The Role of Insurance in Climate Change Mitigation: An Assessment Using the Dynamic Integrated Climate-Economy (DICE) Model

Presenter: Eugenia Fang
School of Risk and Actuarial Studies, UNSW Business School

Joint work with: Qihe Tang, Hong Li

59th Actuarial Research Conference, 20 July 2024

Outline

Outline

Climate Change and Integrated Assessment Models (IAMs)

- Escalating global temperatures brings more frequent extreme weather events, increasing economic damages and societal disruptions.
- Climate change is a complex environmental problem linking multiple physical and economic domains, requiring **integrated assessment models (IAMs)** to solve for economically efficient policies.
- **Purpose**: IAMs have been used in policy-making, particularly in evaluating the costs and benefits of different climate policies.
- **Examples**: U.S. government relies on an ensemble of three IAMs:
  - DICE: Dynamic Integrated Climate and Economy (Nordhaus, 2010)
  - FUND: Climate Framework for Uncertainty, Negotiation, and Distribution (Anthoff and Tol, 2013)
  - PAGE: Policy Analysis of the Greenhouse Gas Effect (Hope, 2013)

William Nordhaus and DICE model

Prof. William Nordhaus (Yale University) was awarded the Nobel Memorial Prize in Economic Sciences in 2018, which he shared with Paul Romer, for his efforts to develop "*an integrated assessment model, i.e. a quantitative model that describes the global interplay between the economy and the climate*".

Limitations of IAMs and Insurance

Where is insurance?

- The DICE model integrates economic theory with climate science to explore the impacts of climate change and policy interventions.
- However, it largely **overlooks** a crucial aspect of risk management: insurance.

Should insurance be included?

- Insurance has historically served as a tool for climate/catastrophe risk management.
- Insurance benefits the macro economy in several ways, e.g., economic growth; stabilization; and distribution (Kessler et al., 2017).

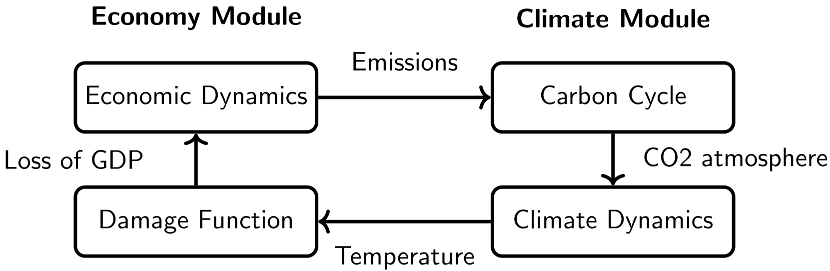
Research gap:

- Limited quantitative assessments of the impact of insurance on climate change mitigation.
- Aim to fill this gap by integrating a mandatory non-profit insurance into the DICE model.

Outline

DICE Overview

- Nordhaus has, over time, developed several successive versions of the DICE model, from the first and simplest one, DICE1992, to the latest version, DICE2023 (Barrage and Nordhaus, 2024).
- We will continue our discussion based on DICE2023, structured as below.



DICE: Objectives

Social welfare function

- The DICE model is an non-linear optimization problem (the Ramsey model).
- To maximize the objective function: social welfare function.

$$W = \sum_{t=2020}^{T\max} U[c(t)]L(t)\Pi(t) \tag{1}$$

- $t = 2020, 2025, 2030, \ldots$: Time periods.
- W: Social welfare.
- Intuition: The social welfare function is increasing in the **discounted sum** of the **population-weighted utility of per capita consumption** of each generation.

DICE: Objectives

Utility function

$$W = \sum_{t=2020}^{T\max} U[c(t)] L(t) \Pi(t) \quad (1)$$

$$U[c(t)] = \frac{c(t)^{(1-\phi)}}{1-\phi} \quad (2)$$

- $U(.)$: Utility function. Assumed to be **constant elasticity utility function**.
- $c(t)$: Per capita consumption.
- $\phi = 0.95$: The constant elasticity of the marginal utility of consumption.
- <u>Intuition</u>: Diminishing marginal utility of consumption.

DICE: Objectives

Discount factor

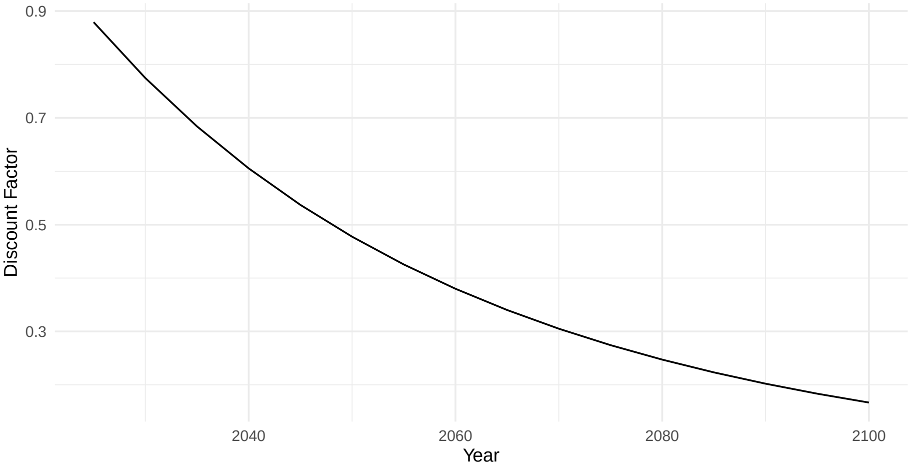
$$W = \sum_{t=2020}^{T\max} U[c(t)]L(t)\Pi(t) \tag{1}$$

$$\Pi(t) = \left(1 + \rho + \beta^{CLIM}\pi - \frac{1}{2}\phi^2\sigma_C^2 t\right)^{-t} \tag{3}$$

- $\Pi(t)$: Discount factor. The discount factor Π contains three elements.
- $\rho = 0.001/\text{yr}$ reflects the welfare weights on the utilities of different generations with a pure rate of social time preference.
- $\beta^{CLIM}\pi$ reflects the nondiversifiable risk of climate investments, with climate beta $\beta^{CLIM} = 0.5$ and capital premium $\pi = 0.05/yr$.
- $\frac{1}{2}\phi^2\sigma_C^2 t$ is a precautionary term reflecting consumption growth uncertainty.
- Intuition: The discount factors are uncertainty-adjusted social time preference.

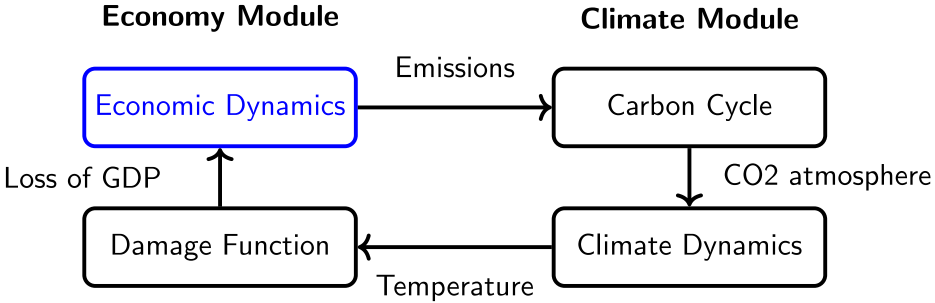
DICE: Objectives

Intuition: Strong preference for **current** period/generation.



DICE: Economic Component

- DICE2023 assumes a single global commodity, where the output can be used for either **consumption** or **investment**.
- Classic **Cobb-Douglas production function** is used, with tailored damage and abatement component.



DICE: Economic Component

Production net of damage&abatement

$$Q(t) = [1 - \Omega(t) - \Lambda(t)]Y(t) \quad (4)$$

- $Q(t)$: Global production net of damages and abatement.
- $Y(t)$: Production before deducting for climate damage and abatement cost.
- $\Omega(t)$: Climate damages (as percentage of output).
- $\Lambda(t)$: Abatement costs (as percentage of output).
- Intuition: The economy suffers from climate damage. The society can give up production/consumption today to mitigate climate change and thus increase well-being in the future through avoided climate damages.

DICE: Economic Component

Production before damage&abatement

$$Y(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{5}$$

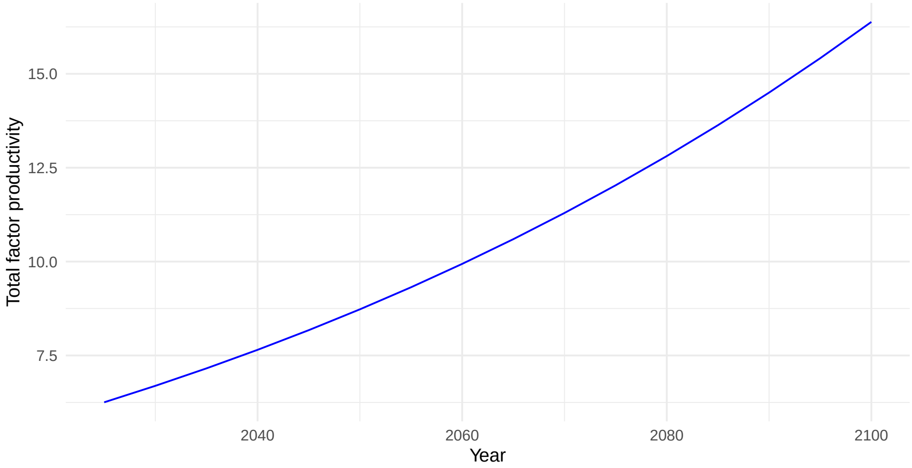
- $K(t)$: Global capital stock.
- $\gamma = 0.3$: Elasticity of capital.
- $A(t)$: Total factor productivity. Exponential growth model with a time-varying growth rate.

$$A(t+1) = \frac{A(t)}{1 - g_A(1)\exp(\delta_A \cdot t)} \tag{6}$$

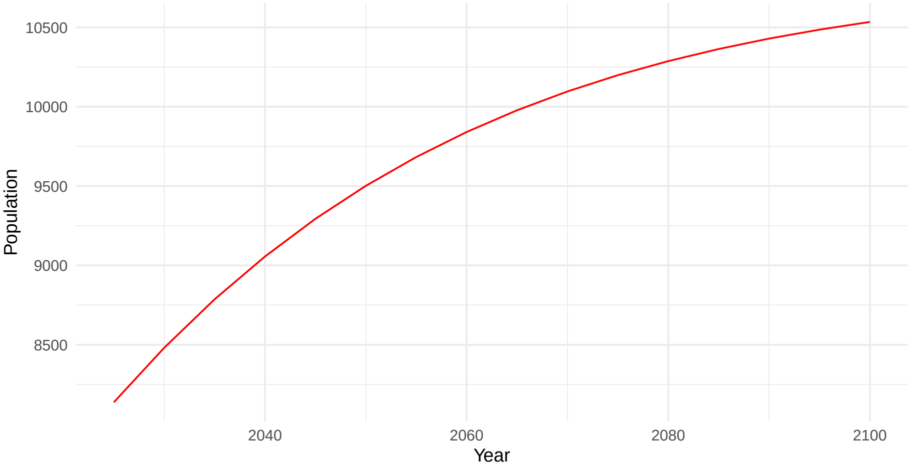
- $L(t)$: Global population and labor. The assumed growth rate declines so that total world population approaches a limit of 10.825 billion ($popasym = 10825$).

$$L(t+1) = L(t)\left(\frac{popasym}{L(t)}\right)^{popadj} \tag{7}$$

DICE: Economic Component



DICE: Economic Component



DICE: Economic Component

Capital stock and investment

$$Y(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{5}$$

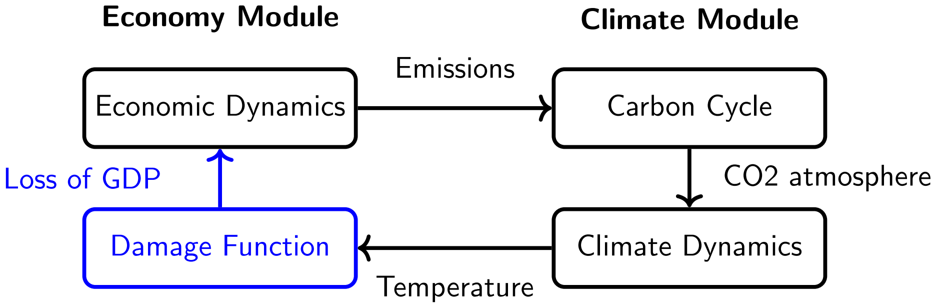
$$Q(t) = C(t) + I(t) \tag{8}$$

$$I(t) = S(t)Q(t) \tag{9}$$

$$K(t+1) = (1-\delta_K)^5 K(t) + 5 \cdot I(t) \tag{10}$$

- $C(t)$: Consumption (trillions 2019 US dollars per year).
- $I(t)$: Investment (trillions 2019 USD per year).
- $S(t)$: Gross savings rate as fraction of gross world product.
- $K(t)$: Global capital stock, with capital depreciation rate of $\delta_K = 0.1$ per year.
- Intuition: The production can be used either for consumption or investment. The investment drives the growth of capital stock.

DICE: Damage


Economy Module
Climate Module
Economic Dynamics
Emissions
Carbon Cycle
CO2 atmosphere
Loss of GDP
Damage Function
Temperature
Climate Dynamics

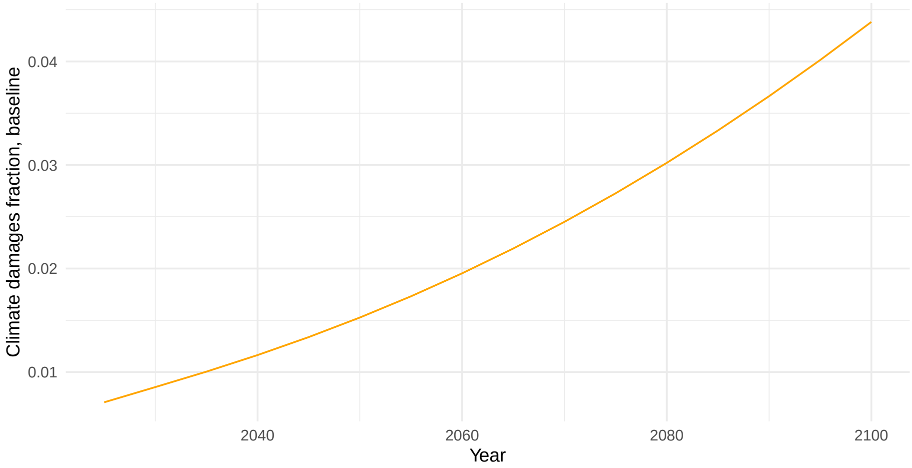
DICE: Damage

Damage function

$$\Omega(t) = \psi_1 T(t) + \psi_2 [T(t)]^2 \tag{11}$$

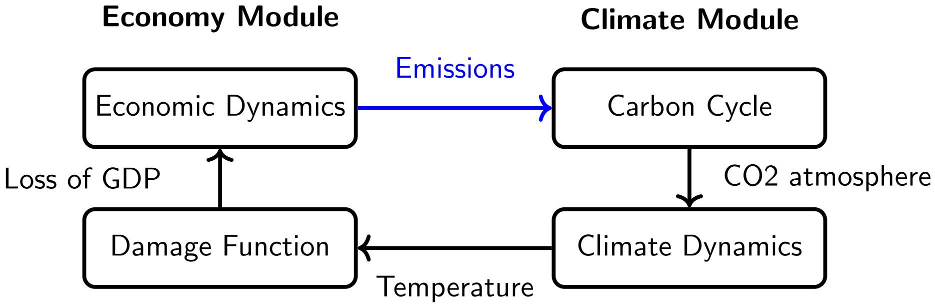
- $T(t)$: Increase in global mean surface temperature from pre-industrial levels.
- $\psi_1 = 0.0$ and $\psi_2 = 0.003467$.
- Damages are estimated to be around 3.12% of production at a 3°C global warming over pre-industrial temperatures.
- Intuition: The percentage damage in a quadratic function of temperature increase.

DICE: Damage



Climate damages fraction, baseline
0.04
0.03
0.02
0.01
2040
2060
2080
2100
Year

DICE: Abatement and Emissions



DICE: Abatement and Emissions

Abatement costs

$$\Lambda(t) = \theta_1(t)\mu(t)^{\theta_2} \tag{12}$$

- $\mu(t)$: **Emissions control rate**. The initial control rate $\mu(0) = 5\%$ for year 2020.
- $\theta_1(t)$: The fraction of output that is required to reduce emissions to zero. $\theta_1(0)$=10.9% for 2020, declining (due to technological advancements) at 1.7 percent per year from 2020 to 2100 to 2.7% of output in 2100.
- $\theta_2 = 2.6$. Abatement cost increases non-linearly with the increase in the control rate.
- Intuition: The cost of abatement is influenced by both how strict the emissions control measures are and how the costs of zero-emission technologies evolve.

DICE: Abatement and Emissions

CO2 emissions

$$ECO2(t) = [\sigma(t)Y(t) + ECO2_{Land}(t)] \cdot [1 - \mu(t)] \tag{13}$$

- $ECO2(t)$: Total CO2 emissions (GtCO2 per year).
- $\sigma(t)Y(t)$: Industrial CO2 emissions (GtCO2 per year).
- $\sigma(t)$: Industrial carbon intensity, or the emissions-production ratio. Declines initially at a rate of 1.5% per year.
- $ECO2_{Land}(t)$: The land-use (or natural) CO2 emissions (GtCO2 per year).
- $\mu(t)$: Emissions control rate.
- Intuition: CO2 emissions are from both industrial human activities and the nature. Carbon intensity parameter is used to translate industrial human activities (production) to CO2 emissions.

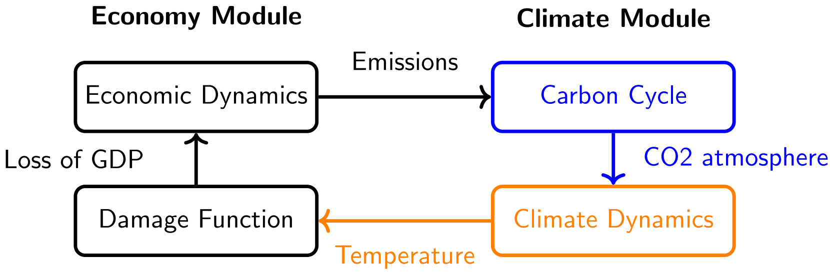
CO2-equivalent emissions

$$ECO2e(t) = [\sigma(t)Y(t) + ECO2_{Land}(t) + ECO2e_{NonCO2GHG}(t)] \cdot [1 - \mu(t)] \qquad (14)$$

- $ECO2e(t)$: Total CO2-equivalent emissions including abatable nonCO2 GHGs (GtCO2 per year).
- $ECO2e_{NonCO2GHG}(t)$: Non CO2 GHGs, such as methane, measured on a CO2-equivalent basis.
- Intuition: Other GHGs that contribute to radiative forcings are considered as well.

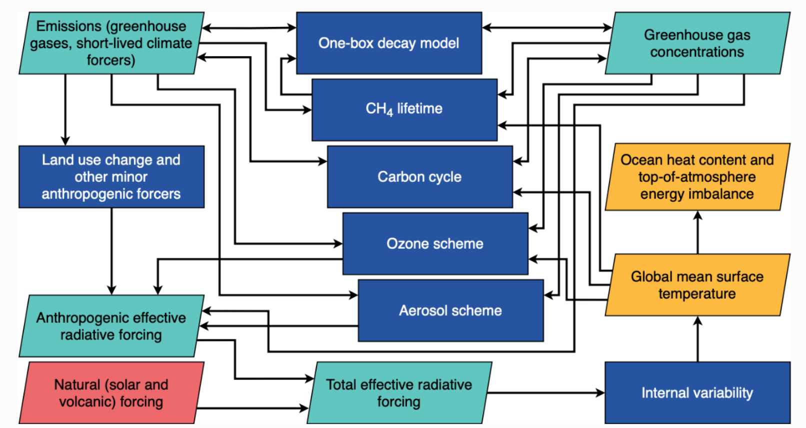
DICE: Carbon Cycle and Climate Component

- Carbon cycle module: DICE2023 modified the Finite Amplitude Impulse-Response (FAIR) model to represent the dynamics of the carbon cycle.
- Climate module: DICE2023 uses a two-box model (the surface/shallow ocean, and the deep oceans) of the temperature response to radiative forcing.



DICE: Carbon Cycle and Climate Component

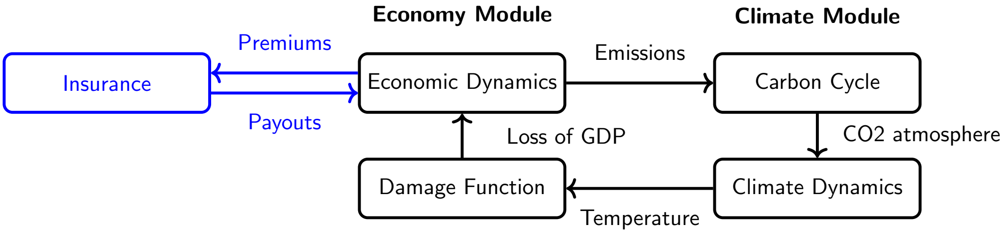
- Accumulations of GHGs - increases in radiative forcing - warming at the earth's surface.



Physical processes in FAIR model. *FAIR documentation*.

Insurance Design

- We consider a hypothetical mandatory non-profit insurance.
- **Payouts**: Proportional indemnity of climate damages.
- **Premiums**: Determined according to actuarial fairness.



Insurance Design

Payouts

$$\text{Indemnity}(t) = \delta\Omega(t)Y(t) \tag{15}$$

- δ: Insured fraction of damaged output.
- Assume the insured damages will be fully compensated by insurance payouts with no cap.

Premiums

$$\text{Premium}(t) = \theta(t)Y(t) \tag{16}$$

- $\theta(t)$: Premiums fraction of gross production. The premium fraction takes a time-varying form.
- Actuarial fair pricing: Let EPV of insurance premium = EPV of insured damage.

Production with insurance

$$Q(t) = Y(t) - \text{AbatementCost}(t) - \text{Damages}(t) + \textbf{Indemnity}(t) - \textbf{Premium}(t) \tag{17}$$

Technical Remarks

- DICE models are written in GAMS (The General Algebraic Modeling Language) and are publicly available at *Nordhaus's website*.
- More than 2,000 equations, 10s to solve.
- Regional version: The RICE model (Regional Integrated model of Climate and the Economy), calibrated to 12 regions.

GAMS

MODEL STATISTICS

BLOCKS OF EQUATIONS	35	SINGLE EQUATIONS	2,741
BLOCKS OF VARIABLES	37	SINGLE VARIABLES	2,915
NON ZERO ELEMENTS	8,054	NON LINEAR N-Z	3,061
CODE LENGTH	21,666	CONSTANT POOL	761

DICE model statistics

Outline

Random Shocks

- We introduce **random shocks** to disturb the **damage function** $\Omega(t)$.
- The distribution of shock $s_{m,t}$ should satisfy: (1) $s_{m,t} \geq 0$; (2) $E(s_{m,t}) = 1$; (3) $P(s_{m,t}\Omega(t) > 1)$ is small.
- We use **Normal** distribution with mean $= 1$ and standard deviation $= 0.3$ as a start.
- We simulate from year 2020 to year 2100 (5-year per period * $T = 16$ periods), repeat $M = 500$ rounds.
- In path m and time t, the realized indemnity is

$$\text{Indemnity}_t = \delta s_{m,t}\Omega(t)Y(t)$$

Premium

- For a specified insured fraction δ, the **time-varying premium fraction** is:

$$\theta(t) = \theta \cdot \left(t + 0.08t^2\right)$$

which is in line with the quadratic growth trend of climate damage along time.

- We report on insured fraction of 0, 40%, and 60%, where 40% represents a realistic scenario (*Munich Re*, 2023), while 60% represents an idealized scenario.

Insured frac δ	**Premium frac θ**	**Mean PV of Damages (2019\$)**	**Mean PV of Premium (2019\$)**
0	NA	NA	NA
0.4	0.00047	16.113	16.125
0.6	0.00073	25.150	25.053

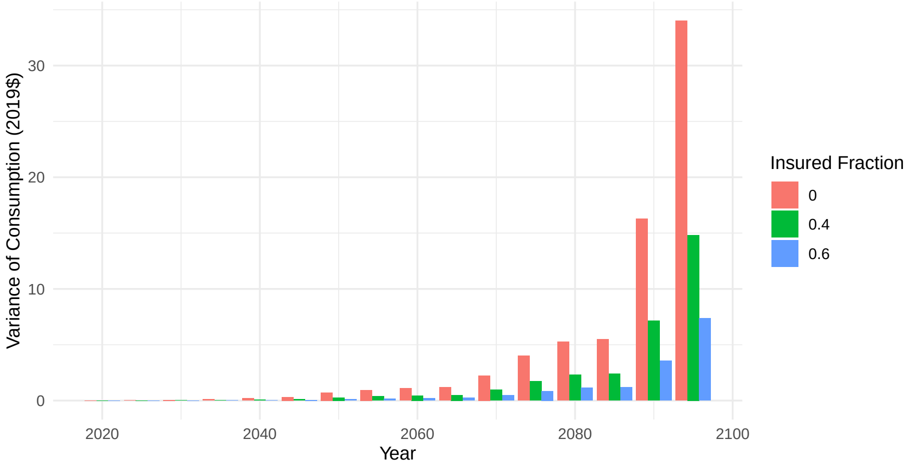
Utility Increase

- Insurance **increases** average social welfare.
- Under our setting, the optimal insured fraction with largest utility improvement is $\delta = 0.6$.
- Note that the absolute values of social welfare (utility) go not have any meaning. Utility is only meaningful for comparison.

Insured frac δ	**Mean Utility (2019$)**	**Utility increase by insurance**
0	953.538	NA
0.3	954.926	0.15%
0.4	955.395	0.19%
0.5	955.432	0.20%
0.6	955.582	0.21%
0.7	954.789	0.13%
0.8	954.152	0.06%

Stabilization

- Insurance **cuts down** the variance of consumption pathways, especially in further future.



Social Cost of Carbon

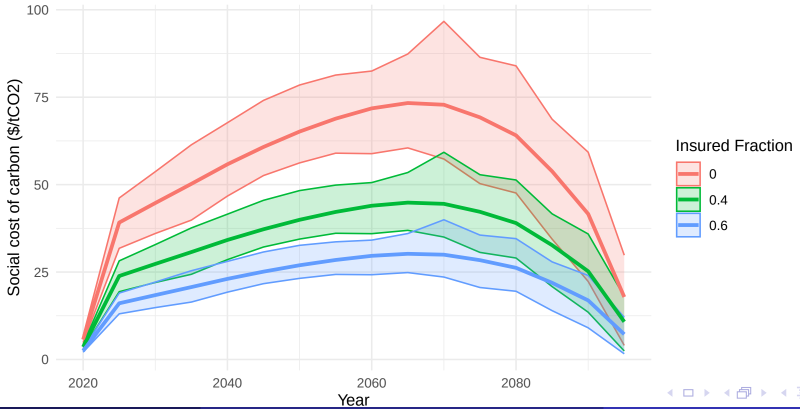
- The **social cost of carbon (SCC)** measures the monetized value of the damages to society caused by an incremental metric tonne of CO2 emissions (Rennert et al., 2022).
- SCC is a key metric informing climate policy.
- Formula:

$$SCC_t = \frac{dC_t}{dE_t} = -\frac{\partial \mathbb{E}\left[W\right] / \partial E_t}{\partial \mathbb{E}\left[W\right] / \partial C_t} \tag{18}$$

- Interpretation: **Any change in emissions dE_t must be offset by a corresponding change in consumption dC_t to maintain the same level of social welfare**.

Social Cost of Carbon

- Insurance **reduces** the SCC. The perceived economic damage from emissions is reduced.
- Myth: Insurance encourages carbon emissions with lower SCC?
- Insurance can be a convenient alternative to abatement control, but it **should not replace mitigation** efforts.



Outline

Concluding Remarks

- Quantitatively examines the **impact of insurance** on climate change mitigation and adaptation.
- Extend the seminal Dynamic Integrated Climate-Economy (DICE) model by incorporating a **mandatory non-profit insurance scheme**.
- The insurance premiums are determined using an **actuarial fair approach**, ensuring that the expected present value of payouts matches the premiums collected.
- Multifaceted benefits of insurance in addressing climate change: **enhanced social welfare, economic stabilization, a reduction in the social cost of carbon**.

Concluding Remarks

- Quantitatively examines the **impact of insurance** on climate change mitigation and adaptation.
- Extend the seminal Dynamic Integrated Climate-Economy (DICE) model by incorporating a **mandatory non-profit insurance scheme**.
- The insurance premiums are determined using an **actuarial fair approach**, ensuring that the expected present value of payouts matches the premiums collected.
- Multifaceted benefits of insurance in addressing climate change: **enhanced social welfare, economic stabilization, a reduction in the social cost of carbon**.

Thank you!