Lecture 2: Determining regulation targets

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Objective of the lecture

Lecture 1: we saw that there were two key questions in environmental economics:

1. how much effort should we put to reduce environmental externalities?;
2. how should we implement this effort (i.e. through which policies)?

Today's lecture: focus on the first question and its corollary: *how much pollution should we keep, how much should we eliminate?* $\rightarrow$ Somewhat provocative question. Why shouldn't we get rid of *all* pollution?

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- heating your personal Jacuzzi requires to transform energy, which pollutes;
- traveling by plane to spend your weekend abroad emits both local pollutants and large quantities of greenhouse gases;
- producing energy to heat your home during winter is also energy-intensive;
- riding your bike to go to work increases your consumption of calories, and therefore your food consumption which pollutes;
- and so does walking, talking to people, thinking, etc.

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Clearly, some activities emit much more and are by far less essential than others. Where should we draw the line?

The welfarist view

Based on the previous lecture, **an efficient allocation** should include all activities whose social benefit (including private benefits) exceeds the social cost (including private costs).

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The market equilibrium leads individuals (producers, consumers) to perform activities as long as their private marginal benefits exceed their private marginal cost.

To restore efficiency, we need to:

1. determine the value of the external effects that create a discrepancy between private and social marginal costs and benefits;
2. lead agents to change their behavior to account for these external effects. This can be done by:
   - forcing agents to consume/produce the "righ" amount;
   - incentivizing them.

A simple example

Let's take a very simple example. Let's assume we have two individuals 1 and 2, one of them (say 1) can chose the quantity x of a polluting good it consumes.

- The utility of 1 is $U_1(x) = B(x) - C(x)$ where $B(x)$ and $C(x)$ are 1's private benefits and costs from consuming x;
- The utility of 2 is $U_2(x) = \bar{u} - D(x)$ where $\bar{u}$ is exogenous and $D(x)$ is the external effect of the consumption of x by individual 1.

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- The utility of 2 is $U_2(x) = \bar{u} - D(x)$ where $\bar{u}$ is exogenous and $D(x)$ is the external effect of the consumption of x by individual 1.

$\rightarrow$ If 1 maximizes its utility, chooses x^{eq} such that:

- $B'(x^{eq}) = C'(x^{eq})$

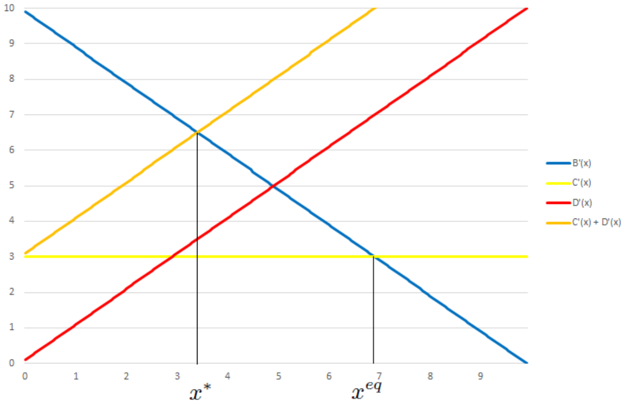
$\rightarrow$ If the planner maximizes the sum of utilities, chooses x^* such that:

- $B'(x^*) = C'(x^*) + D'(x^*)$

$D'(x)$ represents the discrepancy between the socially optimal and the market equilibrium decisions. **Problem:** while x^{eq} is the observed market equilibrium, how to determine the targeted pollution level x^*?

A graphical example

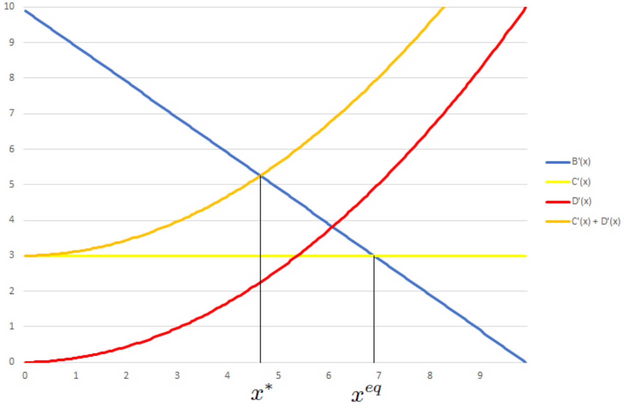
Simple illustration with (arbitrary) linear functions:



In theory, the intersection of the blue and yellow curves (private benefits and costs) is directly revealed by free market equilibrium. **But who knows the shape and level of the red curve?**

A graphical example

Alternative example with quadratic damages:



With non-linear damages, even more difficult to infer what happens as pollution increases.

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The Social Cost of Pollution (SCP) – Definition

Environmental externalities impact social welfare. To compare these welfare costs to other costs and benefits of the polluting activity, need to translate everything into a common unit expressed in monetary value. Thus, **need to find out the "price" of these externalities**.

Problem: externalities are a problem of missing markets, so **we do not observe this price**. What does it correspond to then?

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Problem: externalities are a problem of missing markets, so **we do not observe this price**. What does it correspond to then?

The social cost of pollution (SCP) represents the maximum price that society is willing to pay to reduce pollution by a certain level. It usually refers to a marginal cost, i.e. how much society is willing to pay to reduce emissions by one unit.

- Thus, if the estimated SCP is d€ per unit of pollutant, then society should be willing to spend up to d€ to avoid the emission of an additional unit of that pollutant.
- The red curve in our previous example represents the SCP for the pollutant x.

Eliciting the SCP – Challenges

In practice, computing the SCP is extremely challenging:

- In our simple example, individual 2 can lie about $D'(x)$, and report greater damages to get higher utility;
  - if the planner cannot determine $D'(x)$ by itself, may need to design a (costly) truth revealing mechanism.
- The planner may not have sufficient knowledge to estimate $D'(x)$. Things get worse as:
  - the number of agents impacted increases;
  - these agents value the same damages differently;
  - damages get more diverse;
  - damages get more uncertain.

The social cost of carbon: definition

The most well-known example of social cost of pollution is the **social cost of carbon (SCC)**.

Put simply, the SCC is the marginal social cost of emitting an additional unit of CO_2 (or other greenhouse gases expressed in CO_2-equivalent in terms of global warming potential). Formally:

$$\frac{\partial(\text{€ damages})}{\partial(\text{tons } CO_2 \text{ emissions})} = \frac{\partial(\text{€ damages})}{\partial(°\text{C warming})} \times \frac{\partial(°\text{C warming})}{\partial(\text{tons } CO_2 \text{ emissions})} \tag{1}$$

Although it is simply one specific example of a SCP, the SCC has attracted a lot of attention in the literature because:

1. greenhouse gases impose what might be considered as "the biggest market failure the world has seen" (Stern, 2008);
2. the nature of these gases make the computation of the SCC a very complex challenge.

The social cost of carbon: challenges

The impact of long-lived greenhouse gases such as CO_2 is diffuse in both time and space:

- a unit of CO_2 emitted in the Netherlands will have equivalent warming impacts in Australia than a unit emitted in Australia, or in any other country;
- a unit of CO_2 emitted now will impact current and future generations, including very far away in the future.

$\rightarrow$ Computing the SCC requires to sum *all* the social costs from an additional unit of CO_2, in all countries and over all generations.

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Two key challenges that the literature has tried to address are:

1. identifying all, or at least the main consequences of climate change and their impact on social welfare;
2. finding a proper way to aggregate these impacts, in particular to compare costs and benefits that occur at different periods in time.

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Where to start?

A non exhaustive list of climate change related damages:

- Mortality due to extreme temperatures
  - e.g. Carleton et al
- Impact of climate-related disasters on capital stock
  - e.g. Boustan et al (2019) See more
- Effect on long-run growth
  - e.g. Dell et al (2012) See more
- Productivity losses during heat waves
  - e.g. Graff Zivin et al (2018) See more
- Increased likelihood of armed conflicts
  - e.g. Burke et al (2009) See more
- etc.

Need to assess the causal impact of climate change, predict how this will evolve in the future, and translate damages into a monetary value.

The impact of heat-waves – Some raw data

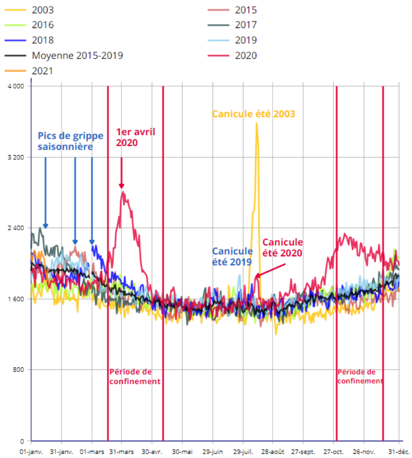


Figure: Number of daily deaths in France

Note: the peaks in the red curve represent the number of excess deaths related to the Covid pandemic in 2020. The peak in the yellow curve represents the number of excess deaths related to the summer 2003 heat-wave. Source: Insee.

Carleton et al (2020) – Objectives

The paper is the outcome of a large project (16 listed authors!) that aims at empirically estimating the welfare costs from climate change's impacts on global mortality risk.

Data: for 40 countries (38% of world's population) gathers historical mortality records, historical climate at a high-resolution level, and projections of future climate, population, and income.

Method: they follow three steps:

1. estimate the temperature-mortality relationship, accounting for heterogeneity w.r.t. countries' age composition, income, and long-run temperatures;
2. use these estimates to predict the temperature related mortality in other countries, and project the impact for future years;
3. using estimates for the value of statistical life (VSL) and accounting for adaptation costs, they compute the social cost from expected climate change related deaths.

Carleton et al (2020) – Main specification

The first step is achieved by fitting the following model:

$$M_{ait} = g_a(T_{it}, TMEAN_s, log(GDP_{pc})_s) + q_{ca}(R_{it}) + \alpha_{ai} + \delta_{act} + \epsilon_{ait} \quad (2)$$

with M_{ait} the age-specific mortality in location i (e.g. US county) and year t, g_a is the age-specific temperature response function that depends on income and historical temperatures, $q_{ca}(R_{it})$ the effect of precipitations, and α_{ai} and δ_{act} fixed effects, s and c being region (higher level than i) and country indexes.

$\rightarrow$ Very rich set of fixed effects: identification relies on temperatures changes over time within countries, controlling for permanent differences between locations within countries.

Carleton et al (2020) – Result (1/2)

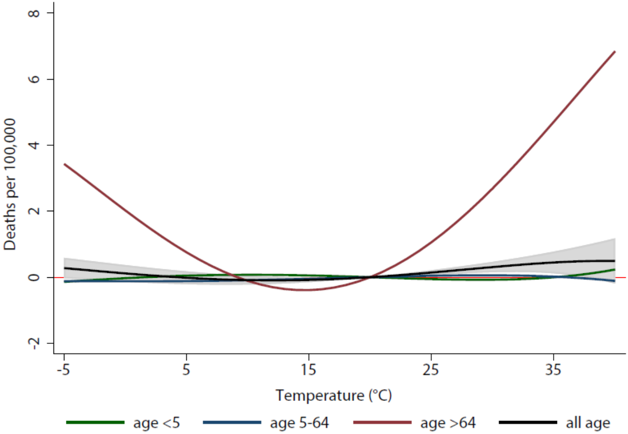


Figure 2: Mortality-temperature response function with demographic heterogeneity.

Carleton et al (2020) – Result (2/2)

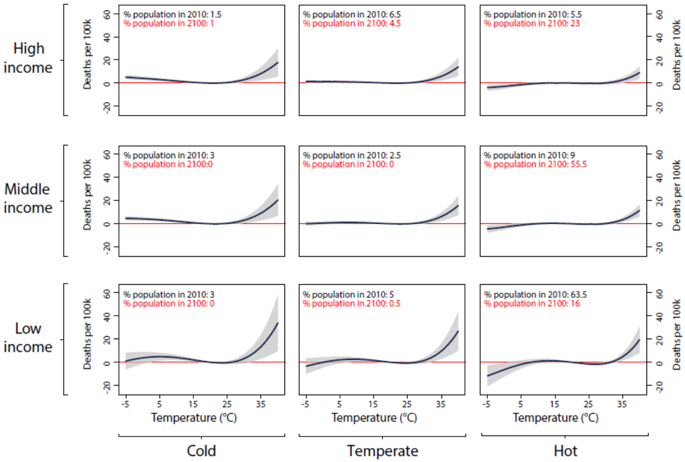
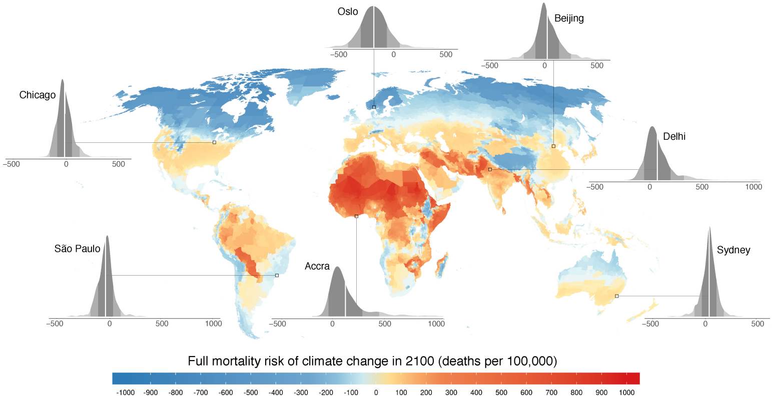


Figure 1: Heterogeneity in the mortality-temperature relationship (age >64 mortality rate).

Carleton et al (2020) – Forecasts



From there, the authors input a "price" to these deaths through the VSL*, estimate adaptation costs, and aggregate everything to estimate a *partial* SCC (i.e. from mortality only). In a high damage scenario, they get \$36.6/tCO_2.

*US' EPA estimate: \$10.95 millions

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Aggregating costs and benefits over time: the concept of discounting

Once all damages are listed, a second challenge is to aggregate them. This raises several questions. Importantly, how to aggregate damages that happen now vs. far away in the future?

Discounting is a very commonly used concept to study dynamic problems in economics. It is essential to make trade-offs between the allocation of resources to different periods of time. For instance:

- you win a game that comes with a prize: either 100€ now or 105€ one year from now. Which of these two options do you take?;
- you want to extract oil to produce gasoline: how much do you extract now, how much do you leave in the ground for the future?;
- you may pay to study now, be more educated and earn a higher wage in the future, or start working and earning a salary earlier.
- etc.

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- etc.

Similarly, discounting is used in **climate change economics** to weight the present costs relative to the future benefits of mitigation efforts. Answers the question "How much mitigation efforts should we do now given the expected impacts of climate change in the future".

How to determine the social discount rate?

The social discount rate (SDR) is **a measure of society's willingness to transfer wealth to the future**. It corresponds to the value of x such that society is indifferent between receiving 100€ now or (1+x)100€ one year from now.

This element is **key in cost benefit analysis**, for instance to determine whether a given project that generates costs in the present and benefits in the future (such as climate change mitigation policies) is worth implementing.

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It can be shown that **when markets work perfectly, the SDR is equal to the market risk-free interest rate**. Put simply, society should invest in an asset only if the reduction in current utility is at least compensated for by the increase in utility in future periods, which is determined by the risk-free return on this asset.

→ In theory, the SDR could thus be determined directly from observing the market's risk-free rate. We will discuss the limits of this approach later in the lecture.

Discounting the future: a framework

Determining the SDR from market's observations is not fully satisfactory. One other approach is to decompose the discount rate in several elements that we can independently calibrate. If utility is defined as a function of consumption, then we can formalize the problem as follows:

- a representative infinitely-lived agent wants to maximize its intertemporal utility, i.e. $\sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t u(c_t)$ with ρ its pure rate of time preference;
- the agent derive its consumption from its total wealth that evolves following the law of motion: $(1+r_t)k_t + y_t \geq c_t + k_{t+1}$, i.e. what it consumes and saves at period t cannot exceed what it already had plus what it earned at this period.

One can therefore formalize the agent's problem as follows:

$$\mathcal{L} = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t u(c_t) + \lambda_t \left((1+r_t)k_t + y_t - c_t - k_{t+1}\right)$$

where the rate of return on capital r_t is also the SDR.

Discounting the future: a framework

The FOCs of this problem give:

$$\frac{\partial \mathcal{L}}{\partial c_t} = \left(\frac{1}{1+\rho}\right)^t u'(c_t) - \lambda_t = 0$$

$$\frac{\partial \mathcal{L}}{\partial k_t} = \lambda_t(1+r_t) - \lambda_{t-1} = 0$$

Putting them together we obtain:

$$\left(\frac{1}{1+\rho}\right)^t u'(c_t) = \lambda_t = \lambda_{t+1}(1+r_{t+1}) = \left(\frac{1}{1+\rho}\right)^{t+1} u'(c_{t+1})(1+r_{t+1})$$

$$\Leftrightarrow \quad u'(c_t) = u'(c_{t+1})(1+r_{t+1})\left(\frac{1}{1+\rho}\right)$$

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$$\Leftrightarrow \quad u'(c_t) = u'(c_{t+1})(1+r_{t+1})\left(\frac{1}{1+\rho}\right)$$

$\rightarrow$ The discount rate r_{t+1} must be such that the agent is indifferent between transfering one unit of consumption from period t to period $t+1$ given its time preference parameter ρ.

Discounting the future: a framework

Let's now make a convenient assumption about the form of the utility, that we will take as being isoelastic: $u(c_t) = \frac{c_t^{1-\eta}}{1-\eta}$. Then we get:

$$\left(\frac{c_t}{c_{t+1}}\right)^{-\eta} = (1 + r_{t+1})\left(\frac{1}{1+\rho}\right)$$

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Now, if we define the consumption growth rate g_t such that $c_{1+t} = c_t(1 + g_t)$, we have:

$$(1 + g_t)^{\eta} = (1 + r_{t+1})\left(\frac{1}{1+\rho}\right)$$

and for g_t and η small enough we can use a binomial approximation: $(1+g_t)^{\eta} \approx 1 + \eta g_t$, to get:

$$1 + \eta g_t \approx (1 + r_{t+1})\left(\frac{1}{1+\rho}\right)$$

$$\Leftrightarrow \quad 1 + \eta g_t + \rho \eta g_t + \rho \approx 1 + r_{t+1}$$

and for ρ and ηg_t small enough we get the standard Ramsey rule:

$$r_{t+1} \approx \rho + \eta g_t$$

Discounting with the Ramsey rule

Ramsey rule: $r_{t+1} \approx \rho + \eta g_t$

The Ramsey rule determines (in a simple framework that assumes perfectly competitive financial markets) the interest rate as a function of:

- the pure rate of time preferences;
  - The more impatient people are (i.e. the higher ρ), the higher r_{t+1} and the more future periods are discounted.

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- the growth rate of consumption;
  - The more wealth one expects to have in the future, the less it wants to transfer money to later periods in order to smooth its consumption path.

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- the growth rate of consumption;
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- the intertemporal elasticity of substitution.
  - The strength of the previous mechanism depends on one's willingness to smooth consumption: the higher η, the more consumption smoothing matters. η is sometimes considered as a parameter capturing inequality aversion: the higher it is, the less the agent is willing to transfer resources to wealthier periods.

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Then, instead of looking at the market value of r to determine the SDR, some people recommend to determine r from the Ramsey equation by choosing values for each of its elements based on economic (g) and ethical (ρ, η) considerations.

Descriptive vs. prescriptive approach

Two opposing approaches to determine the SDR (*cf.* Gollier, 2013):

- Descriptive approach: from an arbitrage argument, argue that the SDR should be consistent with the interest rate observed in the financial markets.
- Prescriptive approach: the discount rate should be set based on ethical criteria, in particular by not giving any preference a priori for present generations (i.e. $\rho \simeq 0$).

$\rightarrow$ These methodological divergences have led to great controversies with critical implications with respect to policy recommendations for climate action. Example: Stern-Nordhaus controversy (see Stern, 2007; Nordhaus, 2007)

Discounting in the short and long run

Table: Present value of 1,000,000€ damages in the future depending on when it occurs and the discount rate applied.

Discount rate	Occurs in 20 yrs.	Occurs in 100 yrs.	Occurs in 300 yrs.
1%	819,545€	369,711€	50,534€
3%	553,676€	52,033€	141€
6%	311,805€	2,947€	0,03€

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$\rightarrow$ For long-run issues, seemingly small differences in discounting can lead to strikingly different policy implications:

- Stern (2007) takes $\rho = 0.1\%$ based on ethical considerations, and assumes $\eta = 1.0$ and $g = 1.3\% \rightarrow r = 1.4\%$;
- Nordhaus (2007) takes $\rho = 3.0\%$ based on observed market behaviors, and assumes $\eta = 1.0$ and $g = 1.3\% \rightarrow r = 4.3\%$.

$\rightarrow$ While the Stern Review recommends rapid and very ambitious action to combat climate change, Nordhaus reaches much less alarming conclusions.

Who is right?

In a world without market failures, the two should coincide. But in such a world, there would be not climate change!

The two approaches lead to conceptually different objects:

- Prescriptive approach: very appealing from a normative point of view.
- Descriptive approach: minimizes opportunity costs from social investments, pragmatic approach to policy.

Example: suppose society can invest in a 1 billion € project to reduce environmental damages that are expected to cause a 20 billions € worth loss 100 years from now. Should society do it?

- Prescriptive approach: yes, since $(1.03)^{100} \simeq 19.2$, with a SDR below 3% the investment is worth it.
- Descriptive approach: if the market interest rate is higher (say 5-6%), then no: society is better off investing in projects that pay the market interest rate and lead to higher future payoffs.

Further considerations about discounting

- When making investment choices, risks matter: it is not only about the expected payoff.
- Specifically, the correlation of risks matters: we may prefer investing in a low-average return project if it pays off in bad states of the world.
  - If climate change happens to be more damaging than expected, even small reductions in its intensity can be worth a lot.
- The Ramsey rule gives $r_{t+1} \approx \rho + \eta g_t$. ρ and η might be fixed preference parameters, but g_t is endogenous. If climate change reduces g_t, lower and possibly even negative SDR.
- The relative price argument (see Sterner and Persson, 2008): as environmental quality decreases, marginal welfare gain from better environment increases.
  - Even if there is consumption growth (i.e. positive g), future generations are poorer w.r.t. the environment. Because of imperfect substituability, leads to high relative price for environmental quality.

Sterner and Persson, 2008

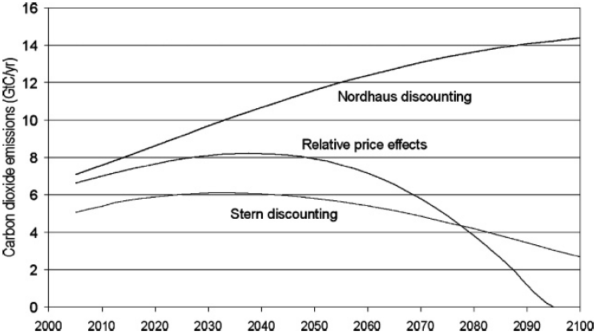

Figure 1. Optimal carbon dioxide emission paths in amended version of the DICE model, showing how conclusions concerning abatement depend crucially on assumptions regarding discounting and relative prices. Note: Emissions paths are shown for three different cases: a high discount rate case (upper line—labeled Nordhaus discounting), a case utilizing the lower discount rate argued for in the *Stern Review* (the lower line—labeled Stern discounting), and a run with the high discount rate, but where the nonmarket impacts are attributed to the consumption of a representative environmental good whose relative price is rising over time (middle line—labeled Relative price effects). See text for further explanation.

A tool: Integrated Assessment Models (IAMs)

- The literature has came up with a wide range of damages associated with climate change, and specific rules to aggregate them. Putting these ingredients together, this has led to the development of Integrated Assessment Models (IAMs).
- IAMs (e.g. DICE, PAGE, FUND, WITCH) are analytical frameworks modelling both the economic and the climate system, as well as their two-sided interaction. They are used to assess how changes in the economic system (such as changes following the implementation of policies) affect the climate system, and how that translates into economic gains and losses expressed in monetary units (that can include other aspects than GDP).

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- They essentially require to specify a certain damage function (i.e. to determine for each additional unit of CO_2 what will be the damages caused at each point in time), aggregate the predicted damages using a specific rule (such as a given discount rate), and assess how the economy would react to the implementation of a new policy.

→ IAMs are the main tool used to determine the social cost of carbon, which is then used to derive recommandations for policy-making. Nordhaus won the 2018 Nobel Prize in Economics for his contribution to IA modelling.

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Costs and benefits of environmental regulation: simple framework

Environmental regulation generates costs and benefits. Typically:

- it has a negative effect on the polluter by decreasing its consumption/production of the polluting good;
- it has a positive effect on the polluted by decreasing the pollution level and associated damages.

Costs and benefits of environmental regulation: simple framework

Environmental regulation generates costs and benefits. Typically:

- it has a negative effect on the polluter by decreasing its consumption/production of the polluting good;
- it has a positive effect on the polluted by decreasing the pollution level and associated damages.

$\rightarrow$ If the policy is set at the appropriate level, net social benefits are maximized.

Basic framework: assumes that the pollution externality is the only market failure. We call this a **first best situation:**

- with one market failure, one policy instrument is sufficient to implement the optimal allocation;
- it is optimal to price pollution at its social cost.

Costs and benefits of environmental regulation in a second best environment

Question: what happens when there are several market failures?

Tinbergen principle (from Jan Tinbergen): to achieve n independent policy targets, at least n independent policy instruments are required. In other words, we can successfully correct market failures as long as we have as many policy instruments as there are market failures.

Costs and benefits of environmental regulation in a second best environment

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Tinbergen principle (from Jan Tinbergen): to achieve n independent policy targets, at least n independent policy instruments are required. In other words, we can successfully correct market failures as long as we have as many policy instruments as there are market failures.

Question: what happens when there are more market failures than there are instruments available?

We call these **second best situations**, i.e. situations where at least one optimality condition cannot be satisfied:

- the optimal allocation generally cannot be reached;
- it is generally not optimal to price pollution at its social cost anymore.

$\rightarrow$ Much more realistic framework. The question is, how big are the deviations from the first-best policies?

Setting environmental targets in second best settings: an example

Example: gasoline consumption pollutes. Imposing a tax on gasoline consumption will reduce this pollution. The level of the tax can be adjusted so as to reduce pollution to the desired level.

Problem: the tax generates redistributive effects and may increase inequalities if it disproportionately hurts low-income individuals.

Setting environmental targets in second best settings: an example

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In a first best situation: if the planner can use targeted non-distortionary lump-sum transfers, then it is not a problem. The winners can compensate the losers without changing incentives to reduce pollution, a Pareto improvement can be achieved.

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In a first best situation: if the planner can use targeted non-distortionary lump-sum transfers, then it is not a problem. The winners can compensate the losers without changing incentives to reduce pollution, a Pareto improvement can be achieved.

In a second best situation: precisely identifying the winners and losers from these taxes is impossible, the tax will necessarily disproportionately hurt some individuals. If society is averse to these transfers, then the level of the tax may have to be adapted to take into account its side effects on welfare.

→ There is no general result as whether second-best environmental policies should set higher or lower pollution targets than first best ones. The side effects depend on the context and the specific policy chosen (see Lecture 4).

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The main caveats of the marginalist approach

The marginalist approach to environmental externalities **provides a consistent framework** to think about how environmental problems relate to market failures. It is useful to identify and quantify both the welfare impact of externalities and the proper policy responses, in order to determine the optimal level of pollution.

The main caveats of the marginalist approach

The marginalist approach to environmental externalities **provides a consistent framework** to think about how environmental problems relate to market failures. It is useful to identify and quantify both the welfare impact of externalities and the proper policy responses, in order to determine the optimal level of pollution.

However, in practical terms, this approach **comes with important caveats**. In particular, it appears *extremely* difficult to:

- sum all the costs and benefits of a given policy;
- account for the deep uncertainty surrounding the consequences of alternative policy scenarios;
- agree on ethical considerations necessary to measure and aggregate costs and benefits.

How to sum all costs and benefits?

As stated by Baumol and Oates (1971), summing all costs and benefits of a given policy amounts to **a "Herculean" task**.

In most cases, **finding a close approximation for this sum can also be very difficult** because the number of effects (including indirect ones) is too large and some of them are unknown.

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This criticism is all the more relevant for large scale problems $\rightarrow$ In the case of climate change, the consequences of emissions are diffuse in space and time: summing all the impacts is simply not possible.

For small scale problems however (e.g. managing wastes at the local level) finding an approximation of the costs and benefits might be doable.

The case of deep uncertainty

Pindyck's critique:

- His 2013 article on IAMs is titled "Climate Change Policy: What Do the Models Tell Us?". His short answer to that question: "Very little."
- "IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading"

Pindyck invokes several reasons why IAMs are not adequate to estimate the SCC, but a key reason is the uncertainty surrounding potential catastrophic damages (see also Weitzman, 2009).

- According to them, the degree of ambition of climate policies should depend mainly not on the known consequences of the phenomenon, but on the possibility of major disasters (e.g. tipping points, see Lenton et al, 2019).

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- According to them, the degree of ambition of climate policies should depend mainly not on the known consequences of the phenomenon, but on the possibility of major disasters (e.g. tipping points, see Lenton et al, 2019).

Beyond climate change, for many environmental problems the consequences of alternative policy scenarios are deeply uncertain: we do not know what are the possible states of the world, and we are even less capable of imputing probabilities $\rightarrow$ cost-benefit analysis therefore becomes inconsistent.

Ethical considerations

Perhaps the deepest critique to IAMs and other methods used to compute the social cost of pollution is their reliance on specific parameter values to capture ethical considerations. In particular, these computations require to determine:

- how society values the welfare of different individuals, which is necessary to construct a social welfare function with heterogeneous individuals;
- how to discount future utility, i.e. which weight to give to future generations;
- how society values risk today, but also how it will value it in the future;
- how society values environmental goods (since the externality comes from the fact that their real price is not revealed by the market)
- how society should value the welfare associated with population growth;
- etc.

Nordhaus revisited: DICE 1992's predictions vs. DICE 2016

	DICE 1992	DICE-2016R	Change 1992 to 2016
	2015	2015	[%]
Major driving variables			
Economic			
Population (billions)	6,868	7,403	8%
Per capita GDP (2010$)	11,293	14,183	26%
Consumption per capita (2020$)	9,195	10,501	14%
Geophysical			
Other Forcings (W/m2)	0.89	0.50	-44%
CO2/output ratio (tCO2/000 2010$)	0.607	0.350	-42%
Outcome variables			
Industrial Emissions (GTCO2 per year)	42.3	35.7	-15%
Output (trillions 2010$)	77.6	105.0	35%
Atmospheric concentration C (ppm)	399	400	0%
Atmospheric concentrations (GtC)	849	851	0%
Atmospheric Temperature (°C)	1.16	0.85	-27%
Total forcings (W/m2)	3.04	2.46	-19%
Social cost of carbon ($/tCO2 2010$)	4.54	30.98	582%

Source: Nordhaus (2017)

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An alternative approach: pricing and standards – Baumol and Oates (1971)

Given the practical limitations of the pigouvian approach, Baumol and Oates (1971) suggest an alternative solution called "pricing and standards". The idea is the following:

1. gather evidence regarding the consequences of a given source of pollution;
2. based on this, define a set of standards to be applied to achieve an acceptable level of pollution;
3. implement a (pricing) policy such that the pollution targets are met;
4. adjust the levels of standards and/or the policy by trial-and-error to reach the appropriate level of pollution and regulation.

An alternative approach: pricing and standards – Baumol and Oates (1971)

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4. adjust the levels of standards and/or the policy by trial-and-error to reach the appropriate level of pollution and regulation.

Example of a standard: *"one may, for example, decide that the sulfur-dioxide content of the atmosphere in the city should not exceed x percent, (...) or that the decibel (noise) level in residential neighborhoods should not exceed z at least 99% of the time."* (Baumol & Oates, 1971)

→ **The main benefit** of the procedure is its ease of practical implementation. Standards are simply set based on the best current knowledge about a given environmental problem and society's willingness to make efforts to tackle it. **The main drawback** is the arbitrary choice of standards that leads to give up the search for an *optimal* policy.

Pricing and standards applied to climate change: the “carbon budget” approach

The idea of fixing somewhat arbitrary standards to deal with complex environmental problems has recently gained some interest in the climate change literature. It has given rise to what we call the “carbon budget” approach.

Pricing and standards applied to climate change: the "carbon budget" approach

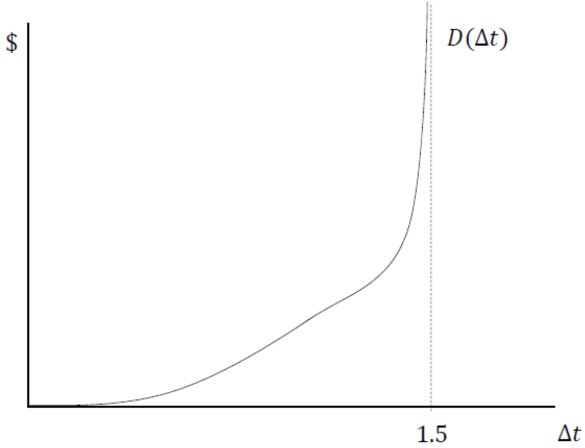
The idea of fixing somewhat arbitrary standards to deal with complex environmental problems has recently gained some interest in the climate change literature. It has given rise to what we call the "carbon budget" approach.

Since determining the SCC is too difficult, an alternative option is to:

1. set a maximum warming target, such as $+2^{\circ}$C;
2. determine the atmospheric concentration of greenhouse gases consistent with meeting this target with a given (say 66%) probability;
3. determine the most efficient path of policies that will ensure that the target is met.

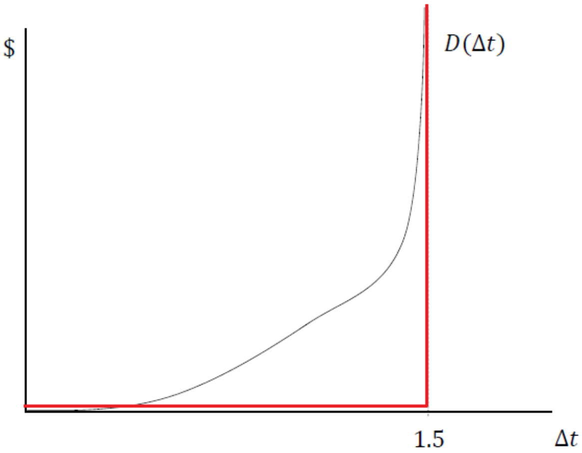
This approach usually leads to far more stringent policies than typical IAMs, suggesting that either 1) the standards chosen are more conservative than the optimal levels, or 2) IAMs are overly optimistic about the consequences of climate change (or about the importance to be given to the present relative to the future).

Carbon budget's damage function equivalent



With damages and a 1.5 °C target.

Carbon budget's damage function equivalent



With no damages and a 1.5 °C target.

A simple model of stock pollution – Set up

Consider a representative agent who seeks to maximize its discount flow of utility net of pollution damages, $u(x_t) - d(m_t)$, subject to two constraints:

1. on the evolution of the resource stock: $s_t = s_{t+1} + \phi x_t$;
2. on the evolution of the pollution stock: $m_{t+1} = (1-\alpha)m_t + \epsilon\phi x_t$.

The Lagrangian of this problem can be expressed as:

$$\mathcal{L} = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t \Bigg(u(x_t) - d(m_t) + \lambda_t \left(s_t - s_{t+1} - \phi x_t\right) \\ + \mu_t \Big(m_{t+1} - (1-\alpha)m_t - \epsilon\phi x_t\Big)\Bigg) \tag{3}$$

To solve this problem, need to take the FOCs w.r.t. x_t, s_t, and m_t.

A simple model of stock pollution – FOCs

At the optimum we have:

$$u'(x_t) = \phi\left(\lambda_t + \epsilon\mu_t\right) \tag{4}$$

$$\frac{\lambda_{t+1} - \lambda_t}{\lambda_t} = \rho \tag{5}$$

$$\frac{\mu_{t+1} - \mu_t}{\mu_t} = \frac{1}{1-\alpha}\left(\rho + \alpha - \frac{d'(m_{t+1})}{\mu_t}\right) \tag{6}$$

See calculation details

Thus:

- with $u' > 0$ and $u'' < 0$, higher value of $\phi\left(\lambda_t + \epsilon\mu_t\right)$ means lower value of x_t;
- λ_t (shadow price of the resource stock) grows at the exogenous constant rate ρ;
- μ_t (shadow price of the pollution stock) grows at the exogenous constant rate $\frac{\rho+\alpha}{1-\alpha}$ plus the endogenous rate $\frac{-d'(m_{t+1})}{\mu_t(1-\alpha)}$.

An alternative approach to stock pollution management – Set up

Consider now a representative agent who seeks to maximize its discount flow of utility, $u(x_t)$, subject to three constraints:

1. on the evolution of the resource stock: $s_t = s_{t+1} + \phi x_t$;
2. on the evolution of the pollution stock: $m_{t+1} = (1-\alpha)m_t + \epsilon\phi x_t$;
3. on the pollution ceiling: $m_t \leq \bar{m}$.

The Lagrangian of this problem can be expressed as:

$$\mathcal{L} = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t \Bigg(u(x_t) + \lambda_t \left(s_t - s_{t+1} - \phi x_t\right) + \mu_t \Big(m_{t+1} - (1-\alpha)m_t - \epsilon\phi x_t \Big) + \gamma_t \left(\bar{m} - m_t\right) \Bigg) \tag{7}$$

To solve this problem, need to take the FOCs w.r.t. x_t, s_t, and m_t.

An alternative approach to stock pollution management – FOCs

At the optimum we have:

$$u'(x_t) = \phi(\lambda_t + \epsilon\mu_t) \tag{8}$$

$$\frac{\lambda_{t+1} - \lambda_t}{\lambda_t} = \rho \tag{9}$$

$$\frac{\mu_{t+1} - \mu_t}{\mu_t} = \frac{1}{1-\alpha}\left(\rho + \alpha - \frac{\gamma_{t+1}}{\mu_t}\right) \tag{10}$$

See calculation details

Thus:

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Numerical illustration

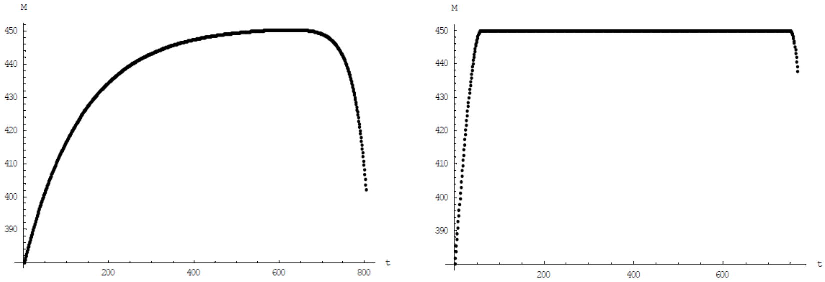


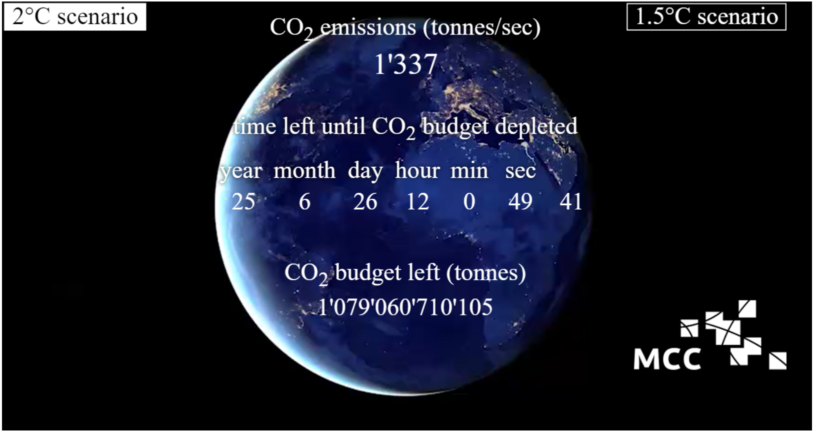
Figure: Optimal carbon concentration paths with pollution damages (left) and carbon budget (right)

Source: Schubert (2008)

Optimal policy

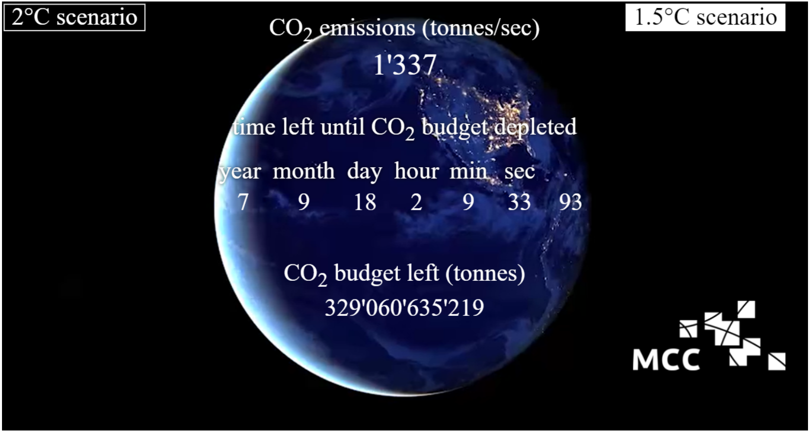
- In both models, if the agent ignores the pollution externality, then the consumption is determined by $u'(x_t) = \phi\lambda_t$.
- Thus, if the agent pays a tax $\tau_t = \phi\epsilon\mu_t$ for each unit of x_t it consumes, then when choosing $u'(x_t) = \phi\lambda_t + \tau_t$ it will fully internalize the externality.
- The exact shape of τ_t depends on initial conditions, but likely to grow at a rate close to ρ at least in the initial phase.
- With a carbon budget, once the ceiling $\bar{m}$ is attained, we have $\bar{m} = (1-\alpha)\bar{m} + \epsilon\phi x_t$ which implies $x_t = \frac{\alpha\bar{m}}{\epsilon\phi}$.
  - With α close to zero, big political risk that once at $\bar{m}$, the ceiling will be redefined to a higher level.
- With $\alpha = 0$, if $s_0\epsilon > \bar{m}$ then carbon budget is attained before the resource is fully depleted: resources must be kept in the ground forever.
  - Actual estimates indicate that if we were to use all fossil fuel resources, global mean warming would go up to +6.4-9.5°C and mean Arctic warming would be in the range of +14.7-19.5°C (see Tokarska et al, 2016).

Where we stand relative to the 2 °C target



Source: screen capture (October 4th, 2021) from the Mercator research institute on global commons and climate change.

Where we stand relative to the 1.5 °C target



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- how to determine regulation targets, i.e. how to decide on the best (i.e. efficient/optimal) level of pollution to reach?;
- how to attain these targets, i.e. which policies to implement?

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This week, we have seen how the **standard framework of welfare economics** could be applied to determine regulation targets that would enable to reach an efficient/optimal level of pollution.

Although **very useful to think about environmental externalities** and policies, this framework **also raises a number of practical difficulties**. For this reason, some environmental economists have preferred to give up the first of their two key research ambitions. They acknowledge that, at least for some environmental problems, they are not well equipped to determine what is the right environmental target to set. They instead focus on the second question, the "how".

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From next week, this is also what we will investigate.

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Solving the model with pollution damages (1/2)

Equation (4) can be easily shown using the FOC w.r.t. x_t:

$$\frac{\partial \mathcal{L}}{\partial x_t} = \left(\frac{1}{1+\rho}\right)^t \Big(u'(x_t) - \lambda_t \phi - \mu_t \epsilon \phi\Big) = 0$$

$$\Leftrightarrow \quad u'(x_t) = \phi\,(\lambda_t + \epsilon \mu_t)$$

Equation (5) requires to take the FOC w.r.t. s_t:

$$\frac{\partial \mathcal{L}}{\partial s_t} = \left(\frac{1}{1+\rho}\right)^t \lambda_t - \left(\frac{1}{1+\rho}\right)^{t-1} \lambda_{t-1} = 0$$

$$\Leftrightarrow \quad \lambda_t = (1+\rho)\lambda_{t-1}$$

$$\Leftrightarrow \quad \frac{\lambda_t - \lambda_{t-1}}{\lambda_{t-1}} = \rho$$

so that for any period t, the shadow price of the resource stock is $\lambda_0(1+\rho)^t$

Solving the model with pollution damages (2/2)

Equation (6) requires a bit more work. Let's first take the FOC w.r.t. m_t:

$$\frac{\partial \mathcal{L}}{\partial m_t} = \left(\frac{1}{1+\rho}\right)^t \Big(-d'(m_t) - \mu_t(1-\alpha)\Big) + \left(\frac{1}{1+\rho}\right)^{t-1} \mu_{t-1} = 0$$

which simplifies into:

$$-d'(m_t) - \mu_t(1-\alpha) + (1+\rho)\mu_{t-1} = 0$$

$$\Leftrightarrow \quad \mu_t = \frac{1}{1-\alpha}\Big((1+\rho)\mu_{t-1} - d'(m_t)\Big)$$

$$\Leftrightarrow \quad \frac{\mu_t - \mu_{t-1}}{\mu_{t-1}} = \frac{\mu_t}{\mu_{t-1}} - 1 = \frac{1}{1-\alpha}\left((1+\rho) - \frac{d'(m_t)}{\mu_{t-1}}\right) - 1$$

$$= \frac{1}{1-\alpha}\left(1+\rho - \frac{d'(m_t)}{\mu_{t-1}} - 1 + \alpha\right)$$

$$\Leftrightarrow \quad \frac{\mu_{t+1} - \mu_t}{\mu_t} = \frac{1}{1-\alpha}\left(\rho + \alpha - \frac{d'(m_{t+1})}{\mu_t}\right)$$

Back

Solving the model with a carbon budget

Just as in the previous case, we can find equations (8) and (9) by taking the FOCs of the Lagrangian w.r.t. x_t, s_t, and m_t. The first two are the exact same and give:

$$\frac{\partial \mathcal{L}}{\partial x_t} = \left(\frac{1}{1+\rho}\right)^t \Big(u'(x_t) - \lambda_t \phi - \mu_t \epsilon \phi\Big) = 0$$

$$\frac{\partial \mathcal{L}}{\partial s_t} = \left(\frac{1}{1+\rho}\right)^t \lambda_t - \left(\frac{1}{1+\rho}\right)^{t-1} \lambda_{t-1} = 0$$

The FOC w.r.t. m_t gives:

$$\frac{\partial \mathcal{L}}{\partial m_t} = \left(\frac{1}{1+\rho}\right)^t \Big(-\mu_t(1-\alpha) - \gamma_t\Big) + \left(\frac{1}{1+\rho}\right)^{t-1} \mu_{t-1} = 0$$

from which, applying the same reasoning than in the previous case (with simply γ_t instead of $d'(m_t)$ we can find equation (10), i.e.:

$$\frac{\mu_{t+1} - \mu_t}{\mu_t} = \frac{1}{1-\alpha}\left(\rho + \alpha - \frac{\gamma_{t+1}}{\mu_t}\right)$$

Back

Impacts of climate change: damages from environmental disasters

Among the many climate-related damages, the costs from environmental disasters are expected to be important ones. They are also among the most salient, partly because disasters are already striking at an increasing frequency and magnitude!

Boustan et al (2019):

- **What they do:** they estimate the economic impact of environmental disasters in the U.S.
- **How they do it:** they construct a detailed panel data set that includes all environmental disasters that have occured between 1930 and 2010 in the U.S. and study how they have affected several outcomes (migration rates, property prices, and poverty rates) at the county level.
- **What they find:** on top of the casualties they caused, the most severe disasters (that occured on average once every 30 years in each county) increased out-migration rates by 1.5 percentage points and lowered housing prices by 2.5–5.0%. → Disasters cause major declines in asset values.

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Impacts of climate change: growth and development of poor countries

Besides the unfrequent dramatic shocks that may happen, climate change also generates more continuous changes in production capacities, especially in poor countries.

Dell et al (2012):

- **What they do:** they study the link between climate conditions and economic performance in many countries.
- **How they do it:** from a panel dataset, they look at historical short-run fluctuations in countries' temperatures and precipitations and how they explain variations in economic performance.
- **What they find:** temperature increases have large negative effects on growth in poor countries, but not in rich countries. Among other channels, the effect is driven by changes in agricultural and industrial output, and political stability.

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Impacts of climate change: increase in armed conflicts

Weather fluctuations in sub-saharian Africa have historically been linked to increased conflicts. One may wonder whether climate change will have an effect on armed conflicts.

Burke et al (2009):

- **What they do:** they study the link between climate conditions and the number of armed conflicts in sub-saharian Africa;
- **How they do it:** they use a panel data set to study the link between climate variation at the country-level and conflict events (civil wars that caused at least 1000 battle-related deaths) between 1981 and 2002.
- **What they find:** historically, a 1°C warming has led to a 49% increase in the incidence of civil war. Their results predict that by 2030, temperature increases will lead to a 54% increase in the incidence of armed conflicts and an additional 393,000 battle deaths.

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Impacts of climate change: negative effect on health and human capital

A warmer climate may also affect workers' productivity and thereby reduce output. It may also have additional welfare effects by decreasing cognitive ability.

Graff Zivin et al (2018):

- **What they do:** they investigate the relationship between temperatures and cognitive abilities in both the short and long-run.
- **How they do it:** they use repeated assessments of young students' cognitive ability and merge these surveys with meteorological conditions at the county level on the day of the assessment.
- **What they find:** they find that performances in math decrease linearly with warmer tempratures (starting above 21°C, and significantly above 26°C), while performance in reading are not significantly affected by temperatures. They do not find conclusive evidence of an effect of temperatures on long-run human capital accumulation.

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