

The Economics of Climate Change Policy

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AEA Continuing Education

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This lecture draws heavily from:

Becker, Gary S., Kevin M. Murphy, and Robert H. Topel. “On the economics of climate policy.” *The BE Journal of Economic Analysis & Policy* 10, no. 2 (2011).

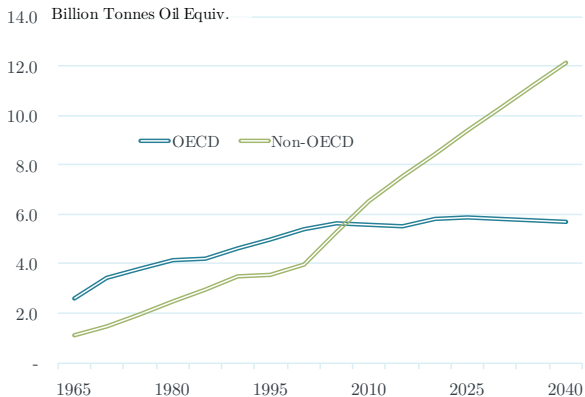
Motivation

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Global Energy Demand, 1965-2040



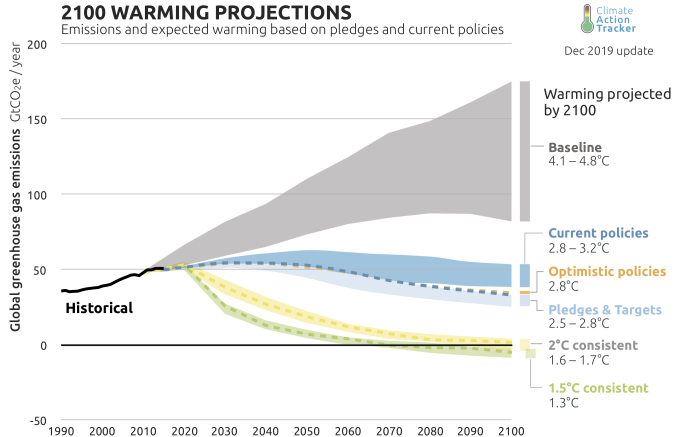
Source: EPIC analysis based on data from BP Statistical Review 2018 and BP Energy Outlook 2019

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 - ▶ Greenhouse gases in atmosphere will change Earth's climate.

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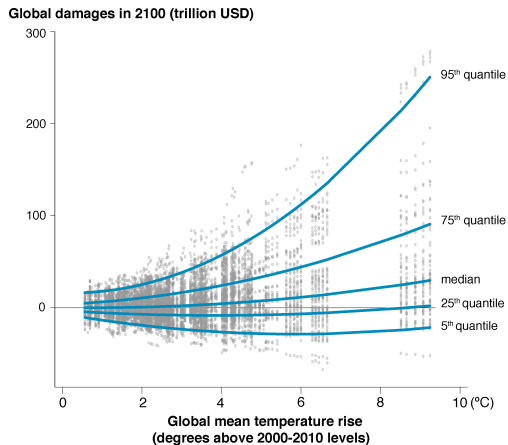
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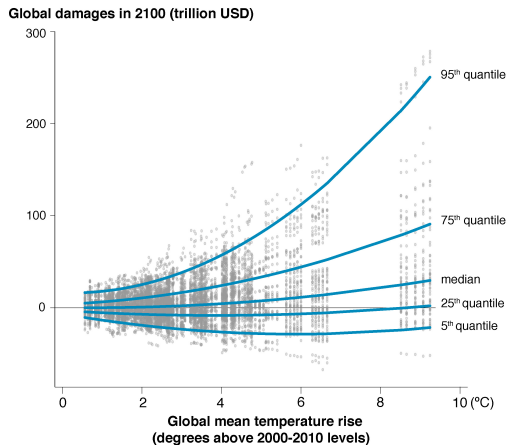


Source: Carleton et al. (2018)

Motivation

Successful energy/climate policy must confront several challenges:

- ▶ Convincing current generations that **future** costs of CO2 matter
- ▶ Convincing current generations to give up fossil fuels to avoid **uncertain** future harm
- ▶ Convincing countries to **cooperate** in reducing CO2 when:
 - ▶ Non-cooperation offers substantial rewards
 - ▶ Trade-offs differ greatly across countries



Source: Carleton et al. (2018)

Motivation

Lecture focuses on issues related to **design** and **effects** of climate change mitigation policies

- ▶ Market responses to carbon prices
- ▶ Innovation responses to and costs of delay in carbon pricing
- ▶ Dealing with uncertain, distant, and heterogeneous costs
 - ▶ Emphasis on potential catastrophic losses

Roadmap

① Climate change is best examined with cost-benefit analysis

- Carbon policy as an exhaustible resource problem
- The role of innovation

② The central role of discounting

- What is the correct discount rate?
- Differences in discount rates across countries

③ Welfare impacts of climate change

- Imminence of climate shocks
- Uncertainty of climate shocks
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The cost-benefit analysis of climate change

- ▶ Current GHG creates environmental and other costs that are:
 - ▶ greatly delayed: temperature lags because of atmosphere, sea level lags because ice melts slowly
 - ▶ long lasting: CO_2 breaks down very slowly
 - ▶ highly uncertain: hard to predict catastrophes
- ▶ Key is to have policy that balances costs and benefits over hundreds of years.
 - ▶ **Yes, even climate change is a cost-benefit analysis.**

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Goal: Maximize utility subject to a emissions cap

- ▶ Policy goal: set a target cap on concentration of GHGs at future date T .
 - ▶ BMT do not say where the cap or T come from or how countries reach agreement on them.
 - ▶ This is a CRITICAL assumption that allows for key insights but limits realism.
- ▶ Q_t = concentration of GHGs in year t .
- ▶ $Q_T = \bar{Q}$ = cap on GHGs.

Very close to a Hotelling (1931) problem for allocating use of an exhaustible resource (ex: coal) over time, where CO_2 below the cap is the resource.

Choose emissions and mitigation to maximize surplus subject to a cap

$$(1) \max_{\{q_t, s_t\}} \int_{t=0}^{\infty} [V_t(q_t) - c_t(s_t/\mu_t)] e^{-rt} dt$$

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 - ▶ s_t = avoided emissions through mitigation
 - ▶ μ_t = efficiency of mitigation (higher μ reduces mitigation costs)

Choose emissions and mitigation to maximize surplus subject to a cap

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 - ▶ s_t = avoided emissions through mitigation
 - ▶ μ_t = efficiency of mitigation (higher μ reduces mitigation costs)
- ▶ r = discount rate on future environmental costs

Choose emissions and mitigation to maximize surplus subject to a cap

$$(1) \max_{\{q_t, s_t\}} \int_{t=0}^T [V_t(q_t) - c_t(s_t/\mu_t)] e^{-rt} dt$$

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$$(1) \max_{\{q_t, s_t\}} \int_{t=0}^T [V_t(q_t) - c_t(s_t/\mu_t)] e^{-rt} dt$$

$$\text{such that } \frac{dQ_t}{dt} = q_t - s_t - aQ_t$$

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Intuition: anything not mitigated or absorbed counts towards the cap

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Absorption implies that CO2 follows exponential decay: of 1 unit emitted at time t , $e^{-a(T-t)} < 1$ units remain in the atmosphere at time T . **This is a modelling simplification.** The constraint thus simplifies to:

$$\text{such that } \int_{t=0}^T (q_t - s_t) e^{-a(T-t)} dt = \bar{Q}$$

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Intuition: early emissions have more time to decay

First order conditions

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In equilibrium, the MB of using and MC of eliminating 1 unit equals a “carbon price” in period t .

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Why does the constraint act like a tax?

- ▶ P_t represents scarcity value of a unit of emissions, or equivalently, the per-period shadow value of relaxing the constraint on Q_T
- ▶ This price is the ideal Pigouvian tax, so that $P_t =$ marginal benefit of q to users and the present value of incremental costs imposed on future generations

Optimal carbon prices increase over time

$$(2a) \quad V'_t(\cdot) = P_0 e^{(r+a)t}$$

$$(2b) \quad \frac{1}{\mu_t} c'_t(s_t/\mu_t) = P_0 e^{(r+a)t}$$

- ▶ At optimal $\{P_t\}$, we should be indifferent between selling (emitting) today and holding for future use (Hotelling).
- ▶ To maintain indifference, optimal price P_t must grow by the **net carbon interest rate** $r + a$ over time. The rising price accounts for:
 - ▶ typical discounting of future costs and benefits (r)
 - ▶ less time for atmosphere to absorb pollution if it happens later (a), which pushes up future prices relative to the case where $a = 0$

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The net carbon interest rate includes absorption

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- ▶ Absorption effectively pushes emissions to the present and mitigation to the future, allowing for more total emissions
- ▶ CO2 absorption thus impacts social value of innovation, incentives to innovate, and the cost of waiting to implement policy

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Recall that P_0 is the shadow value of relaxing the cap by 1 unit. An absorption rate $a > 0$ therefore provides additional surplus:

$$P_0 * [1 - e^{-a(T-t)}]$$

per unit of emissions.

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Carbon Pricing, Timing, and Returns to Innovation

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- ▶ Time profile of values is independent of interest rate r .
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 - ▶ If $a > 0$, present value actually rises with t because absorption becomes less viable alternative
- ▶ For most investments, payoffs in future are worth less. But since carbon prices also rise, **carbon-mitigating innovation is undiscounted and rises in the future**. This is counter to intuition that innovation policy must start yesterday.

Carbon Pricing, Timing, and Returns to Innovation

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$$\begin{aligned}\text{Present value of technology} &= e^{-rt} \frac{\partial C}{\partial \ln(\mu_t)} = e^{-rt} \frac{1}{\mu_t} c'_t(s_t/\mu_t) s_t \\ &= e^{-rt} P_t s_t \\ &= P_0 e^{at} s_t.\end{aligned}$$

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- As before, unit value of innovation is independent of r and increasing in t due to absorption.
- Reduction in incremental cost is scalable because it applies to all units s_t .

Punchline: Since we mitigate more in later periods, innovation gains have larger value if realized further in the future. This is because of absorption.

Carbon Pricing, Timing, and Returns to Innovation

CASE 3: Alter problem so that damages $D(Q_t)$ are incurred along the trajectory to T , making delay costly.

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- ▶ The current optimal carbon price is continuously updated, incorporating the impact of current emissions on future damages.

$$\frac{dP_t}{dt} = r + a - \frac{D'(Q_t)}{P_t},$$

where $D'(Q_t) > 0$ is the current period marginal damages from total emissions.

- ▶ P_t grows at a slower rate, relative to standard Hotelling solution.
- ▶ The broader point still holds: innovation yields greatest value when carbon price is high, and in the optimal policy that price is rising over time.

Carbon Pricing, Timing, and Returns to Innovation

Do the delays in international efforts to mitigate carbon emissions mean that urgency is warranted?

- ▶ **If** we implement a cap of $Q_T = \bar{Q}$ eventually:
 - ▶ **The slow start to global carbon policy (e.g., Copenhagen and Paris) may not be very costly.** Yes, we are losing a few years of benefits, but these are relatively low-value years because P_t is low. Plus, we have pushed R&D costs into future so they are discounted.
 - ▶ **Incentives for future R&D increase.** As we sit on our hands, P_t will grow because the constraint gets tighter and P_t will increase by more than the interest rate r , thus raising s .

Carbon Pricing, Timing, and Returns to Innovation

⇒ The result is that the current value of innovation incentives and the social gain from innovations are not much harmed and may even be increased by delay. Delay isn't costless; it leads to a tighter constraint and higher carbon prices (which increases incentives for innovation).

- ▶ This conclusion hinges on the assumption that we will eventually implement a cap.
- ▶ **Note:** if a carbon tax has insurance value in early years or responds to innovation (rather than vice versa), optimal carbon tax might be decreasing in t (Daniel, Litterman and Wagner PNAS 2019).

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 - 2.1 we discount the benefits of future emissions
 - 2.2 thanks to absorption, earlier emissions may be removed from the atmosphere.
3. A price on carbon incentivizes innovation in carbon-mitigation technologies, especially scalable ones.
 - 3.1 In future years, these innovations may become more valuable as carbon prices rise and absorption is less viable.
 - 3.2 Assuming we eventually cap emissions, the slow start to global carbon policy might not be very costly.

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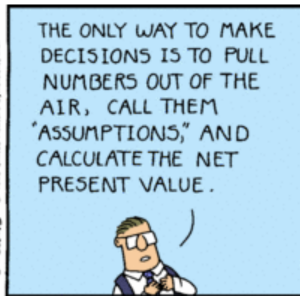
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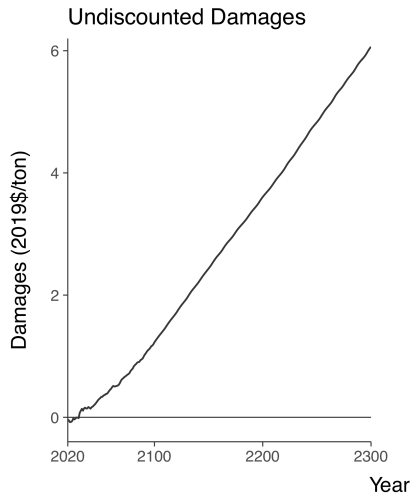
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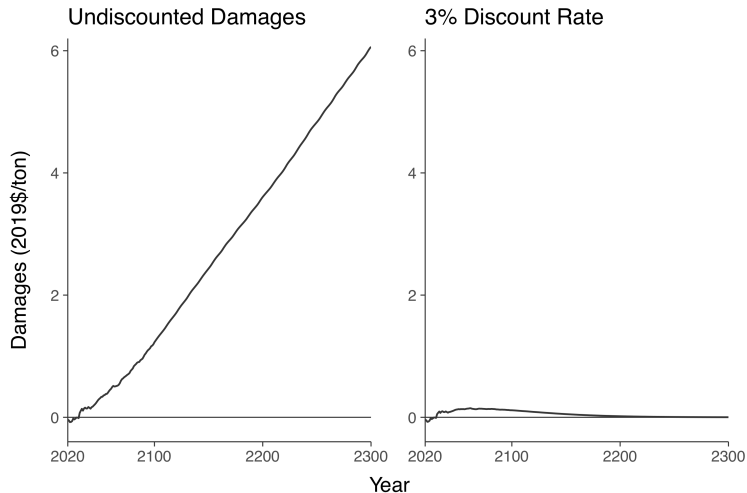
The game of discounting



CO2 emissions today will cause damages over centuries



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Discount rates effectively determine policy choices

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 - ▶ $r = 0.06 \implies P_0 \approx \$1.24$.

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 - ▶ $r = 0.06 \implies P_0 \approx \$1.24$.
- ▶ If r small, high P_0 so conservation and mitigation are front-loaded.
 - ▶ $r = 0.015 \implies P_0 \approx \$112$.

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Discount rates are central! They effectively determine policy choices and account for almost all differences in policy recommendations.

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What is the right social discount rate?

From Ramsey (1928), the optimal intertemporal allocation has:

$$r = \rho + \omega g$$

where:

- ▶ ρ is the rate of time preference
- ▶ ω is the consumption elasticity of marginal utility
- ▶ g is the growth rate of consumption

Intuition: we discount dollars tomorrow both because we care less about future utility **and** because the marginal dollar brings less utility when we are richer.

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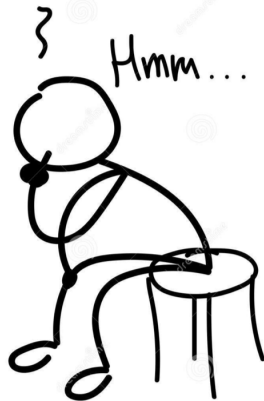
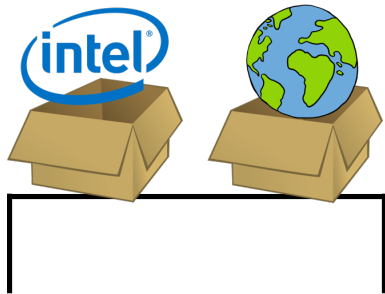
What is the right social discount rate?

From Ramsey (1928), the optimal intertemporal allocation has

$$r = \rho + \omega g$$

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 - ▶ Considers catastrophes that drive c near zero (g large and negative) so $MU(c)$ becomes enormous
 - ▶ Can lead to unbounded PDV of policies that prevent climate change
 - ▶ General point is that uncertainty about damages/payoffs of mitigation greatly affects valuations, so policies that insure against downside risks can be desirable despite low returns

Discount rates reflect opportunity costs



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“From an economic and empirical perspective the choice of a discount rate is not about the philosophical choice of the correct ethical weight to be applied to the welfare of our and other peoples’ great-grandchildren, nor is it about the way we “should” discount marginal dollars of their income because they will be richer. As in all analyses that must balance costs and benefits, the issue is opportunity cost.

“The fact that costs and returns are so uncertain and widely spaced in time adds practical difficulties but not conceptual ones.”

Choosing the highest-return project

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- ▶ Under Stern approach, implement if we value \$1 million for current generation less than \$20 million for the future generation.
- ▶ **This is wrong!** Even if we care only about future generation, we can always invest \$1 million in an outside option (e.g., the stock market) and potentially earn more than \$20 million by 2100

Choosing the highest-return project

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 - ▶ At the **6%** market rate, \$1 million today is \$403 million in 100 years.

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We should only invest in climate mitigation if the payoff exceeds the market rate of return (i.e. \$403 million).

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Choosing the highest-return project

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- ▶ The question is would our great-grandchildren wish that we had undertaken 3% or 6 – 8% investments?

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- ▶ Risks of climate differ across countries, and so do the outside options available to them

Is climate mitigation like stocks or gold?

The New York Times

 **TheUpshot**

COST OF CARBON

What Financial Markets Can Teach Us About Managing Climate Risks

“Investing in gold is a type of insurance policy against tough times. Financial markets are revealing that investors are willing to accept a lower average return for that insurance, precisely because it helps to manage risk.”

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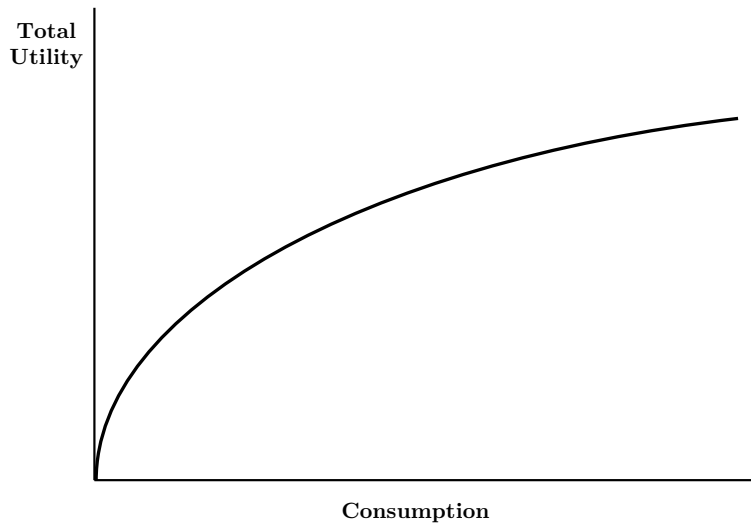
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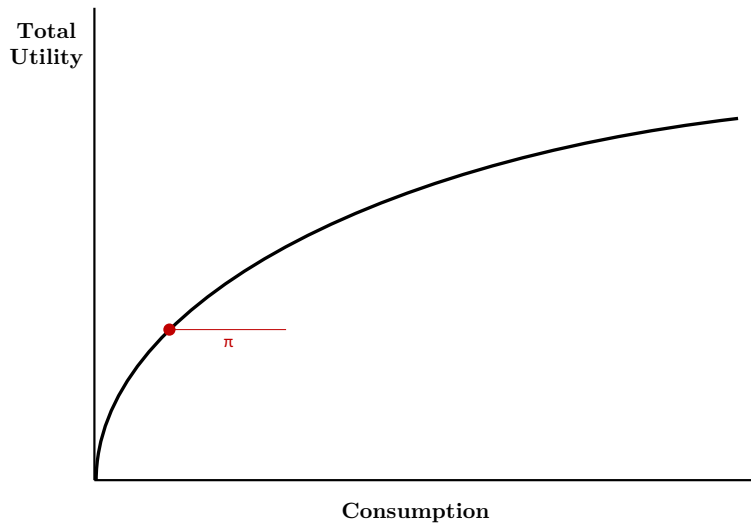
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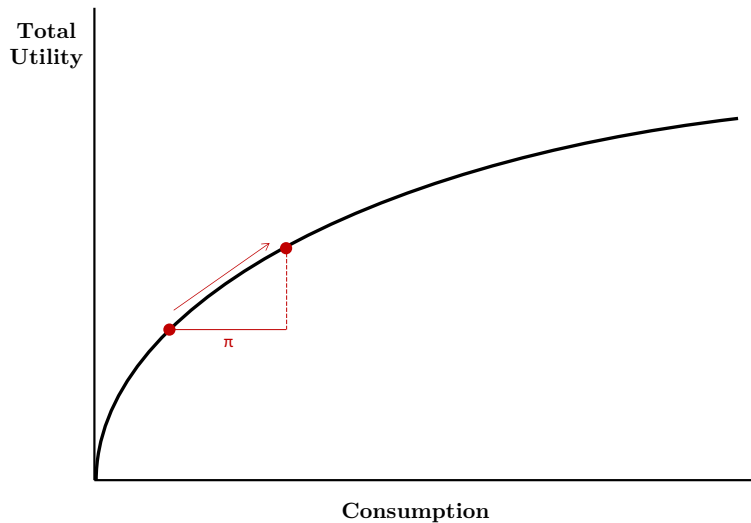
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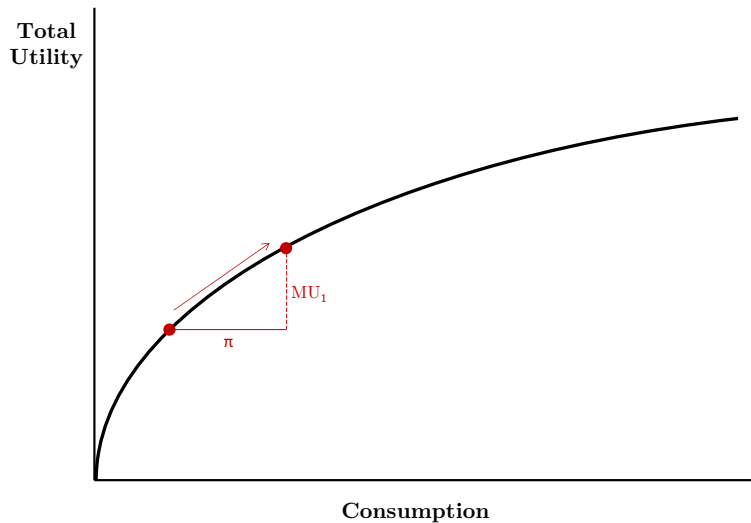
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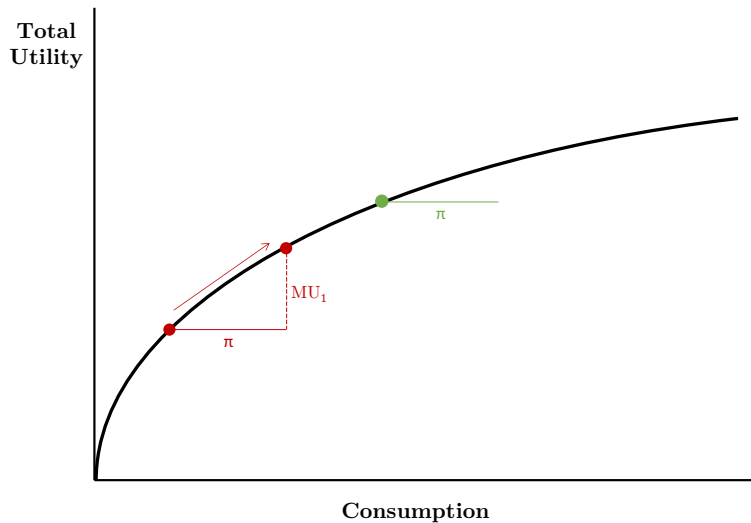
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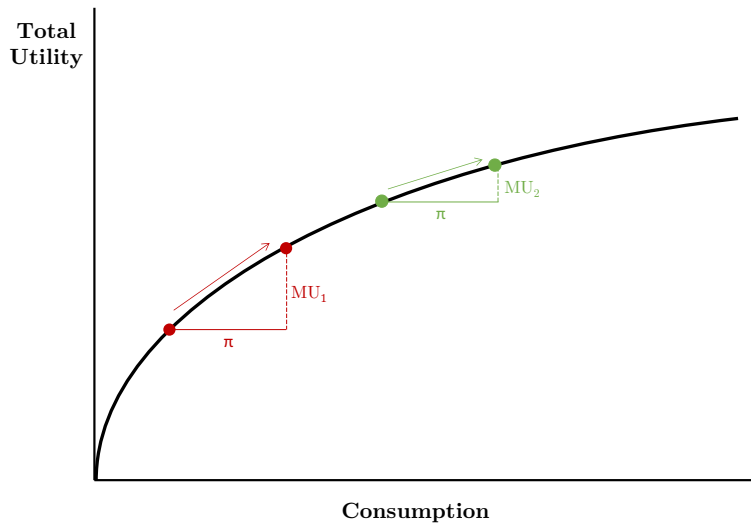
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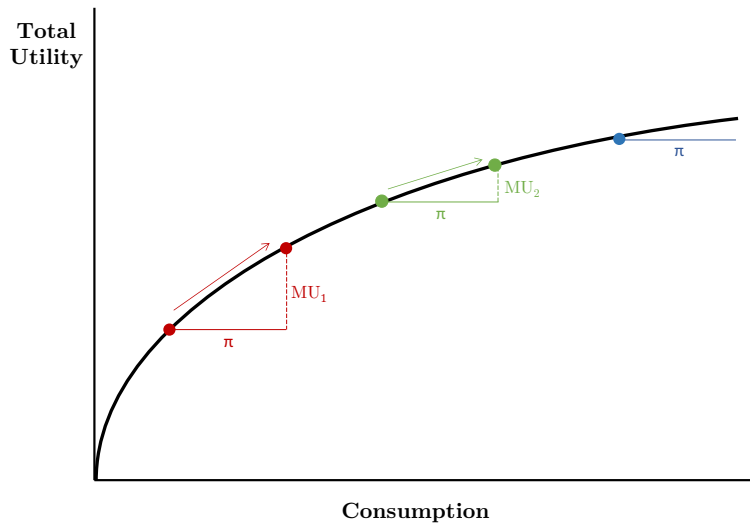
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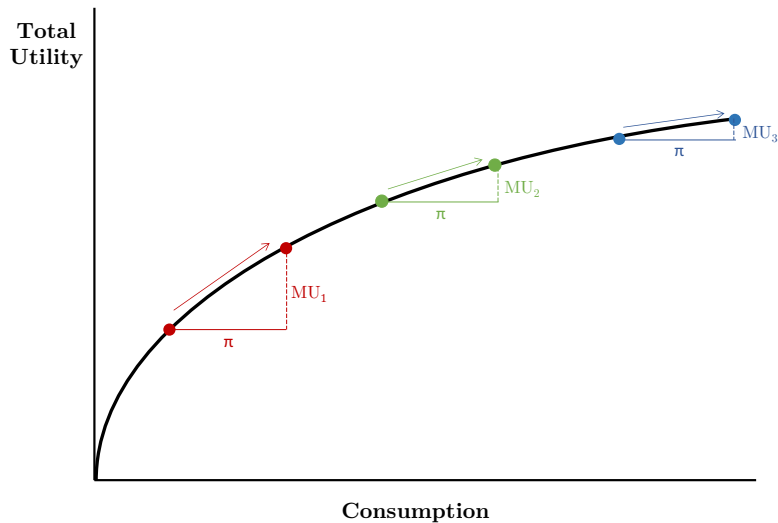
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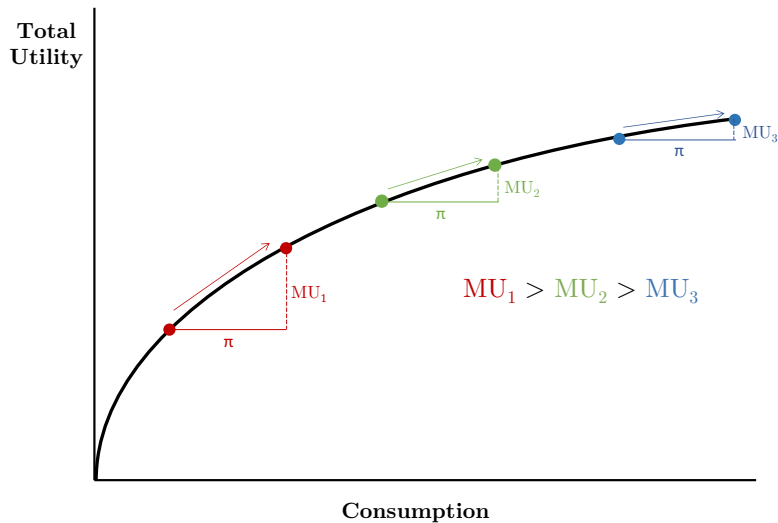
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- ▶ **Effectiveness of current climate investments** in mitigating future harm

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- ▶ Suppose the project starts at **time 0** and offers uncertain returns at some future date **F**.
- ▶ Skipping some steps, we can solve for the required expected return r_E on the environmental asset (based on a standard CAPM model):

$$\begin{aligned} r_E &= r_f - \text{Cov}(m_F, R_F) \\ &= r_f + \beta_{m,R}(r_M - r_f) \\ &= r_M + (\beta_{m,R} - 1)(r_M - r_f). \end{aligned}$$

▶ Details

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If $\beta_{m,R} < 1$ then $r_E < r_M$ (below market rate).

- ▶ The usual risk-return interpretation holds:
 - ▶ Like gold or bonds, the environmental asset offers greater payoff than the market when m_F is high.
 - ▶ It therefore reduces risk and should have a lower than market expected return.

▶ Details

▶ Derivation

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- ▶ A typical investment project (e.g., stocks) has $\text{Cov}(m_F, R_F) < 0$. It pays off when the economy grows and m_F falls.
- ▶ But climate projects alleged to **avert disaster** may have $\text{Cov}(m_F, R_F) > 0$. They pay off precisely when WTP, m , is greatest.
 - ▶ Ex: if climate might kill people, we really want any project that stops climate change, even if the payoff is rare or low expected return. Such projects have low expected return but high market value.

▶ Details

▶ Derivation

Scalable investments warrant low discount rates

- ▶ Scalable technologies are critical in mitigating extreme climate outcomes.
- ▶ They are likely to warrant low rates of discount because they can greatly reduce the risk of extreme climate outcomes. So they pay dividends when WTP or m is highest.
 - ▶ Ex: Geoengineering

Roadmap

① Climate change is best examined with cost-benefit analysis

- Carbon policy as an exhaustible resource problem
- The role of innovation

② The central role of discounting

- What is the correct discount rate?
- Differences in discount rates across countries

③ Welfare impacts of climate change

- Imminence of climate shocks
- Uncertainty of climate shocks
- Heterogeneity across countries
- Mortality risk

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Which countries have higher m under climate change?

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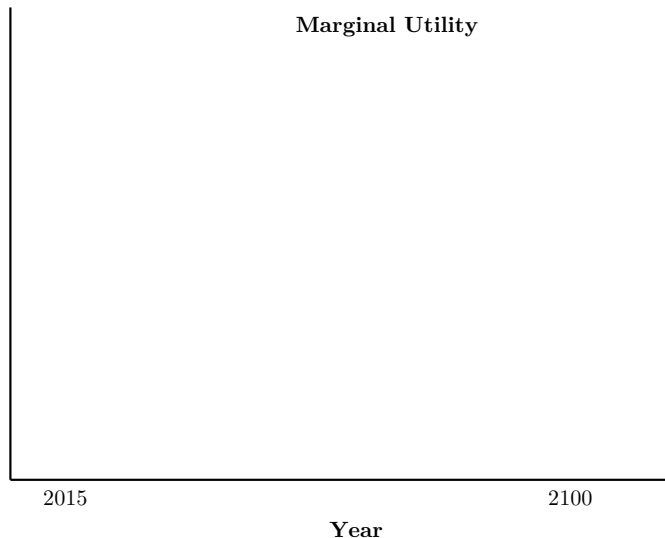
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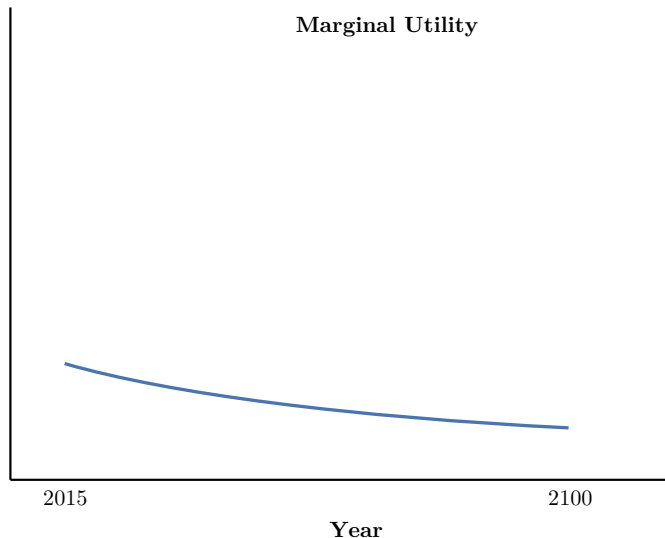
We can compute these marginal utilities, assuming:

- ▶ **USA:** $I_{2015} = \$60000$, $r = 1\%$
- ▶ **China:** $I_{2015} = \$10000$, $r = 3\%$

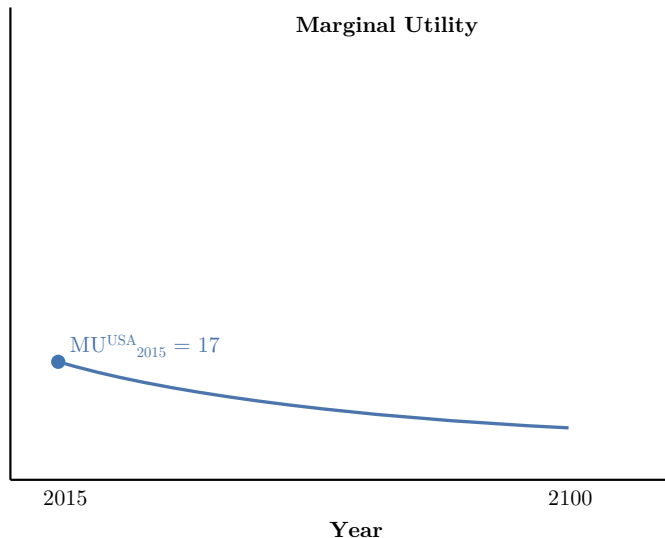
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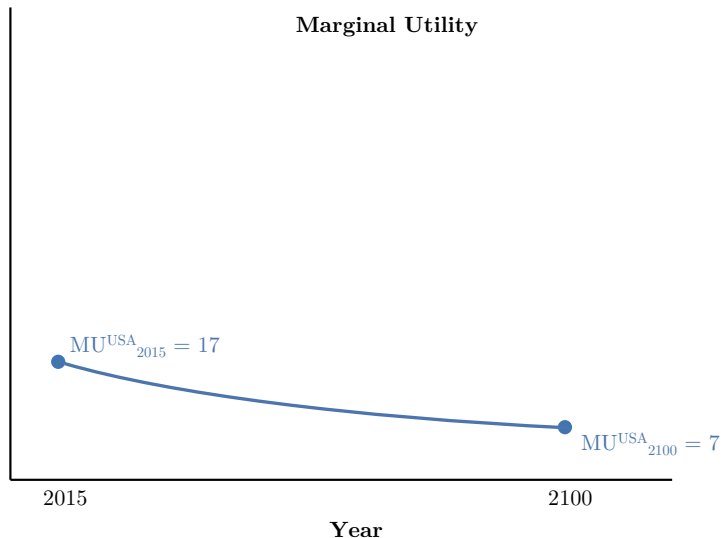
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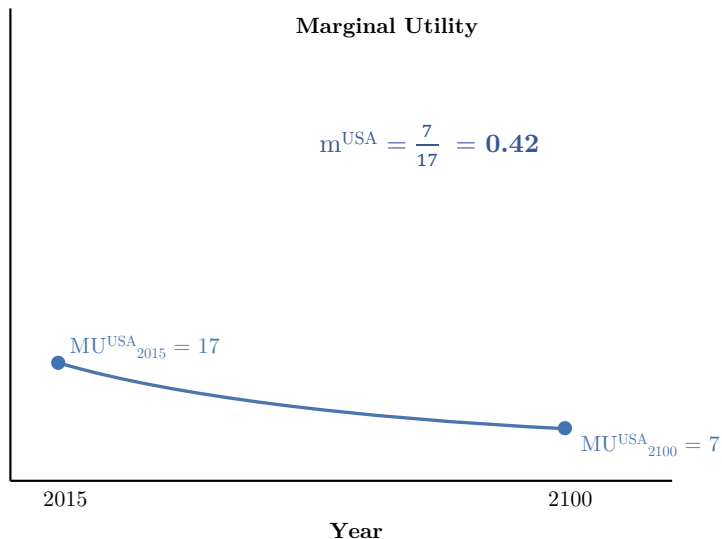
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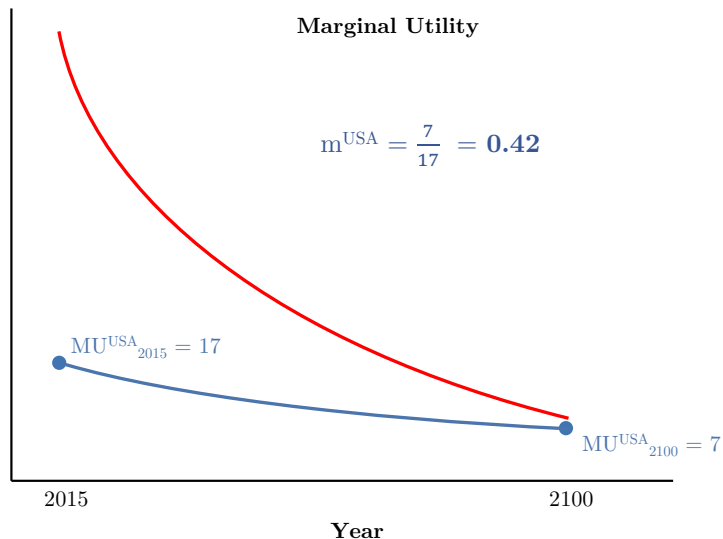
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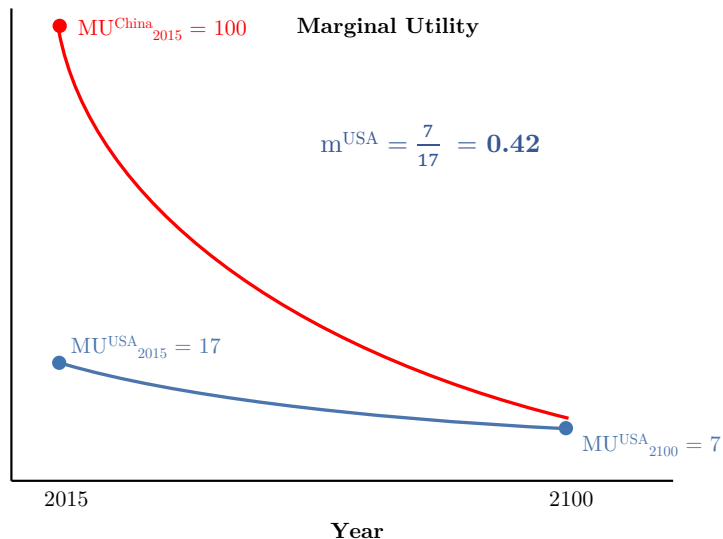
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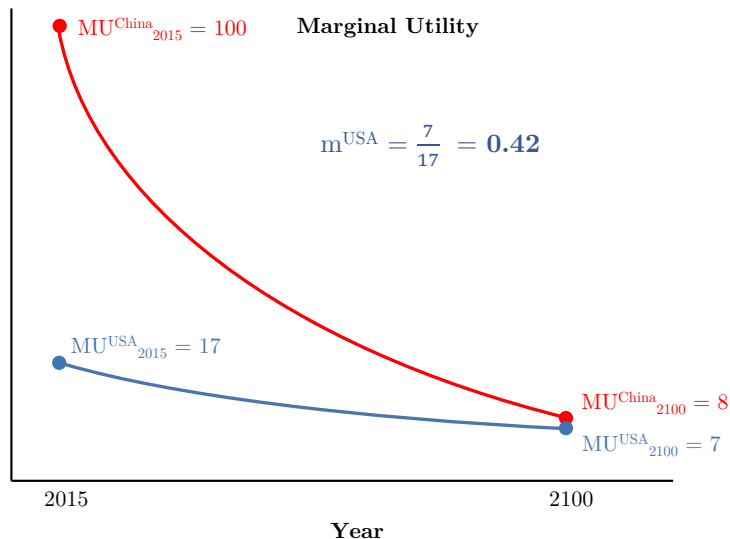
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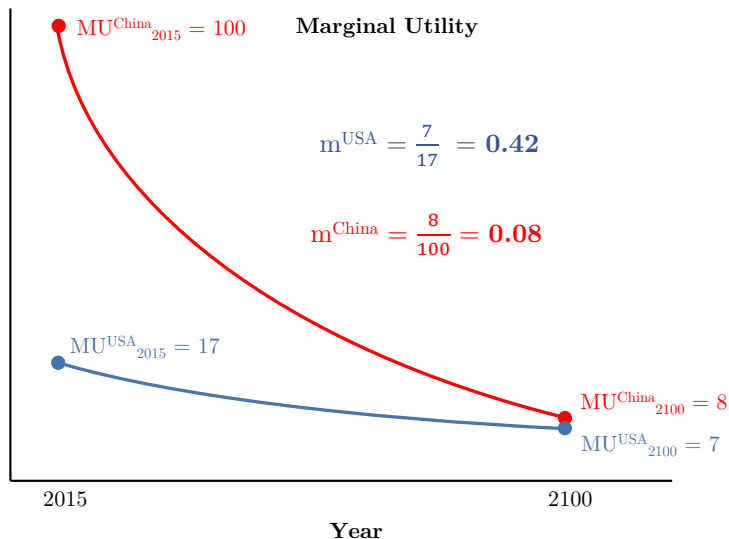
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Developing countries may therefore value mitigation less

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- ▶ Climate projects valued highly by the US because of strong insurance properties (i.e., they payoff in the bad state of the world) may have little value to China.
- ▶ In a world with greater climate damage, China gets rich and they're willing to bear the future cost that US would like to avoid.

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- ▶ The tension is that China (or India) rationally prefers low carbon tax so it can get rich. US wants high carbon tax as insurance for wealth.
- ▶ This dynamic makes settling upon **global** climate policy very challenging, especially when the politics of redistribution are very poor.

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Intuition: by making China richer today, the US can encourage China to “**think like a rich country**” when making climate investments

We can bound the desired compensation

At a minimum, China would accept the present value of its foregone consumption:

$$\sum_{t=2012}^{2100} \frac{c_{0t} - c_{1t}}{(1 + r_t)^t},$$

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- ▶ If the US pays the SCC to mitigate emissions itself, it will happily pay the same amount for reductions elsewhere

Substantial room for Pareto-enhancing payments in practice

Lower bound: value of foregone Chinese consumption, per ton of CO_2

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Table: Cost per ton of CO_2 abated

Impact on GDP	$\omega = 2$	$\omega = 3$	$\omega = 4$
Low	\$1.38	\$0.68	\$0.40
Moderate	\$3.89	\$1.57	\$0.81
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- ▶ Recent estimates (Climate Impact Lab): **\$14 - \$22** per ton solely due to mortality

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- ▶ We should choose climate mitigation projects for which the returns exceed the opportunity cost of the investment (in other words, the market return). **In applying a discount rate, we account for these opportunity costs.**

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- ▶ In choosing a benchmark market return, we should use an asset with a similar structure of risks and payoffs to a climate investment.
 - ▶ If climate mitigation pays off during potential catastrophes, we should use a low-return asset (e.g. bonds or gold) that similarly pays when the MU of consumption is high.
 - ▶ If mitigation magnifies growth, we should use a higher-return asset (such as stocks) that pays only when the economy is growing and the MU of consumption is low.
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 - ▶ If mitigation magnifies growth, we should use a higher-return asset (such as stocks) that pays only when the economy is growing and the MU of consumption is low.
- ▶ Global agreement on climate policy is greatly hampered by different societies (e.g., India/China vs. US/EU) having different marginal rates of substitution between future and present consumption, and therefore different discount rates.
 - ▶ Since developed countries value future payoffs more, there is scope for incentivizing mitigation through Pareto-improving transfers from developed to developing countries.

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- Carbon policy as an exhaustible resource problem
- The role of innovation

2 The central role of discounting

- What is the correct discount rate?
- Differences in discount rates across countries

3 Welfare impacts of climate change

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Valuing costs of future catastrophic outcomes

Start with standard infinite horizon model of intergenerational utility with certainty:

$$U_0 = \int_0^{\infty} u(c_t) e^{-\rho t} dt$$

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$$r = \rho + \omega g$$

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- ▶ Note $d \ln c / (r - g)$ is the damage valued at time T due to reductions from T to ∞ .
- ▶ Then $e^{-(r-g)T}$ discounts the date T value to the present, allowing for growth.

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$$\text{PDV of damages} = c_0 * e^{-(r-g)T} * \frac{d \ln(c)}{r - g}$$

Table: Climate damages based on timing

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Key point: Uncertainty increases damages and motivates more immediate action

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- ▶ At its core, this approach is derived from the representative agent view of the world where the damages are spread equally across the future population.
- ▶ Recall climate change is likely to have heterogeneous impacts.
 - ▶ The impacts in Oslo will be very different than in India or Miami.

Climate change's impacts are likely to be heterogeneous around the world

- ▶ Micro-founded estimates by the Climate Impact Lab (previewing tomorrow's lecture) suggest that the mortality impacts of increasing temperatures vary across countries.

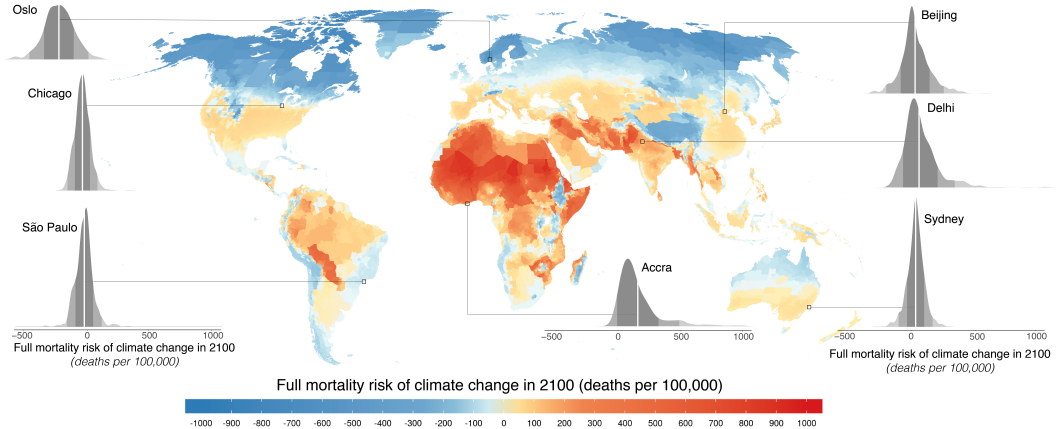
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 - ▶ Mortality risk includes both increased deaths **and** additional costs of adaptation to avert further mortality (e.g. ACs).
- ▶ Accounting for uncertainty in future climate and in the climate-mortality relationship, some tail risk of extremely high mortality.

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For example, suppose that $\omega = 2$ and that a share $s = 2\%$ of population suffers an income loss $d \ln c = 0.5$. Then:

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The key is that $r - g$ **is halved** when we suffer such a large income loss, which increases damages (use Ramsey equation to derive change in $r - g$).

Roadmap

① Climate change is best examined with cost-benefit analysis

- Carbon policy as an exhaustible resource problem
- The role of innovation

② The central role of discounting

- What is the correct discount rate?
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③ Welfare impacts of climate change

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Takeaway: mortality increases PDV of damages dramatically.

Welfare costs of mortality differ across countries

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- ▶ **Intuition:** Every day, we trade off current consumption and investments in avoiding death.
 - ▶ As we grow richer, we obtain less utility from consumption at the margin $u'(c)$.
 - ▶ Since we value consumption less, we value the alternative (avoiding death) higher on the margin

Damages with mortality and an increasing VSL

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- ▶ So randomly occurring event with mortality impact has current value

$$\frac{1}{c_0} \frac{dU_0}{u'(c_0)} = \frac{\Phi(c_0)}{1 + (r - \zeta g)T} \frac{1}{r - \zeta g} d \ln c$$

where ζ is the income elasticity of VSL.

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$$\text{PDV of damages} = \frac{dU_0}{u'(c_0)} = c_0 \frac{\Phi(c_0)}{1 + (r - \zeta g)T} \frac{1}{r - \zeta g} d \ln c$$

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2. They are **uncertain**, because impacts could occur soon even if they are expected many years from now
3. They are **concentrated**, since each additional reduction in individual consumption has a higher marginal utility loss
4. They involve higher mortality, which result in utility losses equivalent to the full value of a statistical life (VSL)

Roadmap

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Key takeaways

- ▶ A **price on carbon**, equal to the marginal cost of emitting and mitigating a ton of CO₂, allows us to maximize welfare while capping CO₂ emissions.
 - ▶ When the atmosphere helps absorb CO₂, carbon prices start low since we want to pollute early on.
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 - ▶ As carbon prices rise, they incentivize innovation, allowing us to address climate change at a lower cost.
- ▶ Discount rates matter enormously for carbon prices and climate mitigation investments. **We should set discount rates based on market rates but incorporating insurance value (when they pay off).**
 - ▶ If climate investments insure against catastrophes, lower returns – like on bonds or gold – are appropriate.

Key takeaways

- ▶ Relative to the US, China and India **rationally prefer their outside option** to investments in climate mitigation.
 - ▶ Rapidly growing developing countries will heavily discount benefits of future mitigation.
 - ▶ The result is limited global agreement on climate policy.

Key takeaways

- ▶ Relative to the US, China and India **rationally prefer their outside option** to investments in climate mitigation.
 - ▶ Rapidly growing developing countries will heavily discount benefits of future mitigation.
 - ▶ The result is limited global agreement on climate policy.
- ▶ Damages from climate change will be most severe if they **arrive soon**, if they are **uncertain**, if they are **concentrated** among certain populations, and if they involve **higher mortality** rather than small changes in consumption.

Roadmap

4 Appendix

Expected returns in an asset pricing framework

Consider a project at time 0 that pays off at future date F .

- ▶ We can purchase λ units at cost $K(\lambda)$, let $K'(\lambda) = k(\lambda)$.
- ▶ Uncertain returns of x per unit (e.g. lower GHG concentrations).

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Social planner's problem is

$$\max_{\lambda} u(y_0 - K(\lambda), \psi_0) + \rho \mathbb{E}[u(y_F(\lambda x), \psi_F(\lambda x))].$$

- ▶ y = consumption.
- ▶ ψ = state of environment.
- ▶ $\rho < 1$ pure time preference between $t = 0$ and $t = F$.
- ▶ $\mathbb{E}$ reflects uncertainty about the joint distributions of y, ψ, x .
- ▶ **Notice** social valuations may differ across countries.

Expected returns in an asset pricing framework

Social planner's problem is

$$\max_{\lambda}$$

Intuition:

maximize

► [Return](#)

Expected returns in an asset pricing framework

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Intuition:

maximize utility from current consumption and environmental quality

► [Return](#)

Expected returns in an asset pricing framework

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Intuition:

maximize utility from current consumption and environmental quality + discounted expected utility from future consumption and environment

► [Return](#)

Define marginal benefit of investment

Define X_F as future generations' value of income and environmental payoffs on a marginal investment λ :

$$\begin{aligned} X_F &= \frac{\partial y_F}{\partial \lambda} + \left(\frac{\partial u / \partial \psi_F}{\partial u / \partial y_F} * \frac{\partial \psi_F}{\partial \lambda} \right) \\ &= (y'_F + v'_F \psi'_F) \lambda \end{aligned}$$

where y'_F is derivative of income and $v'_F = u'_\psi / u'_y$ is future WTP for environmental improvement.

► [Return](#)

Define marginal benefit of investment

The present value of (expected) marginal benefit X_F is therefore:

$$\mathbb{E}[m_F X_F]$$

where $m_F = \frac{\partial u / \partial c_F}{\partial u / \partial c_0}$ is marginal rate of substitution between future and current c .

A high m_F implies the future is **bad** relative to the present.

► Return

Equate marginal benefit and cost in equilibrium

We can now equate marginal benefit and marginal cost $k(\lambda)$ to obtain optimal λ :

$$k(\lambda) = \mathbb{E}[m_F X_F] =$$

The marginal benefit has two parts:

► [Return](#)

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- ▶ $e^{-r_f} \mathbb{E}[X_F]$ is expected marginal benefit at the **risk-free rate** r_f .

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$$k(\lambda) = \mathbb{E}[m_F X_F] = e^{-r_f} \mathbb{E}[X_F] + \text{Cov}(m_F, X_F)$$

The marginal benefit has two parts:

- ▶ $e^{-r_f} \mathbb{E}[X_F]$ is expected marginal benefit at the **risk-free rate** r_f .
- ▶ $\text{Cov}(m_F, X_F)$ is the interesting part.
 - ▶ If $\text{Cov}(m_F, X_F) > 0$, climate investment pays off more in **bad** states of the world when the benefits are more valuable.

▶ Return

What is the expected return on the investment?

- ▶ Let $R_F = X_F/k(\lambda)$ be the (uncertain) marginal returns per dollar invested in the environmental project.
- ▶ Let $r_E = \mathbb{E}[R_F]$ be the expected return we should accept.

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Solving for r_E yields familiar CAPM set-up for required expected returns on investment:

$$\begin{aligned}r_E &= r_f - \text{Cov}(m_F, R_F) \\&= r_f + \beta_{m,R}(r_M - r_f) \\&= r_M + (\beta_{m,R} - 1)(r_M - r_f).\end{aligned}$$

where:

- ▶ r_M is the market return on equities.
- ▶ $r_M - r_f = \text{Var}(m)$, or equity premium.
- ▶ $\beta_{m,R} = \frac{-\text{Cov}(m,R)}{\text{Var}(m)}$ = beta of environmental project.
 - ▶ Note we have expressed β in terms of covariance of R with m instead of more traditional covariance with income to reflect that u depends on environment.