Virtual Seminar on Climate Economics

Federal Reserve Bank of San Francisco

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ASSET DIVERSIFICATION versus CLIMATE ACTION

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OUTLINE

- A. Integrated assessment analysis for one-sector economies: effects of risk and uncertainty on the price of carbon (asset pricing approach)
- B. Motivation for using two-sector economies to analyse policies for climate change: review of empirical literature on effects of green transition risks on stock market returns
- C. Use of 2-sector DSGE model and asset pricing to calculate optimal carbon price, stock market prices and risk premia under wide variety of economic and climatic uncertainties and disasters (paper with Hambel and Kraft)
- D. Possible improvements

A. MOST OF INTEGRATED ASSESSMENT MODELS HAVE ONE SECTOR AND ARE OFTEN DETERMINISTIC

- Quantitative IAMs: DICE-2016 by William Nordhaus, FUND by Anthoff and Tol, PAGE by Hope, etc. Used a lot for policy analysis
- Other numerical energy models are used to assess costs of meeting pre-defined emission targets
- Analytical IAMs: Golosov et al. (2014), Gerlagh and Liski (2018), Lemoine and Rudik (2017); huge number of applications of Brock-Mirman structure of Golosov et al.
- Most of these models have too much temperature inertia but not Golosov et al. see earlier seminar by Simon Dietz
- They have no stochastics and, if they do, they wrongly use Monte Carlo
- Golosov et al. (2014) has EIS=RRA=1 so all effects of uncertainty drop out
- But many now allow for stochastics including tipping points using stochastic versions of DICE: Gollier; Crost and Traeger; Jensen and Traeger; Lemoine and Traeger; Cai and Lontzek (2019); etc. Others appeal to asset pricing: Daniel et al. (2019).

DANIEL, LITTERMAN AND WAGNER (2019, PNAS)

- Uses binomial tree (7 periods) asset pricing model to show that optimal carbon price declines over time
- This requires (i) preference for early resolution of uncertainty (Epstein-Zin with RRA
 I / EIS) and (ii) gradual resolution of damage ratio uncertainty
- Olijslagers et al. (2020): revisits with continuous-time model and shows that optimal carbon price consists of a *rising* component proportional to GDP and a *declining* component that depends on uncertainty considerations; usually, the first component swamps the second component
- Van der Ploeg and de Zeeuw (2018): show that in a tipping model with a *one-off* temperature-dependent risk of a big increase in damages, the carbon price declines after the tip
- Today we look at *recurring* Barro-style disasters, where the incidence of the climaterelated disasters increases with temperature, not *one-off, irreversible* disasters

THE RISK-ADJUSTED CARBON PRICE (VD BREMER AND VD PLOEG)

- Get rule for **optimal** risk-adjusted SSC from stochastic DSGE with correlated risks, skewed distributions with mean reversion and convex damages
- Separate RRA and IIA = I/EIS
- Use perturbation methods and method of multiple scales to get leading-order expressions for SCC:
 - -Make use of climate moving slowly relative to economy
 - -Use power functions for tractability
 - -Damages as share of GDP are "small"
- Ignore 4th moments and fat tails of pdf's, but allow skewed pdf's
- Understand precaution, insurance & hedging motives

THE OPTIMAL CARBON PRICE AND RISK-ADJUSTED DISCOUNTED RATE BOIL DOWN TO:

$$P = \frac{\mu \Theta Y}{r^{\text{a}}} \left(1 + \Delta_{\chi} + \Delta_{\lambda} + \Delta_{CK} + \Delta_{CC} \right)$$

with

$$r^{a} = \rho + (IIA - 1)\left(g^{(0)} - \frac{1}{2}RRA \sigma_{K}^{2}\right) + \varphi$$

for case of proportional reduced-form damages and ignoring carbon stock uncertainty

DRIVERS OF RISK-ADJUSTED DISCOUNT RATE



- Here ρ = utility discount rate, γ is IIA = 1/EIS, and η = RRA
- If IIA = γ = I, the prudence and insurance effects offset each other so that the discount rate boils down to $\rho + \varphi$
- Economic uncertainty has zero effect on the carbon price

• $\frac{1}{2} \theta_{\chi T} (1 + \theta_{\chi T}) \frac{(\sigma_{\chi}/\overline{\chi})^2}{r^* + 2\nu_{\chi}}$ and $\frac{1}{2} \theta_{\lambda} (1 + \theta_{\lambda}) \frac{(\sigma_{\lambda}/\overline{\lambda})^2}{r^* + 2\nu_{\lambda}}$

- Climate sensitivity volatility pushes up price only if relevant distribution is right skewed or damages are more convex ($\theta_{\chi T} > 0$). Effect on carbon price is larger if climate sensitivity is more uncertain and distribution more skewed, climate sensitivity shocks are less temporary and the discount rate is smaller.
- Damage volatility only has direct effect on the carbon price if damage shocks are skewed (θ_λ ≠ 0), especially if they are more volatile ands persistent. But can have indirect effect via correlated risk effects. Differs from earlier negative risk-insurance term stemming from damages being proportional to GDP.

CORRELATED RISKS: HEDGING CLIMATE RISK

Assume "hedging" effect (increasing in RRA = η) dominates the "offsetting" effect (due to damages being proportional to output), i.e. relative risk aversion exceeds unity, $\eta > 1$ (cf. Lemoine, 2018)

The effects are stronger if shocks are more permanent, the discount rate is smaller, RRA is larger and the distribution is more skewed:

$$\Delta_{\rm CK} = -(\eta - 1)\sigma_{\rm K} \left((1 + \theta_{\chi T}) \frac{\rho_{{\rm K}\chi} \sigma_{\chi} / \overline{\chi}}{r^{\star} + v_{\chi}} + \frac{\rho_{{\rm K}\lambda} \sigma_{\lambda} / \overline{\lambda}}{r^{\star} + v_{\lambda}} \right),$$

INTERPRETATION

- Suppose in future states of nature asset returns are negatively associated with temperature, then the temperature beta is negative and it pays to invest more in fighting global warming and push up the SCC
- This may be so for industries selling winter garments, heating systems etc. But for industries producing wine in Sussex this beta is positive and they want a lower SCC
- Suppose in future states of nature assets returns are negatively associated with the damage ratio, then the damage beta is negative and the SCC is pushed up
- Not quite so for the Netherlands which has a strong water defences industry and so their asset returns benefit, i.e. want a lower SCC

B. TWO SECTORS: GREEN AND BROWN EQUITY

- Deterministic world: immediately switch capital to green sector. If there are adjustment costs, full specialisation takes time
- Stochastic world: keep brown production sector open as hedge?
- Negative effects of global warming on (i) production damages, in benchmark (Nordhaus), but also allow for negative effects on (ii) depreciation rate of capital (Dell et al., 2009, 2012) and (iii) risk of macro disaster risks (Barro et al., 2019)
- Not just (i), but 3 reasons to price carbon!
- Pricing carbon speeds up decarbonisation of economy
- Show effects on risk-adjusted carbon price, but also on share prices of carbon-free and carbon-intensive industries

COMPARISON WITH KARYDAS AND XEPAPADEAS (2019)

- Calibrates CAPM with macro disaster risks (cf. Barro) and climate disaster risks to price green and dirty assets
- Also, finds optimal portfolio shares of green & dirty assets
- We have two endogenous Lucas trees; they have one exogenous Lucas tree which can be painted green
- We have fully specified DSGE model with two sectors and two risky financial assets, one safe asset and a risky climate asset
- We find the optimal risk-adjusted carbon price as well as the prices of the green and carbon-intensive assets

MIXED EMPIRICAL EVIDENCE

- Bolton and Kacperzyk (2020a): carbon-intensive firms (steel, cement, oil majors, etc.) in US show higher stock market returns after controlling for size, book to market, momentum, etc. as investors already demand compensation for the carbon risk; this carbon risk premium cannot be explained via unexpected profitability or other risk premia
- Bolton and Kacperzyk (2020a): similar exercise for cross section of 14,400 firms in 77 countries shows evidence of *rising* carbon risk premia for carbon-intensive stocks
- Institutional investors are divesting away from carbon-intensive firms *But:*
- In, Park and Mong (2019, Stanford): looking at 736 US firms from 2005-2015, EMI (carbonefficient minus carbon-inefficient) portfolio has from 2010 onwards positive abnormal returns; investment strategy of going long on carbon-efficient firms and going short on carbon-inefficient firms would earn abnormal returns of 3.5%-5.4% per year (not driven by low *r*'s after GFC); carbon-efficient firms are "good" in terms of financial characteristics and governance

MIXED EMPIRICAL EVIDENCE CTD.

• Garvey, lyer and Nash (2018): firms that have a lower ratio of carbon emissions to sales (the "E in ESG") and are less dependent on carbon have stronger future profitability and higher stock returns

• Plantinga and Scholtens (2020, *CC*): looking at 7,000 companies over 40 years, they find that investment portfolios that exclude fossil fuel production companies do not perform worse than unrestricted portfolios, so they suggest that divesting from fossil fuel companies does no hurt performance

DONADELLI, GRÜNING AND HITZEMANN (2020, CEBRA)

- Focuses at the fossil fuel industry to circumvent classification issues
- Price-dividend ratio high but fell since 2008 at time of bust of commodity price boom
- Better econometrics to explain changes in value along trends in climate change awareness:
 - Explains market to book ratio of about 4,000 firms over 1970-2018
 - Uses panel regression to control for market-wide valuation and other trends
 - Depends on awareness of climate change risks (from Google searches, closely correlated with environmental policy stringency)
 - Controls for cash/assets, debt/assets, log assets, R&D/sales
- Empirical findings:
 - Stock market value of US oil and fossil fuel firms has fallen a lot over last 20 years compared to other firms
 - Markets have started to price in the climate transition (negative coefficient on climate awareness index)

DONADELLI ET AL. (2020, CEBRA)

- They use a similar 2-sector DSGE capital asset pricing model as we do but no disaster shocks and in discrete time instead of continuous time
- They have imperfect substitution between clean and dirty final goods
- Transition is driven by carbon taxes and capital relocates from dirty to clean sectors in responses to changes in financial markets (Tobin's Q's)
- They compare optimal transition with slow transition to optimal carbon prices & examine impulse response functions in both scenarios to understand climate policy risk premia
- Risk premium channel of climate policy: positive response of clean sector's returns leads to positive risk premia and curbs values of clean sector and capital reallocation
- Too low carbon taxes give positive risk premia and lower valuations for clean industry, but this is not desirable from a welfare perspective

RISK OF STRANDED ASSETS

- vd Ploeg and Rezai (2020): shows effects of the risk of policy tipping on market valuations of oil companies; policy uncertainty and costly adjustments of capital stocks leads to stranded assets
- vd Ploeg (2020): game-theoretic approach to "race to burn the last ton of carbon" and risk of stranded assets; mere risk of a cap on global warming at some unknown, future date makes oil extraction more voracious and accelerates global warming (cf. Green paradox)
- Barnett (2020): an uncertain arrival time of policy change generates a run on oil, so falls in spot price of oil and market valuation of companies, increase in green energy price and higher temperature; considers SDF and asset pricing implications; potential carbon bubble

C. OUR APPROACH

- To avoid carbon emissions and global warming, emissions-free technologies and renewable energies must substitute for fossil fuel
- Different opinions on how urgent it is to transition to a carbon-free economy
- Our interest is in the interplay between financial considerations and policies to mitigate climate change:
 - Does financial need to diversify hamper or help the fight against climate change?
 - How does climate change affect pricing of green and dirty assets?
- Subtle dynamic interdependence between financial goal to diversify assets in portfolios and environmental goal to cut emissions

TWO-SECTOR DSGE MODEL OF ECONOMY AND CLIMATE

- Two capital stocks and two energy sources
- Green sector has carbon-free energy as input
- Dirty sector requires fossil fuel whose combustions leads to emissions
- Investments and capital reallocation from dirty to green sector are both subject to adjustment costs; asymmetry
- Growth in capital in each sector is subject to Barro (2006)-style disasters, climate-related disasters and normal macro shocks (GBM)
- Duffie-Epstein preferences and Barro-style disaster shocks, so can calibrate high equity premium and low risk-free rate in the data
- Emissions are proportional to fossil fuel use
- Temperature is linear function of cumulative emissions
- Temperature adversely affects TFP, the depreciation rate and the risk of climate-related disasters

PREVIEW OF RESULTS

- Diversification perspective: diversify until there is a balance between green and dirty capital (cf. Cochrane et al., 2007)
- Environmental perspective: run down dirty capital stock completely
- The latter does not occur with DICE damages, but does occur if damages from climate change are much more severe or different damages are taken together
- Diversification considerations may prevent driving the dirty capital stock to zero
- We analyse dynamics of risk-free rate and risk premia during green transition:
 - The risk-free rate falls with rising temperature
 - Risk premia only significantly affected if risk of disasters increases with temperature (else impact on risk premia is moderate)

TWO PRODUCTION SECTORS

"AK" macroeconomic growth model:

- $I = \text{carbon-free sector with } F_1 = \text{green energy}$
- 2 = carbon-intensive sector with F_2 = fossil fuel

$$Y_n = A_n K_n^{\alpha_n} F_n^{\eta_n} (K_n L_n)^{1 - \alpha_n - \eta_n} \Lambda_i(T),$$

$$Y_n = A_n K_n^{1-\eta_n} F_n^{\eta_n} \Lambda_n(T)$$

Perfect substitution in consumption

 $Y = Y_1 + Y_2.$

INVESTMENTS IN GREEN AND DIRTY CAPITAL

- Intertemporal and inter-sectoral investment adjustment costs
- Temperature-dependent depreciation rates
- Independent Geometric Brownian motions; correlation between capital stocks
- Disaster risks: constant jump intensity λ_e (cf. Barro) and temperaturedependent jump intensity $\lambda_c(T)$ (cf. Karydas and Xepapadeas, 2019)

$$dK_{1} = \left(I_{1} - \frac{1}{2}\phi_{1}\frac{I_{1}^{2}}{K_{1}} + R - \frac{1}{2}\kappa\frac{R^{2}}{K_{1}} - (\delta_{1}^{k} + \xi_{1}T)K_{1}\right)dt + K_{1}\sigma_{1}dW_{1} - K_{1-}\left(\ell_{e}dN_{e} + \ell_{c}dN_{c}\right), dK_{2} = \left(I_{2} - \frac{1}{2}\phi_{2}\frac{I_{2}^{2}}{K_{2}} - R - (\delta_{2}^{k} + \xi_{1}T)K_{2}\right)dt + K_{2}\sigma_{2}\left(\rho_{12}dW_{1} + \sqrt{1 - \rho_{12}^{2}}dW_{2}\right) - K_{2-}\left(\ell_{e}dN_{e} + \ell_{c}dN_{c}\right),$$

CUMULATIVE EMISSIONS DRIVE TEMPERATURE

- Matthews et al. (2009), Allen et al. (2009), IPCC (2014), van der Ploeg (2018), Dietz and Venmans (2019)
- Emissions are vF_2
- cumulative carbon emissions E are integral of vF_2
- so $\beta = \nu \vartheta$ $T_t = T_0 + \vartheta E_t + \int_0^t \sigma_T(T_s) dW_{3s},$

$$\mathrm{d}T = \beta F_2 \mathrm{d}t + \sigma_T(T) \mathrm{d}W_3,$$

• Diffusion coefficient σ_T may capture unpredictable positive feedback loops in climate system

DIVIDENDS, CONSUMPTION AND PREFERENCES

- Following Cochrane et al. (2009), equilibrium dividends equal aggregate consumption (i.e. unleveraged claim on aggregate consumption): $C = D_1 + D_2$
- $D_n = Y_n I_n b_n F_n$ dividends in sector *n* (residual cash flow)
- Recursive Duffie-Epstein utility: IIA = I/EIS = I, RRA = γ

$$J(t, K_{1t}, K_{2t}, T_t) = \sup_{I_1, I_2, R, F_1, F_2} \mathbb{E}_t \left[\int_t^\infty f(C_s, J(s, K_{1s}, K_{2s}, T_s) \mathrm{d}s \right]$$
$$f(C, J) = \begin{cases} \delta(1 - \gamma) J \log\left(\frac{C}{[(1 - \gamma)J]^{\frac{1}{1 - \gamma}}}\right), & \gamma \neq 1\\ \delta [\log(C) - J], & \gamma = 1 \end{cases}$$

THE HAMILTON-JACOBI-BELLMAN EQUATION

The value function $J = J(t, K_1, K_2, T)$ satisfies the Hamilton-Jacobi-Bellman (HJB) equation. Following Duffie and Epstein (1992b), this equation is

$$0 = \max_{I_1, I_2, R, F_1, F_2} \left\{ J_t + \delta(1 - \gamma) J \log \left(\frac{Y_1 + Y_2 - I_1 - I_2 - b_1 F_1 - b_2 F_2}{[(1 - \gamma) J]^{\frac{1}{1 - \gamma}}} \right) + J_T \beta F_2 + \frac{1}{2} J_{TT} \sigma_T^2 + J_{K_1} \left(I_1 - \frac{1}{2} \phi_1 \frac{I_1^2}{K_1} + R - \frac{1}{2} \kappa \frac{R^2}{K_1} - (\delta_1^k + \xi_1 T) K_1 \right) + \frac{1}{2} J_{K_1 K_1} K_1^2 \sigma_1^2 + J_{K_2} \left(I_2 - \frac{1}{2} \phi_2 \frac{I_2^2}{K_2} - R - (\delta_2^k + \xi_1 T) K_2 \right) + \frac{1}{2} J_{K_2 K_2} K_2^2 \sigma_2^2 + J_{K_1 K_2} K_1 K_2 \sigma_1 \sigma_2 \rho_{12} + \lambda_e \mathbb{E} [J(K_1(1 - \ell_e), K_2(1 - \ell_e), T) - J] + \lambda_c(T) \mathbb{E} [J(K_1(1 - \ell_c), K_2(1 - \ell_c), T) - J] \right\}$$

$$(3.1)$$

where subscripts of J denote partial derivatives, e.g., $J_{K_1} = \frac{\partial J}{\partial K_1}$. The first-order optimally conditions give rise to efficiency conditions (3.2) – (3.5).

OPTIMALITY CONDITIONS

give five efficiency conditions, namely for optimal investment

$$I_n = \frac{K_n}{\phi_n} \frac{q_n - 1}{q_n}, \qquad n = 1, 2,$$

where the Tobin's Qs for the two sectors are defined by

$$q_n = \frac{C}{\delta(1-\gamma)} \frac{J_{K_n}}{J}, \qquad n = 1, 2,$$

The optimal sectoral reallocation of capital is given by

$$R = \frac{K_1}{\kappa} \frac{q_1 - q_2}{q_2}$$

The optimal energy uses are

$$\eta_1 A_1 \left(\frac{F_1}{K_1}\right)^{\eta_1 - 1} = b_1, \qquad \eta_2 A_2 \left(\frac{F_2}{K_2}\right)^{\eta_2 - 1} = b_2 + \tau_f,$$

where τ_f denotes the optimal Pigouvian tax on using one unit of fossil fuel that is

$$\tau_f = \frac{\beta C}{\delta(\gamma - 1)} \frac{J_T}{J}.$$

REDUCING NUMBER OF STATE VARIABLES

- Define share of dirty capital as $S = K_2 / K$ with $K = K_1 + K_2$
- Only need to solve reduced-form HJB equation in terms of S and T only, instead of the original HJB equation in terms of K_1 , K_2 and T

Proposition 3.1 (Separation). The solution to the HJB equation (3.1) has the following form

$$J(t, K_1, K_2, T) = \frac{1}{1 - \gamma} (K_1 + K_2)^{1 - \gamma} G(t, T, S(K_1, K_2)) = \frac{1}{1 - \gamma} K^{1 - \gamma} G(t, T, S), \quad (3.9)$$

where the reduced-form value function G satisfies a modified HJB equation given by equation (A.7) in Appendix A.

We solve the modified HJB equation with a finite-differences approach. Since the function G depends on two instead of three state variables, this is computationally less demanding.

OPTIMAL RISK-ADJUSTED SCC

The optimal tax on burning one ton of carbon is thus

$$\tau_c = \frac{\tau_f}{\nu} = \frac{\vartheta C}{\delta(\gamma - 1)} \frac{J_T}{J},$$

Corollary 3.2 (Social Cost of Carbon). The optimal social cost of carbon equals

$$\tau_c = \frac{\vartheta C}{\delta(\gamma - 1)} \frac{G_T}{G},$$

where the reduced value function G satisfies the modified HJB equation (A.7). Optimal consumption C is given by equation (A.6).

Note: we will discuss SDF and asset pricing implications later

BENCHMARK CALIBRATION

	Preferences								
δ	time-preference rate	0.05							
γ	relative risk aversion	5.288							
ψ	elasticity of intertemporal substitution	1							
Economic Model									
Y_0	initial GDP (trillion US \$)	75.8							
<i>S</i> 0	initial share of dirty capital	0.94							
A_1	green productivity	0.851							
A_2	brown productivity	0.828							
b_1	fossil fuel costs (\$ per tC)	540							
b ₂	green energy costs (\$ per etC)	810							
η_n	energy share in production	0.066							
ϕ_{n}	investment adjustment cost parameter	18.12							
σ_n	annual capital volatility	0.02							
α_e	macroeconomic jump size parameter	8							
λ_e	macroeconomic disaster intensity parameter	0.088							
κ	capital reallocation cost parameter	1							
$ ho_{12}$	instantaneous correlation	0							
Climate Model									
T_0	initial temperature ($^{\circ}$ C)	1							
σ_T	temperature diffusion coefficient	0.015							
θ	TCRE (°C/TtC)	1.8							
P_0	emission intensity parameter	11.03							
p_1	emission intensity parameter	0.1979							
<i>P</i> 2	emission intensity parameter	-8.554×10^{-4}							

- Calibrate to business as usual
- Share of energy is 6.6%
- Historically mostly carbon-intensive production: pick adjustment costs to match risk-free rate = 0.8%, average equity premium = 6.3% and Tobin's Q = 1.5
- RRA = 5.3 > ||A = |
- $\sigma_1 = \sigma_2 = 0.02$ matching volatility of consumption/output (Wachter, 2013)
- Choose relocation parameters κ such that global warming is about 4 degrees after 200 years (in line with Nordhaus)
- TCRE is 1.8 degrees Celsius for each trillion ton of carbon
- Calibrate emissions intensity $v = (11.03+0.1979t-8.544E-4 t^2)/K$ such that BAU emissions in DICE-2016R are matched

Calibration of the Climate System



Panel (a) shows carbon dioxide emissions in the BAU-scenario in DICE (black crosses). The gray line depicts the BAU evolution in our model. The emission intensity per unit of fossil fuel is plotted in Panel (b). Panel (c) shows the relation of cumulative emissions and temperature increase in DICE. The gray line shows a linear least-squares fit to this data. The slope of this straight line gives a TRCE of 1.8°C/TtC.

• Three types of climate externalities:

- Following Barro and Jin (2011), average consumption loss is 20% if disaster occurs, so annual 3.8% disaster risk gives λ_e = 0.088 and α_e = 8 where recovery rate 1 l_e follows a power distribution over (0,1) with parameter $\alpha_e > 0$
- Note *n*-th moment of recovery rate is $\alpha_{\rm e}/(\alpha_{\rm e} + n)$

CLIMATE-RELATED DISASTERS

- J-I estimated as in Karydas-Xepapadeas (2019) from EM-DAT data for 42 countries over period 1911-2015
- Climate disaster risk: disaster risk intensity is 0.003 + 0.096 T
- So disaster risk (roughly the probability that a disaster hits within the period of a year) is time varying
- Mean jump size of climate disasters equals $E[\lambda_c] = 1.5\%$
- Hence, using a power distribution for the recovery rate $Z_c = I I_c$ with pdf $\alpha_i Z_i^{\alpha_i 1}$ yields a value of $\alpha_c = 65.67$
- Size of disaster shock l_c has mean value $1/(\alpha_c + 1) = 1.5\%$

Dirty Capital Share for Increasing Intensities of Damages



Simulation of the share of dirty capital and global average temperature for the three damage specifications (level, disaster, growth rate) until the year 2200. The black dotted lines show the results for a hypothetical scenario without damages from climate change. Black solid lines: standard calibration. Gray lines: damage parameters are twice as high. Light lines: damage parameters three times higher.

INTUITION

- Dotted lines: hypothetical scenario with no climate damage, so no benefit from climate action and full diversification results (S tends to 50%)
- If climate damages matter, share of dirty capital stabilises between 20% and 30% if GBM shocks are uncorrelated.
- Pricing carbon leads to a gradual fall in the share of carbon-intensive capital, more than is required for diversification alone
- But unless damages are very severe (2x or 3x), dirty capital is kept in place for the diversification advantages it yields
- Diversification and climate action initially complementary goals, but after a while become conflicting goals & policy makers must counter the positive effects of diversification
- If all three types of damages occur together, dirty capital is driven to zero



Figure 2: Varying the Correlation Coefficient between the Two Sectors. Solid lines depict the optimal evolution of the share of dirty capital and global average temperature for the three damage specifications level impact (1st column), disaster impact (2nd column), and growth rate impact (3rd column) until the year 2200. Black lines (....,) show results for the benchmark case where the correlation between the Brownian shocks affecting the green and dirty sector is $\rho_{12} = 0$. Gray lines (....,) show results with $\rho_{12} = 0.5$. Light lines (....,) depict the results with $\rho_{12} = -0.5$.

DIVERSIFICATION MOTIVE: CORRELATED GBM SHOCKS

- If BM shocks are negatively correlated (light grey), the diversification motive is amplified so get a faster transition to full diversification and decarbonisation of economy at first; but after a while the opposite is true and the economy keeps a higher share of dirty capital to benefit from diversification (less climate action)
- With positive correlation (dark grey), diversification motive is weaker so in short run transition to green economy is slowed down but in longer run it is speeded up and the economy ends up with a lower share of dirty capital
- Note: both capital shocks are hit by common disaster shocks, so true correlation between capital stocks is much higher than ρ_{12} indicates (always higher than 90%)

ASSET PRICING IMPLICATIONS

• Time-zero price of cash flow:

$$P_0 = \mathbb{E} \left[\int_0^T H_s \mathrm{CF}_s \mathrm{d}s \right],$$

• SDF for recursive preferences (Duffie-Epstein):

$$H_s = \exp\left(\int_0^s f_v(C_u, J_u) \, ds\right) f_J(C_s, J_s)$$

• Ito's lemma:

$$\frac{\mathrm{d}H}{H_{-}} = \frac{\mathrm{d}f_c(C_{-}, J_{-})}{f_c(C_{-}, J_{-})} + f_J(C, J)\mathrm{d}t,$$

Proposition 6.1 (Equilibrium). Let σ_k be the three-dimensional volatility vector of the total stock of capital, see (A.8), and σ_g be the three-dimensional volatility vector of G, see (B.1). Let μ_c and σ_c denote the drift rate and the three-dimensional volatility vector of optimal consumption, respectively, see (B.3) and (B.4). The SDF follows the dynamics

$$\frac{\mathrm{d}H}{H_{-}} = -r^{f}\mathrm{d}t + \Theta_{W}^{\top}\mathrm{d}W + \sum_{i \in \{e,c\}} \left((1-\ell_{i})^{-\gamma} - 1 \right) \mathrm{d}N_{i} - \Theta_{N}\mathrm{d}t$$

with $W = (W_1, W_2, W_3)^{\top}$. The equilibrium risk-free rate r^f is

$$r_{t}^{f} = \underbrace{\delta + \mu_{c}(t, S_{t}, T_{t}) - \gamma \|\sigma_{c}(t, S_{t}, T_{t})\|^{2}}_{standard \ diffusion \ risk} - \underbrace{\sum_{i \in \{e,c\}} \lambda_{i}(T_{t}) \mathbb{E}_{t}[\ell_{i}(1 - \ell_{i})^{-\gamma}]}_{disaster \ risk} - \underbrace{\langle \sigma_{g}(t, S_{t}, T_{t}) + (\gamma - 1)\sigma_{c}(t, S_{t}, T_{t}), \sigma_{k}(S_{t}) - \sigma_{c}(t, S_{t}, T_{t}) \rangle}_{temperature \ diffusion \ risk}$$
(6.3)

where $\|\cdot\|$ denotes the Euclidean norm and $\langle \cdot, \cdot \rangle$ the scalar product. The market price of diffusion risk and the market price of jump risk are

$$\Theta_{Wt} = \underbrace{-\gamma \sigma_k(S_t)}_{standard\ risk} + \underbrace{\sigma_g(t, S_t, T_t) + \sigma_k(S_t) - \sigma_c(t, S_t, T_t)}_{temperature\ risk},$$
$$\Theta_{Nt} = \sum_{i \in \{e,c\}} \lambda_i(T_t) \mathbb{E}[(1 - \ell_i)^{-\gamma} - 1].$$

SO RISK-FREE INTEREST RATE EQUALS

- Rate of time impatience δ (high δ means economy wants to borrow but risk-free asset is in zero net supply so r^{f} must rise to counter this)
- Plus affluence effect = IIA x μ_c with IIA = I
- Minus prudence effect = $\frac{1}{2}$ RRA x (I+IIA) σ_c^2 = RRA x σ_c^2 if IIA = I (precautionary motive in response to GBM risk; r^f must fall to keep risk-free asset in zero net supply)
- Minus disaster risk effect (precautionary motive in response to disaster risk, larger for higher T; negative to keep risk-free asset in zero net supply
- Minus temperature diffusion risk effect (i.e. precautionary saving due to uninsurable, unhedged temperature risk)
- Extends Barro (2006, 2009), Wachter (2013), Pindyck and Wang (2013) and Karydas and Xepapadeas (2019)

	r_f	μ_c	$-\gamma \ \sigma_c\ ^2$	$-\langle \sigma_g + (\gamma - 1)\sigma_c, \sigma_k - \sigma_c \rangle$
$T = 1^{\circ}\mathrm{C}$	0.82%	2.92%	-0.11%	0.00%
$T = 2^{\circ}\mathrm{C}$	0.77%	2.87%	-0.11%	0.00%
$T = 3^{\circ}\mathrm{C}$	0.71%	2.81%	-0.11%	-0.00%
$T = 4^{\circ}\mathrm{C}$	0.64%	2.74%	-0.11%	-0.01%
$T = 5^{\circ}\mathrm{C}$	0.55%	2.67%	-0.11%	-0.02%
S = 0.05	0.75%	2.94%	-0.19%	-0.00%
S = 0.25	0.76%	2.89%	-0.13%	-0.00%
S = 0.50	0.73%	2.83%	-0.11%	-0.00%
S = 0.75	0.66%	2.78%	-0.13%	0.00%
S = 0.95	0.53%	2.71%	-0.19%	-0.00%

Table 4: Risk-free Rate Decomposition for the Year 2100. The table shows the statedependent terms in the decomposition of the risk-free rate (6.3). It provides sensitivity analysis for different values of temperature and the share of dirty capital around their median values in 2100 (S = 0.53, T = 2.8). The constant terms in (6.3) are the time preference rate $\delta = 0.05$, the contribution of economic disasters $\lambda_e \mathbb{E}_t[\ell_e(1-\ell_e)^{-\gamma}] = 0.0699$, and the contribution of climate-related disasters $\lambda_c \mathbb{E}_t[\ell_c(1-\ell_c)^{-\gamma}] = 0$.

DRIVERS OF RISK-FREE RATE 2100

- Decomposition is qualitatively similar for other years
- Expected consumption growth (affluence effect):
 - decreases in temperature due to damages
 - decreases in share of dirty capital as (i) optimal fossil fuel use and thus output declines in share of dirty capital and (ii) economy relocates capital at a higher rate and the adjustment costs depress growth
- Negative precautionary savings term:
 - temperature has tiny effect
 - share of dirty capital has a big non-monotonic effect on this term (cf. Cochrane et al., 2007)
- Temperature diffusion risk term: almost negligible

PRICING "TREES"

• For a stream of future dividends, the time-t price is

$$H_t P_{it} = \mathbb{E}_t \Big[\int_t^\infty H_s D_{is} \mathrm{d}s \Big].$$

- Expected excess return in equilibrium (risk premium of asset) is expected ex-dividend stock return *plus* dividend yield D_i/P_i minus risk-free interest rate, where D_i/P_i satisfies a parabolic partial differential equation
- The SCC can be calculated in similar fashion with marginal damages replacing dividends



Figure 4: Asset Pricing versus Temperature and the Share of Dirty Capital. On the horizontal axis is temperature in the range from 0°C to 5°C. The lines represent various levels of the capital share: dark lines (—) depict S = 0.95, gray lines (—) refer to S = 0.5, and light (—) lines to S = 0.05. a) plots Tobin's Q of the green asset, b) shows Tobin's Q of the dirty capital stock, c) depicts the equilibrium risk-free rate, d) shows the risk premium of the green asset, e) depicts the risk premium of the dirty asset. The option to convert dirty capital into green capital generates interesting qualitative effects but the quantitative implications are modereate.

DRIVERS OF RISK PREMIUMS

- Tobin's Q for both green and dirty sector decline in temperature
- Book to market ratio increase in temperature
- So for given capital, market value decreases in temperature for both assets
- Tobin's Q of green asset increases in share of dirty capital, hence for given capital green asset has a higher market value if economy is more carbon intensive; opposite for the carbon-intensive asset (panels a and b)
- Behaviour of risk-free rate is as discussed already (panel c)
- Green and brown equity premiums positively related to clean and dirty share of capital, respectively, and hardly any temperature dependence (panels d and e); similar to Table 5 below
- If carbon is correctly priced, green premium is higher than brown premium (contrast with Bolton and Kacperzyk, 2020ab)

	Green Asset		Dirty Asset		Risk-free rate		
	rp_1	μ_{P_1}	Ω_1^{-1}	rp_2	μ_{P_2}	Ω_2^{-1}	r_{f}
$T = 1^{\circ}\mathrm{C}$	6.45%	2.82%	4.38%	6.30%	1.70%	5.35%	0.82%
$T=2^{\rm o}{\rm C}$	6.47%	2.94%	4.19%	6.28%	1.44%	5.50%	0.77%
$T = 3^{\circ}\mathrm{C}$	6.48%	3.02%	4.02%	6.26%	1.18%	5.64%	0.71%
$T=4^{\rm o}{\rm C}$	6.50%	3.08%	3.88%	6.25%	0.93%	5.78%	0.64%
$T=5^{\circ}\mathrm{C}$	6.51%	3.10%	3.77%	6.24%	0.69%	5.90%	0.55%
S = 0.05	6.22%	1.99%	4.98%	6.03%	2.05%	4.73%	0.75%
S = 0.25	6.21%	2.02%	4.89%	6.09%	2.01%	4.77%	0.76%
S = 0.50	6.46%	2.89%	4.17%	6.29%	1.34%	5.55%	0.73%
S = 0.75	6.63%	4.11%	2.98%	6.21%	0.91%	5.76%	0.66%
S=0.95	6.80%	5.82%	1.26%	6.30%	1.32%	5.25%	0.53%

Table 5: Risk Premium Decomposition for the Year 2100. The table shows the decomposition of the risk-premium rp_i into its components dividend yield Ω_i^{-1} , stock growth rate μ_{P_i} , and risk-free rate r_f . It provides sensitivity analysis for different values of the share of dirty capital and temperature around their median values in 2100 (S = 0.53, T = 2.8). We use the benchmark calibration from Section 4.

DRIVERS OF RISK PREMIUMS IN 2100

- The term μ_{pn} is the expected ex-dividend stock return on asset *n*
- The term Ω_n^{-1} is the dividend yield of asset *n*
- The risk premium rp_1 increases in temperature and especially in the share of dirty capital
- The same holds for the expected ex-dividend green stock return μ_{pl} which increases sharply in the share of dirty capital
- The opposite is true for its dividend yield Ω_1^{-1} so if share of dirty capital is high the green stock pays fewer dividends but after green transition the green asset pays higher dividends
- Hence, positive correlation between share of dirty capital and green Tobin's Q

TIMES SERIES SOLUTIONS

- Left column: only temperature effect on TFP for aggregate production (Nordhaus)
- Middle column: only temperature effect on jump intensity of disasters (Karydas and Xepapadeas)
- **Right column**: only temperature effect on depreciation rate of capital

- Solid lines = optimal;
- Dashed lines = 5 and 95% confidence bounds for optimal
- Dotted lines = BAU





- Share of dirty capital falls over time if government prices carbon but stays fairly flat under BAU
- Emissions and temperature are lower and output higher if the government prices carbon compared with BAU
- Optimal consumption/GDP is first higher and then lower than under BAU for TFP damages, but not for disaster and depreciation rate damages
- Optimal consumption is always higher than under BAU
- The share of dirty capital in the hypothetical case of zero climate damages, goes to 50% (cf. Cochrane et al., 2007) but when the government prices carbon to fight global warming, the share of dirty capital goes down further with 25-30%
- Crucially, it does not go to zero as some positive amount of dirty capital is kept for diversification reasons; this weakens fight against global warming

Evolution of Asset Pricing Quantities



The figure depicts the simulation of asset pricing quantities for the three damage specifications level impact (1^{st} column), disaster impact (2^{nd} column) and growth rate impact (3^{rd} column) until the year 2200. The black dotted lines show the results for the BAU scenario.

- The risk-free rate falls much more strongly over time if carbon is not priced; this is due to precautionary savings to cope with the inevitable growing climate damages that will come under BAU (panel c)
- This manifests itself in a falling risk-free interest rate under BAU. If carbon is optimally priced, the path for the risk-free interest rate is much flatter
- Only for disaster impact (middle column) do we see a significant gradual rise in both the green and the dirty risk premium as temperature rises
- Dirty risk premium depends on dirty capital share and temperature in a nonlinear way, hence the "snake-shaped" evolution of the dirty risk premium over time for level and growth damages
- For the disaster damages, the risk premium are higher and increasing, which is triggered by the additional Poisson shocks giving rise to an extra component in risk premium (Prop 6.1)
- Since jump intensity rises with temperature, this extra component becomes especially important in BAU and asset holders must be compensated for the increasing climate risks

- Both the dirty Tobin's Q and the green Tobin's Q decline over time, but the dirty Tobin's Q is always smaller under optimal carbon pricing
- Since investment rate (I/K) are proportional to Q, we see that investment rates for the dirty sector and the green sector decline albeit the investment rate for the dirty sector is lower; this is why the share of dirty capital falls over time under carbon pricing
- The green Tobin's Q and the green investment rate under BAU decline over time; this is also so for the dirty Tobin's Q and dirty investment rate under BAU
- In case of disaster impact (middle), both the brown equity premium and the green equity premium decline over time as climate risks falls under optimal carbon pricing; both premia rise over time under BAU (pretty stable for TFP and growth rate impact)
- Holders of carbon-intensive assets must be compensated for increasing climate risks over time under BAU; and opposite under optimal carbon pricing (panel e2)



D. POSSIBLE IMPROVEMENTS

- Allow for correlation of disaster shocks; computationally burdensome
- Could replace temperature-dependent disaster risks by stochastic volatilities increase in temperature
- Allow capital reallocation from green to brown companies (symmetry) as now brown risk premium decreases with temperature (when capital is diversified, S about 0.5) because of the option value which does not occur for green assets; hence, brown assets become attractive when temperature increases (see also Pastor et al., 2020, *JFE*; Pedersen et al., 2020, *JFE*; Zerbib, 2020)
- Allow investors to diversify across different green industries; might attenuate conflict between diversification and abatement
- Similarly, investor may have non-pecuniary preferences for green companies and accept a lower Sharpe/reward to variability ratio to speed up greening of economy; is it ethical to keep dirty assets as a hedge?

- Imperfect substitution between clean and dirty final goods
- Environmental impact investing: have a general equilibrium model with a continuum of firms where each of their carbon footprints is made endogenous and where the effect of this via the carbon tax on their capital cost makes them reduce their footprint (cf. Oehmke and Opp, 2020; Landier and Lovo, 2020; Pastor et al., 2020, JFE; De Angelis et al., 2020)
- E.g. if fraction of assets managed by green investors doubles, carbon intensity of companies in portfolio drops by 5% per year (De Angelis et al., 2020)
- Depart from global economy by studying either a small open economy with an agreed carbon budget or a game between countries

• Thanks to Olivier David Zerbib for some of these suggestions and references

GREEN TRANSITION RISK

- Carbon-intensive firms may face risk of default if there is a sudden future stepping up of climate policy (cf. Barnett, 2019) or breakthrough in green technology
- Extend a model with limited liability, average risk pricing of deposits and excessive leverage, and thus need for *differential* capital requirements (Mendecino et al., 2020, JME)
- Does this require differential prudential policies for green and dirty assets?
- Carbon risk premium found by B&K seems related to transition policy risk (Hu et al., 2020) and this transition risk differential is also observed in option markets (Ilhan et al., 2020)
- After Paris agreements firms affected by transition risks have been charged higher interest rates (Delis et al., 2020)

E. CONCLUSION

- The international free-rider problem and intergenerational conflict make internalising the global warming externality extremely difficult
- There may be an additional finance reason which complicates matters even more
- Even if carbon is optimally priced, there may be a need to diversify and keep open the carbon-intensive sector and hold carbon-intensive financial assets in the long run alongside carbon-free financial assets
- Carbon tax increase in temperature and (modestly) in share of carbon-intensive assets

THANK YOU

SOLVE HJB EQUATION IN TERMS OF SHARE OF CARBON-INTENSIVE CAPITAL SAND TEMPERATURE T

- The ratio of the carbon tax to stock of dirty capital K2 rises with temperature and decreases mildly with share of dirty capital, S
- Ratio of consumption to GDP, C/Y, tapers off with temperature
- Fossil fuel use and renewable energy decline with temperature
- Investment in dirty and clean capital fall with temperature, and so do the Tobin Q's
- Rate of green investment increases in S but the rate of fossil investment decreases in S along an optimal path
- The risk-free rate declines with temperature



Figure 2: Optimal Controls and Carbon Tax. The graphs depict policy functions. The lines represent various levels of the capital share: dark gray lines depict S = 0.9, medium gray lines refer to S = 0.5, and light gray lines to S = 0.1. On the horizontal axis is temperature in the range from 0°C to 5°C. (a) plots green investment as a fraction of green capital, (b) shows dirty investment as a fraction of dirty capital, (c) depicts consumption as a fraction of output, (d) shows green energy as a fraction of green capital, (e) depicts fossil fuel use as a fraction of dirty capital, and (f) shows the optimal carbon tax.



Figure 3: Asset Pricing Implications. The graphs depict policy functions. The lines represent various levels of the capital share: dark gray lines depict S = 0.9, medium gray lines refer to S = 0.5, and light gray lines to S = 0.1. On the horizontal axis is temperature in the range from 0°C to 5°C. (a) plots green investment as a fraction of green capital, (b) shows dirty investment as a fraction of dirty capital, (c) depicts consumption as a fraction of output, (d) shows green energy as a fraction of green capital, (e) depicts fossil fuel use as a fraction of dirty capital, and (f) shows the optimal carbon tax.

INTERNALISING ALL THREE GLOBAL WARMING EXTERNALITIES

- Carbon is priced more vigorously (reaches \$1500/GtC in 2150, 30-50 years earlier)
- Emissions are curbed more quickly
- Temperature rises less quickly and stays below 2 degrees
- Share of dirty capital drops down to zero by 2120 (diversification too costly)
- Risk-free interest rate flat instead of declining
- Response is more than sum of individual responses, so the three types of damages reinforce each other



