Climate/transition macro-financial modelling

Emanuele Campiglio[1,2,3]

Climate macroeconomics & finance 2023/24 - Lecture 9+10

[1]University of Bologna - Department of Economics (DSE)
[2]RFF-CMCC European Institute on Economics and the Environment (EIEE)
[3]LSE Grantham Research Institute

Outline of today's lecture

- Neoclassical macro on climate/transition
  - Dynamic Stochastic General Equilibrium (DSGE) models
  - Asset pricing models
- Non-neoclassical macro on climate/transition
  - Stock-Flow Consistent (SFC) models
  - Agent-Based Models (ABM)
  - Behavioural macroeconomics
- Hybrid models
  - NGFS scenario analysis and beyond

Environmental DSGE

Real Business Cycle (RBC) models

- Starting point: Lucas critique
  - Keynesian macro-econometric aggregate models
  - Little theoretical foundations but empirically validated in 60s
  - Lucas (1976): models need to take into account individuals' reactions and expectations to policy implementation!
  - $\rightarrow$ Microfoundations of macroeconomics
- Real Business Cycle (RBC) models
  - Aim: explain drivers and implications of business fluctuations
  - Representative agents; perfect competition; rational expectations; market clearing; labour supply choice
  - Fluctuations explained by exogenous 'real' shocks to TFP
  - Key papers: Kydland & Prescott (1982) in Ecta; Long & Plosser (1983) in JPE

‘New-Keynesian’ DSGE models

- Share the RBC root but include frictions (real world):
    - Habit persistence: consumption in the past (internal) or by others (external) matters for utility
    - Nominal rigidities: wages and prices do not immediately adjust (e.g. staggered pricing à la Calvo, 1983 in JME)
    - Capital/investment adjustment costs to replicate smooth investment patterns (e.g. Christiano et al., 2005 in JPE)
- Financial variables are important too
    - Financial frictions: borrowing constraints (collateral value), bank monitoring costs, regulatory constraints (e.g. Kiyotaki and Moore, 1997 in JPE, Bernanke et al., 1999)
    - Monetary policy shocks as cycle drivers: unexpected change in interest rates (e.g. Taylor, 1993; Clarida et al., 1999 in JEL)

DSGE basic building blocks

- Production function
  - Usually Cobb-Douglas or CES with K and L
  - TFP follows a stochastic process, e.g. AR(1) process
    $\ln A_t = \rho_A \ln A_{t-1} + \varepsilon_t^A$ (real productivity shocks $\varepsilon \sim \mathcal{N}(0, \sigma^2)$)
- Utility function
  - Utility usually a function of consumption and labour, e.g.

$$u(C_t, N_t) = \frac{C_t^{1-\sigma}}{1-\sigma} - \chi \frac{N_t^{1+\varphi}}{1+\varphi}$$

    with N: labour supply; χ: scaling parameter; φ: inverse of Frisch elasticity (Frisch elasticity reflects willingness to adjust labour supply in response to wage changes)
- Public sector
  - Fiscal policy
  - Monetary policy - e.g. Taylor rule:
    $i_t = r^* + \pi_t + \phi_\pi(\pi_t - \pi^*) + \phi_y(y_t - \bar{y})$

E-DSGE

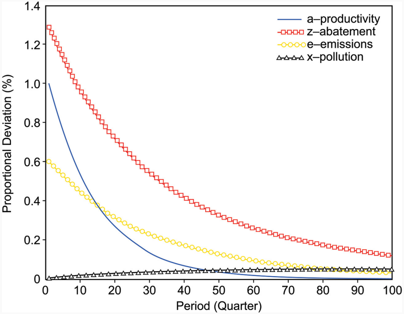
- RBC/DSGE can be used to study climate-related dimensions (see Annicchiarico et al., 2022 for a review)
  - How do emissions move along the business cycle?
  - How should optimal climate policy adapt to cycle dynamics?
- Building blocks to add to standard framework:
  - Emissions (additional input factor or by-product of output)
  - Climate damages (to utility, output or productivity)
  - Abatement options (abatement parameter à la DICE or different policies: tax, caps, emission standards)
- E-DSGE models rely on shocks (to productivity, interest rate or else or other) to create dynamics
  - Model starts on a balanced growth path (or 'steady state'); a shock comes along; we observe system reactions as deviation from steady state

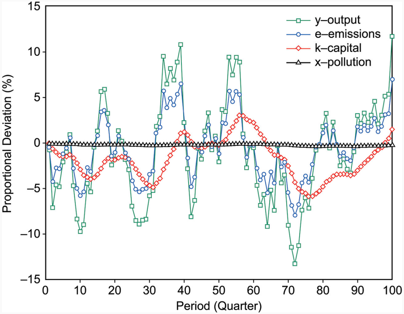
Heutel (2012) in Rev. Econ. Dyn.

- Heutel (2012): Combination of RBC and DICE-like elements
  - Isoelastic utility function: $U(c_t) = \frac{c_t^{1-\varphi}}{1-\varphi}$
  - Output affected by climate damages: $y_t = (1 - d_t) a_t k_t^{\alpha}$
  - Stochastic TFP: $\ln A_t = \rho \ln A_{t-1} + \varepsilon_t$
  - Emissions proportional to output and affected by abatement: $e_t = (1-\mu) y_t^{1-\gamma}$, with γ estimated from US data
  - Stock of pollution: $x_{t+1} = \eta x_t + e_t + e_t^{exog}$
  - Damages function of pollution stock: $d_t = d_0 + d_1 x + d_2 x^2$
  - Abatement costs: $z_t = \theta_1 \mu^{\theta_2}$
- Research question
  - Is optimal climate policy procyclical?

Heutel (2012) results

- Optimal emissions are procyclical
- Abatement mitigates prociclicality wrt unregulated case
- Decentralised equilibrium: optimal tax is also pro-cyclical





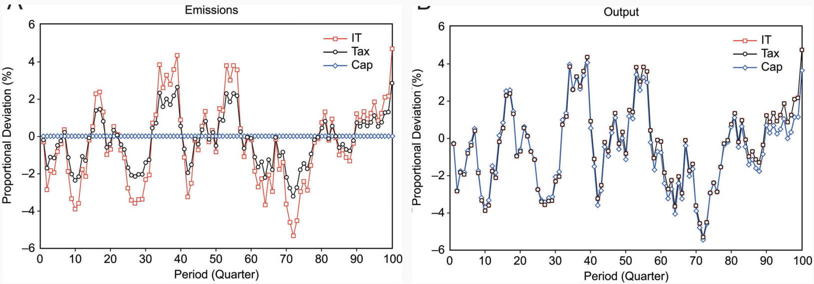
Left: Impulse response functions to a shock in productivity. Right: Reaction to a specific sequence of random productivity shocks. Source: Annicchiarico et al. (2022) using an updated version of Heutel (2012)

Fischer and Springborn (2011) in JEEM

- Fischer and Springborn (2011)
  - Emissions M in production function: $Y = \Theta_t K_t^{\alpha} M^{\gamma} L^{1-\alpha-\gamma}$
  - Utility log function of consumption and leisure ℓ: $U_t = \ln(C) + \omega \ln(\ell)$
  - Stochastic TFP: $\Theta = \exp(\eta z_{t-1} + \varepsilon_t)$
  - Emission constraint: $M_t \leq A_t(.)$
- Research question: compare macro effects of three policies
  - Carbon tax τ
  - Cap-and-trade system $A = \bar{M}$
  - Intensity targets $A = \mu Y$
  - All policies optimal in steady state (i.e. do not adjust to business cycles)

Fischer and Springborn (2011) results

- Cap tames volatility of both emissions and output
- Tax and intensity targets lead to procyclical emissions
- Intensity targets leads to higher growth/welfare in steady state



Reaction to a specific sequence of random productivity shocks. Source: Annicchiarico et al. (2022) using an updated version of Fischer and Springborn (2011)

NK DSGE applications to climate economics

- Annicchiarico and Di Dio (2015) in JEEM
  - Calvo pricing, capital adjustment costs, monetary policy
  - Emissions/climate following Heutel (2012)
  - Policy options: tax, cap, intensity targets (as in F&S 2011)
  - Three shocks: TFP, government expenditure, monetary policy
  - Cap tames macro volatility, intensity targets fuels it
  - Policy welfare ranking depends on price stickiness
- Annicchiarico and Di Dio (2017) in ERE
  - Similar NK setting, but focus on policy interactions
  - Planner choosing both environmental (tax or cap) and monetary policy, or just one of them
  - Optimal emissions are usually, but not always, procyclical, depending on monetary policy reactivity
  - Environmental policy might affect optimal monetary policy

Since then..

- Expanding field investigating macro-financial implications of climate and transition with more sophisticated models
  - Diluiso et al. (2021) in JEEM
  - Comerford and Spiganti (2023) in Scand. J. Econ.
  - Carattini et al. (2023) in Rev. Econ. Dyn.
  - Gibson and Heutel (2023) in JEDC
  - Ferrari and Nispi Landi (2024) in Macroecon. Dyn.
- Let's have a closer look at Carattini et al. (2023)
  - Focus on climate policy, associated transition risks, and macroprudential policies to mitigate risks

Carattini et al. (2023) in Rev. Econ. Dyn. (i)

- Consumption good CES combination of green/brown goods

$$Y_t = \left[(\pi_b)^{\frac{1}{\rho_Y}} \left(Y_t^b \right)^{\frac{\rho_Y - 1}{\rho_Y}} + (1 - \pi_b)^{\frac{1}{\rho_Y}} \left(Y_t^g \right)^{\frac{\rho_Y - 1}{\rho_Y}} \right]^{\frac{\rho_Y}{\rho_Y - 1}}$$

  with ρ_Y elasticity of substitution

- Sectoral output Y^i - with $i \in (b, g)$: Cobb-Douglas function affected by damages d and with stochastic productivity A

$$Y_t^i = [1 - d(X_t)] A_t (K_{t-1}^i)^{\alpha_i} (L_t^i)^{1-\alpha_i}$$

- Pollution a là Heutel (2012)
  - Emissions by-product of brown production $e_t = (1 - \mu_t) Y_t^b$
  - Abatement cost function $Z_t = \theta_1 \mu_t^{\theta_2} Y_t^b$
  - Pollution stock $X_t = \delta_X X_{t-1} + e_t + e_t^{\text{row}}$

Carattini et al. (2023) in Rev. Econ. Dyn. (ii)

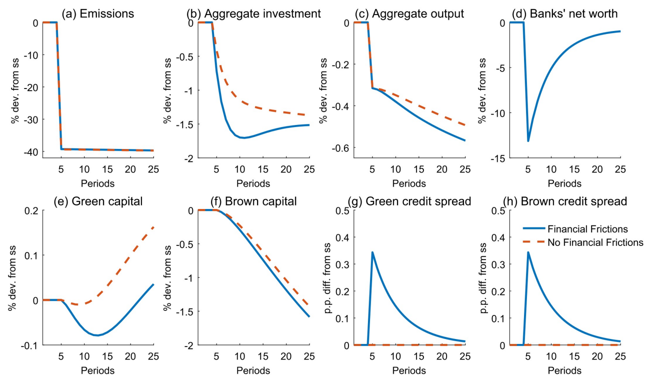
- A proportion ι of households are bankers
  - Banks lend to firms through equity + household deposits (they purchase claims on sector-specific capital returns)
  - Financial frictions: limit to bank ability to raise external funds due to household mistrust
- Household utility function of consumption and labour in two consumption good sectors

$$U_t = \frac{1}{1-\eta}\left(C_t - \varphi\left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L}\right]^{\frac{1+\xi}{1+\rho_L}}\right)^{1-\eta}$$

- Public policy interventions
  - Tax on emissions τ^e
  - Macroprudential tax on bank assets τ^b, τ^g

Carattini et al (2023) results

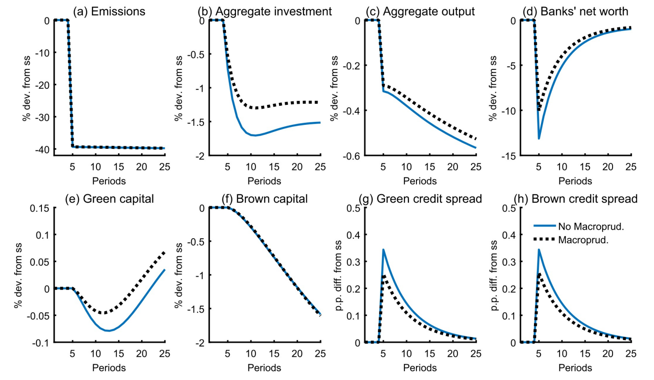
- Banks exacerbate tax-driven recession: brown asset prices decline → banks' net worth drops → generalised credit constraint → lower green/brown investments



Reaction to unanticipated carbon tax of \$17/tCO2, with and without banking sector. Source: Carattini et al. (2023)

Carattini et al (2023) results

- Macropru policy: banks' steady-state exposure to brown sector 40%→32.4%
- Negative effects of carbon tax are partially mitigated



Reaction to unanticipated carbon tax of \$17/tCO2, with and without macroprudential policy. Source: Carattini et al. (2023)

Strengths and weaknesses of E-DSGE models

- RBC/DSGE models very useful
  - Fit to study the interaction between business cycles and environmental policy
  - Explicitly capture several macro-finacial dimensions
  - Well-known tools to most (macro)economists
- However
  - Contested theoretical foundations
    - Romer (2016): Fluctuations driven by 'imaginary causal forces'
    - Krugman (2016): 'Were there any interesting predictions from DSGE models that were validated by events?'
    - Stiglitz (2011): 'core DSGE models is not good theory'
  - They rely on unexpected shocks to generate dynamics
  - Hard to introduce heterogeneity and behavioural dimensions
  - Banks as pure intermediaries
  - Not suitable for more long-term analysis

Climate asset pricing modelling

Asset pricing models

- Traditionally used in finance to establish the value of financial assets (e.g. stocks, bonds, derivatives)
    - See John Cochrane's book and lecture materials
- Foundational idea: the price of an asset is equal to the discounted stream of future cash flows (DCF)

$$P_0 = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t}$$

    - How should we discount future cash flows?
    - We can use expected/required returns
    - These depends on risk: higher risk $\rightarrow$ higher required returns $\rightarrow$ price today should be lower

CAPM and CCAPM

- Capital asset pricing model (CAPM)

$$E(r_i) = r_f + \beta_i(E(r_m) - r_f)$$

  - r_i: return of asset
  - r_f: return of risk-free asset (e.g. long-term government bond)
  - r_m: market return (e.g. S&P500) $\rightarrow$ $r_m - r_f$: market premium
  - $\beta_i = \dfrac{cov(r_i, r_m)}{var(r_m)}$ measures the sensitivity of an asset to market risk (e.g. $\beta > 1$: asset is historically more volatile than market)
- Consumption-based CAPM (CCAPM)
  - Same formula but focus is now on investors' consumption $\rightarrow$ β measures consumption risk
  - Consumption β measures the sensitivity of returns to changes in the marginal utility to consumption
    - $\beta^c > 1$ asset performs better in good times
    - $\beta^c < 1$ asset performs better in bad times (hedge) $\rightarrow$ lower discount rate $\rightarrow$ higher value

Factor models

- Factor models
  - There's more than just market risk
  - 'Factors': relevant dimensions driving asset returns
  - 'Factor loading': sensitivity of asset to factor
- Common factor models
  - Fama-French three-factor model

$$R_i = \alpha_i + \beta_i(R_m - R_f) + s_i \times SMB + h_i \times HML + \epsilon_i$$

    - SMB: Small Minus Big (size factor): return difference between small and large firms
    - HML: High Minus Low (value factor): return difference between high and low book-to-market ratios
  - Carhart four-factor model

$$R_i = \alpha_i + \beta_i(R_m - R_f) + s_i \times SMB + h_i \times HML + m_i \times UMD + \epsilon_i$$

    - UMD: Up Minus Down (momentum factor): return difference between stocks with high and low past returns

Asset pricing insight for climate econ

- Financial asset pricing models applied to climate:
  - Instead of looking for the optimal value of carbon price via 'shadow pricing' (analytical IAMs) we can treat CO2 as an asset with negative returns and compute CO2 price directly
  - Study climate implications on risk-free interest rates or market/sector premia
- Useful features of asset pricing models
  - Multiple stochastic processes: Brownian motions + jumps (e.g. climate disasters)
  - Recursive utility (see Lecture 6)
    - Decision-making under uncertainty
    - Distinguish risk aversion from intertemporal substitution (bundled in power utility)

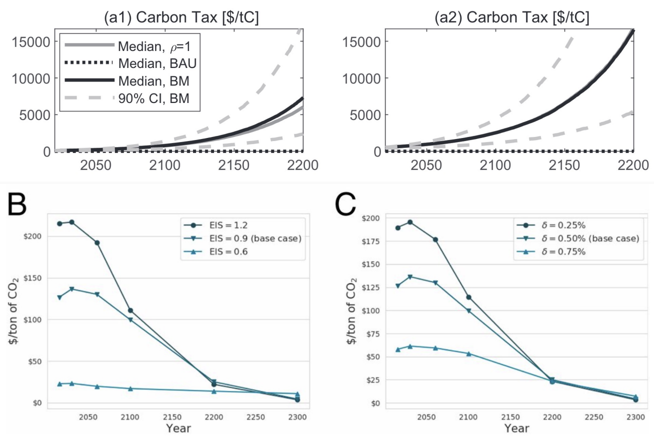
$$V_t = \left((1-\beta)c_t^{1-\rho} + \beta\left(E_t V_{t+1}^{1-\alpha}\right)^{\frac{1-\rho}{1-\alpha}}\right)^{\frac{1}{1-\rho}}$$

Asset pricing insight for climate econ

- Some relevant applications:
  - Bansal et al. (2017) in NBER
  - Dietz et al. (2018) in JEEM calculate the 'climate beta' using a CCAPM approach
  - Daniel et al. (2019) in PNAS find optimal carbon price using a binomial tree structure (usually used in option pricing)
  - Barnett et al. (2020) in Rev.Financ.Stud.
  - van den Bremer and van der Ploeg (2021) in AER with a risk-adjusted formulation of optimal SCC
  - Karydas and Xepapadeas (2022) in J. Financ. Stab.: dynamic CAPM with rare disasters
  - Hambel et al. (2024) in Int. Econ. Rev.: asset diversification desire vs climate action

Is the optimal price increasing in time?

- Usually yes. But depends on model and assumptions



Optimal carbon price paths. Above: with and without climate disasters (Hambel et al. 2024). Below: for values of EIS and pure rate of time preference (Daniel et al. 2019).

Strengths and weaknesses of asset pricing models

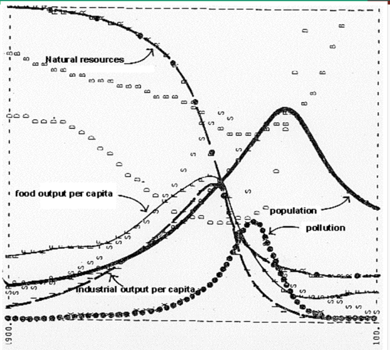
- Climate financial models useful
  - Provide links between climate/transition and financial dynamics
  - Offer tools to study relevant dimensions (uncertainty, disasters)
  - Well-known techniques to most financial economists
- However
  - Analytically and computationally intensive
  - Don't allow to go deep into complexity

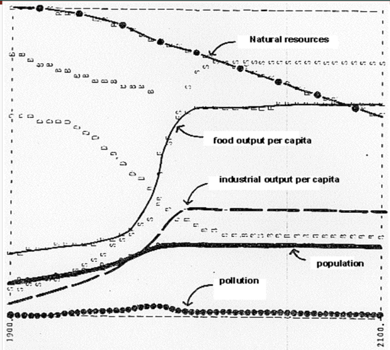
SFC climate/transition modelling

System dynamics

- System dynamics
  - Aim: capture real-world complexity (feedback loops, amplification, emergent behaviours)
  - Focus on stocks and flows (ecological modelling)
  - Macroeconometric approach: behavioural functions driven by estimation/calibration
  - Adaptive expectations (linear extrapolation to next period)
- The Limits to Growth (1972)
  - Forrester and MIT team; Meadows and Club of Rome
  - A continuation of business-as-usual would result into economic collapse driven by exhaustion of resources or pollution damages
  - Suggestion for radical policies
  - Economists were not happy (see Nordhaus, 1973)

The Limits to Growth (1972)





"Population and capital are the only quantities that need be constant in the equilibrium state. Any human activity that does not (..) produce severe environmental degradation might continue to grow indefinitely. In particular, those pursuits that many people would list as the most desirable and satisfying activities of man - education, art, music, religion, basic scientific research, athletics, and social interactions - could flourish."

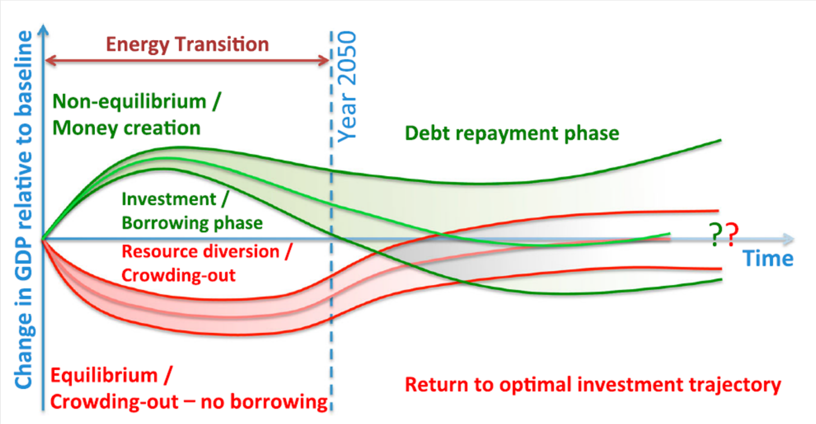
Stock-flow consistent (SFC) models

- Modelling based on a set of interacting balance sheets
  - Institutional sectors: households, firms, banks, government,..
  - Balance sheets made of assets and liabilities (deposits, loans, financial assets)
  - Productive capital only 'net' assets
- Sectoral behavioural functions
  - Usually based on post-keynesian theory
  - Radical uncertainty; no optimisation; adaptive expectations
- Rarely analytical solutions:
  - Numerical simulations of future scenarios (e.g. policy implementation)
- Key references
  - Godley, W., & Lavoie, M. (2007). Monetary Economics.
  - SFC tutorials by Dafermos

Post-keynesian economics

- SD or SFC per se are methodological approaches, not linked to any specific economic theory
    - However, SFC deeply rooted into post-Keynesian thinking
- Post-Keynesian modelling
    - Economies are demand-led: economic activity is driven by expenditure decisions
    - Aggregate behaviour is not an aggregation of individual behaviours (e.g. paradox of thrift)
    - Decisions taken in a context of fundamental uncertainty $\rightarrow$ heuristics, rules of thumb, social conventions, herd behaviour, path dependency, sentiments.. $\rightarrow$ Adaptive expectations
    - Prices are fixed by unit costs plus a mark-up (not by MPK)
    - Wages set by negotiations (not by MPL)
    - Banks do not have to wait for deposits before lending (endogenous money)

Equilibrium vs non-equilibrium models



GDP changes (relative to baseline) of a policy-driven sustainability transition; equilibrium vs non-equilibrium modelling approaches. Source: Mercure et al. (2019)

Behavioural functions

- Consumption
  - Function of disposable income and financial wealth

$$c_t = \alpha_1 Y^d_{t-1} + \alpha_2 v_{t-1}$$

  - Parameters specific to household types (e.g. workers vs entrepreneurs)
- Desired physical investments
  - Function of utilisation, interest rates, market valuation..

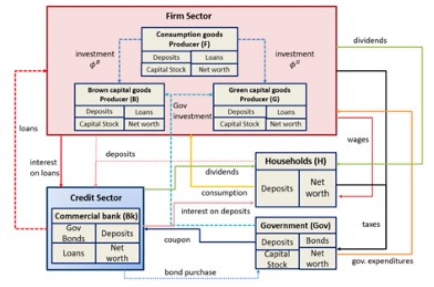
$$g_x = \eta_0 + \eta_1 u^e_x - \eta_2 rr_{l,x} \lambda_{x,-1} + \eta_3 q_{x,-1}$$

- Desired financial investments
  - Portfolio allocation matrix, e.g:

$$\begin{pmatrix} M_f \\ p_{c,e} e_c \\ p_{h,e} e_h \end{pmatrix} = \begin{pmatrix} \lambda_{10} & \lambda_{11} & \lambda_{12} & \lambda_{13} \\ \lambda_{20} & \lambda_{21} & \lambda_{22} & \lambda_{23} \\ \lambda_{30} & \lambda_{31} & \lambda_{32} & \lambda_{33} \end{pmatrix} \begin{pmatrix} 1 \\ \mathrm{R}_m \\ \mathrm{R}_c \\ \mathrm{R}_h \end{pmatrix} V$$

SFC modelling applied to environmental economics

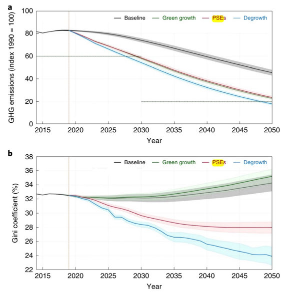
- 'Ecological macroeconomics'
  - See 2016 special issue in Ecol.Econ.
- A few recent SFC climate-macro models:
  - Dafermos et al. (2017) in Ecol.Econ.
  - Bovari et al. (2018) in Ecol.Econ.
  - D'Alessandro et al. (2020) in Nat. Sustain.
  - Jackson and Victor (2020) in Ecol.Econ.

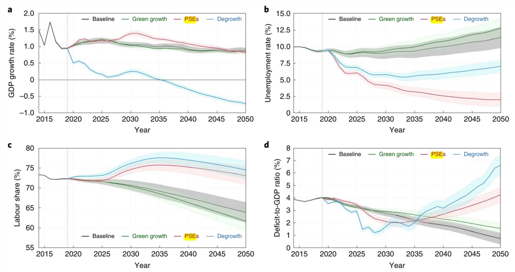


A stylised balance-sheet representation of the economic system, typical of SFC models. Source: Dunz et al. (2021)

D’Alessandro (2020) in Nat.Sust.

- Three policy strategies
  - Green growth: labour productivity, renewables, energy efficiency, carbon tax, CBAM
  - Policies for social equity (PSE): GG + job guarantee programme + working time reduction
  - Degrowth: PSE +consumption/export reduction + wealth tax





Intervals for 500 simulations per scenario. Source: D’Alessandro et al. (2020)

Strengths and weaknesses of SFC models

- Strengths of SFC models
  - Clear accounting rigour
  - Representation of monetary/financial dimensions
  - Focus on feedback loops
- However
  - Often messy: many parameters and macro behavioural relations hard to calibrate
  - Hard to interpret and empirically validate results
  - No forward-looking expectations
  - Weak normative indications (i.e. no optimal paths)
  - Sectoral classification is limiting; lack of agent-level details

Agent-based climate/transition modelling

Agent-based models (ABMs)

- Atomistic representative agents poor representation of reality
    - Individuals are heterogeneous in their preferences, endowments, social networks, decision criteria, planning horizons..
- ABMs
    - Multiple populations of heterogenous agents
    - Interactions among agents (networks) create emerging macro behaviours
    - Heuristic behavioural rules (+ switching)
    - Innovation/imitation dynamics (link to Schumpeterian literature)
    - Out-of-equilibrium dynamics
- Adaptive expectations
    - Methodological stance: bounded rationality
    - Computational limits

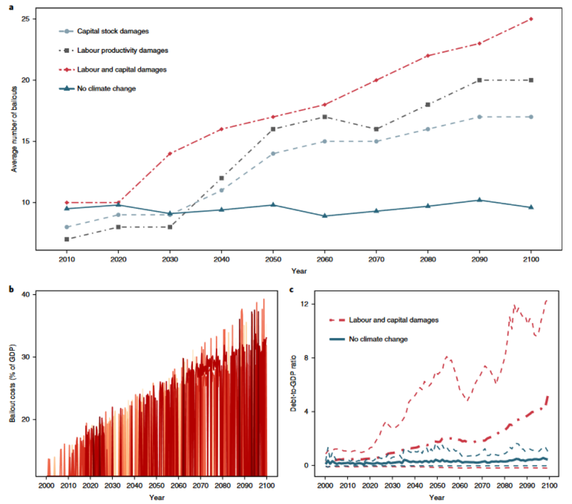
ABMs can be used to study climate-related issues

- They can be used to study diffusion of low-carbon technologies and environment-friendly behaviour
  - See recent review by Castro et al. (2020)
  - See also research agenda by Farmer et al. (2015)
- A limited number of ABMs incorporate both environmental and financial dimensions
  - Safarzynska and van den Bergh, 2017 in Ener.Pol.
  - Raberto et al. (2018) in J.Evol.Econ.
  - D'Orazio and Valente (2019) in JEBO
  - Rengs et al. (2020) in JEBO

Lamperti et al (2019) in Nat. Clim. Change.

- Dystopian Schumpeter meeting Keynes (DSK) model
- Climate change creates damages to:
  - Capital stocks
  - Labour productivity
- Firms' loss of profitability
  - Higher ratio of non-performing loans
- Banks' reduction of equity
  - When equity becomes negative, they are bailed out from the government

Lamperti et al. (2019) in Nat. Clim. Change.



Top: 10-yr average number of bailouts (500 sims). Bottom-left: bailout costs in Labour and capital damages scenario; each line: model run. Bottom-right: Public debt, average + 90% confidence intervals (500 sims). Source: Lamperti et al. (2019)

Strengths and weaknesses of ABMs

- Strengths of agent-based models
  - Granular representation of economic dynamics and behaviours (interactions, complexity)
  - Capture emerging properties of the system
  - Allow for non-rational behaviours
- However
  - Often messy: many parameters and macro behavioural relations hard to calibrate
  - Hard to interpret and empirically validate results
  - No forward-looking expectations
  - Weak normative indications (i.e. no optimal paths)
  - High computational costs

Choice modelling and diffusion theory

Discrete choice modelling

- Focus on decisions out of a discrete choice of options
  - e.g. what mode of transportation: combustion engine or EV?
- Random utility
  - observable components (e.g. prices)
  - unobservable components (e.g. preferences)

$$U_{ni} = V_{ni} + \varepsilon_{ni}$$

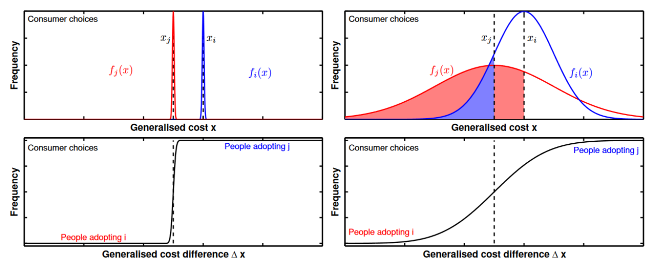
- Probability that individual n chooses option i = probability that U_{ni} is greater than utility of other options j
  - Assuming ε_{ni} is iid with a Gumbel distribution → Logit model

$$P_{ni} = \frac{e^{V_{ni}}}{\sum_j e^{V_{nj}}}$$

  - If ε_{ni} normally distributed → Probit model

DCM applied to technological choices

- Choice of technology depends on
  - Cost differential (observable)
  - Dispersion of perceptions around costs (unobservables)
- Choice allocation
  - Identical average costs → 50-50 split
  - Mean cost $i >$ mean cost j, share of i higher than 50%
  - Strength of effect depends on dispersion (variance of ε)



Technology i (blue) and technology j (red). Left: low diversity → abrupt solutions. Right: high diversity → smooth solutions. Source: Mercure et al. (2018)

Behavioural macroeconomics

- In the meantime, elsewhere..
  - 'Behavioural macroeconomics' (see Hommes 2021 in JEL)
- Individuals use heterogeneous decision heuristics
  - Not everyone (no one?) is fully rational
  - In complex environments, individuals use simpler routines
  - This applies to forecasting and expectation formation too
  - Heuristic switching: move to better-performing heuristics
- Fraction of population (or: probability of) adopting rule n:

$$n_{ht} = \frac{e^{\beta U_{h,t-1}}}{\sum_h e^{\beta U_{h,t-1}}}$$

  where U: measure of performance (e.g. distance from realised variable); β: 'intensity of choice' (function of belief dispersion)
- Combine the two streams:
  - Campiglio, Lamperti and Terranova (2024) in JEDC

Campiglio, Lamperti and Terranova (2024) in JEDC (i)

- Policymaker announces exponential carbon tax schedule

$$\bar{\tau}_t = \bar{\tau}_0(1 + \bar{g}_\tau)^t$$

- Two belief categories: believers ($j = b$) trust announcements more than sceptics ($j = s$). Expected tax growth rate:

$$E_j(g_\tau) = \epsilon_j \bar{g}_\tau$$

- Policy credibility assessed comparing actual and target taxes

$$U_{j,t} = \eta \left| E_{j,t-1}(\tau_t) - \tau_t \right| + (1 - \eta) U_{j,t-1}$$

- Believers' share $n \in (0, 1)$ depends on belief performance and belief responsiveness β

$$n_t = \frac{\exp(-\beta U_{b,t-1})}{\sum_j \exp(-\beta U_{j,t-1})}$$

Campiglio, Lamperti and Terranova (2024) in JEDC (ii)

- Firms compute expected net present value Θ_i of production costs for technologies $i = h, l$ (function of expected tax)

$$E_{j,t}(\Theta_{i,t}) = \sum_{r=1}^{R} D^r \theta_{i,t+r} \left[1 + E_{j,t-1}(\tau_{i,t+r})\right]$$

- Low-carbon investment share $\chi_{j,t} \in (0,1)$, function of expected tech costs and investment responsiveness γ:

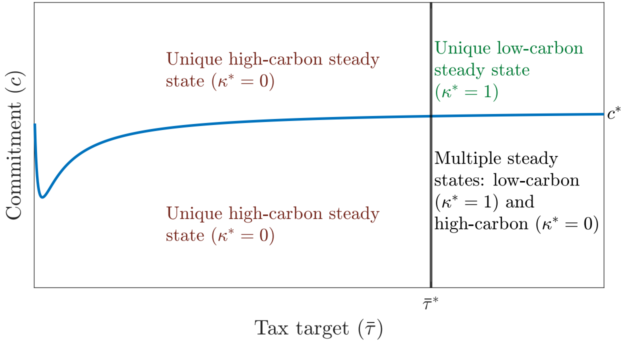
$$\chi_{j,t} = \frac{\exp(-\gamma E_{j,t}(\Theta_{l,t}))}{\sum_i \exp(-\gamma E_{j,t}(\Theta_{i,t}))}$$

- Policymaker evalutes transition risks $\pi_t = 1 - \frac{1}{1+a(1-\kappa_t)\bar{\tau}_t}$ and fixes tax depending on its climate commitment c

$$\tau_t = c\bar{\tau}_t + (1-c)\bar{\tau}_t(1-\pi_t)$$

Campiglio, Lamperti and Terranova (2024) results

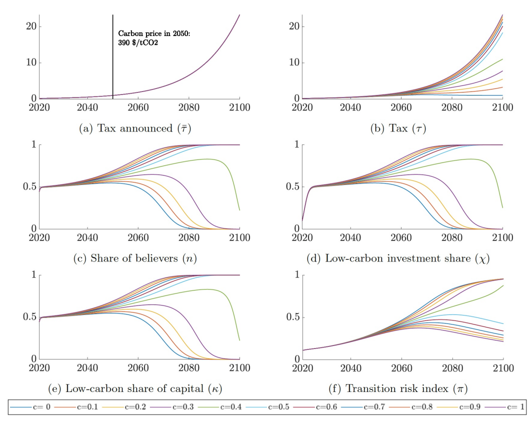
- Multiple equilibria and high-carbon traps
- Unambitious or non-credible policies $\rightarrow$ transition failures



Existence of low- and high-carbon steady states depending on commitment c and tax target $\bar{\tau}$ in the neoclassical limit case ($\beta \rightarrow \infty$). Source: Campiglio et al. (2024)

Campiglio, Lamperti and Terranova (2024) results

- weak commitment → credibility loss → high-carbon investments → higher transition risks → further distance from target → further loss of credibility → .. and so on



Source: Campiglio et al. (2024)

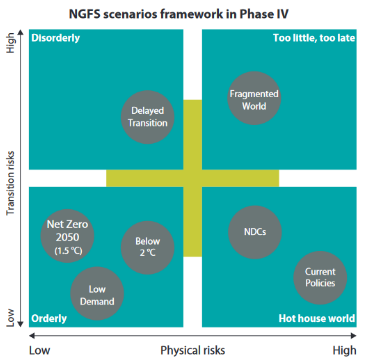
Coupling models

Alternative strategy: model coupling

- Instead of trying to do everything with one model..
  - ..create links between independent models ('hybrid models')
- Types of links
  - One-way link: a model provides inputs to another model
  - Two-way links: feedbacks loops between models (much harder)
- Any type of model potentially works
  - Most common: IAM + neoclassical macro + financial model
  - Some earlier attempts from central banks (Vermeulen et al., 2018; Allen et al., 2020)
  - → Scenario analysis from the Network for Greening the Financial System (NGFS)
  - An alternative: IAM + ABM (Fierro et al., 2024)

NGFS framework - Four representative scenarios

- Orderly transition:
  - Climate policies introduced early and gradually more stringent
- Disorderly transition:
  - Late/unanticipated but stronger policies → transition costs
- Hot house world:
  - Weak climate policies → physical costs
- Too little too late
  - Late and unsuccessful transition → physical and transition costs



Source: NGFS (2023)

NGFS framework - Scenario details

- NGFS scenarios encompass a range of possible policy/technological futures
- Current vintage: ‘Phase IV’ scenarios

Quadrant	Scenario	Physical risk: End of century warming (model averages)	Transition risk: Policy reaction	Transition risk: Technology change	Transition risk: Carbon dioxide removal [-]	Transition risk: Regional policy variation [+]
Orderly	Low Demand NEW	1.4 °C (1.6 °C)	Immediate	Fast change	Medium use	Medium variation
	Net Zero 2050	1.4 °C (1.6 °C)	Immediate	Fast change	Medium-high use	Medium variation
	Below 2 °C	1.7 °C (1.8 °C)	Immediate and smooth	Moderate change	Medium use	Low variation
Disorderly	Delayed Transition	1.7 °C (1.8 °C)	Delayed	Slow/Fast change	Medium use	High variation
Hot house world	Nationally Determined Contributions (NDCs)	2.4 °C (2.4 °C)	NDCs	Slow change	Low use	Medium variation
	Current Policies	2.9 °C (2.9 °C)	None – current policies	Slow change	Low use	Low variation
Too-little-too-late	Fragmented World NEW	2.3 °C (2.3 °C)	Delayed and Fragmented	Slow/Fragmented change	Low-medium use	High variation

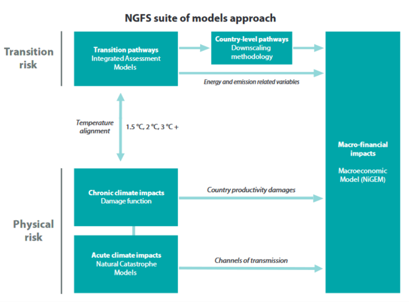
Colour coding indicates whether the characteristic makes the scenario more or less severe from a macro-financial risk perspective[^]

- Lower risk
- Moderate risk
- Higher risk

Source: NGFS (2023)

NGFS framework - Models involved

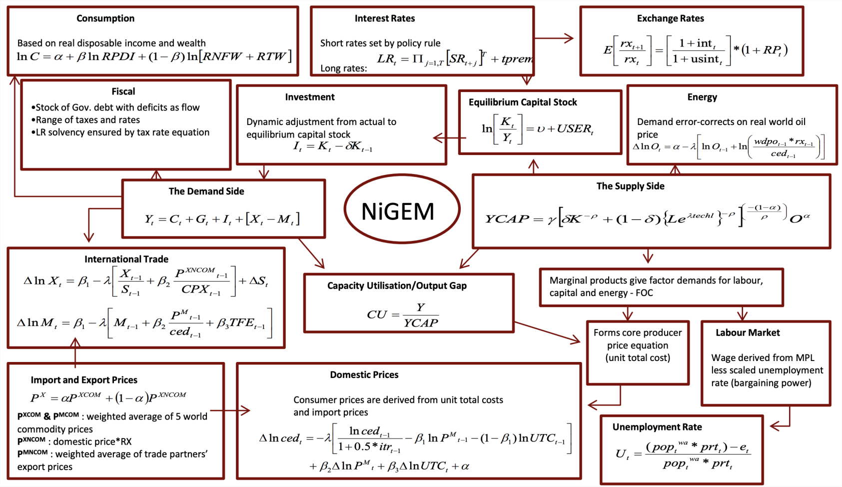
- NGFS analysis combines physical models, IAMs and a macroeconomic model
- Three large-scale numerical models involved



Source: NGFS (2023)

Integrated Assessment Model	GCAM 5.2	MESSAGEix_GLOBIOM 1.0	REMIND1.7-MagPIE3.0
Short name	GCAM	MESSAGEix-GLOBIOM	REMIND-MAgPIE
Solution concept	Partial Equilibrium (price elastic demand)	General Equilibrium (closed economy)	REMIND: General Equilibrium (closed economy) MAgPIE: Partial Equilibrium model of the agriculture sector
Anticipation	Recursive dynamic (myopic)	Intertemporal (perfect foresight)	REMIND: Inter-temporal (perfect foresight) MAgPIE: recursive dynamic (myopic)
Solution method	Cost minimisation	Welfare maximisation	REMIND: Welfare maximisation MAgPIE: Cost minimisation
Temporal dimension	Base year: 2015 Time steps: 5 years Horizon: 2100	Base year: 1990 Time steps: 10 years Horizon: 2100	Base year: 2005 Time steps: 5 (2005-2060) and 10 years (2060-2100) Horizon: 2100
Spatial dimension	32 world regions	11 world regions	11 world regions
Technological change	Exogenous	Exogenous	Endogenous for Solar, Wind and Batteries
Technology dimension	58 conversion technologies	64 conversion technologies	50 conversion technologies

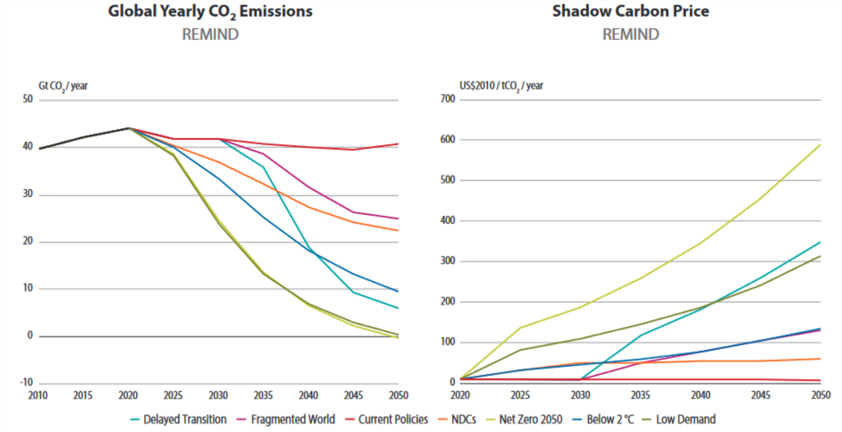
NiGEM econometric model



Source: NiGEM (2024)

IAM results

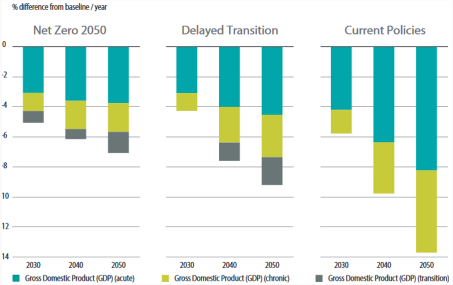
- IAMs provide results on emissions, carbon prices, energy mix and other transition related variables

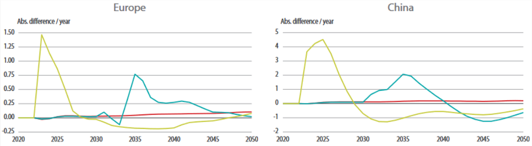


Source: NGFS (2023)

NiGEM results

- NiGEM returns results on GDP, inflation, interest rates and other macro-financial variables

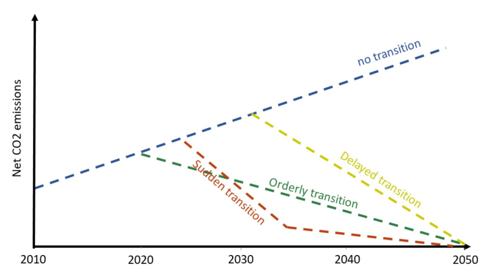




Above: GDP change wrt baseline with no climate change. Below: regional inflation variation. Source: NGFS (2023)

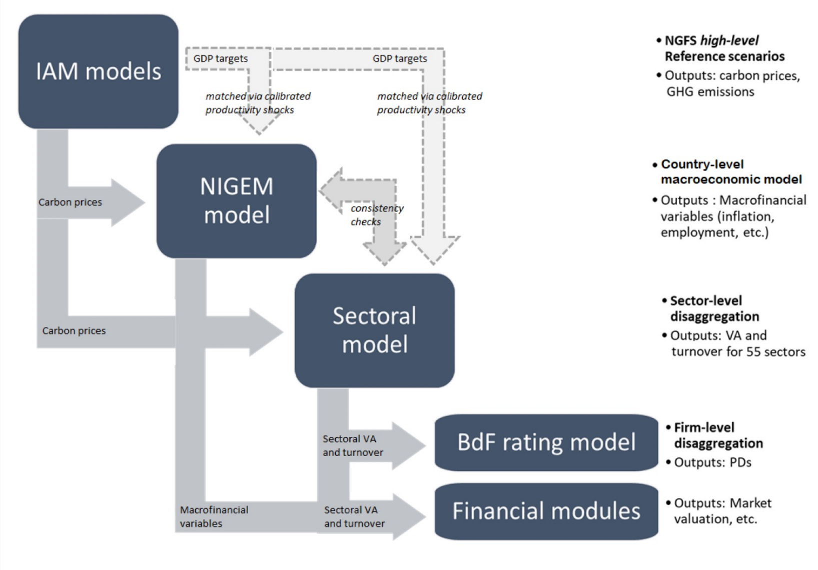
Allen et al. (2020): Banque de France

- They choose the orderly transition as a baseline
  - Different from usual IAM approach (baseline set to BAU)
  - Follows the stress testing logic
- Two disorderly transition narratives:
  - 'Delayed': follows NGFS delayed scenario with carbon price jumping in 2030
  - 'Sudden': carbon price jumps in 2025 but no low-carbon technological progress



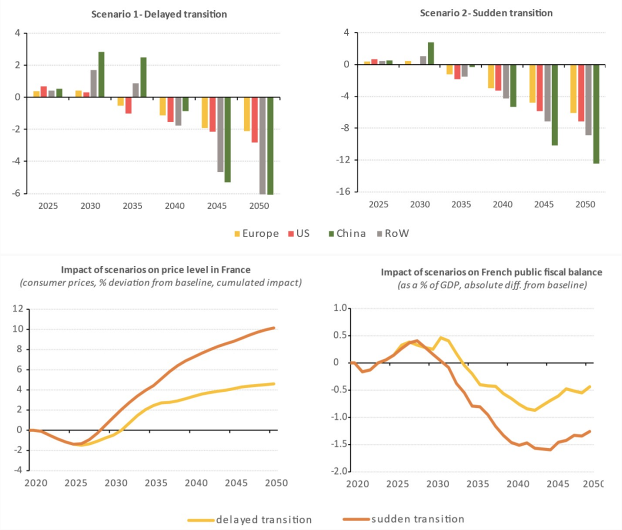
Source: Allen et al. (2020)

Allen et al. (2020): An ensemble of models

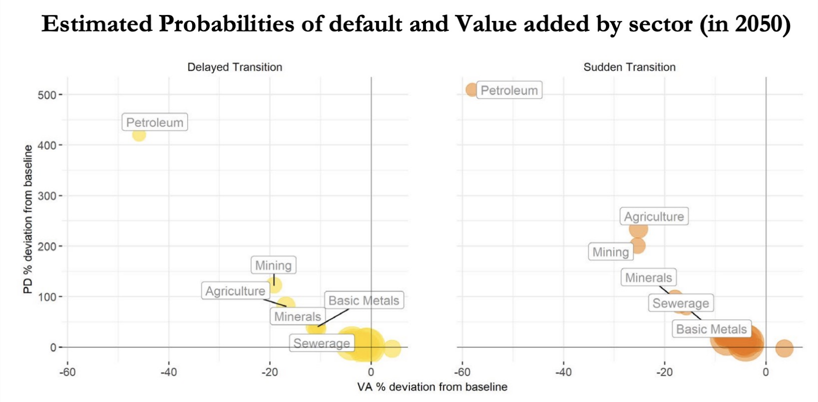


Source: Allen et al. (2020)

Allen et al. (2020): Macro results

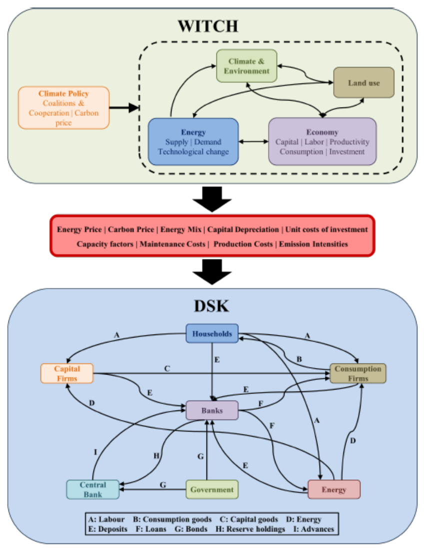


Above: GDP levels (% deviation from baseline). Below: impact on prices and fiscal balance. Source: Allen et al. (2020)



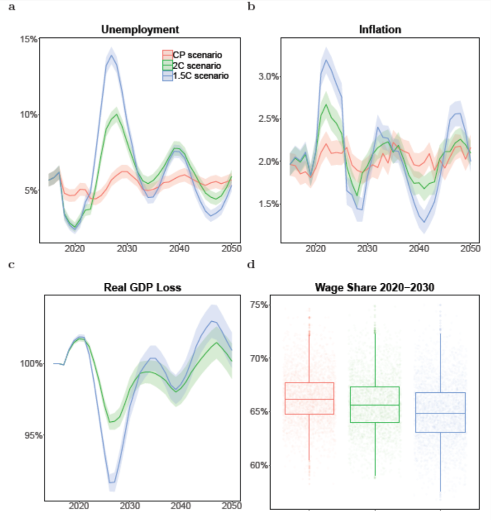
Estimated probabilities of default and value added by sector (France in 2050). Size of the bubble proportional to size of sample. Source: Allen et al. (2020)

Fierro et al. (2024): model coupling



Coupling of WITCH (IAM) and DSK (ABM). Source: Fierro et al. (2024)

Fierro et al. (2024): results



Different scenario dynamics (Current policies, 2°C, 1.5°C) across 300 simulations. GDP loss as deviations from Current Policies GDP. Source: Fierro et al. (2024)

Conclusions

Conclusions

- Variety of macro-financial modelling streams able to provide insights on climate change and low-carbon transitions
  - Modify standard framework by adding emissions, damage functions, heterogeneous technologies and other dimensions
- Multiple methodological approaches
  - DSGE macro models
  - Asset pricing models from finance
  - SFC models and heterodox models
  - Complexity: ABM and behavioural macro
  - All needed $\rightarrow$ pluralism!
- Hybrid models
  - Connect models from different streams in a consistent fashion