solved, but unrealistic. It certainly does not apply to climate change. One of the key features of the UNFCCC is internationally standardized monitoring and reporting of greenhouse gas emissions. Countries also report their climate policies to the UNFCCC, it is the subject of active diplomacy, and there is a large academic literature on the subject. Governments know what other government do and plan to do about climate change, and adjust their actions accordingly.

The structure of open-loop and static games is therefore much the same, with one important qualification. In a static game, agents decide whether or not to cooperate. In a public good game, such as the provision of greenhouse gas emission reduction, non-cooperation is typically the best course of action. The costs of cooperation are fully internalized, but other agents reap most of the benefits. In a public good game on a stock problem like climate change, the costs of non-cooperation accumulate over time. As agents reduce their emissions only by a little, the climate problem keeps getting worse. The costs of cooperation do not grow nearly as fast.

In an open-loop game, the decision not to cooperate is a decision not to cooperate *forever*. This may be very expensive. If the discount rate is sufficiently low, it may be in the agents' self-interest to cooperate.

To illustrate this, let us return to linear-quadratic game discussed in Section 12.3. The central example was a large region, suffering one-quarter of the global damages of climate change. See Table 12.1. The top row of Table 12.2 reproduces this case. Despite suffering a quarter of the consequences of its own emissions, in a static game, it is not individually rational to cooperate with other agents.

The second row of Table 12.2 has an open-loop game, infinitely repeated. The costs and benefits of climate policy are assumed to be constant. The discount rate is 5%. Instead of the costs and benefits, the agent now considers the present value of costs and benefits. The net present value is $\frac{1-r}{r} = 19$ times higher than the current value. Because costs and benefits change by the same amount, their relative position does not change. The costs of cooperation have increased.

In the third row, the costs of emission reduction are constant over time, but the benefits increase by 4% per year. This is equivalent to using a 5% discount rate for the costs but a 5% - 4% = 1% discount rate for the benefits. Consequently, the present benefits grow larger, much larger than the present costs. Cooperation is individually rational—at least for this agent and these parameters.

As the benefits of climate policy tend to grow faster than its costs, free-riding is less likely in an open-loop game than in a static one.

12.8.2 Closed-loop games

Closed-loop games are very different than open-loop games, in that in every round—say, an annual meeting to negotiate climate policy—agents decide what to do, based on what has happened previously and what they expect the others to do now and later. Of course, with perfect foresight and common knowledge, the best strategy in a closed-loop game is the same as in an open-loop game. Under more realistic assumptions, strategies differ.

Dynamics of incentives, information and interactions between agents are many. Game theorists have studied a large variety of dynamic games. A common approach is to start in the final period—or if there is no final period, assume that there is a final period and solved it as an open-loop game—and the rational solution for every possible situation in the final period. Then, in the period before that, maximise the net present value of the last and second-last period, using the best response functions of oneself in the last period and the best response functions of all other agents in both periods. And so work your way back to the first period. This is much more complicated than it sounds.

This approach assumes rationality. Greenhouse gas emission reduction is a public good now, and it will remain so in the future. Therefore, free-riding is individually rational. Voluntary provision of public goods is not. A closed-loop game with rational agents is therefore unlikely to give an answer that is very different from the static games discussed above.

There are also games with heuristic strategies. Tit-for-tat is one example. As with free-riding, the starting point is global cooperation. However, if one agent defects, then the others respond by no longer cooperating with that agent. The difference in abatement costs is still 12.5 but the difference in benefits is now:

$$D_i' - D_i^* = (\psi\psi_i - \psi_i^2)\sum_j \frac{M_j^2}{2\beta_j} = (\psi\psi_i - \psi_i^2)\left(\frac{M_i^2}{2\beta_i} + \sum_{j\neq i}\frac{M_j^2}{2\beta_j}\right)\forall i \tag{12.23}$$

This is much larger and therefore deters free-riding.

A tit-for-tat strategy seems appealing but it has two drawbacks. First, all agents but one are assumed to play cooperatively, even if it is not individually rational to do so. Second, the "tat" is to provide less of a public good. The "tit" in response is to provide even less. This inflicts pain not just on the tatter but also on the titter. This threat may not be credible: If you hurt me I will hurt me more.

Other heuristic strategies to induce cooperation suffer similar drawbacks. At the end of the day, it is individually rational to underprovide a public good. Any strategy that gets around that is to a greater or less extent irrational.

12.9 International climate policy**

> International climate policy has a long history of good intentions but little to show for 25 years of negotiations.

International climate policy has a long history of good intentions but few successes.

Anthropogenic climate change was put on the academic agenda in 1896 by Svante Arrhenius, winner of the 1903 Nobel Prize for Chemistry. His analysis was textbook material within decades, but although many meteorologists were employed by the state, it was not until 1988 that climate change was put on the political agenda. Four years later, the United Nations Framework Convention on Climate Change (UNFCCC) was negotiated in Rio de Janeiro—see Box 12.3.

The UNFCCC entered into force in 1994. It has been ratified by all UN members (except South Sudan) and a few non-UN entities as well (notably the European Union). This is no surprise, as the UNFCCC does not contain many commitments. Four are worth mentioning. The UNFCCC sets up an international system to standardize and report measurements of greenhouse gas emissions. This is important because it permits international comparison of data and performance, and thus confidence in other countries' climate action. The UNFCCC calls for a stabilization of the atmospheric concentration of greenhouse gas, which implies 100% emission reduction for carbon dioxide (cf. Chapter 8). The UNFCCC further establishes that the responsibilities for climate policy are "common but differentiated" which is typically seen to indicate that rich countries should take the lead. Finally, the UNFCCC commits countries to negotiate. There is one big conference per year. In recent years, the number of participants was measured in the tens of thousands. Over the years, the number of smaller, preparatory, intermediate, committee and subcommittee meetings has grown steadily so that there are now civil servants who are employed full-time on the international climate negotiations.

Box 12.3: The Framework Convention on Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) was negotiated at the United Nations Conference on Environment and Development, held in Rio de Janeiro in June 1992. It entered into force in March 1994 when 50 nations had ratified it. The UNFCCC has now been ratified by 197 countries.
The UNFCCC has 26 articles. Arguably, the key ones include:

> **Article 2** The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Article 2 binds countries to avoid dangerous anthropogenic interference with the climate system, but without clearly defining what that means.

> **Article 3.1** The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.

> The UNFCCC sets the rules for international climate negotiations, says that rich countries should cut emissions first.

Article 3.1 introduces common but differentiated responsibilities, which is climate-speak for saying that although climate change is a global problem, rich countries should take the lead in solving it. This is reinforced by grouping rich countries in Annex I, and obliging them to take action:

> **Article 4.2.a** The [...] Parties included in Annex I [...] shall adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs. These policies and measures will demonstrate that developed countries are taking the lead in modifying longer-term trends in anthropogenic emissions [...].

The richest countries are grouped into Annex II. These countries cover the costs of other countries incurred under the UNFCCC (Article 4.3). Furthermore:

> **Article 4.4** The [...] Parties included in Annex II shall also assist the developing country Parties that are particularly vulnerable to the adverse effects of climate change in meeting costs of adaptation to those adverse effects.

> **Article 4.5** The [...] Parties included in Annex II shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and knowhow to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention.

> **Article 4.1.a** All Parties [...] shall [...] [d]evelop, periodically update, publish and make available to the Conference of the Parties, in accordance with Article 12, national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the Conference of the Parties[.]

> **Article 12.1.a** [E]ach Party shall communicate to the Conference of the Parties, through the secretariat [...] [a] national inventory of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, to the extent its capacities permit, using comparable methodologies to be promoted and agreed upon by the Conference of the Parties[.]

Article 4.1.a obliges countries to report their greenhouse gas emissions according to the format proscribed in Article 12.1.a.

> **Article 7.2** The Conference of the Parties, as the supreme body of this Convention, shall keep under regular review the implementation of the Convention and any related legal instruments that the Conference of the Parties may adopt, and shall make, within its mandate, the decisions necessary to promote the effective implementation of the Convention.

Article 7.2 establishes international climate negotations. The UNFCCC further creates a Secretariat (Article 8) and a Subsidiary Body on Scientific and Technical Advice (Article 9).
The full text of the UNFCCC can be found here:
http://unfccc.int/essential_background/convention/items/6036.php.

The Kyoto Protocol put obligations on a few countries only and there were no meaningful sanctions for missed targets.

These UNFCCC conferences aim to create international climate policy. Countries were close to a breakthrough in 1995 in Berlin. A deal was done in 1997 in Kyoto —see Box 12.4. The Kyoto Protocol establishes two things. First, the Kyoto Protocol sets up a (widely used) system through which rich countries can invest in greenhouse gas emission reduction in other, poorer countries; and a (rarely used) system through which rich countries can internationally trade emission permits. Second, the Kyoto Protocol defines emission targets for rich countries for the period 2008–12. Unfortunately, the Kyoto Protocol puts an undefined limit on the use of international flexibility mechanisms, it does not define emissions, and it does not specify sanctions for failing to meet the targets.

These issues were revisited in The Hague in 2000, with vice-president Gore eager to do a deal in support of his bid for the presidency. However, the countries of the European Union so vigorously disagreed with one another that the meeting collapsed. Since then, the EU has agreed on a common position well in advance of the international negotiations. As this position is public, the EU has de facto withdrawn from the negotiations: The EU position is known and immutable. Other countries do not need to talk to the EU as they can read the EU response in advance.

Shortly after the meeting in The Hague, George W. Bush was elected 43rd President of the USA. Although Bush had campaigned with a promise of a tax on greenhouse gas emissions, one of his first acts in office was to pull out of the Kyoto Protocol.[2] Over time, and perhaps partly in response to the strong reaction from Europe, the Bush administration grew increasingly hostile to climate policy. Regardless of the position of the president, it is unlikely that the Kyoto Protocol would ever have been ratified by the Senate.

In 2001, in Marrakesh, the finishing touches were put on the Kyoto Protocol. Emissions were defined (with an interpretation of carbon dioxide fluxes between the atmosphere and terrestrial biosphere that was very generous to Australia and Russia), no limits were set on the use of flexibility instruments, and no sanctions were imposed on violation of targets.[3]

> The targets of the Kyoto Protocol ended in 2012, but its international flexibility mechanisms did not expire.

After much toing and froing, the Kyoto Protocol came into force in 2005 after ratification by Russia (upon which the Kyoto Protocol imposes no obligations). Australia and Canada have been ambivalent about their commitments. Essentially, the Kyoto Protocol is a treaty between the European Union and Japan. Both are committed to climate policy in the absence of international treaties, so that the Kyoto Protocol is both narrow and shallow (in contrast to cartel theory which predicted that the Kyoto Protocol would be either narrow or shallow).

> Game theory predicts that environmental agreements either have many signatories who do little, or a few who do lots. Either way, the impact on emissions is small. The Kyoto Protocol and Paris Agreement are consistent with the predictions of game theory.

Box 12.4: The Kyoto Protocol and the Marrakesh Accords

The Kyoto Protocol is an agreement under UNFCCC. See Box 12.3. It was adopted in December 1997 in Kyoto. Important details were added in November 2001 in Marrakesh. The Protocol entered into force in February 2005 after 55 countries accounting for at least 55% of the total 1990 carbon dioxide emissions had ratified.
The Kyoto Protocol consists of 28 articles. Arguably the key ones include:

> **Article 3.1** The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emis-

[2]Unconfirmed rumour has it that this was a solo action of a junior political appointee.

[3]Or rather, countries in breach of their obligation will have to make up the gap, plus 30%, at some later time, on top of an unspecified future obligation.

> sions of the greenhouse gases listed in Annex A do not exceed their assigned amounts, calculated pursuant to their quantified emission limitation and reduction commitments inscribed in Annex B and in accordance with the provisions of this Article, with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012.

The Kyoto Protocol imposes emission caps on the countries specified in Annex I of the UNFCCC.

> **Article 4.1** Any Parties included in Annex I that have reached an agreement to fulfil their commitments under Article 3 jointly, shall be deemed to have met those commitments.

Annex I countries are allowed to pool their emission reduction efforts. The emission budgets of new entrants could thus be added to that of the European Union.

> **Article 17** The Conference of the Parties shall define the relevant principles, modalities, rules and guidelines, in particular for verification, reporting and accountability for emissions trading. The Parties included in Annex B may participate in emissions trading for the purposes of fulfilling their commitments under Article 3. Any such trading shall be supplemental to domestic actions for the purpose of meeting quantified emission limitation and reduction commitments under that Article.

Annex B countries are allowed to trade their emission reduction obligations.

> **Article 12.3** Under the Clean Development Mechanism:
>
> (a) Parties not included in Annex I will benefit from project activities resulting in certified emission reductions; and
>
> (b) Parties included in Annex I may use the certified emission reductions accruing from such project activities to contribute to compliance with part of their quantified emission limitation and reduction commitments under Article 3, as determined by the Conference of the Parties serving as the meeting of the Parties to this Protocol.

Annex I countries are allowed to fund emission reduction in other countries.
The full text of the Kyoto Protocol can be found here:
http://unfccc.int/kyoto_protocol/items/2830.php.
Although the Kyoto Protocol defines emission targets, it does not spell out the consequences for missing said targets. These are defined in the Marrakesh Accords:

> **Decision 24/CP.7 Article XV.5** Where the enforcement branch has determined that the emissions of a Party have exceeded its assigned amount [...] it shall declare that that Party is not in compliance with its commitments under Article 3, paragraph 1, of the Protocol, and shall apply the following consequences:
>
> (a) Deduction from the Party's assigned amount for the second commitment period of a number of tonnes equal to 1.3 times the amount in tonnes of excess emissions;

(b) Development of a compliance action plan in accordance with paragraphs 6 and 7 below; and

(c) Suspension of the eligibility to make transfers under Article 17 of the Protocol until the Party is reinstated in accordance with section X, paragraph 3 or paragraph 4.

If a country is out of compliance, it will have to make up the difference plus interest later. However, at the time of the Marrakesh Accords, the second commitment period had yet to be negotiated. It never was. The country that is out of compliance would also be suspended from the international trade in emission permits, another feature of the Kyoto Protocol that never came to be.
The full text of the Marrakesh Accords can be found here:
http://unfccc.int/meetings/marrakech_oct_2001/session/6273/php/view/decisions.php#c.

Hopes were high for Copenhagen, but the final attempt at legally binding targets failed.

Since 2007, efforts have been undertaken to negotiate a successor to the Kyoto Protocol. The Kyoto Protocol did not expire in 2013, but its emission reduction targets became obsolete. A roadmap was agreed in Bali in 2007. Hopes for a stringent and binding agreement were high for the 2009 meeting in Copenhagen, but the disappointment was greater. It was agreed in 2010 in Cancun to keep talking, and again in 2011 in Durban. Another roadmap was agreed in 2012 in Doha.

In Paris, international climate policy switched to pledge-and-review. Countries are obliged to do whatever they want.

Things changed in 2014 in Lima. *Intended Nationally Determined Contributions* to greenhouse gas emission reduction were introduced. This ugly mouthful has two operative concepts. "Intended" refers to an aspiration, rather than a binding target. "Nationally determined" means that these aspirations are set through whatever process is appropriate in the countries in question, rather than through international negotiations. The Paris Agreement of 2015 confirms this: It essentially obliges countries to set a climate policy of their own choice. Climate policies are supposed to become more ambitious over time, but there are no sanctions if this intention is not met. National policies will be periodically totted up and compared to a global target, but there is no mechanism to alter national policies if need be.

At the same time, the Paris Agreement set long-term targets for the global mean surface air temperature (not to exceed 1.5 to 2.0℃ above pre-industrial) and emissions (zero). However, without corresponding measures, these targets can best be interpreted as aspirational.

Box 12.5: The Paris Agreement

The Paris Agreement is an agreement under UNFCCC. See Box 12.3. It was adopted in December 2015 in Paris, and entered into force in November 2016 after 55 countries accounting for at least 55% of the total greenhouse gas emissions had ratified.
The Paris Agreement consists of 29 articles. Arguably the key ones include:

Article 2.1.a Holding the increase in the global average temperature to well below 2℃ above pre-industrial levels and pursuing efforts to limit the

> temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change[.]

Article 2.1.a replaces the vague aim of Article 2 of the UNFCCC by a specific goal.

> **Article 4.2** Each Party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions.

> **Article 4.3** Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

Article 4.2 is a key departure from the Kyoto Protocol. Instead of an emissions target that is specified in an international treaty, targets are now aspirational and set by the countries themselves. Article 4.3 imposes the condition that intentions should become more ambitious over time, but without defining what that means.

> **Article 14.1** The Conference of the Parties serving as the meeting of the Parties to this Agreement shall periodically take stock of the implementation of this Agreement to assess the collective progress towards achieving the purpose of this Agreement and its long-term goals (referred to as the "global stocktake"). It shall do so in a comprehensive and facilitative manner, considering mitigation, adaptation and the means of implementation and support, and in the light of equity and the best available science.

Article 4.2 defines the pledge, Article 14.1 the review. Where the Kyoto Protocol was based on legally binding targets, the Paris Agreement uses pledge-and-review.

> **Article 15.2** The mechanism [to facilitate implementation of and promote compliance with the provisions of this Agreement] shall consist of a committee that shall be expert-based and facilitative in nature and function in a manner that is transparent, non-adversarial and non-punitive. The committee shall pay particular attention to the respective national capabilities and circumstances of Parties.

Article 15.2 confirms the voluntary nature of greenhouse gas emission reduction.

> **Article 18.1** At any time after three years from the date on which this Agreement has entered into force for a Party, that Party may withdraw from this Agreement by giving written notification to the Depositary.

Article 18.1 underlines the voluntary nature of the Paris Agreement as any country can walk away at any time.
The full text of the Paris Agreement can be found here:
http://unfccc.int/paris_agreement/items/9485.php.

In sum, the international negotiations on climate policy confirm that it is difficult to agree on the provision on a global public good. After 20 years of trying, international climate policy has abandoned legally binding targets in favour of pledge-and-review, centred on voluntary contributions.

Box 12.6: The Kigali Amendment

There is a threeway interaction between the hole in the ozone layer and climate change. First, ozone is a greenhouse gas. The hole in the ozone layer thus cools the planet. Second, CFCs are greenhouse gases, warming the planet. Third, the replacements of CFCs, HFCs, are also greenhouse gases, and much stronger than CFCs. The net effect of the Montreal Protocol—see Box 12.1—is warming: More ozone, less CFCs, more HFCs.

> The Kigali treaty phases out HFCs, particularly powerful greenhouse gases for which there is a substitute.

The 2016 Kigali Amendment to the Montreal Protocol intends to put an end to that. The Kigali Amendment extends the Montreal Protocol by including HFCs in the list of controlled gases. It has two reduction schedules, with hot countries on a more leisurely schedule—HFCs are used in air conditioners.
As with the Montreal Protocol (Box 12.1) and the Sofia Protocol (Box 12.2), HFCs have a narrow range of application, and a technical solution is available—while the adoption of the Kigali Amendment would spur companies to invest in making these substitutes cheaper and more convenient.
The full text of the Kigali Amendment can be found here: http://ozone.unep.org/.

Further reading

Joseph Aldy and Robert Stavins' 2010 book *Post-Kyoto International Climate Policy:1 Implementing Architectures for Agreement* and Scott Barrett's 2010 *Why Cooperate? The Incentive to Supply Global Public Goods* are excellent treatises on international climate agreements. Richard Benedick's 1998 book *Ozone Diplomacy: New Directions in Safeguarding the Planet* gives a good introduction to the realpolitik of international environmental negotiations, and David Victor's 2011 book *Global Warming Gridlock: Creating More Effective Strategies for Protecting the Planet* provides further insight into international climate policy.

IDEAS/RePEc has a bibliography: http://biblio.repec.org/entry/tdI.html.

Exercises

12.1. Free-riding, as discussed in Section 12.3, is evaluated with respect to the grand coalition. Evaluate the difference in costs and benefits between full cooperation and no cooperation at all.

12.2. Graphically represent the two-player game of Section 12.4 as an Edgeworth Box.

12.3. For the two-player LQ game of Section 12.4, derive the costs and benefits of cooperation for both players. How does this change with β and ψ? Interpret the results.

12.4. Assume that the first Conference of the Parties (COP) to the United Nations Convention on Climate Change, in 1995 in Berlin, had a 50% chance of success. Assume that each COP is an independent try. What is the probability that COP28, in 2023 in Dubai, will be a success?

12.5. S. Sharma, J.B. Ang and P.G. Fredriksson (2021) Religiosity and climate change policies, *Energy Economics*, 101 (105414) and T.V. Vu Do genetically fragmented societies respond less to global warming? Diversity and climate change policies, *Energy Economics*, 104 (105652) econometrically test the impact of cost–benefit analysis in setting national climate policies. Discuss their results.

12.6. Read and discuss:

- ***J.C. Murdoch and T. Sandler (1997), The voluntary provision of a pure public good: The case of reduced CFC emissions and the Montreal Protocol, *Journal of Public Economics*, 63, 331–349.
- ***A. Dannenberg (2016), Non-binding agreements in public goods experiments, *Oxford Economic Papers*, 68, 279–300.
- ***A. Dannenberg and S. Barrett (2016), An experimental investigation into 'pledge and review' in climate negotiations, *Climatic Change*, 138, 339–351.
- ***R. Hasson, A. Loefgren and M. Visser (2010), Climate change in a public goods game: Investment decision in mitigation versus adaptation, *Ecological Economics*, 70, 331–338.
- ***S. Barrett (2008), Climate treaties and the imperative of enforcement, *Oxford Review of Economic Policy*, 24, 239–258.
- ****S. Barrett (1994), Self-Enforcing International Environmental Agreements, *Oxford Economic Papers*, 46, 878–894.
- ****D. Osmani and R.S.J. Tol (2010), The case of two self-enforcing international agreements for environmental protection with asymmetric countries, *Computational Economics*, 36, 93–119.
- ****A.M. Ulph and D.J. Maddison (1997), Uncertainty, learning and international environmental policy coordination, *Environmental and Resource Economics*, 9 (4), 451–466.
- ****S. Barrett (2006), The strategy of trade sanctions in international environmental agreements, *Resource and Energy Economics*, 19, 345–361.
- ****M. Battaglini and B. Harstad (2016), Participation and duration of environmental agreements, *Journal of Political Economy*, 124, 160–204.

Chapter 13

Building an integrated assessment model

Introduction

All models are wrong, but some are useful. In this chapter, we will construct an integrated assessment model, that is, a model that combines the natural science and economic aspects of the climate problem—hence, "integrated"—to shed light on policy choices—hence, "assessment". The model will be built in Excel, an environment all have access to and most are familiar with. Model construction is done in 10 steps, roughly corresponding to Chapters 1–12—although your lecturer may decide to skip some steps or divide an assignment over two weeks. The data needed to do this are available at the resource site and locally. The model is then applied in a series of exercises.

On the same site, there is a version of the same exercise using Matlab. Detailed instructions are not given, because the Excel instructions below suffice for someone who can programme in Matlab.

13.1 Carbon cycle and climate

We start with two components: a carbon cycle model and a climate dynamics model.

The input (or *forcing*) to the carbon cycle model are annual emissions of CO_2, measured in Mt C (megatonne carbon = million metric tonnes of carbon).[1] The output of the carbon cycle model is the atmospheric concentration of CO_2, measured in ppm (parts per million by volume).

The input (or forcing) to the climate model is the atmospheric concentration of carbon dioxide, again measured in ppm. The output of the climate dynamics model is the yearly average temperature increase over pre-industrial temperatures in ℃. The model will run in yearly time steps. It will start in 1750 and end in 2300.

The two components are coupled via the atmospheric concentration of CO_2, i.e., the output of the carbon cycle model is an input to the climate dynamics model.

[1] Note that carbon dioxide emissions are sometimes reported in tonnes of carbon and sometimes in tonnes of carbon dioxide. The difference is a factor 44/12, or the atomic weight of carbon (2×6) plus twice the atomic weight of oxygen (2×2×8) over the atomic weight of carbon (2×6); 6 and 8 are the number of protons in carbon and oxygen atoms, respectively.

13.1.1 Carbon cycle module

The carbon cycle model is a five-box model. The five boxes do not correspond to anything in the physical world; they are a mathematical abstraction that as a whole mimics the results from much more complicated models. In this model, all atmospheric CO_2 concentrations live in one of five boxes. If you want to compute the total atmospheric CO_2 concentration at any point in time, you add the amount of CO_2 in the five boxes. Over time, CO_2 disappears from all of these boxes, at different rates for each individual box. New anthropogenic CO_2 emissions are added every year to the atmosphere. In the five-box model these yearly influxes of new CO_2 are distributed by fixed shares into the five boxes: 13% go into the first box, 20% into the second, 32% into the third, 25% into the fourth and the remaining 10% into the fifth box.

There are consequently five *variables* that represent the five boxes and each of these variables takes on a different value in each year. The equation that is used to compute the amount of CO_2 in box i (which takes values from 1 to 5) at time t (which takes on values from 1750 to 2020) is:

$$L_{i,t} = (1 - \delta_i)L_{i,t-1} + \vartheta_i \chi M^*_{t-1} \tag{13.1}$$

Variable $L_{i,t}$ is the atmospheric load, the amount of CO_2 in box i at time t, measured in ppm. Parameter δ_i is the degradation rate, the share of CO_2 that disappears each year from box i; $1 - \delta_i$ is the share of CO_2 in box i that stays in the atmosphere until the next time period. ϑ_i is the share of emissions that goes into box i. χ is a unit conversion factor: CO_2 emissions in our model are measured in Mt C, but atmospheric CO_2 concentrations are measured in ppm; χ converts from the unit Mt C to CO_2 ppm. M^*_t are world total emissions of CO_2 in year t, measured in Mt C.

The values for past emissions M^*_t are provided to you as an Excel file. $\chi = 0.00047$. You should use the following values for δ_i and ϑ_i:

$\vartheta_1 = 0.13$ $\quad\vartheta_2 = 0.20$ $\quad\vartheta_3 = 0.32$ $\quad\vartheta_4 = 0.25$ $\quad\vartheta_5 = 0.10$

$\delta_1 = 0$ $\quad\delta_2 = 1 - e^{-\frac{1}{363}}$ $\quad\delta_3 = 1 - e^{-\frac{1}{74}}$ $\quad\delta_4 = 1 - e^{-\frac{1}{17}}$ $\quad\delta_5 = 1 - e^{-\frac{1}{2}}$

The values for some of the δ_i parameters are little equations themselves, you can enter them directly in Excel as a formula, e.g., for δ_2 you would enter "=1-EXP(-1/363)" as the Excel formula.

Equation (13.1) is a *difference equation*.[2] You cannot used it to compute the values for each box in the first time period, i.e., in the year 1750: The equation for that year would rely on the previous year, for which we do not have a value. Therefore, we should *initialize* the equation, as we should for any difference equation. That is, for the first year only, you should not use Equation (13.1), but instead use initial values: $L_{i,1750} = 0$ except $L_{1,1750} = 275$.

The final step in the carbon cycle model is to compute atmospheric CO_2 concentrations at each point in time:

$$L_t = \sum_{i=1}^{5} L_{i,t} = L_{1,t} + L_{2,t} + L_{3,t} + L_{4,t} + L_{5,t} \tag{13.2}$$

L_t is the atmospheric concentration of CO_2 at time t, it is the sum of the five boxes at that time.

[2] More specifically, Equation (13.1) is a first-order, linear difference equation. It is a difference equation because the variable's level depends on its past level. It is a first-order difference equation because the current level only depends on the previous period. Furthermore, the relationship is linear. A differential equation is a difference equation with an infinitesimally small time-step.

13.1.2 Climate module

The climate model has two parts: the first part computes the extra energy in the atmosphere and the long term temperature effect. The second part computes the yearly temperature increase over time.

The amount of extra energy caused by rising CO_2 concentrations is called the *radiative forcing* and is measured in Watts per square metre, Wm^{-2}. The equation to compute this variable is

$$F_t = 5.35 \ln\left(\frac{L_t}{L_{pre}}\right) \tag{13.3}$$

F_t is the radiative forcing at time t caused by CO_2 in Wm^{-2}. C_t is the atmospheric CO_2 concentration at point t in ppm, as computed by the previous component. C_{pre} is the pre-industrial level of atmospheric CO_2 concentrations, and you should use 275 ppm for this. $\ln(x)$ is the natural logarithm, its Excel function is "=LN(x)".[3]

The next step in the model is to global mean surface air temperature. The equation for that is

$$T_t^A = T_{t-1}^A + \varphi_1\left(\varphi_2 F_t - T_{t-1}^A\right) + \varphi_3\left(T_{t-1}^O - T_{t-1}^A\right) \tag{13.4}$$

Here T_t^A is the increase in global average surface temperature; $\varphi_2 = 1.15$ is a parameter; $5.35\varphi_2 \ln(2) = 4.26$ is the climate sensitivity, the equilibrium warming due to a doubling of the atmospheric concentration of carbon dioxide; $\varphi_1 = 0.0256$ is a parameter that determines how fast the atmosphere responds to a deviation between the actual and the equilibrium temperature; $\varphi_3 = 0.00738$ is a parameter that determines how fast the atmosphere responds to a deviation between the temperature of the atmosphere and ocean; and T_t^O is the temperature of the ocean, which follows:

$$T_t^O = T_{t-1}^O + \varphi_4\left(T_{t-1}^A - T_{t-1}^O\right) \tag{13.5}$$

where $\varphi_4 = 0.00568$ is a parameter that determines how fast the ocean responds to a deviation between the temperature of the atmosphere and ocean.

The temperatures of atmosphere and ocean are government by a system of *coupled* difference equations. The ocean's temperature depends on its own past and on the atmosphere's past, and so does the atmosphere's temperature. We therefore need to initialize the temperatures for the year 1850. The initialization is $T_{1850}^A = T_{1850}^O = 0$. As a result, our model yields temperature *anomalies*, that is, warming relative to pre-industrial times.

13.1.3 Exercises

13.1. What happens to projected temperatures if CO_2 emissions were held constant at 2020 levels in the model? What happens if CO_2 emissions grow by 2% per year? Hint: You should copy the Excel sheet that contains your model for this exercise. The new sheet should have the model output with constant emissions. Introduce the annual growth rate of CO_2 emissions as a parameter. Store the results as values. Interpret the results.

13.2. If emission are reduced by a fixed percent each year, by how much would we need to reduce emissions from 2020 to keep global warming below 2°C in the year 2300? And between 2020 and 2300? Hint: First, copy the model sheet and do all your analysis in the new sheet. The easiest approach is to modify the line that has emissions in such a way that starting

[3] Other greenhouse gases also contribute to climate change, as do a range of other human and natural factors. We will ignore these here because adding them brings more work than insight. However, the numerical results are biased because of this.

with the second time step you use an equation to compute emissions. Assuming that the cell for emissions in the year 2011 is C24, the Excel formula might look like "=B23*(1-B20)". In this case the cell B20 would have the percent reduction in emission per year in it and you could quickly change the emissions profile by changing the value in cell B20. Finally, you might want to have one cell that displays the maximum temperature increase over the model time horizon. Assuming the predicted temperatures are in cells B48 to KF48, you might add a cell that has the equation "=MAX(B48:KF48)" in it to help you. Interpret the results.

13.3. If emissions grow by 2% per year until the year 2030, and are then reduced by a fixed percent each year, how much would they have to be reduced in percent in each year to keep global warming below 2℃ in the year 2300? And between now and 2300? Hint: Again copy the model sheet and do your analysis on the new sheet. The steps for this exercise are similar to the steps for the previous question. Interpret the results.

13.4. Create three graphs, one for CO_2 emissions, one for CO_2 concentrations and one for temperature. The x-axis should have years on it for all three graphs. Then plot each of the six cases analyzed (constant emissions, growing emissions, emission reduction starting in 2020 with a temperature target in 2300, emission reduction starting in 2020 with a temperature target for every year, emission reduction starting in 2030 with two alternative temperature targets) as one line. Hint: You should create a new empty sheet in Excel, and then reference the values in all the other sheets as data for your chart.

13.2 Scenarios

You will add two components to your integrated assessment model: one that computes anthropogenic CO_2 emissions over time and an economic growth component that forecasts economic growth, both for three regions: rich, middle-income, and poor.

The output of the emissions component replaces the arbitrary emissions scenario for the carbon cycle component of Section 13.1.1. That is, instead of using emissions provided in a data file, you will compute emissions and couple the carbon cycle component to the emissions component. The growth component computes output, or GDP, and that will be an input into the emissions component.

13.2.1 Emissions module

The emissions component starts out with the Kaya Identity:

$$M^*_{r,t} = \underbrace{N_{r,t}}_{\text{population}} \underbrace{\frac{Y_{r,t}}{N_{r,t}}}_{\substack{\text{per capita}\\ \text{income}}} \underbrace{\frac{E_{r,t}}{Y_{r,t}}}_{\substack{\text{energy}\\ \text{intensity}\\ \text{of output}}} \underbrace{\frac{M^*_{r,t}}{E_{r,t}}}_{\substack{\text{emission}\\ \text{intensity}\\ \text{of energy}}} \tag{13.6}$$

where $M^*_{r,t}$ are industrial CO_2 emissions in million metric tonnes of carbon (MtC) in region r at time t, $N_{r,t}$ is the number of people in region r at time t, $Y_{r,t}$ is output (or GDP) in region r at time t and $E_{r,t}$ is primary energy use in region r at time t.

The data file has population numbers for 1960–2010. If we assume, from 2011 onwards, that the population growth rate is 0.95 times the population growth rate in the previous year, then the world population stabilizes around 8.5 billion people.

The data file also has output for 1960–2020. Compute output per capita and its growth rate. For now, just assume that output per capita continues to grow at its 2020 rate. Compute total output for 2021–2300. The data file further has primary energy use for 1960–2020 or a slightly shorter period, depending on the region. Compute the energy intensity and its growth rate. Assume that energy intensity continues to fall at the average rate over the entire period for which there are observations. Compute total primary energy use for 2021–2300.

Finally, the data file has carbon dioxide emissions for 1960–2020. Compute the carbon intensity and its growth rate. Assume that carbon intensity continues to fall at the average rate over the entire period for which there are observations. Compute total carbon dioxide emissions for 2021–2300.

At this point we have computed emissions from industrial activities, assuming no specific climate policy is implemented. The economic part of the scenarios needs to be improved, though.

13.2.2 Growth module

You will build a simple growth model—the Solow model, named after the 1987 Nobelist—that will replace output $Y_{r,t}$ in the emissions component above.

Output in a particular year is computed by a production function—the Cobb–Douglas production function—that depends on three things: the amount of capital (i.e., factories, machines etc.), the amount of labour (in our case equal to the population size) and a technology index, also called total factor productivity, i.e., a measure of how efficient we are in using the inputs capital and labour to produce things. The production function used is called a Cobb–Douglas production function. It has the following form:

$$Y^*_{r,t} = A_{r,t} K^{\alpha}_{r,t} N^{1-\alpha}_{r,t} \tag{13.7}$$

where $Y^*_{r,t}$ is gross output in trillion dollars[4] in region r at time t. $A_{r,t}$ is the total factor productivity in region r at time t. $K_{r,t}$ is the amount of capital available for production in region r at time t. $N_{r,t}$ is the number of people; note that this assumes a constant dependency ratio, the number of workers is a constant fraction of the number of people. Parameter $\alpha = 0.2$ is called the capital share.

The capital stock is modelled in a similar way to our modelling of the concentration of CO_2 in the atmosphere: we assume that there is an inflow of new capital (i.e., new factories and machines are built) and that some capital breaks over time, so there is an outflow of capital. The equation of motion for the capital stock is another first-order linear difference equation:

$$K_{r,t} = (1-\delta) K_{r,t-1} + I_{r,t-1} \tag{13.8}$$

$\delta = 0.1$ is the depreciation rate of capital. $I_{r,t}$ is investment, i.e., a measure of how much new capital is built every year.

The amount of new investment in capital for year t should be modelled as:

$$I_{r,t} = s Y_{r,t} \tag{13.9}$$

$s = 0.2$ is called the *savings rate*. Because we assume thae capital market to be in equilibrium, and because we assume the economy to be closed, the savings rate equals the *investment rate*.

[4]We discuss why it is called "gross" output in Section 13.3.

As with all equations of motion, you cannot use Equation (13.9) to compute the level of the capital stock for the initial period. Instead, we initialize it at its steady state:

$$K = (1-\delta)K + sAK^{\alpha}P^{1-\alpha} \Leftrightarrow \delta K = sAK^{\alpha}P^{1-\alpha} \Leftrightarrow$$
$$\delta K^{1-\alpha} = sAP^{1-\alpha} \Leftrightarrow K = \left(\frac{sA}{\delta}\right)^{\frac{1}{1-\alpha}} P \quad (13.10)$$

The initial level of total factor productivity is found by calibration. Start with a value of 1 and change it until modelled output equals observed output in 1960.

Let total factor productivity grow at a constant rate between 1960 and 2020. Start with a value of 2%, and change it to ensure that the modelled output in 2020 equals the observed output.

For 2011–2300, let the growth rate of total factor productivity equal 0.99 times the total factor productivity growth in the previous period.

13.2.3 Coupling

At this point we can couple the growth component with the rest of the model. First, replace the arbitrary growth rate of emissions. Let the emissions that drive the carbon cycle model, grow at the same rate as the modelled emissions.

13.2.4 Exercise

13.5. Decompose the main drivers of climate change in the scenario used in the model and rank their relative contribution to future climate change. Interpret the result. Hint: First, add one period to the model. The equations will be safely stored in the year 2301. Change the equations for the years 2021–2300. Save the results. Change the equations back by copying the equations for 2301 to 2011–2300. Copy and paste/values the global mean temperature in the exercises sheet. Then assume that population is frozen at its 2020 level. Store the results in the exercises sheet. Restore population to its scenario values. Repeat this exercise with per capita income frozen, energy intensity frozen, and carbon intensity frozen. Briefly describe the effect each of these has on average temperatures, and rank them in terms of the size of their effect.

13.3 Abatement

The emissions module of Section 13.2 lacks an option for greenhouse gas emission reduction. In order to model this, we will have to introduce a so-called *choice variable*: the emission control rate. This is a new type of variable. Unlike a scenario variable that is an external driver, or a state variable, which is computed by some equation, a choice variable is something for which we use our model to find an “appropriate” value. The emission control rate is such a choice variable. We want to use our model to compute the amount we should reduce CO_2 emissions per year in order to reach a given objective—that objective may be some balancing act of costs and benefits of reducing emissions, or it may be a temperature target. For now, just introduce a new column in your Excel spreadsheet for this choice variable, it will have a value for each year and you can initially set the control rate to 0% (i.e., no climate policy). We will designate the emission control rate by $R_{r,t}$.

The final equation for emissions therefore is

$$M_{r,t} = (1 - R_{r,t})M^{*}_{r,t} \quad (13.11)$$

Make sure you now couple the carbon cycle model to this new variable M_t!

We assume throughout our model that carbon policy is costly. So any choice of $R_{r,t}$ larger than 0% will impose a burden on the economy. We compute the relative size of this burden, also called relative abatement cost, by a simple function:

$$B_{r,t} = \beta R_{r,t}^2 \tag{13.12}$$

$B_{r,t}$ is the relative cost of climate policy at time t, $\beta = 0.1$ is a parameter.

We called output so far *gross* output because it does not account for the cost of climate policy. The equation for *net* output includes abatement costs and is given as

$$Y_{r,t} = (1 - B_{r,t})Y_{r,t}^* \tag{13.13}$$

So this equation picks up the effect of the control variable from the emissions component. Note that emissions now fall for two reasons: First, we lower emissions. Second, we slow down the economy.

In order to compute the marginal abatement cost, substitute Equation (13.12) into Equation (13.13) to compute total emission reduction costs as a function of *relative* emission reduction. The absolute cost of emission reduction is given by

$$B_{r,t}^* = B_{r,t}Y_{r,t}^* = \beta R_{r,t}^2 Y_{r,t}^* \tag{13.14}$$

Add $B_{r,t}^*$ to your Excel sheet. It computes the cost of climate policy in trillion dollars.

Absolute emission reduction equals $R_{r,t}M_{r,t}^*$. Rework Equation (13.14) to

$$B_{r,t}^* = \beta \left(R_{r,t}M_{r,t}^*\right)^2 \left(\frac{1}{M_{r,t}^*}\right)^2 Y_{r,t}^* \tag{13.15}$$

The marginal abatement cost then follows

$$\frac{\partial B_{r,t}^*}{\partial R_{r,t}M_{r,t}^*} = 2\beta \left(R_{r,t}M_{r,t}^*\right) \left(\frac{1}{M_{r,t}^*}\right)^2 Y_{r,t}^* = 2\beta R_{r,t}\frac{Y_{r,t}^*}{M_{r,t}^*} \tag{13.16}$$

Note that we need to rescale β as we have expressed economic activity in billion dollars and emissions in million tonnes of carbon.

13.3.1 Exercises

13.6. Set $R_{r,t}$ equal to 0% for every region and every year in the period 2020–2300. Increase $R_{r,t}$ to 5% for all years, and then to 10% for all years. What happens to emissions, concentrations, and temperature? What are the costs of these policies? Interpret the results.

13.7. Compute the marginal abatement costs. What are the regional emission reduction rates if the marginal abatement costs are equal for the three regions and global emission reduction is 5% or 10%? Hint: Equation (13.16) gives marginal abatement costs as a function of emission reduction. Equating the marginal abatement costs in two regions means that you can express relative emission reduction in one region as a function of emission reduction in the other region. Do this for 2020–2029 only, and keep uniform emission reduction elsewhere. Impose these emission cuts. What is the difference in costs with the previous exercise? Interpret the results.

13.8. *In the previous exercise, you computed the marginal abatement costs in each period for a given emission reduction. Keep the marginal abatement costs as is in the first period, and compute the emission reduction in later periods such that the marginal abatement cost rises with the rate of discount. What are implications for emissions, concentrations and temperature? Change the emission reduction in period 1 such that the temperature in 2100 is the same as in the first exercise. What is the difference in costs? Interpret the results.

13.4 Tradable permits

You will add a component to the model to simulate an international market in emission permits.

As above, each region faces an abatement cost function that is quadratic in relative emission reduction—see Equation (13.12)—and linear in emission permit purchases and sales:

$$B^*_{r,t} = \beta_{r,t} R^2_{r,t} Y_{r,t} + \pi_t P_{r,t} \tag{13.17}$$

where π_t is the permit price at time t and $P_{r,t}$ is the number of permits bought (if $P < 0$) or sold (if $P > 0$) by region r at time t. Each region has an emissions target $G_{r,t}$, so that

$$R_{r,t} M^*_{r,t} + P_{r,t} \geq G_{r,t} \tag{13.18}$$

Each region minimizes abatement costs by choosing the optimal amount of in-house emission reduction and permit sales. Form the Lagrangean

$$\mathcal{L}_{r,t} = \beta_{r,t} R^2_{r,t} Y_{r,t} + \pi_t P_{r,t} - \lambda_{r,t} \left(R_{r,t} M^*_{r,t} + P_{r,t} - G_{r,t} \right) \tag{13.19}$$

Assume that all companies are price-takers: $\frac{\partial \pi_t}{\partial R_{r,t}} = 0 \forall r, t$. The first-order conditions for optimality are

$$\frac{\partial \mathcal{L}_{r,t}}{\partial R_{r,t}} = 2\beta_{r,t} R_{r,t} Y_{r,t} - \lambda_{r,t} M^*_{r,t} = 0 \tag{13.20}$$

$$\frac{\partial \mathcal{L}_{r,t}}{\partial P_{r,t}} = \pi_t - \lambda_{r,t} = 0 \tag{13.21}$$

Combining and rearranging

$$2\beta R_{r,t} Y_{r,t} - \pi_t M^*_{r,t} = 0 \Leftrightarrow R_{r,t} = \frac{\pi_t M^*_{r,t}}{2\beta_{r,t} Y_{r,t}} \tag{13.22}$$

There is of course a third first-order condition

$$\frac{\partial \mathcal{L}_{r,t}}{\partial \lambda_{r,t}} = R_{r,t} M^*_{r,t} + P_{r,t} - G_{r,t} = 0 \Rightarrow R_{r,t} M^*_{r,t} + P_{r,t} = G_{r,t} \tag{13.23}$$

This says that in-house emission reduction plus permits bought equal the emission reduction obligation. For sellers of emission permits, $P_{r,t} < 0$ so that in-house emission reduction exceeds the target. Substituting (13.22) into (13.23)

$$\frac{\pi_t M^*_{r,t}}{2\beta_{r,t} Y_{r,t}} M^*_{r,t} + P_{r,t} = G_{r,t} \Leftrightarrow P_{r,t} = G_{r,t} - \frac{\pi_t {M^*_{r,t}}^2}{2\beta_{r,t} Y_{r,t}} \tag{13.24}$$

We now know $R_{r,t}$ and $P_{r,t}$, but only as a function of π_t. We do not know π_t, however.

Impose the market clearing condition—permits sold equal permits bought—to derive the market equilibrium

$$\sum_r P_{r,t} = 0 = \sum_r \left(G_{r,t} - \frac{\pi_t {M^*_{r,t}}^2}{2\beta_{r,t} Y_{r,t}} \right) \Leftrightarrow$$
$$\sum_r G_{r,t} - \pi_t \sum_r \frac{{M^*_{r,t}}^2}{2\beta_{r,t} Y_{r,t}} = 0 \Leftrightarrow \pi_t = \frac{\sum_r G_{r,t}}{\sum_r \frac{{M^*_{r,t}}^2}{2\beta_{r,t} Y_{r,t}}} \quad (13.25)$$

We now have a solution for π_t that only depends on variables that we know, so we solve π_t first. Use π to solve $R_{r,t}$, and use R to solve for $P_{r,t}$. Implement this in the Excel model. Note that we only include the solutions to the first-order and market clearing conditions in the model.

13.4.1 Exercises

13.9. Assume that $R_{r,t}$ is 5% or 10% for all years and all regions. This sets the *initial* allocation of permits. Now impose trade. What happens to total and marginal abatement costs? How does this compare to the solution with a tax? Interpret the results.

13.10. Assume that the poorest region has no emission reduction obligations, $R_{poor,t} = 0$. Halve the obligations of the middle-income regions. Increase the abatement obligations of the richest region such that global emissions are as above. Hint: The emissions target for the rich region follows from the global target and the targets of the other two regions. What are the marginal and total costs without emission permit trade? And with? How does this compare with the previous exercise? Interpret the results.

13.5 Impacts of climate change

We now add a component for the impacts of climate change to the model. You also need to modify the output model to pick up the estimate of climate impacts. With that component, you have a model that provides estimates of everything needed to do a benefit–cost analysis of climate change policy.

13.5.1 Impact module

We assume that the harm done from rising temperatures in a given year as a share of output is

$$D_t = \psi_1 T_t + \psi_2 T_t^2 + \psi_6 T_t^6 \quad (13.26)$$

where D_t is impact as a share of output in year t, T_t is global average temperature in ℃ above pre-industrial levels at time t and ψ_1, ψ_2 and ψ_6 are parameters that you should set to:

	Model 1			Model 2		
Region	Rich	Mid	Poor	Rich	Mid	Poor
ψ_1	5.88	3.57	1.96	0	0	0
ψ_2	-2.31	-1.70	-1.26	0.5563	0.2561	0.0655
ψ_6	0	0	0	-0.0113	-0.0106	-0.0101

You should pick up the temperature from the climate dynamics component you have built previously.

13.5.2 Growth module

To close the loop, you should modify the equation for net output in the growth model to not only subtract the costs of abatement from gross output, but also the damages from climate change that you just added to the model. You have to figure out the precise new equation for net output yourself. Have a look at how abatement costs were subtracted from gross output and try to do the same for the impacts of climate change.

The last addition to our model is two variables: consumption (in trillion dollars) and per capita consumption (in dollar per person). The equation for consumption is straightforward: whatever is left of gross output once the costs of abatement, the damages from climate change and investment in the capital stock are subtracted can be consumed and thus equals consumption. To compute per capita consumption you divide consumption by population. Be careful with the units, though!

And last, but not least, make sure that your emissions component is coupled to the economic growth component before you answer the policy questions.

13.5.3 Exercises

13.11. For Model 1, find out in which year the net change in per capita consumption from two different policies turns beneficial. The policies you should analyze are characterized by a constant reduction in emissions, i.e., the same percentage reduction in each year. The two policies you should analyze are a 5% and 10% emission reduction for each year and region. For each policy, compute how the per capita consumption in each year changes compared with the no-policy scenario. For each policy, find the first year in which per capita consumption is higher with policy compared with the no-policy case. Interpret the results.

13.12. Create a graph that plots the change in per capita consumption for both policies, one that plots abatement costs as percent of output and one that plots damages as percent of output. The horizontal axis should be years in all three figures. The vertical axes should be percentage change in per capita consumption for the first figure, and percent of output for the second and third figure. Each policy should be one line in each figure. Interpret the results.

13.13. *Repeat the first exercise but now with ψ_1, ψ_2 and ψ_6 according to Model 2. Interpret the difference in results between Models 1 and 2. Interpret the results.

13.6 Social cost of carbon

We can now use the model to compute the social cost of carbon (SCC). Recall that the social cost of carbon is the net present value of the impact caused by an extra emission of one tonne of carbon today. The social cost of carbon is the *marginal* cost of climate change. Taking derivatives is easy for a human, but integration is hard. For a computer, it is the other way around: Integration is easy, but derivation is hard. In this case, however, the first partial derivate of the impact of future climate change to current emissions is difficult, as the cause-effect chain includes three difference equations. We therefore need to teach the computer to take a derivative.

The general strategy for computing the SCC is as follows: you run your model twice. The first run (base run) is identical to the model set-up as you have been using it. In the second run there should be an additional emission of one million tonnes of carbon dioxide into the atmosphere in the year 2020. This second run (the marginal run) will therefore have slightly more warming, and that will cause slightly larger damages from climate change.

You then compute the difference in damages between the base and marginal run for each year in dollars. We call this *marginal damages*, i.e., this is the time series of additional damages caused by one additional tonne of carbon emitted today.

The next step is to compute the net present value of marginal damages. This is a simple step: you just multiply the marginal damages in each year with the discount factor for that year. This gives you a new time series of the net present value of marginal damages. You will do this for different discounting schemes that are described in more detail below. So in practice you will have a separate time series of discount factors for each of the schemes, and then a separate time series of net present values of marginal damages for each scheme.

The final step is to add up the net present value estimates of marginal damages over time for each of the discounting schemes. This will give you one number for each discounting scheme. That number is called the social cost of carbon.

13.6.1 Some practical advice

You should start by creating a copy of the sheets with your model in Excel, so that you have one sheet for the base run and one for the perturbed run. You then need to modify the sheet with the model for the perturbed run to have an additional tonne of carbon emitted in the year 2020. Careful with units there, you just want to add one million tonnes of carbon! It is easiest if you do this as close to the carbon cycle model as possible, i.e., do not try to modify your Kaya Identity or something even earlier to increase emissions. You should disregard the differential feedback on economic growth. Just keep growth as it is. This makes programming easier, and it avoids some potential problems in welfare analysis.

You then want to create a new third sheet where you compute marginal damages and do all the discounting and remaining other calculations.

Careful again with units: we want the SCC estimate to be in \$, not in trillion \$, so at some point you have to make sure you convert accordingly. Finally, the SCC can be expressed as \$/tC or as \$/tCO_2. The natural units of our model will give you a \$/tC estimate—recall that emissions are given in million tonnes of carbon—but virtually all SCC estimates in the literature are expressed as \$/tCO_2. You should first make sure you clearly label the units, and second make sure that you compute the SCC using both conventions, so that you can compare it, e.g., with the official US government numbers. The conversion factor is 12/44.[5]

13.6.2 Discount factors

In total you will use three (six for master's students) different discount factor time series, which will give you three (six) different estimates of the social cost of carbon. They are split into two groups: the first three are based on a constant discount rate, the last three (master's only) are based on the Ramsey rule.

Constant discount rate

For the constant discount rate, the equation for the discount factor is

$$\mathbb{D}(t)^c = \frac{1}{(1+r^c)^t} \tag{13.27}$$

[5]The atomic number of carbon is 6, so its atomic mass is $2 \times 6 = 12$. The atomic number of oxygen is 8, so the molecular mass of CO_2 is $12 + 2 \times 16 = 44$. The weight of carbon in carbon dioxide is thus 12/44.

where $\mathbb{D}(t)^c$ is the discount factor for region c for time step t. Careful, t here is not year, but the time step counted from the start of the model, so $t = 0$ corresponds to the year 2020, $t = 1$ to 2021 and so on. r^c is the discount rate. You should use the constant discount rate approach for three different discount rates: 2%, 3% and 5%. These three rates constitute the first three discount schemes.

Ramsey discount rate*

The Ramsey discount rate is a bit more complicated. Because the discount rate for each year depends on that year's per capita consumption growth rate we first need to compute the Ramsey rate for each year:

$$r_t^r = \rho + \eta g_t \tag{13.28}$$

r_t^r is the Ramsey discount rate for year t, ρ is the pure rate of time preference (PRTP), η is the rate of risk aversion, and g_t is per capita consumption growth from year $t-1$ to year t (so $g_t = \frac{c_t - c_{t-1}}{c_{t-1}}$, with c_t being world average per capita consumption in year t). Due to the definition of the Ramsey discount rate you cannot compute it for the first year, so you should compute it for the second and all following years.

The equation for the Ramsey discount factor is

$$DF_t^r = \prod_{s=0}^{t} \frac{1}{1 + r_s^r} \tag{13.29}$$

This is tricky to put into Excel right away. Instead, you can use a recursive formulation that is mathematically equivalent:

$$DF_t^r = \frac{1}{1 + r_s^t} \prod_{s=0}^{t-1} \frac{1}{1 + r_s^r} = \frac{DF_{t-1}^r}{1 + r_t^r} \tag{13.30}$$

This gives you the discount factor for all but the first year. The discount factor in the first year is one by definition: $DF_0^r = 1$.

You should compute three different discount schemes based on the Ramsey equation, one for each of three different values for the pure rate of time preference: 0.1%, 1% and 3%.

13.6.3 Exercises

13.14. Compute the social cost of carbon for the three alternative constant discount rates and Impact Model 1. Interpret the results.

13.15. *Repeat the exercise for the Ramsey discount rate. Interpret the difference.

13.16. *Repeat the exercise for Impact Model 2 for the constant discount rates. Interpret the results.

13.17. Does the social cost of carbon change if we implement carbon policy? The original set-up computed the social cost of carbon assuming no climate policy. We can also ask the question: if we already reduce emissions by 5% from 2020 onwards, how much additional damage is caused if we then reduce emissions by one extra tonne? Do this for the high discount rates and Model 1 only. Interpret the results.

13.18. How does the SCC change for different values of the climate sensitivity? The IPCC states the equilibrium warming for a doubling of CO_2 concentrations is likely in the range of 1.5 to 4.5℃ with a best estimate of 2.5℃. Note that in Section 13.1.2 we found a climate sensitivity of 4.26℃ by calibration. The equation we use to compute the equilibrium warming is:

$$\Delta T_t = \lambda_2 \times 5.35 \ln \underbrace{\frac{C_t}{C_{pre}}}_{\substack{\text{This is 2 for a} \\ \text{doubling of} \\ \text{concentrations}}} \tag{13.31}$$

We got the value for λ_2 (the climate sensitivity parameter in our model) by plugging in the numbers from IPCC and solving for λ_2:

$$2.5 = \lambda_2 \times 5.35 \ln 2 \Rightarrow \lambda_2 = 0.67 \tag{13.32}$$

You should solve this equation to compute the climate sensitivity parameter that gives a warming of 1.5℃ and a warming of 4.5℃ for a doubling of CO_2 concentrations, and then run your model with these alternative climate sensitivity parameters. How does the SCC change for these alternative climate sensitivities? Do this for the high constant discount rates and Impact Model 1 only. Interpret the results.

13.7 Development

We will add a slight twist to the damage function this week. Previously, we had assumed that a given temperature increase would always cause the same loss as a share of income, independently of the level of income. So whether we assumed a high income or a low income, a 3℃ warming would always cause the same loss as a percent of income. In other words, we assume that vulnerability to climate change is constant. At the same time, we assume that the poorer regions are more vulnerable. This is inconsistent.

You will therefore extend the damage function in Equation (13.26) to include an additional parameter, namely an income elasticity of impacts. We can specify a more nuanced relationship between economic impacts and income levels with this new parameter.

$$D_t = (\psi_1 T_t + \psi_2 T_t^2 + \psi_6 T_t^6) \left(\frac{y_t}{y_0}\right)^{\epsilon} \tag{13.33}$$

where $\epsilon = -0.25$ and $y_0 = y_{2020}$.

Make sure that you change both the base and the perturbed model.

Note that this change may cause a numerical problem. The impact of climate change affects economic growth. If the impact is too large, economic growth turns into economic shrink. With a negative impact elasticity, this makes the impact of climate change even larger and economic shrink turns into economic ruin. In fact, there is nothing in the model to prevent *negative* economic output. This would lead to a numerical error. There are two possible solutions to this, both involving Excel's "Max" function that we encountered before. You should either put a cap, say of 99%, on your maximum damage—or rather, place a bottom of -99% under your income. Or you should put a bottom under you income, say of \$1 per person per day. The maximum function puts a bottom under: "=Max(-99, D_t)" equals -99% if D_t equals -100%.

13.7.1 Exercises

13.19. Vary ϵ between -0.25, 0.00, and 0.25. Using Model 1 and constant discount rates, what are the implications for the social cost of carbon? Interpret the results.

13.20. Reconsider emission reduction of 5% in the richest region in 2020. Assume that the richest region does not reduce emissions but instead donates the money to the poorest region. What are the implications for emissions? What are the implications for the impact of climate change? Interpret the results.

13.21. *In the specification above, we assume that the impacts of climate change scale down output, or drive a wedge between gross and net output. This implies that the impacts of climate change reduce both consumption and investment. First, assume that all impacts fall on consumption. What are the implications for economic growth and emissions? Now let all impacts fall on investment. That is, keep consumption as it would have been without climate change, but reduce investment. What are the implications for economic growth and emissions? Interpret the results.

13.7.2 Adaptation policy*

Equation (13.33) gives the economic impact of climate change. It makes implicit assumptions about adaptation. Let us make the assumptions explicit. We define gross impact G as the impact without adaptation A, and residual impact as $G(1 + A)$. If G and A have the same sign, adaptation increases positive impacts and reduces negative impacts. Total impact is then residual impact minus adaptation costs. More specifically,

$$D_t = \psi_3 T_t (1 - Z_t) - \psi_4 Z_t^{\psi_5} \tag{13.34}$$

where Z is adaptation effort. The first term on the right-hand side is now gross impact, or impact before adaptation. Impact now equals residual impact, or impact after adaptation, plus adaptation costs. Note that we need to define ξ_1 such that adaptation costs are defined as a share of output.

The optimal level of adaptation follows from

$$\frac{\partial D_t}{\partial Z_t} = -\psi_3 T_t - \psi_4 \psi_5 Z_t^{\psi_5 - 1} = 0 \Rightarrow Z_t = \left(\frac{-\psi_3 T_t}{\psi_4 \psi_4} \right)^{\frac{1}{\psi_5 - 1}} \tag{13.35}$$

Because gross impact can be positive as well as negative, ψ_5 has to be a natural number. Because gross impact and adaptation need to have the same sign, ψ_5 has to be an even number. So $\psi_5 = 2$. The other parameters are:

	rich	middle	poor
ψ_3	-5.46	-5.05	-4.43
ψ_4	59.5	36.4	32.0

13.7.3 Exercises*

13.22. Compute the social cost of carbon with explicit adaptation. Do this for the three constant discount rates. Compare the results with those for Model 1. Interpret the results.

13.23. Assume that there is an international adaptation fund: Transfer $100 billion dollars from the rich region to the poor region. How does this affect adaptation decisions in the poor region? Interpret the results.

13.8 Optimal climate policy

For this assignment, you compute the optimal climate policy trajectory over time. There are three steps that you need to finish in order to do so: (1) you need to add a welfare function to the model, (2) you need to set things up so that you can use a numerical optimization package that is part of Excel, and (3) you need to run this numerical optimization package to find the optimal policies for a variety of different assumptions.

13.8.1 Welfare component

The first step is to add a component that computes the overall social welfare for a given policy. This will be one number, and the policy that gives us the highest number for this metric is the one we will label "optimal". The welfare function of region r you should add as a component has the following equation:

$$W_{r,t_0} = \sum_{t=t_0}^{T} \frac{P_{r,t} U_{r,t}}{(1+\rho)^t} = \sum_{t=t_0}^{T} \frac{P_{r,t} \ln c_{r,t}}{(1+\rho)^t} \tag{13.36}$$

P_t is the population size at time t and c_t is per capita consumption at time t. Both are variables you are computing in other parts of the model already; ρ is the pure rate of time preference or the utility discount rate, and you should set the component up in a way that you can easily change its value. T is the time horizon of your model, and t_0 is the base year.

Global welfare is defined as

$$SWF_{t_0} = \sum_r W_{r,t_0} \tag{13.37}$$

This is what we want to maximise.

13.8.2 Preparing the model

The way our model is set up at this point allows us to set a different mitigation level (emission control rate) for each year of our analysis. This amounts to $3 \times (2300 - 2020) = 763$ decision variables, and the numerical optimization package we intend to use therefore needs to find the best value for each of these decision variables. This would not be a problem for state-of-the-art optimization packages, but it is a problem for Excel. The next step therefore is to transform our problem with 855 decision variables into one that has only 9 decision variables.

We will do this by creating nine new decision variables: for 2020–2029, 2030–2039, and 2040–2300, per region. Put these in a little matrix somewhere, and let the columns that contain relative emission reduction refer to this matrix.

The next step is to enable the numerical optimization package in Excel. The name of it is "Solver" and it is switched off by default (so that the programme starts slightly faster). Here is how you can enable it in Excel:

- Click on File → Options → Add-Ins
- Make sure "Excel Add-ins" is selected in the "Manage" field
- Click "Go"
- Select "Solver Add-in"
- Click "Ok"

This adds an item "Solver" under Data → Analysis in the main Excel window, and you can start Solver by clicking on that new item.

The next step is to tell Solver what cell it should try to maximize, and which cells it can modify in order to find the best combination of values for the decision variables. To do so, start Solver, and then select the cell with the value for your social welfare function for the "Set Objective" field. Make sure you have selected the option to maximize that cell (and not minimize it or find a specific value). Next, you need to select the range of your nine new decision variables for the field "By changing variable cells". At this point Solver knows that it should try different values for these nine cells, and try to find the combination of values that gives the highest value for the cell that you selected as the objective (in our case gives the highest social welfare).

Before we can run Solver, we need to tell it one more thing: what is the range of values that makes sense for our decision variables. In our case the decision variables are emission control rates that can take values from 0 to 1 (i.e., 0% to 100%). So we do not want Solver to try any values that are outside that range. We can configure that by setting up constraints in Solver. You will have to add two separate constraints, one that says the decision variable always has to be greater than or equal to 0, and one that says it always has to be smaller than or equal to 1. You can add a constraint by clicking the "Add" button. For the cell reference you then select the same cells that you already picked as the decision variables, then you need to select the correct condition (i.e., >= for the first and <= for the second constraint) and finally in the field constraint you simply add either 0 for the first and 1 for the second constraint. When you are done, you should have both constraints listed in the main window of Solver in the field "Subject to the Constraints".

Note that you may also try without constraints and see whether they are violated.

13.8.3 Exercises

13.24. Find the optimal policy for impact model 1. What are the implications for concentrations, temperature and per capita consumption? Interpret the results.

13.25. *Do the same for impact model 2. Interpret the difference.

13.8.4 Equity*

You can now add equity weights to the model. Equity weights do not affect the inner workings of the model. They reinterpret the results. However, as the optimal carbon tax is affected, equity weights do affect the outcomes.

With equity weights, the welfare function is defined as

$$GWF_{t_0} = \sum_{r=1}^{R} \left(\frac{\bar{y}_{t_0}}{y_{r,t_0}} \right)^{\eta} SWF_{r,t_0} \tag{13.38}$$

That is, equity weights are the ratio of global average per capita income to regional average per capita income, raised to the rate of risk aversion. Note that we first discount future impacts to today before we apply the equity weights.

13.8.5 Exercises*

13.26. Find the optimal policy for impact model 1 and with equity weights for $\eta = 0.0$, $\eta = 1.0$, and $\eta = 2.0$ and for $\rho = 3$. Interpret the result.

13.27. Change the pure rate of time preference from 3% per year to 4%, 2%, 1% and to 0.1% and re-compute the optimal emission reduction policy for $\eta = 0.0$. Interpret the result.

13.28. *Repeat the exercise for all combinations of ρ and η. Interpret the result.

13.29. *Repeat the exercise for impact model 2. Interpret the result.

13.9 Uncertainty

13.9.1 Exercise

13.30. Optimize the emissions control rate for climate sensitivities 1.5, 3.0 and 4.5℃/2×CO_2. Hint: Climate sensitivity is *proportional* to λ_2 in Equation (13.4). We previously changed the climate sensitivity in Exercise 13.18. Interpret the results.

13.9.2 Parametric uncertainty

Modelling uncertainty is not that difficult but the two-dimensional representation of the model in Excel gets in the way. So far, we have worked in two dimensions: Different years were found in different rows, and different variables in different columns. We now need a third dimension: State of the world. So far, we had one state of the world. We assumed that variables and parameters were perfectly known and therefore could be represented by a single number. We now introduce three states of the world for one parameter: The climate sensitivity. Previously, this was 4.26℃/2×CO_2. Here, it has three alternative values:

- 1.5℃/2×CO_2 with a 15% probability;
- 3.0℃/2×CO_2 with a 70% probability; and
- 4.5℃/2×CO_2 with a 15% probability.

This means that you need to split the column that contains the atmospheric temperature variable into three: one low temperature, one middle, and one high. This also means that you need to split every variable that depends on the temperature, directly or indirectly, into three. Because we have built an integrated assessment model in which everything depends on everything, the entire model needs to be split. For instance, emissions depend on economic output, and economic output depends on climate change.

So, it is best to create three separate sheets, each containing the same model, but one with a low climate sensitivity, one with a middle climate sensitivity, and one with a high climate sensitivity.

You now understand why we have only three states of the world, with three alternative values for one parameter. We could have had seven or seven hundred alternative values for the climate sensitivity, but then we would have needed seven (hundred) sheets. We could have had two uncertain parameters (in fact, every parameter in the model is uncertain), but then we would have needed 3×3=9 sheets (if both parameters can assume only three alternative values). Other programming environments than Excel have data structures that are more amenable to uncertainty analysis.

We have created three separate sheets with three alternative versions of the model. There are two components, however, that are common: emission reduction and expected weflare. Optimal emission reduction follows from maximizing the expected value of the net present value of welfare. Expected net present welfare equals 0.15 times net present welfare in the low model, plus 0.70 times net present welfare in the middle model, plus 0.15 times net present welfare in the high model. Compute expected net present welfare in the middle sheet. Set the emission control rates in the low and high model variants equal to the control rate in the middle variant.

13.9.3 Exercise

13.31. Compute the expectation of the optimal emission reduction rates in Exercise 13.30., using probabilities 0.15/0.70/0.15.

13.32. Optimize the emissions control rate under uncertainty. Compare the results with the emissions control rate under certainty. Interpret the results.

13.33. *Repeat Exercise 13.32. with climate sensitivities of 1.5, 2.5 and 4.5℃/2×CO_2. Interpret the differences.

13.34. *Repeat Exercise 13.32. with climate sensitivities of 1.5, 3.0 and 4.5℃/2×CO_2 probabilities 0.05/0.70/0.25 and with 0.25/0.75/0.05. Interpret the differences.

13.9.4 Learning*

Let us now assume that the truth about the climate sensitivity will be revealed in 2030. This will not happen, but this assumption teaches us something about the impact of learning on optimal emission reduction. We do not know what truth will be revealed, but we do know that it will be.

This changes the way we set up the optimization. First, copy the existing spreadsheet to a new one. From 2030 onwards, we have three separate optimizations. The emissions control in the low model is set by maximizing the net present value (in 2030) of welfare in low model. Ditto for the middle and high models.

For the period 2020–2029, the emissions control rate is set by maximizing the expected net present value over the entire period. Thus decisions on the emission control rate in 2020–2029 depend on decisions about the control rate in 2030–2300. Vice versa, emission control in 2030–2300 depends on emission control in 2020–2029. Emissions and atmospheric concentration of carbon dioxide in 2030 obviously matter, but the temperature has inertia too.

One way to solve this is by iteration. Take the control rate without learning as the starting point. Optimize 2030–2300 assuming that 2020–2029 as is without learning. Optimize 2020–2029. Reoptimize 2030–2300. Reoptimize 2020–2029. And so on until nothing much changes.

Alternatively, because emission control in one state of the world does not directly affect emission control in another state of the world, we can just maximize a weighted sum of welfare in alternative states of the world. In the same optimization, we can include 2020–2029. There are now four control variables per region: 2020–2029, and low / mid / high for 2030–2300.

13.9.5 Exercise*

13.35. *Optimize the emissions control rate under uncertainty and learning. Compare the results with the emissions control rate under certainty, and under uncertainty. Interpret the results.

13.9.6 Monte Carlo analysis**

Overview

You will modify your model so that we can analyze what effect uncertainty about the climate sensitivity will have on your estimate of the social cost of carbon (SCC). You will run a so-called *Monte Carlo* simulation to do so: instead of computing the SCC for only one value of the climate sensitivity, you will run your model for many hundred different values of the climate sensitivity. The values you will use for those runs for the climate sensitivity are sampled from a probability distribution that characterizes our uncertainty about the true value for the climate sensitivity. For each of these runs you will get a different SCC estimate. To summarize all these results you will compute the expected (or average) SCC over all runs, and also create a histogram that visually shows the uncertainty about the SCC.

One way to do this exercise is to take your Excel sheet, update the number for the climate sensitivity, make a note of the corresponding SCC, and repeat this step manually a couple of hundred times. Clearly this is not a very practical approach. Instead, we will write a little Visual Basic macro that automates this procedure for us.

Preparation

You should start with the version of your global model that includes the SCC calculation. Next, make sure you reset any parameters to their default values in case they are still set to values from some sensitivity analysis. Finally, you should set up the sheet for the marginal run in such a way that it picks up the climate sensitivity value from the base run model, i.e., just reference the cell with the climate sensitivity in the base model sheet from the cell for the climate sensitivity in the marginal run sheet. This will make things easier later on because you only have to update on place with a new climate sensitivity, but can be sure that both the base and marginal model use the same value at all times. If you use Excel on Windows, you need to enable the DEVELOPER tab on the Excel ribbon by going to File→Options→Customize Ribbon and then selecting Developer.

Setting up the random variable

Next create a new sheet "Monte Carlo" in your main Excel file with the model. In column B, create 1000 random numbers between 0 and 1 using the Excel command "rand()". Label this column "rnd". The values are sampled from a uniform distribution, i.e., every number between 0 and 1 was equally likely to be sampled in this procedure.

But for our climate sensitivity parameter we actually want to use a different probability distribution: we know that certain values are much more likely than others, and so we want to use a distribution that reflects that. In particular, we are going to use a gamma distribution to characterize the uncertainty about the climate sensitivity. The particular parameterization we are using is a gamma distribution with shape parameter 6.48 and scale parameter 0.55.

As a next step we need to convert our sample from a uniform distribution into a sample from this gamma distribution. To do this, we can use the so-called inverse cumulative distribution function for the gamma distribution. Add a new column to the Monte Carlo sheet that is called "rnd (gamma)". This column will have a sample from the gamma distribution. The formula you should use for the first data row in this column is "=GAMMA.INV(B2, 6.48, 0.55)". You should use the same formula for each row, i.e., for each sample from the uniform distribution, but each time picking up the sample value from the uniform distribution as the first argument of the GAMMA.INV function.

You now have a sample of equilibrium climate sensitivity values from a gamma distribution (where the climate sensitivity is interpreted as the warming we would get in equilibrium for a doubling of CO_2 concentrations). We are almost ready to run our full model once for each of these values. But first we need to make one more conversion: our model is actually parameterized in terms of the narrow definition of climate sensitivity that you multiply by radiative forcing, so we next need to convert our sample from warming in ℃ you will get for a doubling of CO_2 concentrations into our definition of climate sensitivity. You did this step once before already. You should add another column to the Monte Carlo sheet that does this conversion for each row, i.e., for each run.

At this point your Monte Carlo sheet should have four columns, where the last three columns are (a) random numbers from a uniform distribution, (b) random numbers from a gamma distribution for the colloquial definition of climate sensitivity and (c) random numbers for the definition of the climate sensitivity that we use in our model.

Coding the Monte Carlo loop

Next, you will add a macro that runs the model once for each of the random values for the climate sensitivity and records the corresponding SCC value.

Windows Click on Macros on the DEVELOPER ribbon tab.

Mac Click on Tools and then Macros→Macros

As the macro name type in "RunMonteCarlo", and then click on "Create" to create the new macro. This will create an empty macro called RunMonteCarlo and will look like this in the macro editor:

```
Sub RunMonteCarlo()

End Sub
```

You should replace this empty macro with the following template for a macro that runs the model many times:

```
Sub RunMonteCarlo()
For i = 1 To 1000
Sheets(''Base model'').Range(''E35'').Value = Sheets(''Monte Carlo'').Cells(1+i,4).Value
Sheets(''Monte Carlo'').Cells(1+i,5).Value = Sheets(''MD'').Range(''B51'').Value
Next

End Sub
```

You need to adjust this macro slightly so that it works with the specific layout of your Excel sheet. In particular, you need to adjust the text with a green background to reference the cell in your model that has the climate sensitivity parameter. The code will replace the value in that cell for each of the 1000 runs with a value from the sample for the climate sensitivity. You also need to replace the reference with the blue background to the cell in your model that has the SCC value for a 3% constant discount rate. This line of the code copies that value back onto the Monte Carlo sheet. Once you have coded your macro, you can run your macro. This might take a while if you have an older computer. When the macro finishes, you should have a fifth column on your Monte Carlo sheet that is the SCC at a 3% constant discount rate for the climate sensitivity value in column 4 of the same row. You just finished a complete Monte Carlo simulation with a 1000 runs!

Summarizing your results

You should summarize the 1000 different SCC values you just compute in a couple of different ways. First, you should compute the average, minimum and maximum value of the SCC in your sample by using the appropriate Excel functions to do so.

Second, you should create a histogram of the distribution of values, using 50 bins. If you have never made a histogram in Excel, you should follow the instructions on how to do this from this YouTube video: https://www.youtube.com/watch?v=asEuFvWGJDs.

13.10 Non-cooperative climate policy

Let us now return to the deterministic model of Section 13.8. There, we maximized the net present welfare of the world as a whole, which was equal to the sum of the net present welfare of the three regions. Each region had its own emission control rate, because the first order conditions have that the marginal abatements costs are equalized rather than the control rate. This assumes either a global social planner or cooperation between regions to maximize joint welfare. This provides a yardstick—you cannot do better than a philosopher-queen—but it is not realistic. We therefore let the three regions maximize their own welfare.

You have encountered game theory before. Chapter 12 applies it to climate policy. A key difference between social planning and game theory is that we have multiple optimizations in the latter. This is no problem if we solve things analytically. Both joint and individual maximization lead to a system of first-order conditions. However, we previously found the social optimum not by its first-order conditions, but by numerical optimization. But a computer can optimize only one thing at a time. The exercise below will teach you how to trick a computer to solve a set of individual optimizations for interacting agents.

13.10.1 Exercises

13.36. Optimize the emissions control rate separately for each of the three regions by maximizing net present regional welfare. Do this iteratively. In the first iteration, assume that the other regions do not reduce their emissions. In later iterations, assume that other regions reduce their emissions as in the previous iteration. Repeat until convergence. Compare the results of this non-cooperative solution with the cooperative solution above (under certainty). Interpret the results.

13.37. *Compare the welfare levels of the three regions with and without cooperation. Can the winner of cooperation compensate the losers if welfare can be transferred? What if welfare is not transferable but money is? Hint: A welfare change times the inverse of marginal welfare is the willingness to pay or willingness to accept compensation in dollar terms. Interpret the results.

Chapter 14

How to solve the climate problem?

Thread

- Putting more greenhouse gases in the atmosphere will change the climate but it is uncertain how and how much. #climateeconomics
- Climate change has positive and negative impacts. Net effect is negative but small compared with economic growth. #climateeconomics
- A gradually rising carbon tax reduces emissions at minimum cost. Cost would be small for reasonable target. #climateeconomics
- Climate alarmism meets the religious demand for eternal doom, sinful emissions, and atonement. #climateeconomics
- Climate policy allows politicians to promise the world, postpone major action, and blame Johnny Foreigner. #climateeconomics
- Climate policy lets bureaucrats build new bureaucracies. It feeds fears of right-wing conspiracy theorists. #climateeconomics
- Greenhouse gas emission reduction is a global public good. It is better if someone else does it. #climateeconomics
- There is a clear and sustained public demand for climate policy, even if it means more expensive energy. #climateeconomics
- Abatement is easier if in step with trade partners. UNFCCC data standards plus pledge and review are enough. #climateeconomics
- Abatement is easier if it can be bought wherever it is cheapest. Kyoto Protocol allows for this. #climateeconomics
- There is not enough conventional oil and gas to cause substantial climate change. Alternatives might. #climateeconomics
- Climate policy should ride with, rather than against, the ongoing revolution in energy supply. #climateeconomics

14.1 The problem

Greenhouse gases are transparent to visible light but not to infrared radiation. Energy from the sun thus easily enters the planet. Energy re-emitted by Earth finds it more difficult to leave: It is absorbed by greenhouse molecules in the atmosphere, and scattered in any direction—including back to the surface. This is the natural greenhouse effect. See Figure 1.3. Planet Earth is warmer than it would have been without greenhouse gases in the atmosphere. If greenhouse gas concentrations increase, then you would expect from first principles that the planet would become hotter.

The concentrations of three of the main greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), have increased steadily since the start of the Second Industrial Revolution (1750 say). The increase is dramatic if we consider that greenhouse gas concentrations had been more or less stable since the last Ice Age and the Agricultural Revolution. See Figure 1.1. The increase in concentrations is no surprise as greenhouse gas emissions are associated with fossil fuel combustion and deforestation (CO_2), with population growth and affluence (via meat and rice production and waste generation CH_4), and with artificial fertilizers (N_2O).

> Putting more greenhouse gases in the atmosphere will change the climate but it is uncertain how and how much.

Over the course of the 20th century, a rise in temperature has been observed, as well as a decrease in snow cover, and a rise in sea level (due to thermal expansion as water warms). See Figure 1.2. The impact of the enhanced greenhouse effect on the climate does not follow from first principles alone. The climate is a complex system. Any initial change sets in motion a cascade of feedback effects, some positive and some negative. The most powerful feedbacks relate to water. A warmer atmosphere contains more water vapour, and water vapour is a powerful greenhouse gas. Cloud formation would be affected. Clouds can either cool—e.g., on a summer day—or heat—e.g., in a winter night. Ice is white and reflects sunlight. Water is dark and absorbs lights. Climate is also affected by a range of other things, some natural—variations in solar radiation, volcanoes, ocean dynamics—and some human—aerosols, land use change, nutrients.

State-of-the-art climate models include these feedbacks and many more. These models project that the warming observed in the 20th century will continue during the 21st century and beyond. Models differ on the detail, though, and the range of future projections is enlarged because emission projections are highly uncertain too. See Figure 1.7. Besides warming, climate change would also entail changes in wind and precipitation patterns.

14.2 Costs and benefits of climate policy

Some people argue that climate change is bad, as all change is for the worse. This is an odd position. Universal education for girls would be a radical departure from the past, but is generally welcomed. Ditto for women's rights, discrimination on sexual orientation or ethnicity, and democracy. Research has shown that climate change would bring both positive and negative impacts. Positive impacts include a reduced demand for energy for winter heating, fewer cold-related deaths, and CO_2 fertilization which makes crops grow faster and reduce their demand for water. Negative impacts include sea level rise, the spread of tropical diseases, and increases in storm intensity, droughts, and floods.

> Climate change has positive and negative impacts. Net effect is negative but small compared with economic growth.

Adding up all these impacts after having expressed them in welfare equivalents, the impact of initial climate change is probably slightly positive. This is irrelevant for policy, because initial climate change cannot be avoided. More pronounced climate change would have net negative effects, and these impacts would accelerate with further warming. Even so, the impacts would be moderate: The welfare impact of a century of climate change is comparable with the welfare impact of a year of economic growth. Uncertainties are large, though, but even the most pessimistic estimates show that a century of climate change is comparable with a decade of growth. See Figure 6.2.

Greenhouse gas emissions can be reduced in a number of ways. More efficient energy use and a switch to alternative energy sources are the two main options. This is best stimulated by a carbon tax. Incentive-based policy instruments are better suited for reducing emissions from diffuse and heterogeneous sources than rule-based instruments. Taxes are more appropriate for stock pollutants than tradable permits. A carbon tax, a uniform carbon tax and nothing but a carbon tax is therefore the cheapest way to reduce greenhouse gas emissions.

> A gradually rising carbon tax reduces emissions at minimum cost. Cost would be small for reasonable target.

Net present abatement costs are lowest if all emissions from all sectors and all countries are taxed equally and if the carbon tax rises with the interest rate. Higher carbon taxes would lead to deeper emission cuts. Only a modest carbon tax is needed to keep atmospheric concentrations below a high target but the required tax rapidly increases with the stringency of the target. If concentrations are to be kept below 450 ppm CO_2eq, the global carbon tax should reach some \$700/tC in 2015 or so—ten times the recent price of permits in the Emissions Trading System which covers about half of emissions in Europe. Such a carbon tax would roughly double the price of energy in Europe. A 450 ppm CO_2eq concentration would give a 50/50 chance of meeting the declared goal of the European Union and the United Nations to keep global warming below 2°C. However, less ambitious targets would require far lower carbon taxes, and would hardly affect economic growth.

The above discussion about the impacts of climate change suggests that a modest carbon tax can be justified, but that more ambitious goals may be hard to defend.

14.3 Complications

I argue above that climate change is a relatively small problem that can easily be solved. A casual observer of climate policy and the media would have a different impression. Seven things stand in the way of a simple solution.

> Climate alarmism meets the religious demand for eternal doom, sinful emissions, and atonement.

First, there is a demand for an explanation of the world in terms of Sin and a Final Reckoning This is often referred to as Millenarianism. Although many Europeans are nominally secular, fewer are in practice. The story of climate change is often a religious one: emissions (sin) lead to climate change (eternal doom); we must reduce our emissions (atone for our sins). This sentiment is widespread. Religiosity may be hardwired into the human brain. Clever marketeers cast new messages in old and familiar stories.[1] This has led to an environmental movement (a priesthood) that thrives on preaching climate alarmism, often separated from its factual basis.

[1] The old stories are the best, or rather, good stories grow old.

In order to maximize their membership and income, environmental NGOs meet the demand for scaremongering and—as the environmental movement also offers an identity and a tribe to belong to, another deep human desire—moral superiority.

Extinction Rebellion is a good example. It is a movement that rebels against the climate-change-induced extinction of humankind. That would be a worthy goal if there were anything in the scientific record to suggest that climate change could cause human extinction. There is not. Climate change may well cause many species to go extinct, but *Homo sapiens* is not at risk. Climate activists refer to 1.5°C warming as dangerous. The world is likely to hit that temperature sometime in the 2020s. It will be interesting to watch the response of those who predicted the end of the world.

Such extremism is dangerous. Climate anxiety is become more widespread. Some young people seem to genuinely believe they will die of climate change. The first suicide was attributed to climate despair in April 2022. Some hailed the victim as a martyr.

> Climate policy allows politicians to promise the world, postpone major action, and blame Johnny Foreigner.

Second, climate policy is perfect for politicians. Climate change is a problem that spans centuries. Substantial emission reduction requires decades and global cooperation. A politician can thus make grand promises about saving the world—the ultimate legacy—while shifting the burden of actually doing something (and hurting constituents) to her successor and blaming some foreigner for current inaction. Over the years, many targets for greenhouse gas emission reduction have been set, typically to be met two or three elections in the future. As the target year approached, promises were quietly forgotten and replaced by bigger promises, to be met after the current president or prime minister will have left office.

> Climate policy lets bureaucrats build new bureaucracies. It feeds fears of right-wing conspiracy theorists.

Third, climate policy allows bureaucrats to create new bureaucracies. Climate policy has been a political priority for about three decades. Emissions have hardly budged, but a vast number of civil servants and larger numbers of consultants and do-gooders have occupied themselves with creating a bureaucratic fiction that something is happening. This is not needed. The best policy is a carbon tax, a uniform carbon tax, and nothing but a carbon tax. This would require only a small team of civil servants. Actual climate policy is much, much more complex than the textbook recommendation and employs a great many people.

I am not aware of any estimates of the size of this bureaucracy. However, the costs of international climate negotiations, see Box 12.3, have been estimated, and are shown in Figure 14.1. The international negotiations started with a few meetings per year. The first full negotiations, in Berlin in 1995, involved fewer than 800 people. The three most recent conferences attracted 30,000 people or more. There used to be one round of negotiations per year, but there are now four rounds each year, plus committee meetings and dialogue sessions, and training for newcomers in climatespeak. There is now more than one meeting per week. Annual costs, for travel and subsistence and salaries for attendence, are well over $150 million per year. The UNFCCC called on countries to negotiate international climate policy—and negotiated they have.

Fourth, besides expanded bureaucracies, climate policy can be used to create rents in the form of subsidies, grandparented emission permits, mandated markets and tax breaks. A uniform carbon tax treats every emission in the same way and therefore offers no possibilities for special treatment of this class of voters or that group of companies. Climate policy thus serves

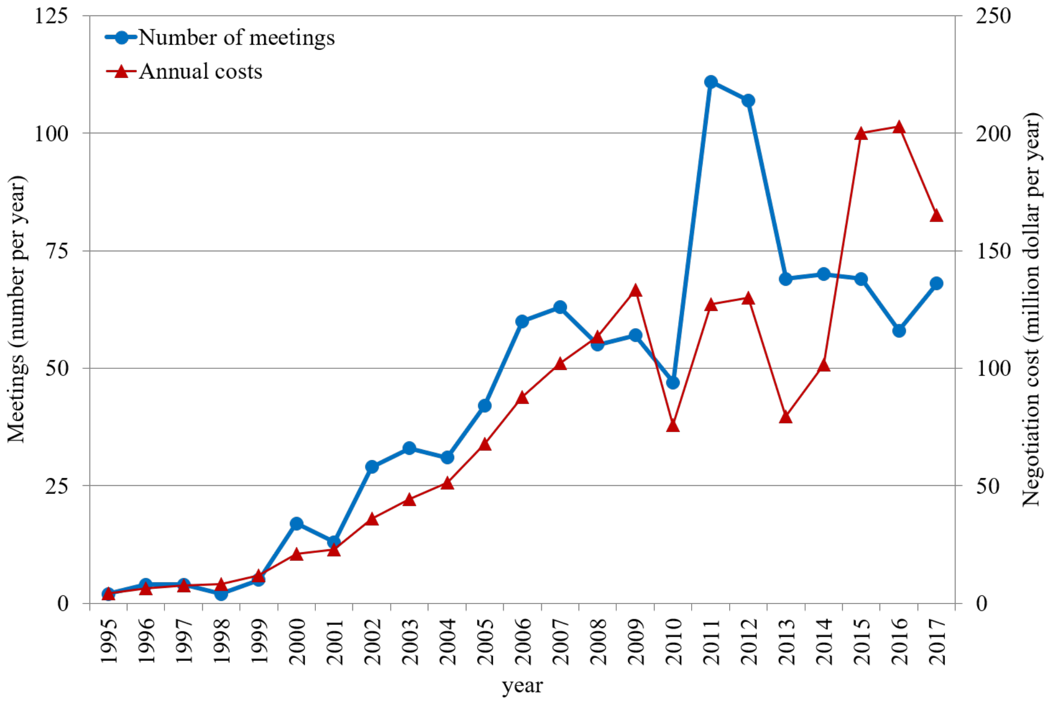


Figure 14.1: The number of meetings organized under the United Nations Framework Convention on Climate Change and its annual cost

the interests of rent seekers, as well as the interests of policy makers who use rent creation to reward allies and lure voters. Just like the bureaucrats above, their incentive is to complicate climate policy.

Fifth, climate policy requires government intervention at the global scale. The prospect of a world government antagonizes many, and feeds the fears of right-wing conspiracy theorists. Ditto for the expansion of domestic government power over the activities that emit greenhouse gases: energy use, transport, and agriculture. This had led to a movement that attacks climate policy at any opportunity, and extends those attacks to the climate science that underpins that policy, and the scientists who conduct the research. Alarmists have retaliated in kind. The result is polarization, which hampers reasoned discussion on climate policy.

> Greenhouse gas emission reduction is a global public good. It is better if someone else does it.

Sixth, greenhouse gas emission reduction is a global public good. The costs of emission abatement are borne by the country that reduces the emissions. The benefits of emission reduction are shared by all of humankind. It is thus individually rational to do very little, and hope that others will do a lot. As every country reasons the same way, nothing much happens. There is no solution to this short of installing a world government.

Seventh, global climate policy has been used as a tactical argument by those who desire a world government for other reasons. Because climate change is such a prominent issue, champions of other worthy causes too have joined the bandwagon. Climate change is now an issue of human rights, of feminism, of racism, of anti-capitalism, and so on and so forth. This antogonizes more people and further polarizes the climate debate. Furthermore, the ultimate goal of climate policy—decarbonization of the economy—is obscured as climate policy now serves many masters and is supposed to solve many problems.

Box 14.1: Employment

It is sometimes argued that switching to renewable energy would create jobs. Obviously, there is job displacement as renewables expand at the expense of fossil fuels. As the former are more labour-intensive than the latter, there would be net job creation, *all else equal.* Throughout history, productivity has increased, and wages with it, as capital and energy were used to complement labour. Needing more workers for the same output of energy—the very definition of an increase in the labour-intensity of energy supply—is thus a sign of *regress* rather than *progress.*

Baumol's Cost Disease, a rise in wages without a concomitant rise in labour productivity, affects renewable energy, particularly the installation, repair and removal of small-scale, decentralized power generation. In the standard model, wage equal marginal productivity. But in the competitive labour market, wage also equals the wage in the next-best job. If photovoltaic panels are installed in a random order, installers spend a lot of their time driving around. In physical terms, their productivity is low. But they do need to be paid a wage that reflects their skills and education. So they charge a high price. The same is true at the macro-scale. If more workers are needed to generate and transmit the same amount of electricity, and if they will not accept a lower wage, then the price of electricity has to go up.

But *all else is not equal.* Only a small fraction of the labour force is employed in the energy sector. Changes in the labour-intensity of the energy sector therefore cannot have a substantial impact on overall employment. However, energy is used throughout the economy. More expensive energy has only a small, negative effect on employment in sectors other than energy, but this small proportional effect can, in absolute terms, outweigh the impact in the energy sector as it applies to so many more workers—unless the revenue of a carbon tax or permit auctions is used to stimulate the economy or reduce the cost of labour.

Box 14.2: Grand plans

Some have called for a Manhatten Project, an Apollo Programme or a Marshall Plan for climate change. The Manhatten Project developed new weapons of mass destruction. The Apollo Programme restored technological supremacy over an adversary; some say it create a white elephant so big it reached into outer space. The Marshall Plan helped to recover from devastation and decentralized the economy. There is a call for a non-proliferation treaty for fossil fuels, centuries after fossil fuels have proliferated to every country in the world. The Treaty on the Non-Proliferation of Nuclear Weapons did not succeed in restricting nuclear weapons to the five recognized nuclear powers.

The misnomers aside, calls for a major public investment programme are misguided. This is the wrong approach. The government should levy a carbon tax to incentivize private investment, and improve regulations to attract investment in natural monopolies such as transport networks and power grids. Greenhouse gas emission reduction does not require an expansion of the public sector.

Full decarbonization of the economy will take a long time. The costs of doing so depend on technological change. If the costs of renewable energy will continue to fall rapidly, relative to the costs of fossil fuels, then emission reduction policies will be cheap—and may even become redundant as renewables outcompete fossil fuels on merit. This is generally accepted. But there is some confusion about the nature of this technological progress, and the role of public policy. Technological progress comes in three stages: invention (a new blueprint), innovation (taking the blueprint to its first sell), and diffusion (taking a product from its first sell to market saturation). The public sector is best placed to provide invention and the pre-competitive parts of innovation, but the private sector is better at competitive innovation and diffusion (with the government retreating to guaranteeing property rights and correcting externalities). The bulk of the desired decarbonization of the economy can be done with proven technologies, so the government should take a back seat in directly stimulating technological progress.

14.4 The solution

> There is a clear and sustained public demand for climate policy, even if it means more expensive energy.

Any solution to the climate problem should start with acknowledging that we live in a world of many countries, the majority of which jealously guards their sovereignty. That means that climate policy should serve a domestic constituency. Opinion polls in democratic countries have consistently shown over a period of 30 years that a majority is in favour of greenhouse gas emission reduction, even if that means more expensive energy.

> Abatement is easier if in step with trade partners. UNFCCC data standards plus pledge and review are enough.

Unilateral climate policy is expensive, however. If a country raises its price of energy, but its trading partners do not, business will shift abroad. A country will be more ambitious if it is confident that its neighbours will adopt roughly the same climate policy. The United Nations Framework Convention on Climate Change (UNFCCC) foresees an annual meeting at which countries can indeed pledge their near-term abatement plans and review other countries' progress against previous pledges. This is facilitated by internationally agreed standards on emissions monitoring and reporting. As the actions of trading partners matter most, regional trade organizations, such as the EU, NAFTA, MERCUSOR and ASEAN, should play a bigger role in this process.

> Abatement is easier if it can be bought wherever it is cheapest. Kyoto Protocol allows for this.

The costs of emission reduction vary greatly. It therefore makes sense if countries were allowed to reduce emissions by investing in abatement in other countries. The Kyoto Protocol of the UNFCCC establishes exactly this. Unlike the emissions targets of the Kyoto Protocol, its flexibility mechanisms do not expire. The Paris Agreement further strengthened reporting standards.

Therefore, three of the crucial ingredients to a successful climate policy are already in place.

> There is not enough conventional oil and gas to cause substantial climate change. Alternatives might. Climate policy should ride with, rather than against, the ongoing revolution in energy supply.

Carbon dioxide is the main anthropogenic greenhouse gas. Fossil fuel combustion is the main source of carbon dioxide emissions. The world would not warm by much if we burn all reserves of conventional oil and gas, the mainstays of the current energy system. Substantial warming requires that we burn considerable amounts of unconventional oil and gas, or use more coal, also in unconventional ways.

Fossil fuel reserves are finite, and the end of conventional oil and gas is in sight. See Figure 2.4. The future energy sector will look radically different from today. The revolution in energy has already begun in the form of tar and shale. Instead of riding the waves of the ongoing revolution, climate policy has focused on creating another energy revolution, hitherto without success. Instead, climate policy should seek to harness the forces of creative destruction that are sweeping the energy sector.

Further reading

There are many books on climate policy. Good ones include Dieter Helm's *The Carbon Crunch: How We're Getting Climate Change Wrong and How To Fix It* (2012), Nigel Lawson's *An Appeal to Reason: A Cool Look at Global Warming* (2008), William Nordhaus's *The Climate Casino* (2013), and Roger Pielke's *The Climate Fix* (2010). Nick Stern's *Review of the Economics of Climate Change* (2007) is popular but not that good. Naomi Klein's *This Changes Everything* (2014), David Wallace-Wells *The Uninhabitable Earth* (2019) and Patricia MacCormack's *The Ahuman Manifesto* (2020) are good examples of what Amitav Ghosh has called *The Great Derangement* (2016).

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

$$\max_{C_0, C_1, \ldots} \sum_t U(C_t)(1+\rho)^{-t} \text{ s.t. } \Delta K_t = -\delta K_t + (Y(K_t) - C_t) \tag{A.1}$$

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 Y the production function.

In order to solve this, form the Lagrangian:

$$\mathcal{L} = \sum_t U(C_t)(1+\rho)^{-t} - \lambda_t \left(-\delta K_t + Y(K_t) - C_t - \Delta K_t\right) \tag{A.2}$$

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.

These first-order conditions are not particularly informative. We do 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—at the margin, the value of consumption equals the value of investment—but we discern nothing about the evolution of the shadow price over time.

A.2 Continuous time

You could also write the maximisation problem in continuous time

$$\max_{C(t)} \int_t U(C(t)) \mathrm{e}^{-\rho t} \mathrm{d}t \text{ s.t. } \dot{K}(t) = -\delta K(t) + (Y(K(t)) - C(t)) \tag{A.5}$$

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.[1] So, in order to solve this, we form the Hamiltonian, or more specifically the current-value Hamiltonian:

$$\mathcal{H} = U(C(t)) + \kappa(t)\dot{K}(t) \tag{A.6}$$

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, $\kappa(t)$, 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

$$\frac{\partial \mathcal{H}}{\partial C(t)} = U_{C(t)} - \kappa(t) = 0 \tag{A.7}$$

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. The result here is that the marginal value of consumption be equal to the marginal value of capital, just like above.

The second first-order condition has no analogue with LaGrange. It is

$$\dot{\kappa}(t) - \rho\kappa(t) = \frac{\partial \mathcal{H}}{\partial K(t)} = \kappa(t)\left(Y_{K(t)} - \delta\right) \tag{A.8}$$

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

$$\frac{\dot{\kappa}(t)}{\kappa(t)} = Y_{K(t)} - \delta + \rho \tag{A.9}$$

The left-hand side is the proportional rate of change of the shadow price of capital. This is a variable with an economic interpretation.

The elements on the right-hand side are intuitive too: the marginal productivity of capital $Y_K(t)$, 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 the 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.

[1] Actually, you would use LaGrange to prove Hamilton, but let's not go there.

A.3 Conclusion

Optimization in continuous time is daunting at first sight. However, it is just a trick. Constained 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.

Appendix B

Notation

Table B.1: Variables and parameters

Symbol	Meaning
$\mathcal{L}$	Lagrangian
$\mathcal{H}$	Hamiltonian
$\mathbb{A}$	ambiguity premium
$\mathbb{C}$	certainty equivalent
$\mathbb{D}$	discount factor
$\mathbb{E}$	expectation
$\mathbb{L}$	lucidity equivalent
$\mathbb{R}$	risk premium
A	total factor productivity
B	abatement costs
C	consumption
D	impact, damage of climate change
E	energy use
F	radiative forcing
G	goal, target
H	health impact
I	investment
K	capital
L	atmospheric concentration, or load
M	emissions
N	population size
P	emission permit
Q	transfer income
R	emission reduction
S	labour supply
T	temperature
U	utility
V	indirect utility
W	welfare
X	generic symbol

Continued on next page

Table B.1 – *Continued from previous page*

Symbol	**Meaning**
Y	output, income
Z	adaptation
c	constant
g	growth rate
i, j	index
p	probability
q	quantity
r	consumption discount rate
s	savings rate
t	time
$\bar{t}$	final time
w	wage
x	variable
y	per capita income
Θ	stock of energy
Π	profit
α	capital share, consumption share
β	unit cost of emission reduction
γ	risk amplification
δ	depreciation rate of capital, degradation rate of CO2
ε	income elasticity
ζ	intertemperal elasticity of substitution
η	risk aversion or risk sensitivity
ϑ	weight
ι	loss aversion
κ, λ	shadow price, Lagrange multiplier, co-state variable
μ	mean
ν	hyperbolicity of the discount factor
ξ	present bias
π	price, permit price
$\bar{\pi}$	choke price
ρ	pure rate of time preference, utility discount rate
ς	carbon subsidy
σ^2	variance
τ	tax, carbon tax
υ	scale parameter
φ	parameters of the climate model
χ	conversion factor
ψ	parameters of the impact function of climate change
ω	rate of inequity aversion
$\aleph$	population growth rate

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