Modelling climate-economy interactions

Climate macroeconomics & finance course 2022/23 - Lecture 6

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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

- Some basic categories
  - Environmental vs macro; neoclassical vs behavioural; analytical vs numerical
- Basic modelling blocks
  - Production; utility+optimisation; macro behaviours; discounting; uncertainty; expectations
- How to put climate and transition in
  - Productive sectors; emissions; economic impacts; abatement
- 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

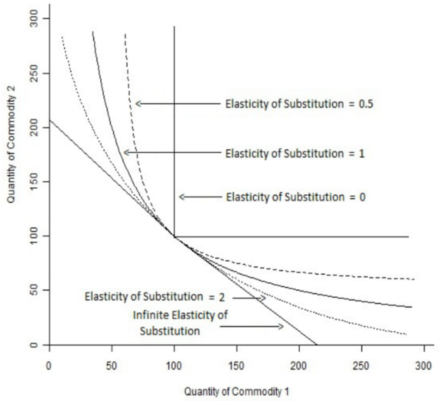
Key modelling blocks

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)
  - $Y = A\left(\alpha K^{\rho} + (1-\alpha)L^{\rho}\right)^{\frac{1}{\rho}}$
  - Elasticity of substitution: $\sigma = \dfrac{1}{1-\rho}$
  - CES nesting:
    $Y = A\left[\alpha\left(\alpha_1 K^{\rho_1} + (1-\alpha_1)L^{\rho_1}\right)^{\frac{\rho}{\rho_1}} + (1-\alpha)ES^{\rho}\right]^{\frac{1}{\rho}}$
  - Possible to include intermediate inputs

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
    - $u = \frac{Y}{\xi_K K}$; $\lambda = \frac{Y}{\xi_L L}$

Welfare function choice

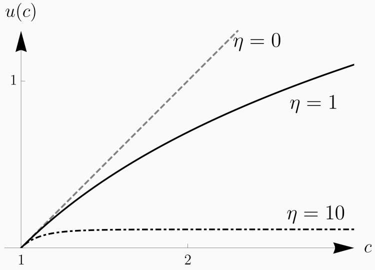
- Are we interested in measuring utility/welfare?
  - Yes, if we then try to maximise it
  - Otherwise, societal welfare inferred from macro variables (GDP, employment, environmental quality, etc.)
- Most common utility function:

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

  - Isoelastic (i.e. with constant elasticity), power, or CRRA (constant relative risk aversion) utility function
  - η is the elasticity of marginal utility of consumption (EMU): % 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

- Multiple interpretations of η
- Inter-generational inequality aversion, with intertemporal elasticity of substitution (IES) $\frac{1}{\eta}$
- Intra-temporal inequality aversion
- Here relative risk aversion $RRA = \frac{-cu''(c)}{u'(c)} = \eta \rightarrow$ decision-making unaffected by scale (i.e. fraction of wealth placed in risky assets independent of initial wealth).
- But $\eta = RRA$ hard to reconcile with data



Source: Wikimedia

Other welfare function options

- What else can appear into the utility function?
    - Relatively common: leisure (i.e. not working). E.g. $U(c_t, l_t) = c_t^{\nu} l^{1-\nu}$
    - Sometimes environmental dimension, 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
- CES utility function

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

- Epstein-Zinn preferences (recursive utility)
    - Allow to separate prudence (desire to smooth consumption across time) and risk aversion (desire to smooth consumption across different future states of the world)
    - Suitable choice when including uncertainty
    - E.g. $U_t = \left[c_t^{\rho} + \beta \mathbb{E} U_{t+1}^{\rho}\right]^{\frac{1}{\rho}}$

Optimisation vs macro-econometric approach

- Optimisation
  - Maximisation of (inter-temporal) welfare
    - eg. $W = \sum_{t=1}^{T} \beta^t U(C_t)$, where $\beta = \dfrac{1}{(1+\rho)^t}$ is discount factor
  - 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

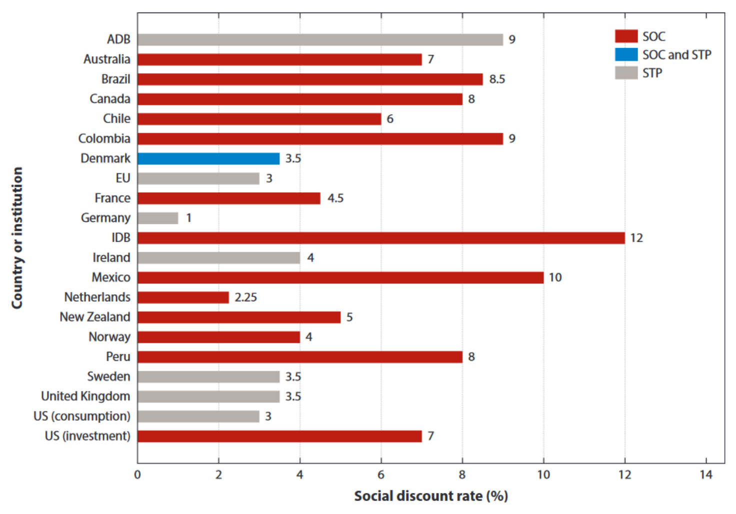
$$SDR = \delta + \eta g$$

    where
  - δ: pure rate of time preference
  - η: consumption elasticity of marginal utility
  - g: growth rate
- 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)

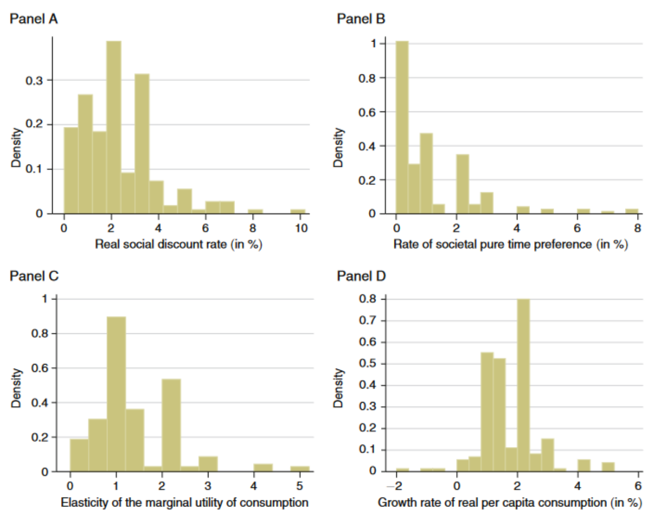
Discounting in climate economics

- 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 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. $E = \mu\psi Y$ 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?

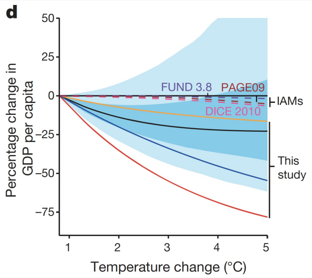
Environment to economy links

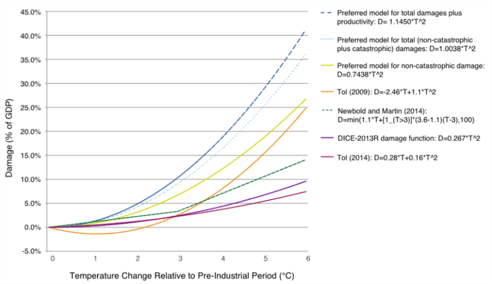
- Emissions go into atmosphere $\rightarrow$ climate change (e.g. ΔT)
  - How do account for climate change impacts in our models?
- Harder way
  - Include climate/physical modules able to capture (sectoral) impacts and associated economic losses
  - e.g. see the Climada model incorporating cyclones, 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: $\Omega_t = \psi_1 T_t + \psi_2 T_t^2$
  - But critiques: "..damage functions used in most IAMs are completely made up, with no theoretical or empirical foundation" (Pindyck 2013)
- 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





Damage function estimates. Left: Burke et al. (2015). Right: 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)

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

US 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
- Waiting for updates..

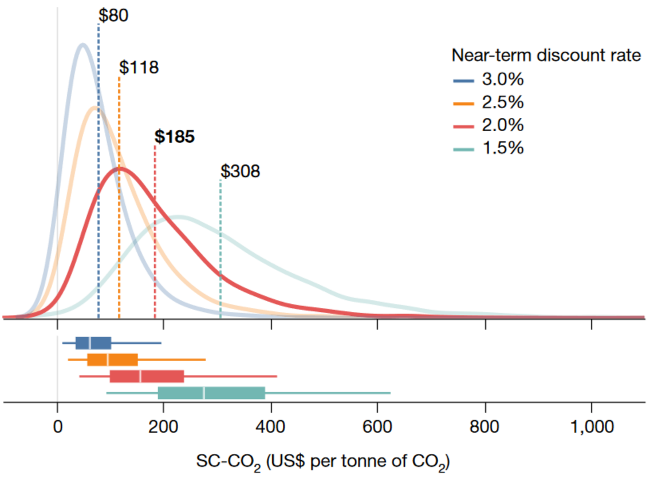
Table 3. Estimates of SCC for 2020 from US Interagency Working Group and comparison with DICE model in 2010 US$

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.

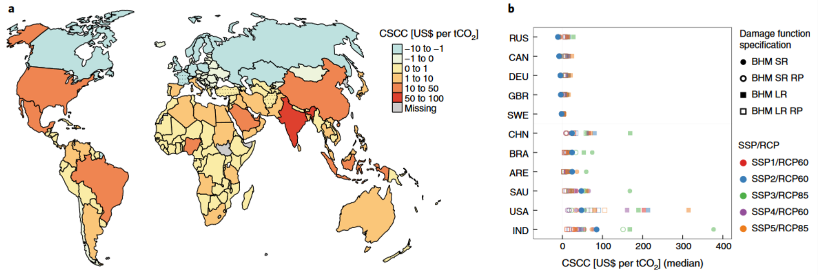
Estimates of SCC for 2020. Source: Nordhaus (2017)

Recent research suggests higher SCC values



SCC estimates. Source: Rennert et al. (2022)

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)

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.)

Support slides: alternative taxonomies

Alternative taxonomies: Mercure et al. (2019)

Table 1. Schools of economic thought.

	School Name		Micro-foundations: Rationality / Agent	Money	Parameter-isation method	Innovation Technology	Economic change
Equilibrium/Supply-led	Neoclassical	Solow[1]	Rational expectations/ Representative Agent	Commodity	Optimization	Exogenous	Capital accumulation
		Endogenous Growth[2]	Rational Expectations/ Representative Agent	Commodity	Optimization	Knowledge in production functions	Capital & knowledge accumulation
		General[3] Equilibrium	Rational Expectations/ Representative Agent	Commodity	Optimization	Knowledge in production functions, learning curves, knowledge spillovers[10]	Capital & knowledge accumulation
Non-equilibrium/ demand-led	Post-Schumeterian	Evolutionary Economics[4]	Behavioural[8] Heterogeneous	Asset (Credit creation)	Dynamical systems, Historical approach[9]	Knowledge networks, Diffusion, learning	Entrepreneur, Innovation clustering, creative destruction
		Transitions Theory[5]				Historical	
		Technology Innovation Systems[6]				Case studies	
	Post-Keynesian[7]	Horizontalists	Behavioural[8] Heterogeneous	Asset (Credit creation)	Time series Econometrics	Sectoral tech. progress functions	Cumulative causation of knowledge accumulation
		Structuralists					
	Behavioural[8]		Numerous agents	–	Empirical	–	–
	Marxian		Classes	–	Econometrics	–	–

Representative Models: [1]RICE/DICE (Nordhaus, 2013), [2]REMIND (PIK, 2016), [3]IMACLIM (CIRED, 2018), AIM (NIES, 2012), GEM-E3 (E3MLab, 2018a), [4]Evolutionary Economics (Safarzyńska & van den Bergh, 2010), [5]Geels (Geels, 2002), [6]Technology Innovation Systems (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007), [7]E3ME-FTT (Mercure et al., 2018a), GINFORS (Lutz, Meyer, & Wolter, 2009), Giraud stock-Flow (Giraud, Mc Isaac, Bovari, & Zatsepina, 2016), DEFINE (Dafermos et al., 2017), MINSKY (Keen, 1995), [8]Prospect theory (Kahneman & Tversky, 1979), Discrete choice theory (Domencich & McFadden, 1975), [9]historical approach (Freeman & Louçã, 2001; Geels, 2002), [10]Note that although the method is in use (e.g. in GEM-E3), some but not all GE models feature learning curves or knowledge spillovers.

Source: Mercure et al. (2019)

Alternative taxonomies: Mercure et al. (2019)

Table 2. Types of macro-models and summary of their assumptions regarding energy-related innovation and investment behaviour.

	Assumption type		Micro innovation	Macro innovation	Micro agent	Macro agent
Supply-led / Optimization	Optimal growth[1]		Does not have detailed disaggregated sectors	Knowledge accumulation in economy production function	Normative social planner optimizing utility inter-temporally	
	General Equilibrium	Computable General Equilibrium[2]	Can be linked to detailed technology models	Endogenous productivity in sectoral production functions	Representative agent with rational expectations (deterministic) optimizing utility, prices adjust to clear all markets	
		Dynamic Stochastic General Equilibrium	Can be linked to detailed technology models	Exogenous technological change	Heterogeneous stochastic representative agent	
	Partial equilibrium Cost-optimisation[3]		Learning curves, exogenous diffusion rates, vintage capital	Productivity not defined, can be linked to a CGE model	Can be heterogeneous, market segments	The normative social planner
Demand-led / Simulation	Macro-econometric[4]		Can be linked to detailed technology models	Technology progress indicators (fn. of cumulative investment)	Can be linked to detailed technology models	Investment behaviour derived econometrically
	Systems Dynamics	Discrete choice[5]	Vintage capital (fleets), learning curves	Productivity not defined, but can be linked to any macro-model	Multinomial logit regressions, heterogeneous agents	Can be linked to macro-model
		Diffusion[6]	Selection-diffusion evolutionary model, learning curves	Can be linked to a path-dependent economic model	Decision-making under bounded rationality, social influence	Can be linked to macro-model
	Agent-based	Sectoral[7]	Vintage capital (fleets), learning curves	Can be linked to a path-dependent economic model	Decision-making under bounded rationality, social influence	Can be linked to macro-model

Model examples: [1]RICE/DICE (Nordhaus, 2013), FUND (Anthoff & Tol, 2014), QUEST (DG ECFIN, 2015), [2]GEM-E3 (E3MLab, 2018a), IMACLIM (CIRED, 2018), [3]MESSAGE (IIASA, 2014), (PNNL, 2017), TIMES (IEA/ETSAP, 2016), PRIMES (E3MLab, 2018b), [4]E3ME (Mercure et al., 2018a), GINFORS (Lutz et al., 2009) Giraud stock-Flow (Giraud et al., 2016), DEFINE (Dafermos et al., 2017), EIRIN (Monasterolo & Raberto, 2018) [5]IMAGE-TIMER (Bouwman et al., 2006) [6]FTT (Mercure et al., 2014) [7]MATISSE (Köhler et al., 2009).

Source: Mercure et al. (2019)

Alternative taxonomies: Ciarli and Savona (2019)

Table 2
Aspects of structural change in different modelling traditions. Some models are better equipped than others to capture the relation between aspects of structural change and environmental impact. In particular those that do not require a closed form solution in equilibrium.

Models	Aspects of structural change					
	Sectors	**IO**	**Technical change**	**Employment**	**Demand**	**Institutions**
IAM	No: aggregate & exogenous – no sectoral changes	No	Partial: Exogenous, LBD, induced TC, but aggregate	No	Limited: time preferences change with pollution	No (policy experiments)
CGE	Partial: many sectors, with technical change that may affect GHG	No: I/O maps diversification, but static	Partial: Semi-exogenous, LBD, induced TC, but aggregate	No	Limited: change consumption patterns, not preferences	No (policy experiments)
SCM	Yes	Yes, but only a couple of models	Yes, but only a couple of models	No	Limited: two populations	No (policy experiments)
EMK	Partial: labour composition	Not yet	No	Yes	Limited: wage distribution	No (policy experiments)
EABM 1	Partial: weaker on the environmental effects	Limited: firm size & industrial dynamics	Largely Yes	Yes	Yes, although not developed	Partial: interaction & response to policies
EABM 2	No	Limited: mainly industrial dynamics	Yes	No	Yes	Partial: evolution of power and tech. opportunities

Notes: IAM: integrated assessment models; CGE: computable general equilibrium models; SCM: structural change models; EMK: ecological macroeconomics (Keynesian); EABM 1: evolutionary and multi agent models (macro); EABM 2: evolutionary and multi agent models (innovations).

Source: Ciarli and Savona (2019)

Alternative taxonomies: Nikas et al (2019)

Category	Economy	Impacts	Energy	Climate
Optimal growth models	Neoclassical growth Highly aggregated Tracks long-term trajectory of economy (dynamic) Single production function Single representative agent Policy optimisation Global	Highly aggregated monetary damage function that translates temperature change to loss of GDP All damages in monetary terms	Aggregated energy sector (top-down)	Reduced-form equations linking emissions to temperature
General equilibrium models	Multisectoral (multiple production functions) Single representative agent Optimising behaviour of producers and consumers Global, regional, national, local More difficult to incorporate dynamics	Shocks introduced into production functions, e.g. reduction in crop yields reflected in agricultural production function leading to a shift in supply Shocks can be based on expert judgements or drawn from biophysical or statistical models of impacts	Often detailed description of energy system (multiple energy sources explicitly modelled) Often linked to bottom-up energy system models	Climate scenarios are exogenous and used to drive climate variables and impacts
Partial equilibrium models	Detailed modelling of a single sector, e.g. agriculture Static and dynamic Often combined or linked with other top-down models	(a) Detailed biophysical model of impacts to specific sector relating key climate variables to impacts (b) Statistical analysis leading directly to monetary value of impacts	Little or no representation of energy sector	Exogenous climate scenarios used to drive impacts
Energy system models	Can be considered as a subcategory of partial equilibrium models (with some instances including a macro feedback) Often linked to top-down models (making them "hybrid")	Used to assess costs of reducing emissions; no need to represent impacts	Detailed representation of alternative energy technologies and mitigation opportunities and policies	Focus on emissions rather than climate change
Macroeconometric models	Input-output econometric (multisectoral) Macroeconomy components Simulation: agents not assumed to feature optimising behaviour "Keynesian" Dynamic	Used primarily to evaluate mitigation and adaptation policies rather than evaluate damages arising from climate change	Detailed description of energy system	Exogenous scenarios
Other models	Various simple representations of economy or exogenous scenarios of economic growth	Variety of detailed representations of impacts and damages both physical and monetary	Various aggregated and detailed energy models	Reduced-form equations linking emissions to temperature and other variables

Source: Nikas et al. (2019)