Modelling climate-economy interactions

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Last lectures

- Conceptual and empirical research on climate-related macro-financial dynamics
  - Strategy: reduce GHG emissions
  - However, decarbonisation could come with costs
  - Common conceptual framework: drivers $\rightarrow$ costs for firms $\rightarrow$ costs for financial institutions $\rightarrow$ macro-financial disruptions
- Empirical research
  - Calculate exposure to risks (e.g. physical/financial asset stranding)
  - Capture climate-related 'sentiments' (asset pricing, text analysis, surveys, experiments)
- Today:
  - What could the future look like? How should we intervene?
  - $\rightarrow$ Prospective modelling methods

Outline of today's lecture

- Basic modelling blocks
  - Some basic categories
  - Main blocks: Production functions; welfare functions
  - Focus on time discounting
- How to put climate and transition in
  - Economy to environment links
  - Environment to economy links
  - Focus on damage functions and social cost of carbon
- Overview of modelling strategies
  - Put macro in climate econ modelling
  - Put climate/transition in neoclassical macro
  - Put climate/transition in behavioural macro
  - Model coupling

Some basic categories

- Environmental vs macro
  - Environment/ecological/climate economics: study of relation between human societies and resources/nature/climate
  - Macro/growth economics: study of aggregate economic dynamics and drivers of development
- Neoclassical vs behavioural
  - Neoclassical school rooted in rational and forward-looking economic agents optimising (utility, profits, social welfare)
  - Behavioural: not using neoclassical tools (complexity, non-equilibrium, heterodox)
- Analytical vs numerical
  - Analytical: smaller models $\rightarrow$ derive equilibrium points/conditions (neoclassical or not)
  - Numerical: medium/large/massive models numerically calibrated/estimated and run on computer software

Two main methodological avenues

	Equilibrium	Non equilibrium
Behaviour drivers	Intertemporal optimisation of a welfare function	Macro-econometric relations
Determination of output	Supply-driven: output (production) is allocated between different uses (consumption and investment) Y=AKL	Demand-driven: output (income) is determined by the expenditure desires (consumption and investment) Y=C+I+G
Expectations	Forward-looking expectations by rational agents	Adaptive expectations by agents in a context of deep uncertainty
Decisions	Rational	Routines in a context of deep uncertainty
Equilibrium	The system moves to an equilibrium state (balanced growth path)	There is not necessarily an equilibrium (cycles, emergent behaviours)
Money	Money as a 'veil' (banks as intermediaries)	Endogenous money (credit creation by commercial banks)
Modelling approaches	IAM, CGE, DSGE, CAPM	SD, SFC, ABM
Communities	Economics, Finance, Environmental/Energy Economics	Social sciences, Ecological/Evolutionary Economics

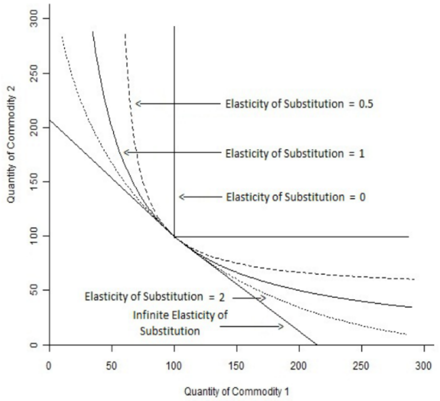
Key modelling blocks

Key modelling choices to make

- Production
    - How is output produced?
    - Supply- vs demand-side production functions
- Welfare optimisation
    - Welfare function of? consumption, leisure, environment
    - inter-temporal optimisation methods
    - Rooted in neoclassic econ, forward-looking rational agents
    - How do we discount the future?
- Macro behaviours
    - Macro behavioural functions: consumption, investment etc.
    - Calibrated or estimated
    - Backward-looking expectations, heuristics

Production function choice

- How is output produced?
  - Supply side: input factors $\rightarrow$ output (demand accepts)
  - Demand side: demand sources $\rightarrow$ output (supply provides)
- Ultimately a choice about elasticity of substitution
  - Change in $\frac{x_1}{x_2}$ when $\frac{p_1}{p_2}$ changes?



Types of production functions. Figure source

Supply-side production functions

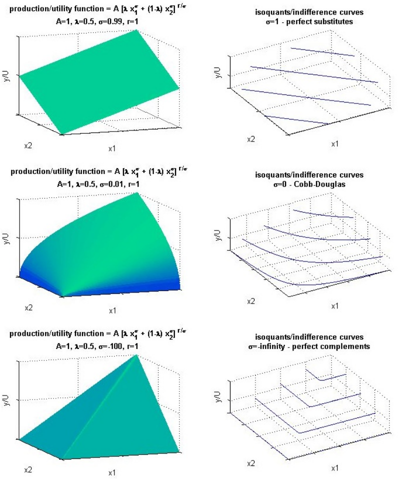
- Cobb-Douglas (CD)
  - $Y = AK^{\alpha}L^{\beta}$
  - Elasticity constant and equal to 1
  - Include energy? $\rightarrow Y = AK^{\alpha}L^{\beta}E^{\gamma}$
- Constant elasticity of substitution (CES)
  - $Y = A(\alpha K^{\rho} + (1-\alpha)L^{\rho})^{\frac{1}{\rho}}$ where ES $\sigma = \dfrac{1}{1-\rho}$
  - Include intermediate inputs:
    $Y_t = \left(Y_{ct}^{(\epsilon-1)/\epsilon} + Y_{dt}^{(\epsilon-1)/\epsilon}\right)^{\epsilon/(\epsilon-1)}$ (with ES ϵ)
  - Include energy into nests:
    $Y = A\left[\alpha\left(\alpha_1 K^{\rho_1} + (1-\alpha_1)L^{\rho_1}\right)^{\frac{\rho}{\rho_1}} + (1-\alpha)E^{\rho}\right]^{\frac{1}{\rho}}$

Demand-side production function

- Demand for goods determines production
  - $Y = C + I + G$ (consumption+investment+public expenditure)
  - Sometimes supply bottlenecks considered
- Ultimately a Leontief production function:
  - $Y = \min(\xi_K uK; \xi_L \lambda L)$
  - ξ_K and ξ_L: productivities
  - u and λ: input utilisation rates
- $Y \rightarrow$ Input factor utilisation
  - $u = \frac{Y}{\xi_K K}$; $\lambda = \frac{Y}{\xi_L L}$

Production function comparison

- Most neoclassical models use Cobb-Douglas (especially if looking for analytical closure) or CES (with one or more nests).
- Most non-neoclassical models use Leontief (or demand-led) production functions.
- Sometimes distinction between long-term and short-term functions (in the s-t one can't change inputs)



3d production functions under constant returns to scale (r=1). Figure source

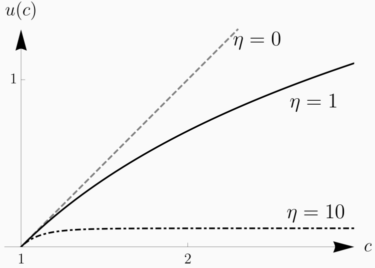
Social welfare

- Are we interested in measuring social utility/welfare?
  - Yes, if we then try to maximise it
  - Otherwise, societal welfare inferred from macro variables (GDP, employment, environmental quality, etc.)
- If interested, what criterion should we follow to aggregate personal welfare?
  - Usual setting in climate econ: discounted utilitarianism
  - Utilitarian: aggregate utility is the sum of individual utilities, equally weighted
  - Not the only choice! Prioritarianism; Maximin principle (Rawlsian), Rank-discounted utilitarianism; and other welfare principles

Welfare function choice: isoelastic

- Most common utility function:

$$u(c) = \begin{cases} \frac{c^{1-\eta}-1}{1-\eta} & \eta \geq 0, \eta \neq 1 \\ ln(c) & \eta = 1 \end{cases}$$



Source: Wikimedia

- Isoelastic (i.e. with constant elasticity), power, or CRRA (constant relative risk aversion) utility function
- η is the elasticity of marginal utility of consumption (EMUC): % change in marginal utility due to % change in consumption
- The term –1 can be dropped (only purpose is to find the *ln* limit for $\eta = 1$)

The elasticity of marginal utility of consumption (i)

- Multiple interpretations of η
  - Aversion to different consumption levels across individuals, generations or states of the world
  - Wildly different estimates depending on interpretation
- Intra-generational inequality aversion
  - The higher η the more social welfare you get by expanding consumption of poorer households
- Inter-generational inequality aversion
  - Connected to the intertemporal elasticity of substitution (IES), i.e. the change in consumption due to a change in interest rate (intertemporal rate of return): $\sigma = \frac{1}{\eta}$
  - When $\eta \to \infty$ ($\sigma \to 0$): consumption smoothing maximises overall welfare (transfer consumption from richer period/generation to poorer)
  - When $\eta \to 0$ ($\sigma \to \infty$) consumption in different periods are close substitutes: no smoothing

The elasticity of marginal utility of consumption (ii)

- Risk aversion
  - More risk-averse individuals prefer stable consumption across possible states of the world
  - Arrow–Pratt relative risk aversion (RRA) $RRA = \frac{-cu''(c)}{u'(c)}$
  - In CRRA utility functions $RRA = \eta \rightarrow$ Constant RRA: willingness to invest in risky assets independent of wealth.
  - This also means $RRA = \frac{1}{IES}$
  - But $\eta = RRA$ hard to reconcile with asset price data! $\rightarrow$ Equity premium puzzle
- $\rightarrow$ Epstein-Zin-Weil recursive preferences
  - Allows to separate prudence (desire to smooth consumption across time) and risk aversion (desire to smooth consumption across different future states of the world)
  - Utility depends on both current consumption and the expected utility of future consumption

Other welfare function options

- Epstein-Zin-Weil preferences (recursive utility)

$$U_t = \left((1-\beta)C_t^\rho + \beta\left[\mathbb{E}_t\left(U_{t+1}^\alpha\right)\right]^{\frac{\rho}{\alpha}}\right)^{\frac{1}{\rho}}$$

  - with IES$=\frac{1}{1-\rho}$; RRA$=1-\alpha$; and β as discount factor
- What else can appear into the utility function?
  - Leisure (i.e. not working). E.g. $U(c_t, l_t) = c_t^\nu l^{1-\nu}$
  - Environment, e.g. Acemoglu et al. 2012: $u = \dfrac{[\phi(S_t)C_t]^{1-\sigma}}{1-\sigma}$ where S is the quality of the environment
  - Local amenities (spatial economics)
- CES utility function

$$U_t = \left[\alpha C_c^\rho + (1-\alpha)C_d^\rho\right]^{\frac{1}{\rho}}$$

Optimisation vs macro-econometric approach

- Optimisation
  - Maximisation of (inter-temporal) welfare
  - eg. $W = \sum_{t=1}^{T} \beta^t U(C_t)$, where $\beta = \dfrac{1}{(1+\rho)}$ is discount factor and ρ the rate of pure time preference
  - Alternatively: Minimisation of (inter-temporal) (energy/abatement) costs
  - $\rightarrow$ Optimal consumption and investment paths
- Behavioural functions
  - Consumption and investment choices modelled as (linear) functions of other variables
  - e.g. $I = \eta_0 + \eta_1 u + \eta_2 \Pi$
  - Underlying theoretical assumptions + econometric estimation
  - Non-neoclassical schools of thought

Forward- vs backward-looking expectations

- Forward-looking expectations
  - Agents formulate (correct?) expectations about the future and act accordingly
  - Usually (but not necessarily) combined with optimisation
  - To what extent agents look into the future? $\rightarrow$ Infinite vs finite planning horizons
- Backward-looking expectations
  - Choices under radical uncertainty: agents cannot formulate reliable expectations
  - They look at the present/past, and linearly extrapolate into the next period
  - e.g. $I_t = \eta_0 + \eta_1 u_{t-1} + \eta_2 \Pi_{t-1}$

Discounting

- Individuals tend to 'discount' the future
  - Are you willing to exchange 100€ in one year time with 10€ today? What about 90€ today?
- Conceptually similar to an interest rate
  - Deposit 100€ today with a 5% (r) interest rate. In five years: $x_0 * (1 + r)^t = 127.62$€
  - $\rightarrow$ 127.62€ five years from now are worth 100€ today (the 'present value')
  - Problem: compounding $\rightarrow$ long-term future becomes almost irrelevant..
- Cost-benefit analysis
  - Look for the highest net present value: $NPV = \sum_0^T \frac{B_t - C_t}{(1+r)^t}$
  - How do we evaluate the future costs and benefits of public project/policies/plans? $\rightarrow$ social discount rate (SDR)

What discount rate should societies use?

- Two main ways to define the SDR (see Groom et al. 2022)
  - Social opportunity cost of capital (SOC)
  - Social rate of time preference (STP)
- Social opportunity cost of capital (SOC)
  - What is the opportunity cost of employing funds for public investments (diverting them from other uses e.g. consumption or private investment)?
  - It should be in line with the private market returns
  - Typically higher discount rates than STP approach
- Social rate of time preference (STP)
  - Captures trade-off btw consumption today and in the future
  - One could look at risk-free market interest rate..
  - .. or derive it from a social welfare function

The Ramsey equation

- Start from simple welfare function and capital accumulation
  - $\rightarrow$ You can derive the value of the SDR (=market interest rate=marginal rate of return to capital) (see Polasky & Dampha, 2021)

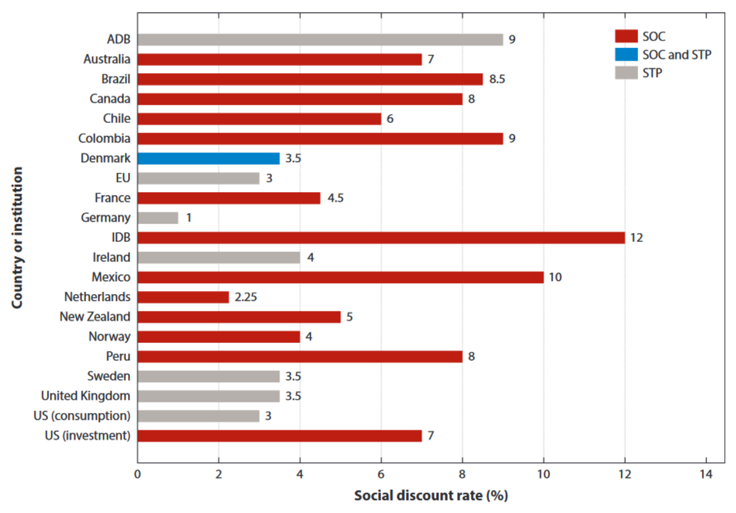
    $$SDR = \rho + \eta g$$

    where
  - ρ: pure rate of time preference
  - η: elasticity of marginal utility wrt consumption
  - g: growth rate of consumption
- Two main reasons to discount the future
  - Impatience, all else equal
  - Richer in the future $\rightarrow$ unit of consumption will have lower marginal utility

Finding the 'right' discount rate

- Two options:
  - Positive/descriptive: capture values from markets, surveys, experiments
  - Normative/prescriptive: choose values based on ethical considerations
- Time profile
  - Common approach: fixed discount rate
  - However: inconsistent with empirical data on preferences
  - Do you prefer 100€ today or 105€ next week? Do you prefer 100€ in one year or 105€ in one year + one week?
  - $\rightarrow$ Discount rates declining with longer time horizons (e.g. hyperbolic discounting)

Social discount rates in reality



Social discount rates by country. Source: Groom et al. 2022

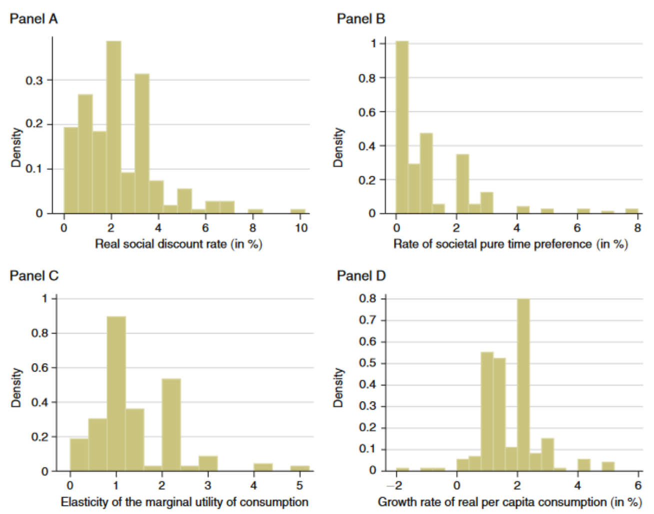
Discounting in climate economics

- Discounting particularly relevant for climate economics
  - Cost and benefits in the long-term
- The Nordhaus-Stern debate
  - The Stern Review in 2006 advocated for very low SDRs (in part. rate of time preference close to zero on ethical grounds)
  - Nordhaus prefers to refer to market rates (descriptive approach)

Source	Approach to discounting	Parameter values			Social discount rate (%)
		δ (%)	η	g (%)	
Stern (88)	Prescriptive	0.1	1	1.3	1.4
Garnaut (134)	Prescriptive	0.05	Used 1 and 2	0.85 and 1.65	1.35 and 2.65
Cline (85)	Prescriptive	0	1.5	1.6	2.4
Nordhaus (81)	Descriptive	1.5	2	2	5.5
Weitzman (135)	Descriptive	2	2	2	6

Parameter values used in the Ramsey discounting equations. Source: Polasky & Dampha (2021)

What do ‘experts’ nowadays think?



Responses from a survey of 197 field experts. Source: Drupp et al. (2018)

A large number of additional modelling choices to make

- How many sectors, and how are they distinguished?
- How many households/populations, and how are they distinguished?
- Are there banks and/or non-bank financial institutions?
- Do we consider production or financial networks?
- Are there sources of uncertainty in the model?
- Is there a government? What policies can it implement?
- Is there a central bank? What policies can it implement?
- Etc. etc. etc....

Putting climate and transition in

Key modelling dimensions

- Structure of the economy
  - Aggregate approach (Y or K dirty to some extent)
  - Sectoral approach (dirty $K_d \rightarrow$ clean K_c)
- Economy $\rightarrow$ Environment
  - Y_d or $K_d \rightarrow$ GHG emissions E
  - Abatement can drive down emissions, but at a cost
- Environment $\rightarrow$ Economy
  - Emissions $E \rightarrow$ Temperature $T \rightarrow$ Damages Ω
  - Impacts on output/productivity/utility..
- What do we study?
  - Cost-benefit: inter-temporal maximisation of net benefits
  - Cost-effectiveness: minimise abatement costs under T constraint
  - Scenarios: what-if investigations (e.g. carbon price trajectories)

Economy to environment links

- Typically GHG emissions function of output/capital/energy
  - e.g. $E = \psi Y$ where ψ is carbon intensity
  - How does ψ move? Exogenous and endogenous innovation
- Sometimes also resource use
  - Production leads to resource depletion $\dot{R}_t = -q_t$
  - Focus on energy/material intensity

Abatement mechanisms

- Abatement technologies decreasing emissions
  - e.g. $E = (1 - \mu)\psi Y$ where μ is abatement parameter
  - Abatement cost function
- Structural change from dirty to clean capital ($K_d \rightarrow K_c$)
  - Shift to cleaner technologies decreases emissions
  - Capital stock inertia? $\rightarrow$ Irreversibility or adjustment costs
  - Abatement cost linked to differences across technologies (e.g. different productivities/prices)
  - $\rightarrow$ Underutilisation of capital stocks?

Environment to economy links

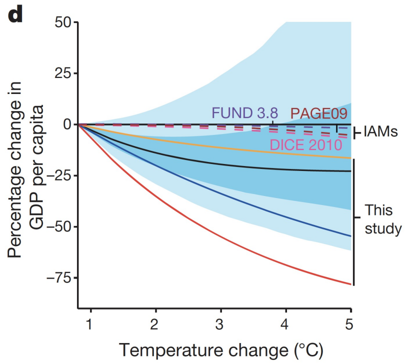
- Emissions go into atmosphere → climate change (e.g. ΔT)
    - How do account for climate change impacts in our models?
- Harder way
    - Include climate/physical modules able to capture (sectoral) impacts and associated economic losses
    - e.g. see the Climada model incorporating cyclones, river floods and other extreme events
- Simpler way
    - Design and calibrate an aggregate damage function connecting $E \rightarrow \Delta T \rightarrow \Omega$
    - Damages Ω are usually modelled as a % of output (GDP)
    - But they can also affect capital stocks, growth, utility..

Damage functions

- First wave of climate damage functions
  - Enumerative approach + expert solicitation → damage function calibration
  - Nordhaus DICE damage function: $\Omega_t = \dfrac{1}{1 + \psi_1 T_t + \psi_2 T_t^2}$
- But critiques:
  - "..damage functions used in most IAMs are completely made up, with no theoretical or empirical foundation" (Pindyck 2013)
  - Damage on output, capital or productivity?
  - Catastrophic risk: Weitzman (2010) damage function: $\Omega_t = \dfrac{1}{1 + \left(\frac{T_t}{20.46}\right)^2 + \left(\frac{T_t}{6.081}\right)^{6.754}}$

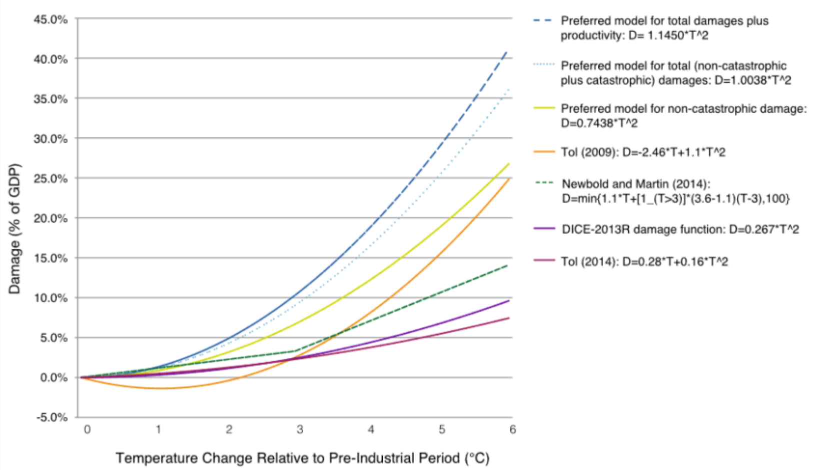
Empirical damage functions

- Rise of the empirical damage functions
  - Panel data techniques linking weather and socioeconomic variables (see Lecture 2)
  - Burke et al. (2015) → linear damage function?
  - Issue: based on only small variations (they don't tell us what a 6°C world would look like)



Damage function estimates. Source: Burke et al. (2015).

Damage function estimates



Damage function meta-analysis. Source: Howard and Sterner (2017)

The social cost of carbon (SCC)

- SCC is the monetary present value of all net future damages deriving from emitting an additional tonne of CO_2.
- Application in cost-benefit analysis
  - Used in some jurisdictions (e.g. USA) to define public policies/regulations
  - Europe and others just set targets (e.g. on ΔT)
- SCC values usually obtained via IAMs
  - Sensitive to discount rate and damnage function assumption
  - SCC typically increases over time (larger damages plus larger GDP in the future)
  - SCC identifies optimal carbon price
- Nordhaus calculates it as a shadow price (cost of emitting an additional unit of CO_2 in terms of consumption)

$$SCC_t \equiv \frac{\partial W}{\partial E_t} \bigg/ \frac{\partial W}{\partial C} \equiv \frac{\partial C_t}{\partial E_t}$$

US first SCC estimates

- Obama 2009 → Interagency Working Group (IGW)
- From 2013: central SCC value of $51/tCO2 for 2020
- Disbanded by Trump in 2017; reinstated by Biden in 2021

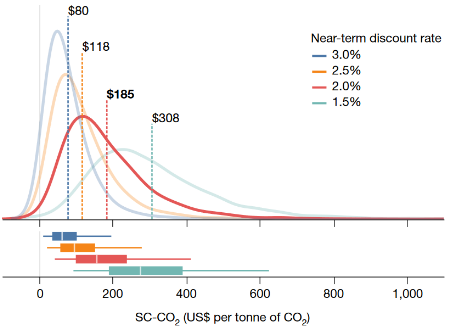
Table 3. Estimates of SCC for 2020 from US Interagency Working Group and comparison with DICE model in 2010 US$

Model and scenario	5% per year discount rate on goods	DICE	4% per year discount rate on goods	3% per year discount rate on goods	2.5% per year discount rate on goods
Estimates of 2020 SCC from US Working Group, 2013 (2010$)					
DICE-2010	12	na	na	40	59
PAGE	23	na	na	74	105
FUND	3	na	na	22	37
Average	13	na	na	**45**	67
Estimates for different DICE model versions (2010$)					
DICE-2013R	15	24	26	50	74
DICE-2016R	23	**37**	41	87	140

Upper rows show estimates of the 2020 SCC from the IAWG. The three models have harmonized outputs, emissions, populations, and ETS distribution and use constant discount rates. Lower rows show the results of the estimates from the two latest versions of the DICE model for the baseline (Table 1) and using constant discount rates.

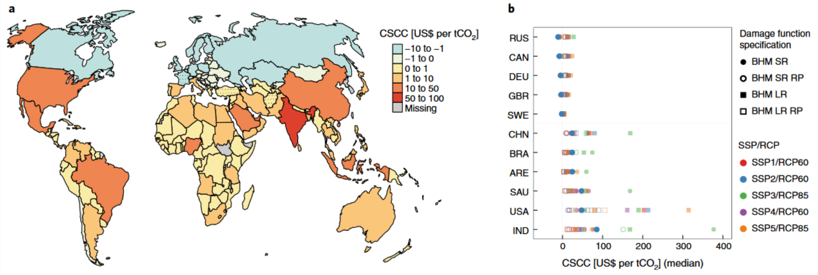
Estimates of SCC for 2020. Source: Nordhaus (2017)

Recent research suggests higher SCC values



SCC estimates. Left: Rennert et al. (2022). Right: RFF SCC explorer

Country-level SCC



Country-level SCC estimates. Left: reference case of scenario SSP2/RCP6.0, BHM-SR and a growthadjusted discount rate ($\rho = 2\%$, $\eta = 1.5$). Right: BHM: Burke-Hsiang-Miguel damage function; SR-LR: short and long run; RP: rich-poor distinction. Source: Ricke et al. (2018)

US more recent SC-GHG estimates

- Report from Environmental Protection Agency in 2022
- Central estimate of 190$/tCO2

Emission Year	Near-Term Ramsey Discount Rate and Damage Module: 2.5% DSCIM	2.5% GIVE	2.5% Meta-Analysis	2.0% DSCIM	2.0% GIVE	2.0% Meta-Analysis	1.5% DSCIM	1.5% GIVE	1.5% Meta-Analysis
2020	110	120	120	190	190	200	330	310	370
2030	140	150	150	230	220	240	390	350	420
2040	170	170	170	280	250	270	440	390	460
2050	210	200	200	330	290	310	500	430	520
2060	250	220	230	370	310	350	550	470	570
2070	280	240	250	410	340	380	600	490	610
2080	320	260	280	450	360	410	640	510	650

Emission Year	SC-GHG and Near-term Ramsey Discount Rate: $SC\text{-}CO_2$ (2020 dollars per metric ton of CO_2) 2.5%	$SC\text{-}CO_2$ 2.0%	$SC\text{-}CO_2$ 1.5%	$SC\text{-}CH_4$ (2020 dollars per metric ton of CH_4) 2.5%	$SC\text{-}CH_4$ 2.0%	$SC\text{-}CH_4$ 1.5%	$SC\text{-}N_2O$ (2020 dollars per metric ton of N_2O) 2.5%	$SC\text{-}N_2O$ 2.0%	$SC\text{-}N_2O$ 1.5%
2020	120	190	340	1,300	1,600	2,300	35,000	54,000	87,000
2030	140	230	380	1,900	2,400	3,200	45,000	66,000	100,000
2040	170	270	430	2,700	3,300	4,200	55,000	79,000	120,000
2050	200	310	480	3,500	4,200	5,300	66,000	93,000	140,000
2060	230	350	530	4,300	5,100	6,300	76,000	110,000	150,000
2070	260	380	570	5,000	5,900	7,200	85,000	120,000	170,000
2080	280	410	600	5,800	6,800	8,200	95,000	130,000	180,000

Above: Social Cost of Carbon (SC-CO2) by damage module; Below: Social Cost of GHG (for 2020-2080, in 2020$/t). Source: EPA (2022)

What do we do then?

- Cost-benefit analysis
  - NPV of climate damages vs NPV of abatement costs
  - Choose a social welfare function and maximise the inter-temporal sum of discounted welfare values
- Cost-effectiveness analysis
  - Set temperature goals: 1.5-2°C upper limits $\rightarrow$ carbon budget
  - Modelling choices: overshoot; NETs; delayed policies?
  - Minimise inter-temporal sum of discounted abatement costs
- Scenarios exploration
  - Set a baseline scenario (e.g. a BAU without policies)
  - Change some exogenous climate-related dimension (e.g. a carbon price schedule)
  - How does this change affect the rest of the system?

Climate/transition modelling strategies

Put macro in climate econ modelling

- Integrated Assessment Modelling
  - Aim: assess in an integrated manner interactions between economy, energy systems and climate
  - The father of IAMs: the DICE model
- Types of IAMs
  - Large-scale numerical IAMs
  - Analytical IAMs
  - Computable General Equilibrium (CGE) models
- Traditionally small economy modules and no finance
  - Can they expand to include macro-financial dimensions?
  - Analytical IAMs might be the most flexible, but limited granularity

Put climate/transition in neoclassical/behavioural macro

- Neoclassical ‘equilibrium’ modelling
  - Dynamic Stochastic General Equilibrium (DSGE) models
  - Asset pricing models (e.g. CAPM)
  - Growth theory ($\rightarrow$ Analytical IAMs)
- Non-neoclassical ‘disequilibrium’ modelling
  - Stock-Flow Consistent (SFC) models
  - Agent-Based Models (ABMs)
  - Diffusion / discrete choice theory

Model coupling

- Use multiple models creating links among them
    - E.g. Allen et al., 2020: IAMs $\rightarrow$ DSGE $\rightarrow$ Input-output model $\rightarrow$ financial valuation model
    - Alternative: IAMs $\rightarrow$ ABM (Lamperti et al.)
- Still limited in scope
    - Usually one-way linkages, no feedback effects
    - But maybe this is the best we can hope for?

Conclusions

Conclusions

- We want modelling methodologies to explore what climate/transition means for the macro-financial system (and viceversa)
- Lots of choice to make
  - Some choices typical of econ modelling: production, welfare (or not), expectations, discounting, uncertainty etc.
  - Other choices focused on climate-economy interactions: damages, abatement etc.
- Next lectures
  - Let's look at how this was and is being done
  - Climate econ modelling (IAMs, CGE)
  - Macro modelling (DSGE, SFC, ABM etc.)