Climate Change:

Uncertainty and Economic Policy

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Dutch National Bank Research Conference

Uncertainties and Nonlinearities:

Policy Challenges and New Perspectives

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Quantitative Storytelling

Use mathematical models with numerical inputs to further our understanding and support policy analysis.

Ingredients:

- substantive knowledge
- formal models
- empirical evidence

Where does Uncertainty emerge?

Quantitative storytelling with multiple stories

- multiple models give rise to multiple "stories" with different implications
- each model has random impulses and requires numerical inputs
- each model is an abstraction: stories not intended to be detailed recordings of actual histories or complete descriptions of reality

Dangers of Being Naive

The Cheat, Georges de La Tour

Conceptual Tools

- ▷ decision theory under uncertainty - how to make “sensible” or “rational” decisions
  - ○ statistics
  - ○ control theory
  - ○ economics
- ▷ asset valuation under uncertainty
  - ○ “assets” include financial, physical, human, organizational and environmental “capital”
  - ○ associated with each asset is a prospective sequence of net payoffs to investments

  How do we assess the investment opportunities in the face of uncertain future net payoffs?

decision-making and valuation are symbiotically linked

Navigating Uncertainty

Probability models we use in practice are misspecified, and there is ambiguity as to which among multiple models is the best one.

- Aim of robust approaches:
  - use models in sensible ways rather than discard them
  - use probability and statistics to provide tools for limiting the type and amount of uncertainty that is entertained
- aversion - dislike of uncertainty about probabilities over future events
- implementation - target the uncertainty components with the most adverse consequences for the decision maker

Uncertainty, climate change and economic valuation

- market valuation fails to account for full social impact of human inputs on the climate
- uncertainty can have a big impact on the measurement of the social cost of carbon - an idealized target defined formally as a socially efficient (Pigouvian) tax
- two interacting sources of uncertainty
  - impact of CO_2 emissions on temperature changes - geophysics
  - impact of temperature changes on well being - economics

Climate Science and Uncertainty

> *... the eventual equilibrium global mean temperature associated with a given stabilization level of atmospheric greenhouse gas concentrations remains uncertain, complicating the setting of stabilization targets to avoid potentially dangerous levels of global warming.*

Citation: Allen *et al*: 2009

Climate Impacts

Climate literature suggests an approximation that simplifies discussions of uncertainty and its impact.

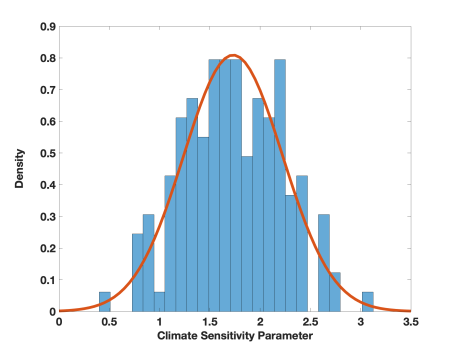
- ▷ Matthews *et al* and others have purposefully constructed a simple "approximate" climate model:

$$T_t - T_0 \approx \beta \int_0^t E_\tau d\tau = \beta_f F_t.$$

- ▷ F cumulates (adds up) the emissions over time.
- ▷ Abstract from transient changes in temperature.

Emissions today have a permanent impact on temperature in the future where β is a climate sensitivity parameter.

Climate Sensitivity Uncertainty



Histograms and density for the climate sensitivity parameter across models. Evidence is from MacDougall-Swart-Knutti (2017).

Carbon Budgeting

Some in the climate science community and elsewhere argue for a carbon budgeting approach as a simplified way to frame the discussion of environmental damages.

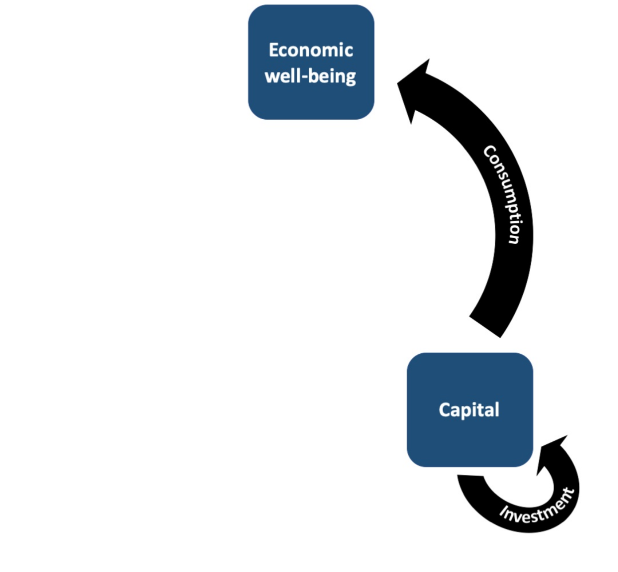
- exploit the Matthews approximation linking emissions to temperature
- design policy to enforce a Hotelling-like restriction on cumulative carbon emissions because of climate impact

Still must confront uncertainty: the constraint should be because it depends on the unknown climate sensitivity parameter.

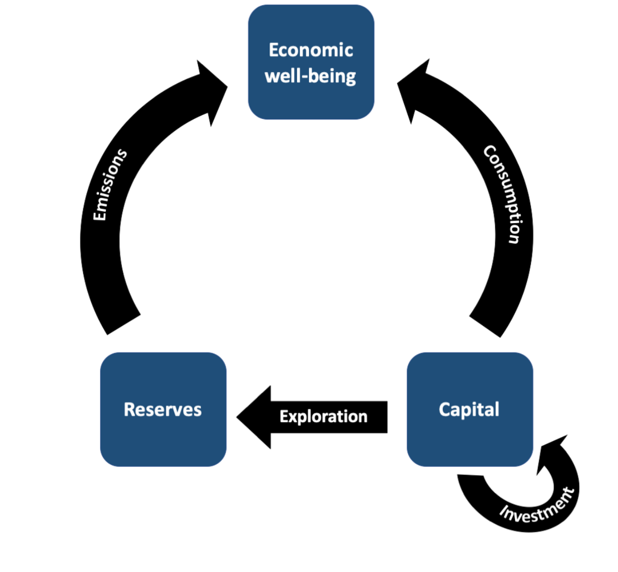
Beyond Carbon Budgeting

- explicitly model economic dynamics
- incorporate economic "damages" to measure the social cost climate change on the economic environment
- treat formally uncertainty and its interconnected components

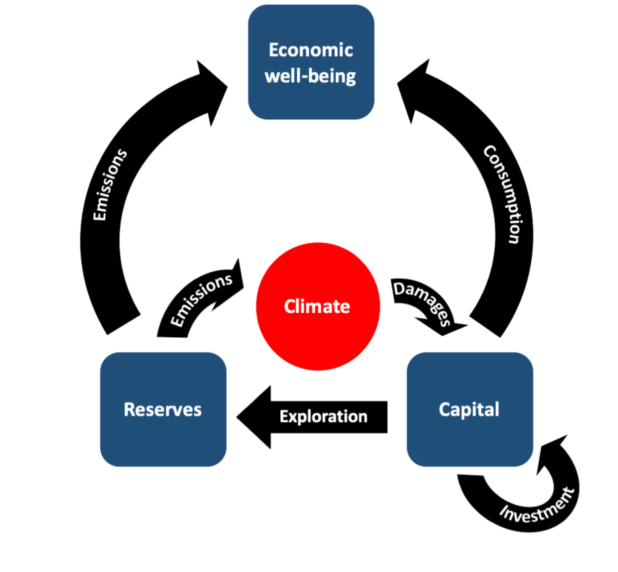
Modeling Framework



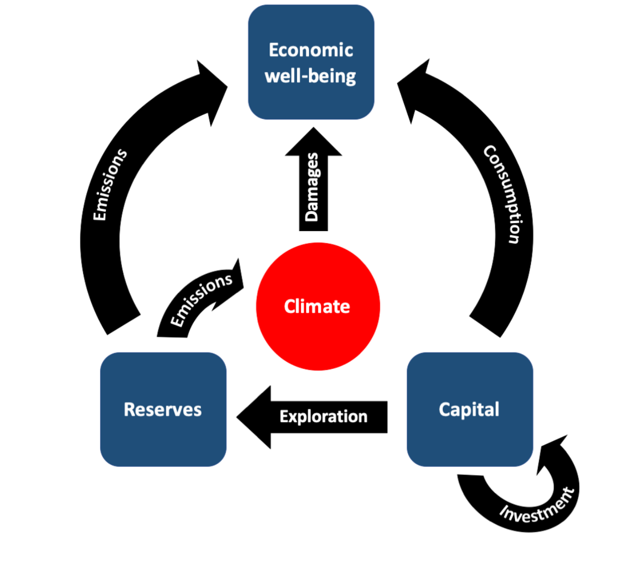
Modeling Framework



Modeling Framework



Modeling Framework



Economic Environment: Information

- $W \doteq \{W_t : t \geq 0\}$ is a multivariate standard Brownian motion and $\mathcal{F} \doteq \{\mathfrak{F}_t : t \geq 0\}$ is the corresponding Brownian filtration with $\mathfrak{F}_t$ generated by the Brownian motion between dates zero and t.
- Let $Z \doteq \{Z_t : t \geq 0\}$ be a stochastically stable, multivariate forcing process with evolution:

$$dZ_t = \mu_z(Z_t)dt + \sigma_z(Z_t)dW_t.$$

Economic Environment: Production

AK model with adjustment costs

- Evolution of capital K

$$dK_t = K_t \left[\mu_k(Z_t)dt + \phi_0 \log \left(1 + \phi_1 \frac{I_t}{K_t} \right) dt + \sigma_k \cdot dW_t \right].$$

  where I_t is investment and $0 < \phi_0 < 1$ and $\phi_1 > 1$.

- Production

$$C_t + I_t + J_t = \alpha K_t$$

  where C_t is consumption and J_t is investment in the discovery of new fossil fuel reserves.

Economic Environment: Reserves

- Reserve stock, R, evolves according to:

$$dR_t = -E_t dt + \psi_0 (R_t)^{1-\psi_1} (J_t)^{\psi_1} + R_t \sigma_R \cdot dW_t$$

  where $\psi_0 > 0$ and $0 < \psi_1 \leq 1$ and E_t is the emission of carbon.
- Hotelling fixed stock of reserves is a special case with $\psi_0 = 0$.

Economic Impacts of Climate Change

Explore three specifications:

i) adverse impact on societal preferences

ii) adverse impact on production possibilities

iii) adverse impact on the growth potential

Measurement challenges

- ▷ little historical experience to draw upon
- ▷ impacts are likely different for regions of the world that are differentially exposed to climate change
- ▷ potentially big differences between long-run and short-run consequences because of adaptation

Damage Specification

Posit a damage process, D, to capture negative externalities on society imposed by carbon emissions.

$$\log D_t = \Gamma(\beta F_t) + \nu_d(Z_t)$$

where in our illustration, for $y \leq \overline{\gamma}$:

$$\Gamma(y) = \gamma_1 y + \frac{\gamma_2}{2} y^2$$

with an additional penalty for $y > \overline{\gamma}$:

$$\frac{\gamma_2^+}{2} \left(y - \overline{\gamma}\right)^2 .$$

- γ_2 gives a nonlinear damage adjustment
- $\gamma_2^+ > 0$ gives a smooth alternative to a carbon budget
- damage evolution deduced by Ito's formula

Uncertainty in the economic damages (Γ) and climate sensitivity (coefficient β) multiplies!

Proportional damages

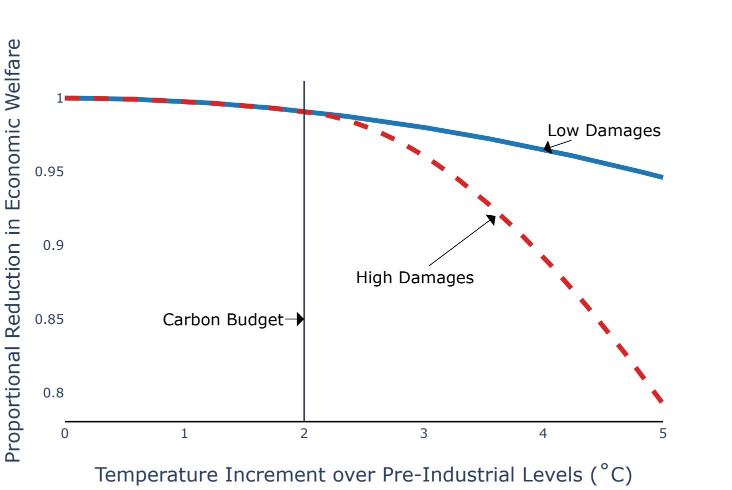
- the per period (instantaneous) contribution to preferences is:

$$\delta(1-\kappa)\left(\log C_t - \log D_t\right) + \delta\kappa \log E_t$$

  where $\delta > 0$ is the subjective rate of discount and $0 < \kappa < 1$ is a preference parameter that determines the relative importance of emissions in the instantaneous utility function.

- equivalently this is a model with proportional damages to consumption and or production.

Proportional Damage Uncertainty



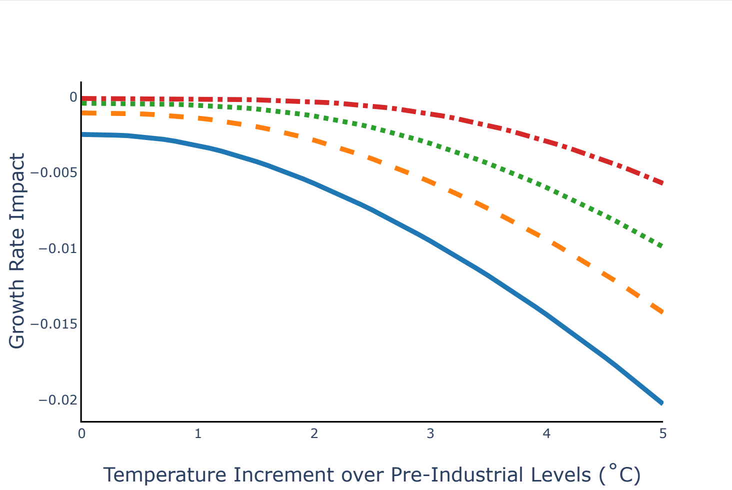
Damages to Growth

Climate change diminishes growth in the capital evolution:

$$dK_t = K_t \left[\mu_k(Z_t)dt - \log D_t dt + \phi_0 \log \left(1 + \phi_1 \frac{I_t}{K_t} \right) dt + \sigma_k \cdot dW_t \right]$$

- ▷ no threshold
- ▷ no extra penalty ($\gamma_2^+ = 0$).

Growth-Rate Damage Uncertainty



Quintiles from Burke et al (2018)

Uncertainty in Decision Making

Explore three components to uncertainty:

- risk - uncertainty *within* a model: uncertain outcomes with known probabilities
- ambiguity - uncertainty *across* models: unknown weights for alternative possible models
- misspecification - uncertainty *about* models: unknown flaws of approximating models

We incorporate these explicitly into the social planning problem and to assess the quantitative impact on the solution.

Decision Theory I

Ambiguity over alternative (structured) models and concerns about model misspecification. Hansen-Sargent (2019) show how to combine two approaches:

- Chen- Epstein (2002) recursive implementation of max-min utility model axiomatized by Gilboa-Schmeidler(1989). Confront structured model uncertainty.
- Hansen-Sargent (2001) a recursive penalization used to explore model misspecification building on robust control theory.

Decision Theory II

Hansen-Miao (2018) propose a recursive implementation of the smooth ambiguity model in continuous time. Discrete time version originally axiomatized by Klibanoff-Marinacci-Mukerji (2005).

- ambiguity about local mean specification in the state dynamics
- axiomatic defense justifies a differential aversion to ambiguity over models
- equivalence between the smooth ambiguity and recursive robust choice of priors (Hansen-Sargent, 2007)
- additional adjustment for potential model misspecification as in Hansen and Sargent (2009)

Constructing the Adjusted Measure

- State evolution:

$$dX_t = \mu_x(X_t, A_t)dt + \sigma_x(X_t, A_t)dW_t$$

  where A is decision process.

- Girsanov transformation

$$dW_t = H_t dt + dW_t^H$$

  with dW_t^H a Brownian increment under the change of measure.

Constructing the Adjusted Measure

- For misspecification include a penalty

$$\frac{\xi_m}{2} H_t \cdot H_t$$

  and minimize.
- For structured uncertainty:
  - Chen-Epstein implementation of max-min decision theory:

$$\min_{\theta \in \Theta_t} \mu_x(X_t, A_t; \theta)$$

  - Hansen-Miao implementation of smooth ambiguity

$$-\xi_a \log E \left(\exp \left[-\frac{1}{\xi_a} \mu_x(X_t, A_t; \theta) | X_t \right] \right)$$

    where the expectation is take over θ. Equivalent to a change in the probabilities over θ with a relative entropy penalty

Social Cost of Carbon as an Asset Price

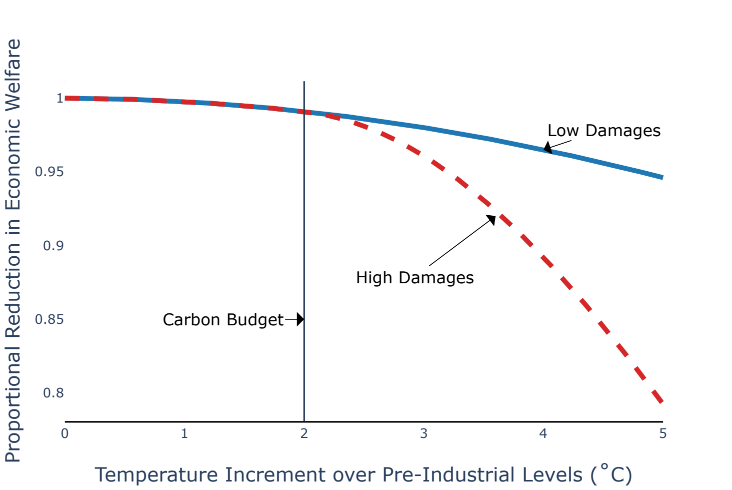
- ▷ Interpret the outcome of a robust social planner's problem
- ▷ Discounting is stochastic and adjusted to accommodate concerns for ambiguity and model misspecification
- ▷ Shadow prices are computed using an efficient allocation and not necessarily what is observed in competitive markets

Construct a decomposition of the SCC in terms of economically meaningful components.

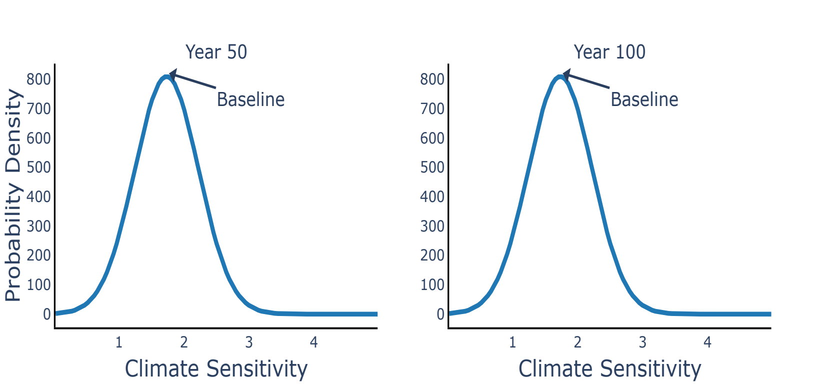
An Uncertainty Adjustment for Valuation

- Deduce uncertainty-adjusted probabilities via a max-min problem.
- Consider a social cash flow given by the impact of emissions today on future log damages
  - form nonlinear impulse responses
  - incorporate marginal utility adjustments
  - adjust for interacting uncertainty about economic damages and climate change
- compute the difference between two discounted expected value measures.
  - one integrates over the uncertainty.
  - another uses ambiguity-adjusted probabilities deduced from the planners problem
- Quantify the impact of uncertainty on the SCC (social cost of carbon).

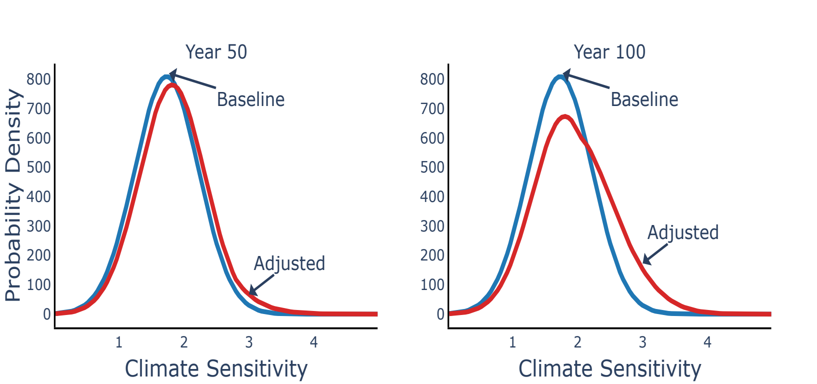
Proportional Damage Uncertainty: Reconsidered

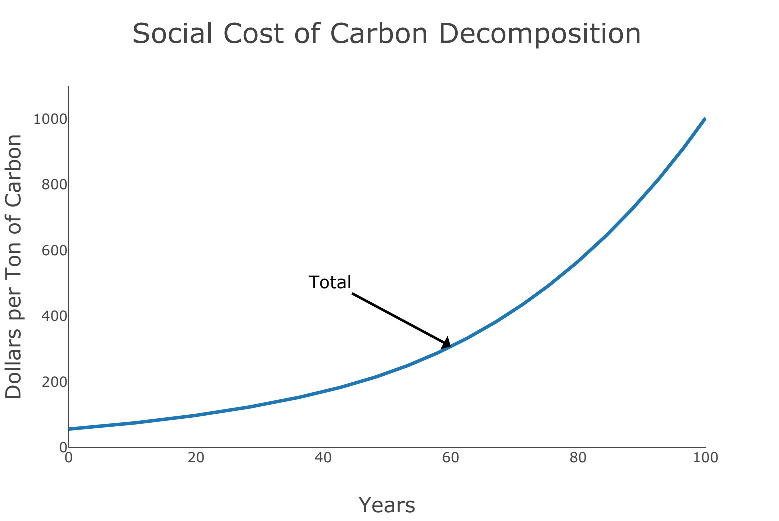


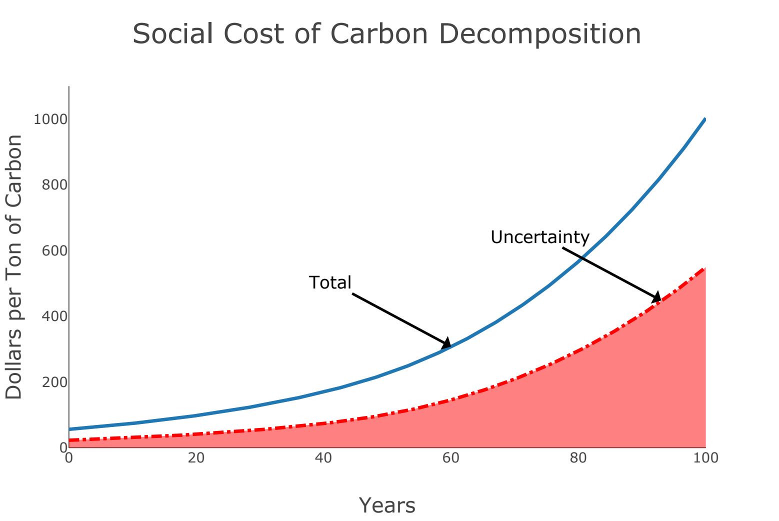
Ambiguity Adjusted Probabilities



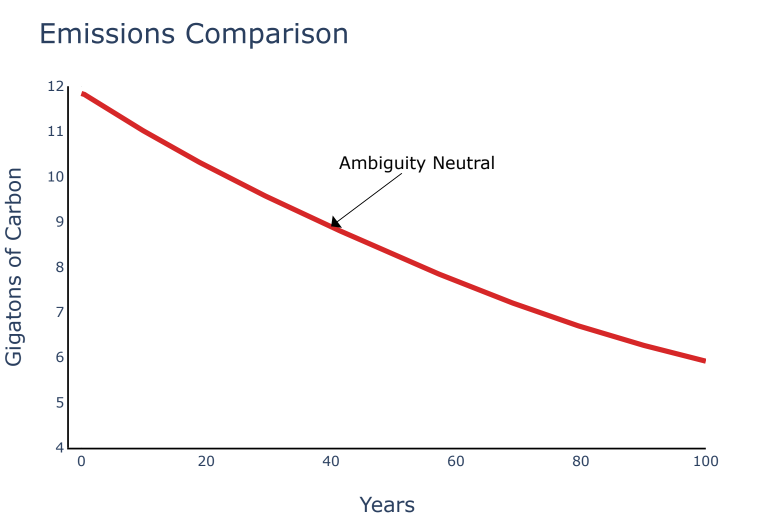
Ambiguity Adjusted Probabilities



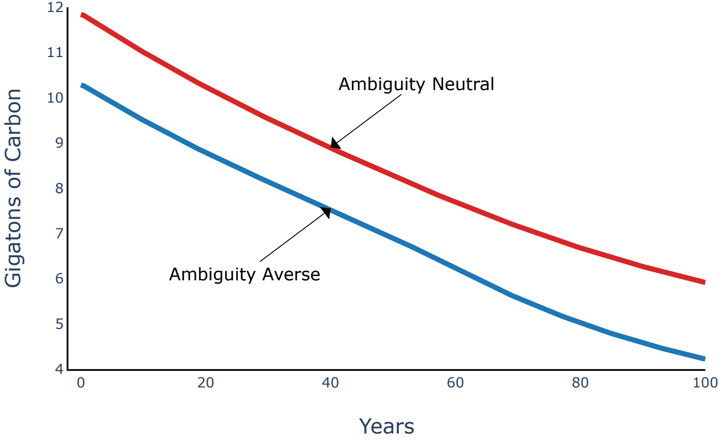

Social Cost of Carbon Decomposition
Dollars per Ton of Carbon
0
200
400
600
800
1000
0
20
40
60
80
100
Years
Total



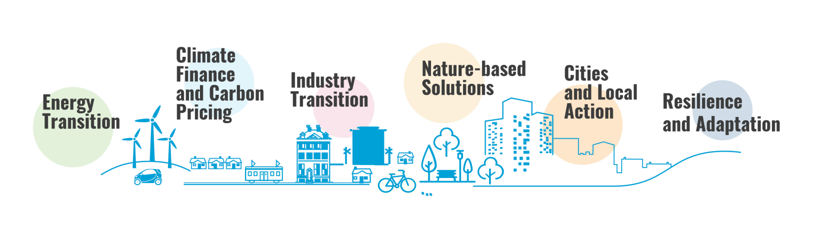
Social Cost of Carbon Decomposition
Dollars per Ton of Carbon
1000
800
600
400
200
0
0
20
40
60
80
100
Years
Total
Uncertainty


Emissions Comparison
Ambiguity Neutral
Gigatons of Carbon
12
11
10
9
8
7
6
5
4
0
20
40
60
80
100
Years

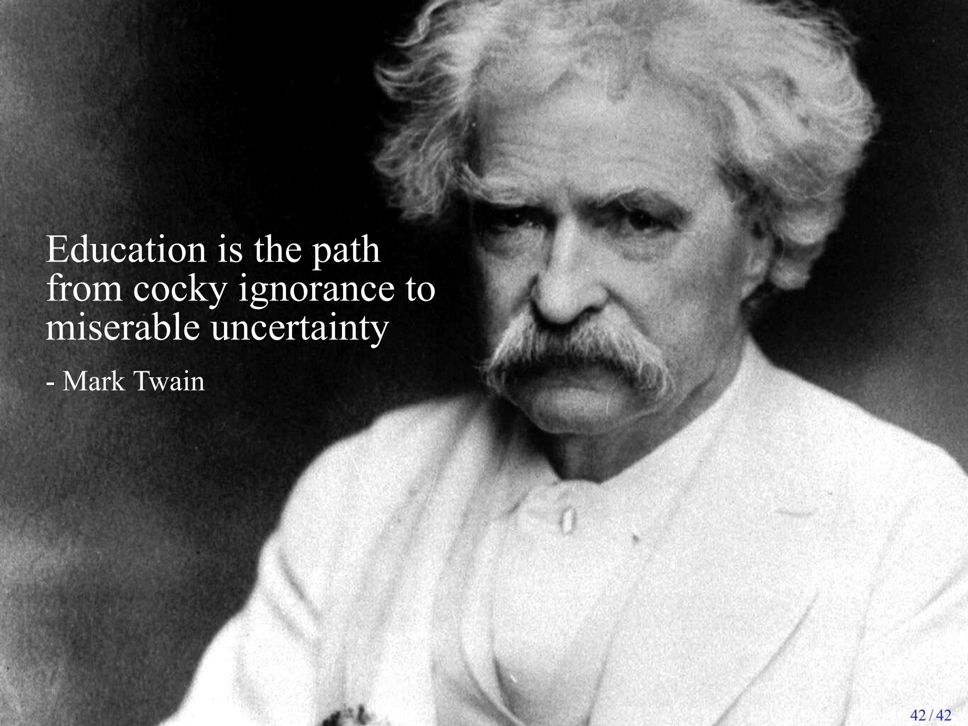
Emissions Comparison



Future Responses to Climate Change



Opens additional channels with uncertain consequences


Education is the path from cocky ignorance to miserable uncertainty
- Mark Twain