

Climate-Economy Models: New Frontiers and Critical Challenges

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AEA Continuing Education: Climate Change

January 2020

Topics

1. **Endogenous Technical Change**
2. **International Spillovers and Strategic Considerations**
3. **Tipping Points and Catastrophic Climate Change**

Endogenous Technical Change

- ▶ Benchmark IAMs often treat technology as exogenous
- ▶ Hicks (1932): Change in relative factor prices should spur innovation to economize use of newly more expensive factor
- ▶ Empirical evidence: *Innovation responds to energy prices*

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- ▶ Calel and Dechezleprêtre (2016, ReStat): E.U. Emissions Trading Scheme increased low-carbon patenting $\approx +9.1\%$

Endogenous Technical Change

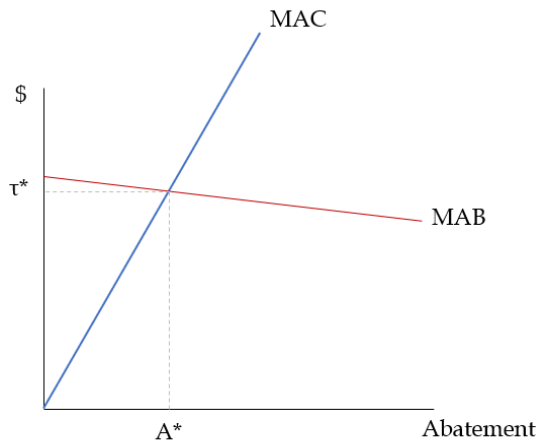
- ▶ IAM modelers have integrated, studied various forms of ETC
 - ▶ Direct price-induced technical change
 - ▶ Learning-by-doing
 - ▶ Knowledge stocks (R&D) investments

Survey: Gillingham et al. (2008, EE)

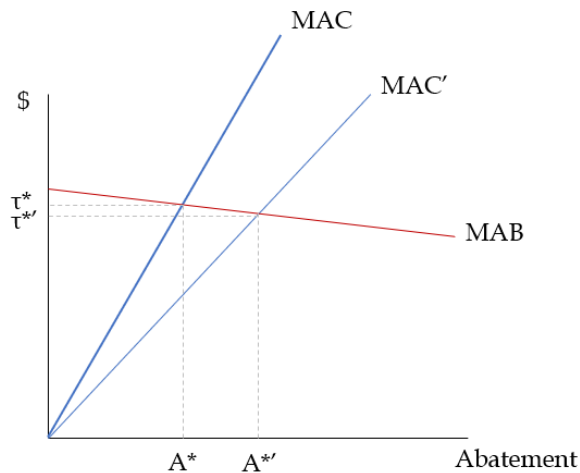
⇒ Common findings (e.g., Goulder and Mathai, 2000; Nordhaus, 2002; Popp, 2004; Fried, 2018):

1. **Small effect of ETC on optimal carbon price**
2. **Lower carbon tax required to meet ex. emissions targets**
 - ▶ Lower abatement costs increase optimal abatement *level*

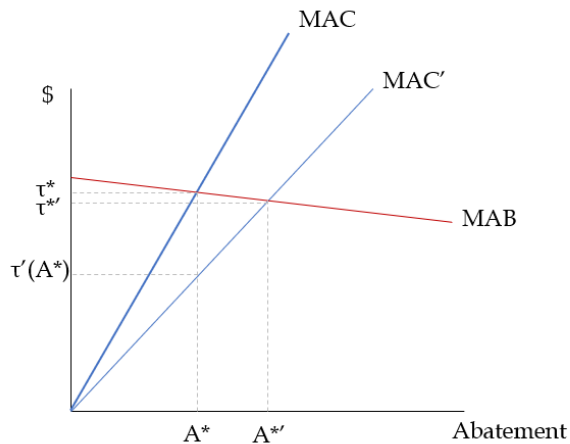
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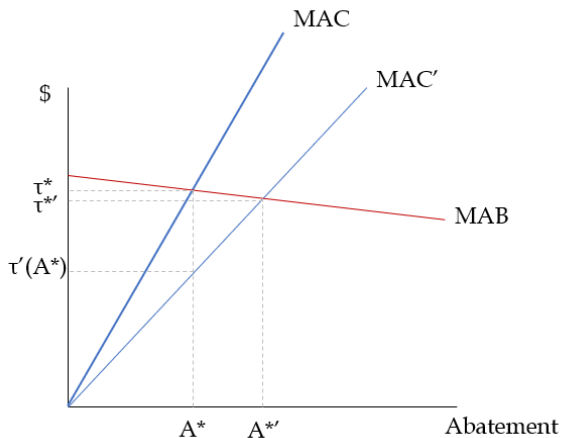
Endogenous Technical Change



Endogenous Technical Change



Endogenous Technical Change



- Fried (2018): Quantitative model of directed technical change in U.S. Economy $\Rightarrow$ Carbon tax required for 30% emissions reduction is *20% lower* with ETC

Acemoglu, Aghion, Bursztyn, Hémous (2012)

- ▶ Climate in *directed technical change* model (à la Acemoglu 2002)
- ▶ Designed to analyze *direction* of technical change
 - ▶ Innovation in clean vs. dirty energy technologies
- ▶ Micro-founding innovation: Scientists decide where to do research based on expected profitability of patents if successful

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- ▶ 3 Lessons:
 1. *Path Dependence*: If fossil initially sufficiently advanced technology, economy remains on fossil path in laissez-faire

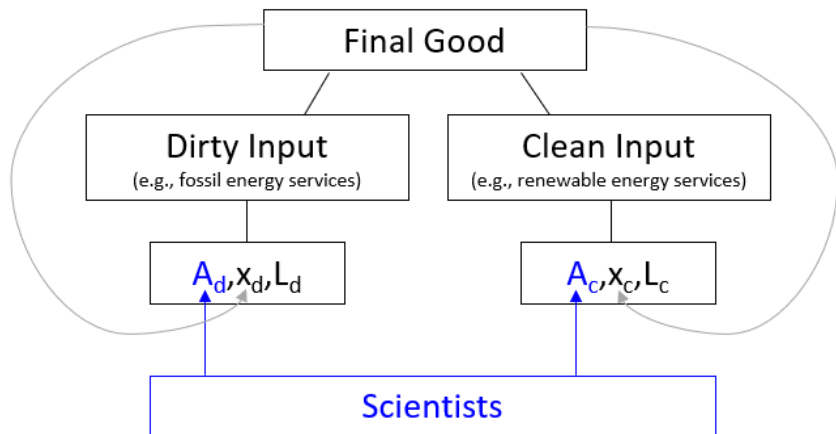
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 3. *Two Instruments*: Decentralizing first best requires both carbon tax *and* clean research subsidy

AABH (2012): Setup



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- ▶ Representative household with intertemporal utility:

$$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} u(C_t, Q_t)$$

- ▶ C_t is consumption good, $Q_t \in [0, \overline{Q}]$ environmental quality
- ▶ u incr., concave, $\lim_{Q \rightarrow 0} u(C, Q) = -\infty$; $\partial u / \partial Q(C, \overline{Q}) = 0$

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- ▶ Final good Y_t produced using "clean", "dirty" inputs Y_{ct} , Y_{dt}

$$Y_t = \left[Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}}$$

- ▶ Assume $\varepsilon > 1 \rightarrow$ Clean, dirty inputs are substitutes

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- ▶ Assume $\varepsilon > 1 \rightarrow$ Clean, dirty inputs are substitutes
- ▶ **Dirty input decreases env'tal quality** $\frac{\partial Q_{t+j}}{\partial Y_{dt}} \leq 0 \quad \forall j \geq 0$

AABH: Intermediate Input Production

- ▶ Clean, dirty inputs Y_{jt} $j \in \{c, d\}$ produced competitively with labor L_{jt} and continuum of *machines* x_{jvt} :

$$Y_{jt} \propto L_j(t)^\beta \int_0^1 A_{jvt}^\beta x_{jvt}^{1-\beta} dv$$

- ▶ A_{jvt} is *quality* of machine of type v used in sector j at time t
- ▶ E.g.: Fossil energy services produced using coal mining machines, oil drilling machines, coal power plants, etc.
 - ▶ Paper also consider non-renewable resource in Y_{dt} production

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 - ▶ Paper also consider non-renewable resource in Y_{dt} production
- ▶ Machines produced monopolistically with the final good
- ▶ Innovation in machine technology A_{jvt} endogenous!

AABH: Innovation

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 - ▶ if successful, proportional improvement in quality by $\gamma > 0$ and the scientist gets monopoly rights for one period

$$A_{jvt} = (1 + \gamma) A_{jvt-1}$$

- ▶ if not successful, no improvement and monopoly rights in that machine randomly allocated to an entrepreneur

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⇒ Law of motion of technology in input in sector $j \in \{c, d\}$ is:

$$A_{jt} = \left(1 + \gamma \eta_j s_{jt}\right) A_{jt-1}$$

→ "Build on the shoulders of giants"

AABH: Equilibrium price ratio and labor ratio

- ▶ Wage equalizations across the two sectors leads to

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{A_c(t)}{A_d(t)} \right)^{-\beta}$$

→ **The more advanced good has a lower price**

- ▶ Final good producer maximization problem gives

$$\frac{Y_c(t)}{Y_d(t)} = \left(\frac{p_c(t)}{p_d(t)} \right)^{-\varepsilon} \implies \frac{L_c(t)}{L_d(t)} = \left(\frac{A_c(t)}{A_d(t)} \right)^{(\varepsilon-1)\beta},$$

→ **The more advanced good hires more labor** because the two goods are gross substitutes ($\varepsilon > 1$)

AABH: Innovation allocation

- **Scientists choose sector with higher expected profits Π_{jt} :**

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \underbrace{\left(\frac{p_{ct}}{p_{dt}} \right)^{\frac{1}{\beta}}}_{\text{price effect}} \underbrace{\frac{L_{ct}}{L_{dt}}}_{\text{market size effect}} \underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{\text{direct productivity effect}}$$

- Price effect pushes innovation to less advanced sector
 - ~ Innovate in production of truffles vs. portobello
- Market size effect pushes innovation to more advanced sector
 - More employment, larger market for machines
- Direct productivity effect pushes inn. to more advanced sector
 - Standing on the shoulder of giants

AABH First lesson: path dependence

- In equilibrium innovation profit ratio becomes:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \left(\frac{1 + \gamma \eta_c s_{ct}}{1 + \gamma \eta_d s_{dt}} \right)^{-(\beta(1-\varepsilon))-1} \left(\frac{A_{ct-1}}{A_{dt-1}} \right)^{-(\beta(1-\varepsilon))}.$$

⇒ **Innovation in relatively advanced sector if $\varepsilon > 1$**

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⇒ **Innovation in relatively advanced sector if $\varepsilon > 1$**

- ▶ If initial dirty technology (A_{d0}) is sufficiently advanced relative to clean technology (A_{c0}), then innovation is entirely directed towards dirty technologies in laissez-faire
 - Laissez-faire leads to environmental disaster!

AABH Second lesson: redirecting growth and costs of delay

- ▶ Research subsidies can push scientists towards the clean sector
 - ▶ If maintained sufficiently long, then A_{ct} will catch-up with A_{dt}
 - ▶ Afterwards market forces will push towards clean innovations
- ⇒ **Temporary research subsidies can ensure sustainable growth** (i.e., consumption grows, disaster avoided) if $\varepsilon > 1/\beta$
- ▶ Early action: If planner waits, cost of intervention (namely low growth when clean catches up with dirty) increases

AABH: Third lesson: two instruments

Theorem

The social planner can implement the social optimum through (i) a carbon tax on the use of the dirty input, (ii) a clean research subsidy, and (iii) a subsidy for the use of all machines (all taxes/subsidies are financed lump sum). The optimal carbon tax and research subsidy are temporary if the clean and dirty inputs are strong substitutes ($\varepsilon > 1/\beta$), not otherwise.

- ▶ This is quite intuitive: 3 distortions require 3 instruments
 - knowledge externality: research subsidy
 - environmental externality: carbon tax
 - monopoly distortion: subsidy to machines

AABH: Why is the carbon tax not enough?

- ▶ Inefficiency in laissez-faire: Innovators do not take into account the future benefits from innovation
 - ▶ Even with infinite patents, social value of an innovation depends on technologies that will build on the current innovation (building on the shoulder of giants externality)
- ▶ Most of social value from clean innovation is in the future (when clean will be the leading technology)
- ▶ Hence the innovation externality is larger for clean
- ▶ Hence the need to subsidize clean innovations even in the presence of a carbon tax

Directed Technical Change: Beyond AABH

- ▶ Growing number of studies building on AABH framework, e.g.:
- ▶ Hémous (2016): Trade and technological change (up next!)
- ▶ Acemoglu, Akcigit, Hanley, Kerr (2016): Quantitative micro-macro model (partly estimated)
- ▶ Fried (2018): Quantitative U.S. macro model
- ▶ Lemoine (2018): Energy transitions
- ▶ Casey (2019): DTC in Energy Efficiency
- ▶ Acemoglu, Aghion, Barrage, Hémous (2019): Shale gas boom

2) International Spillovers and Strategic Considerations

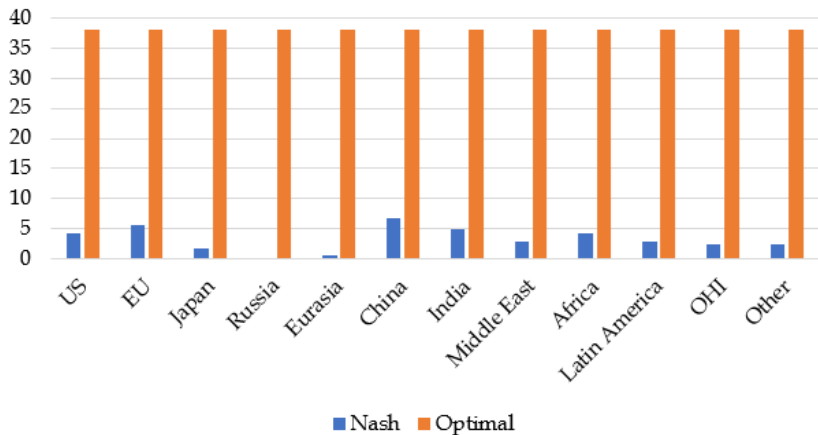
International Considerations

- ▶ Benchmark models often assume global economy, globally uniform optimal carbon price
 - ▶ Aside: Might think optimal carbon price globally uniform to equate *marginal abatement costs* across countries
 - ▶ However, even with benevolent global planner, price only uniform (i) if cross-country transfers are possible, or (ii) if planner adopts welfare weights that 'justify' baseline inequality (Chichilnisky, Heal, 1994; Nordhaus, Yang 1996)

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 - ▶ Reality: Non-cooperative world! Countries with heterogeneous climate vulnerabilities, endowments, abatement costs, etc.
- ⇒ Classic public goods problem: Free-riding incentives first order
- ⇒ Need to understand effects of uni-lateral climate policies
- ▶ "Emissions leakage", energy markets, trade effects, etc.

Optimal vs. Nash Global 2015 Carbon Prices (\$/mtC)



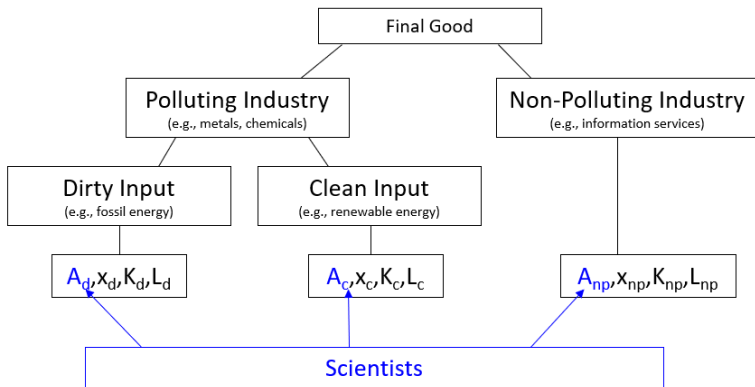
Estimates from Nordhaus (2010) based on RICE model

International Climate Agreements

- ▶ Certain countries have historically been more willing to commit to emissions reductions
 - ▶ Kyoto Protocol "Annex I" countries: European Union, Japan...
- ▶ Two concerns about non-coalition countries (Harstad, 2012):
 1. Emit too much CO_2
 2. "Might undo the climate coalition's effort. When the coalition introduces regulation, world prices change, markets shift, industries relocation, and *non-participants may end up emitting more than they did before*" (italics added)

Case Study #1: Trade and Technology - Hémous (2016)

- ▶ What are the effects of uni-lateral environmental policies in a world with trade and endogenous technological change?
- ▶ Ricardo-Heckscher-Ohlin Model: Global "North" & "South"



Trade and Technology - Hémous (2016)

- ▶ Comparative advantage (CA), trade:
 - ▶ Depends on relative productivities, endowments
 - ▶ Could be both regions produce both goods, or specialization
- ▶ **Amplification of Comparative Advantage Effect:**
 - ▶ Incentive to innovate $\propto$ revenue of sector
 - ▶ Countries have larger market size in sector they export
 - More scientists allocated to export sector
 - Country grows more productive in export sector
 - ⇒ Countries specialize more and more in sector of CA!

Trade and Technology - Hémous (2016)

- ▶ Clean, dirty inputs to polluting industry not traded
- ▶ As in AABH, more scientists in dirty input if $A_{d,0} > A_{c,0}$
- ▶ Assume initially dirty inputs more productive in both regions

⇒ **Uni-lateral dirty input taxes cannot prevent disaster**

Proposition 1: *No combination of dirty input (carbon) tax + tax on dirty research in the North can prevent disaster if (i) $A_{c,0}^{South} / A_{d,0}^{South}$ sufficiently small and (ii) South has weak initial comparative advantage in polluting industry.*

Proposition 1: Intuition

- ▶ Initial CA for South → Specializes in polluting industry
- ▶ North implements carbon tax
- Production of polluting industry in South increases
 - ▶ Pollution haven effect
- More dirty innovation in South
 - ▶ CA amplification effect
- ▶ Also: Clean technologies in North do not take off
 - ▶ Market size too small!

Trade and Technology - Hémous (2016)

- ▶ Assume now North can implement (i) wage subsidy to scientists in clean input and (ii) *trade tax* on polluting industry
- ⇒ **Uni-lateral trade tax, clean research subsidy can prevent environmental disaster!**
- ▶ *Proposition 2: A temporary trade tax and clean research subsidy in the North can prevent environmental disaster.*

Proposition 2: Intuition

- ▶ Trade tax mimics autarky $\rightarrow$ South innovates in both polluting, non-polluting industries
 - ▶ Clean research subsidy: North builds comparative advantage in polluting industry but with clean inputs!
 - ▶ North innovates cleaner ways to make polluting goods
 - ▶ After some time: Drop tariff, re-open to trade
 - ▶ Amplification effect: South specializes in non-polluting industry
 - ▶ Path dependence: North continues to innovate in clean input
- $\Rightarrow$ Combo of trade, research policies ensures sustainable growth!

Case Study #2: Global Energy Markets

- ▶ Certain features of oil markets make it harder to achieve emissions reductions with (uni-lateral) demand-side policy

1. Non-Renewable Resource Dynamics $\Rightarrow$ Inter-temporal leakage

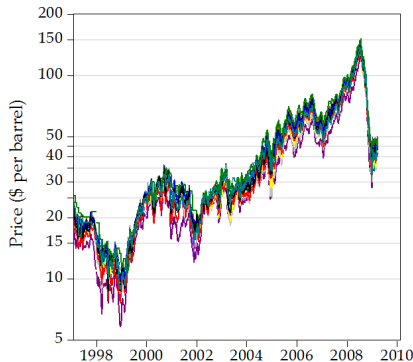
- ▶ Hotelling: Profit-maximizing finite resource extraction $\leftrightarrow$ price increases at the rate of interest
 - ▶ Announcement today that oil demand will be reduced in the future $\rightarrow$ Expected future price declines
- $\Rightarrow$ Oil producers have incentive to extract more today!
- ▶ "Green Paradox" (Sinn, 2008)

2. Globally Integrated Market $\Rightarrow$ Demand leakage, supply leakage

- ▶ Next...

Case Study #2: Global Energy Markets

- ▶ Petroleum markets are globally highly integrated



Nordhaus (2009): Prices for 31 crudes, Algerian Sahara, Angola Cabinda, U.K. Brent, Ekofisk Norway, Canada Par, China Daqing, Indonesia Minas, Australia Gippsland, Iraq Kirkuk, Saudi Arabia Heavy, Libya Es Sider, Venezuela Tia Juana Light, etc.

- ▶ "Bathtub Model": Equilibrium determined by the *sum* of global demands and supplies

Case Study #2: Harstad (2012) - Setup

- ▶ Harstad (2012, JPE) "Buy Coal! A Case for Supply-Side Environmental Policy"
- ▶ Each country i consumes energy y_i for benefit $B_i(y_i)$
- ▶ Each country i extracts energy x_i at cost $C_i(x_i)$
- ▶ Energy freely traded across countries $\Rightarrow$ global price p
- ▶ Country group "M" experiences harm $H(\cdot)$ from emissions:

$$U_i = B_i(y_i) - C_i(x_i) - p(y_i - x_i) - H(\sum x_i) \text{ if } i = M$$

- ▶ Country group "N" does not:

$$U_i = B_i(y_i) - C_i(x_i) - p(y_i - x_i) \text{ if } i \in N$$

Harstad (2012): First-Best

- ▶ The socially optimal allocation equates marginal energy benefits across countries:

$$B'_i(y_i^*) = B'_j(y_j^*)$$

- ▶ And equates marginal extraction costs to marginal social benefits (net of pollution damages):

$$B'_i(y_i^*) - H'(\sum_{M \cup N} x_i^*) = C'_i(x_i^*)$$

- ▶ For all $i, j \in M \cup N$

Note: Exposition differs slightly from Harstad (2012) for ease-of-illustration.

Harstad (2012): Equilibrium - Non-participants

- ▶ Non-participant countries in N consume according to:

$$\begin{aligned}B'_i(y_i) &= p \\ y_i &= D_i(p) \equiv B'^{-1}(p)\end{aligned}$$

- ▶ Similarly, they produce energy according to:

$$\begin{aligned}C'_i(x_i) &= p \\ x_i &= S_i(p) \equiv C'^{-1}(p)\end{aligned}$$

- ▶ Define non-participants' total supply and demand:

$$\begin{aligned}S(p) &\equiv \sum_N S_i(p) \\ D(p) &\equiv \sum_N D_i(p)\end{aligned}$$

Harstad (2012): Equilibrium - Coalition

- ▶ Member countries in M enact policies to implement consumption y_M and extraction x_M
- ▶ **Result 1:** Coalition M 's equilibrium policy implements:

$$H' \left[\frac{S'(p)}{S'(p) - D'(p)} \right] + \left[\frac{y_M - x_M}{S'(p) - D'(p)} \right] = B'_M(y_M) - p$$
$$H' \left[1 - \frac{S'(p)}{S'(p) - D'(p)} \right] - \left[\frac{y_M - x_M}{S'(p) - D'(p)} \right] = p - C'_M(x_M)$$

- ▶ Intuition:...

Harstad (2012): Equilibrium - Coalition

$$\underbrace{H'}_{\text{Marginal Damages}} \underbrace{\left[\frac{S'(p)}{S'(p) - D'(p)} \right]}_{\text{Leakage Adjustment}} + \underbrace{\left[\frac{y_M - x_M}{S'(p) - D'(p)} \right]}_{\text{Terms of Trade Adjustment}} = \underbrace{B'_M(y_M) - p}_{\text{Consumption wedge (tax)}}$$

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- Imagine first there were **no non-participants**:

$$\underbrace{H'}_{\text{Marginal Damages}} = \underbrace{B'_M(y_M) - p}_{\text{Consumption wedge (tax)}}$$

⇒ Pigouvian tax equal to marginal damages

Harstad (2012): Equilibrium - Coalition

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- ▶ **Leakage adjustment:**
- ▶ If M reduces consumption $\rightarrow$ global oil price p decreases $\rightarrow$ N consumes more!
 - ▶ *Demand-side leakage* large if $|D'(p)|$ large

Harstad (2012): Equilibrium - Coalition

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► Leakage adjustment:

- If M reduces consumption $\rightarrow$ global oil price p decreases $\rightarrow$ N consumes more!
 - *Demand-side leakage* large if $|D'(p)|$ large
- If M reduces production $\rightarrow$ global oil price p increases $\rightarrow$ N produces more!
 - *Supply-side leakage* large if $S'(p)$ large

Harstad (2012): Equilibrium - Coalition

$$\underbrace{H'}_{\text{Marginal Damages}} \underbrace{\left[\frac{S'(p)}{S'(p) - D'(p)} \right]}_{\text{Leakage Adjustment}} + \underbrace{\left[\frac{y_M - x_M}{S'(p) - D'(p)} \right]}_{\text{Terms of Trade Adjustment}} = \underbrace{B'_M(y_M) - p}_{\text{Consumption wedge (tax)}}$$

► Leakage adjustment:

- If M reduces consumption $\rightarrow$ global oil price p decreases $\rightarrow$ N consumes more!

- *Demand-side leakage* large if $|D'(p)|$ large

- If M reduces production $\rightarrow$ global oil price p increases $\rightarrow$ N produces more!

- *Supply-side leakage* large if $S'(p)$ large

$\Rightarrow$ M focuses relatively more on reducing demand (higher consumption tax) if $S'(p)$ large relative to $D'(p)$

Harstad (2012): Equilibrium - Coalition

$$\underbrace{H'}_{\text{Marginal Damages}} \underbrace{\left[\frac{S'(p)}{S'(p) - D'(p)} \right]}_{\text{Leakage Adjustment}} + \underbrace{\left[\frac{y_M - x_M}{S'(p) - D'(p)} \right]}_{\text{Terms of Trade Adjustment}} = \underbrace{B'_M(y_M) - p}_{\text{Consumption wedge (tax)}}$$

$$\underbrace{H'}_{\text{Marginal Damages}} \underbrace{\left[1 - \frac{S'(p)}{S'(p) - D'(p)} \right]}_{\text{Leakage Adjustment}} - \underbrace{\left[\frac{y_M - x_M}{S'(p) - D'(p)} \right]}_{\text{Terms of Trade Adjustment}} = \underbrace{p - C'_M(x_M)}_{\text{Production wedge (tax)}}$$

- Imagine now there was no externality $H' = 0$

Harstad (2012): Equilibrium - Coalition

$$\underbrace{\left[\frac{y_M - x_M}{S'(p) - D'(p)} \right]}_{\substack{\text{Terms of Trade} \\ \text{Adjustment}}} = \underbrace{B'_M(y_M) - p}_{\substack{\text{Consumption} \\ \text{wedge (tax)}}}$$
$$-\underbrace{\left[\frac{y_M - x_M}{S'(p) - D'(p)} \right]}_{\substack{\text{Terms of Trade} \\ \text{Adjustment}}} = \underbrace{p - C'_M(x_M)}_{\substack{\text{Production} \\ \text{wedge (tax)}}}$$

► Terms-of-Trade Adjustment:

- If M is *importing* fossil fuels ($y_M < x_M$) $\Rightarrow$ Tax consumption, subsidize production
- Both policies lower world fuel price, thus M 's import expenditures ("Monopsony premium")

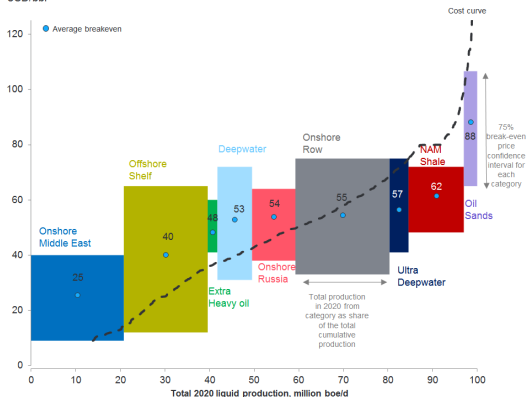
Harstad (2012): Deposits Market

- ▶ So far, equilibrium looks generally inefficient
 - ▶ Free-riding: N does not take H' into account
 - ▶ Consumption-leakage
 - ▶ Production-leakage
 - ▶ M' 's market power
 - ▶ Key innovation: Introduce market for fossil fuel *deposits*
 - ▶ M can purchase right to fossil deposits from non-participants
- ⇒ Can shift N' 's supply, choose not to extract!

Harstad (2012) Energy Extraction

- ▶ Each country has convex energy supply curve $C_i(x_i)$
 - ▶ Marginal extraction costs $C'_i(x_i)$ increasing
 - Continuum of deposits ordered by extraction costs

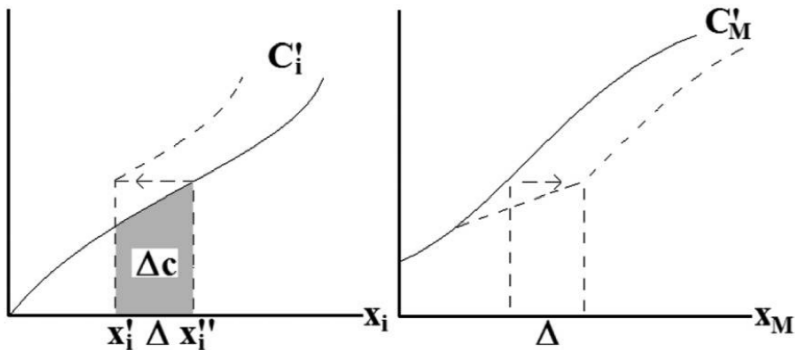
Global liquid supply cost curve
USD/bbl



Source: Rystad Energy research and analysis

Harstad (2012): Deposit Markets

- ▶ Assume M buys fossil deposit Δ from $i \in N$
- Shifts supply curve in both countries:



Harstad (2012): Timing

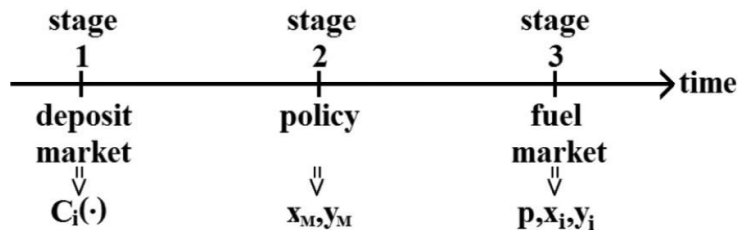


FIG. 3.—Timing of the game

Harstad (2012): Main Result

- ▶ Deposit market equilibrium: No pair of countries would both strictly benefit from trading their deposits at some price.

Theorem

In every equilibrium of the deposit market, M' 's equilibrium tax policies implement the first-best allocation.

⇒ **Combination of deposit markets and domestic taxes allow Coalition to achieve first-best!**

- ▶ Deposits that are profitable but socially inefficient to exploit ($c \in (p - H', p)$) are purchased and preserved

International Issues Case Study #3: Climate Clubs

- ▶ Nordhaus (2015): International free-riding still most vexing climate change issue
 - ▶ Proposes "Climate Clubs" to overcome public goods problem:
 1. Member countries agree to harmonized carbon price
 2. Members levy small uniform tariffs on non-participants
 - ▶ Develops Coalition-DICE model to analyze coalition stability under different tariff, carbon price combinations
 - ▶ 15 world regions as in RICE model
- ⇒ All regions would want to join climate club with \$25/ton CO_2 price given non-participation tariff of only 3%!

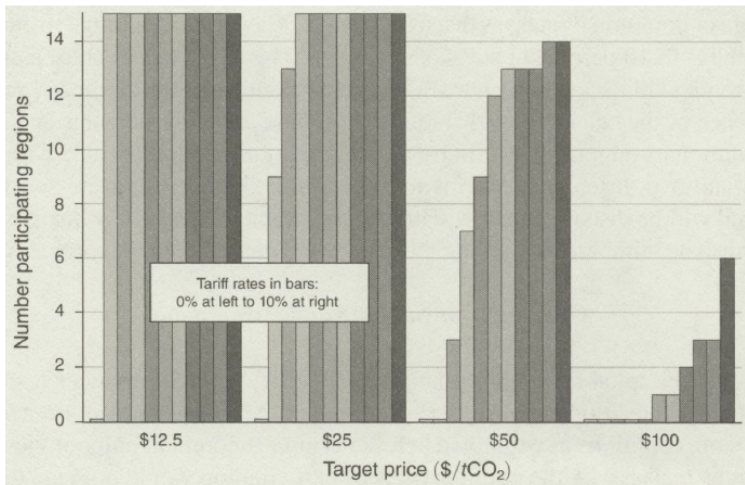
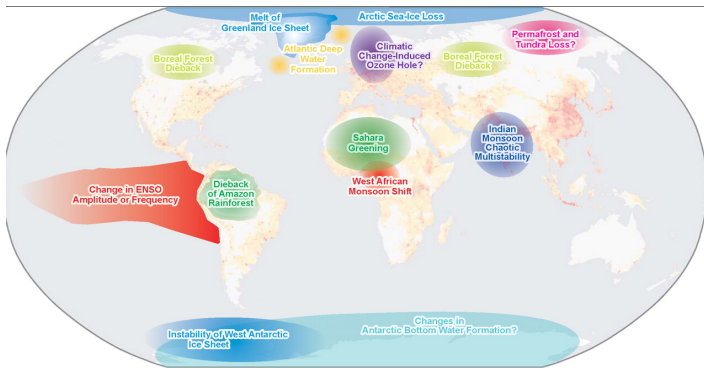


FIGURE 3. NUMBER OF PARTICIPATING REGIONS BY INTERNATIONAL TARGET CARBON PRICE AND TARIFF RATE

3) Tipping Points and Catastrophic Climate Change

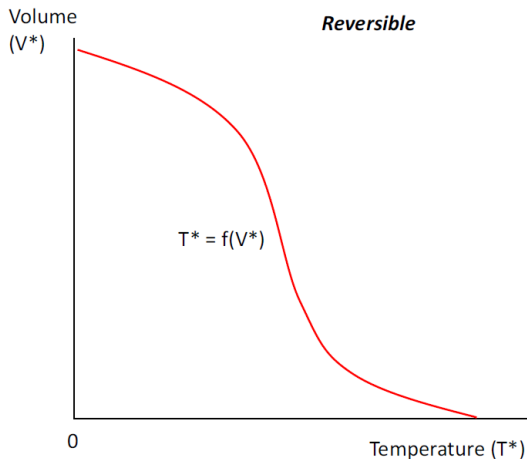
Catastrophic Climate Change: Tipping Points

- Lenton et al. (2008): Tipping point a "critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system"



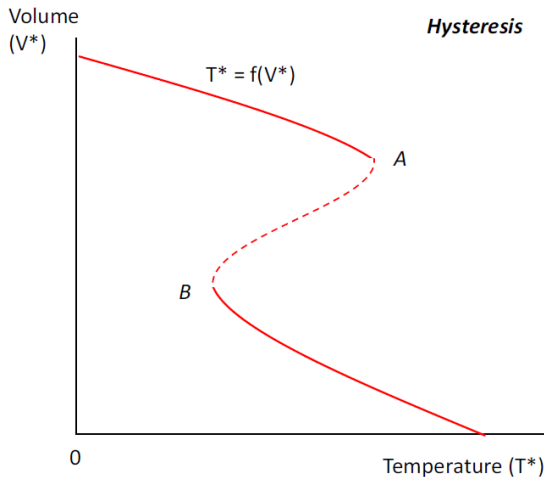
Tipping Points: Intuition

- From Nordhaus (2019) on Greenland Ice Sheet dynamics



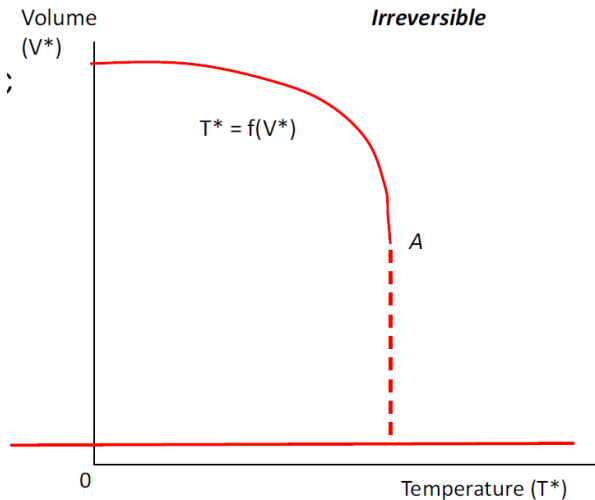
Tipping Points: Intuition

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Tipping Points: Intuition

- From Nordhaus (2019) on Greenland Ice Sheet dynamics



Tipping Points: Irreversible vs. Abrupt

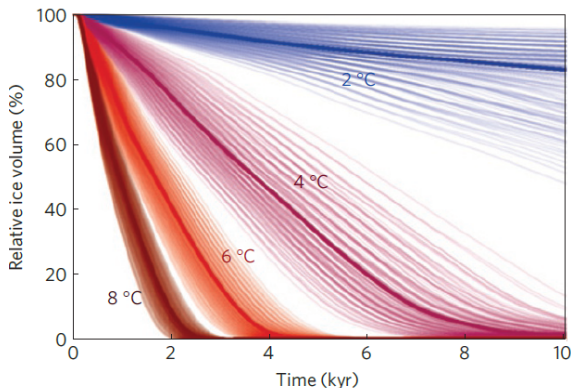
- ▶ Note: Tipping point need not imply *abrupt* change
 - ▶
- ▶ Greenland Ice Sheet: Disintegration estimated to increase global sea levels +7m (22 feet)





Tipping Points: Irreversible vs. Abrupt

- ▶ Greenland Ice Sheet tipping point estimates: 1°C to 4°C (IPCC, 2014); Robinson et. al.: $0.8 - 3.2^{\circ}\text{C}$, best guess: 1.6°C
- ▶ However, ice sheet loss has millennial time scale:

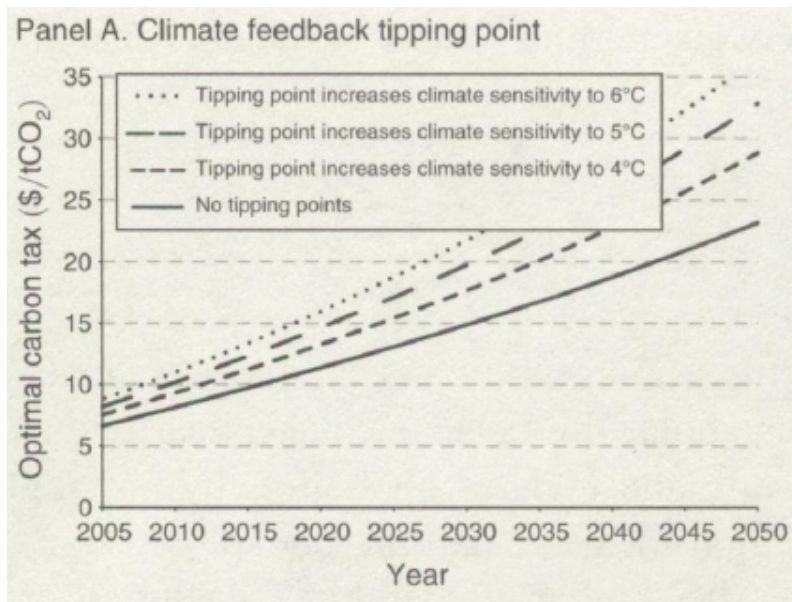


- ▶ Melting may be reversible depending on *duration* of temperature exceedence (IPCC, 2014); Better threshold measure may be degree-years (Nordhaus, 2019)

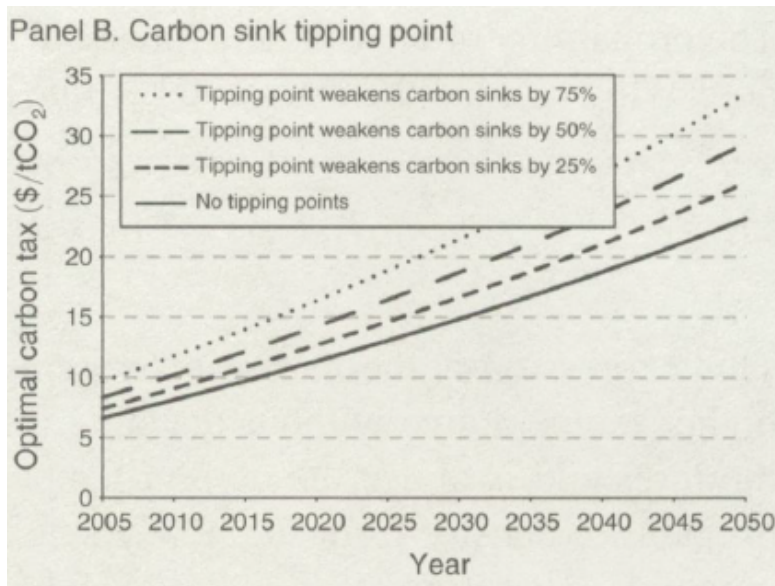
Tippoint Points: Lemoine and Traeger (2014, AEJ:P)

- ▶ "Watch Your Step: Optimal Policy in a Tipping Climate"
- ▶ Add tipping points to stochastic recursive DICE-variant:
 1. Increase climate feedbacks that amplify warming
 - ▶ Increase climate sensitivity from 3°C to 4, 5, or 6°C
 2. Decrease earth CO_2 uptake from atmosphere
 - ▶ Decrease CO_2 transfer from atm. by 25, 50, or 70%
- ▶ Tipping immediate (1yr) after crossing temp. threshold
- ▶ Policy-maker has uniform prior over tipping temp. (up to $\overline{T}$)
- ▶ Policy-maker learns if they have not yet crossed tipping point
- ▶ Policy-maker knows effects of tipping point if crossed

Tippoint Points: Lemoine and Traeger (2014, AEJ:P)



Tippoint Points: Lemoine and Traeger (2014, AEJ:P)



Tippoint Points: Lemoine and Traeger (2014, AEJ:P)

TABLE 1—THE CARBON TAX (*social cost of carbon*), LOSS FROM CROSSING A THRESHOLD, AND CHANCE OF CROSSING A THRESHOLD ALONG THE OPTIMAL POLICY PATHS

	With learning		Without learning		With learning	
	2015	2050	2015	2050	Peak	
<i>Panel A. Unaware of tipping possibility</i>						
Optimal carbon tax (\$/tCO ₂)			10	23	11.4	Emissions (Gt C y ⁻¹)
Tipping probability: i) that year (%)	0.57	0.76	5.5	26	637	CO ₂ concentration (ppm)
ii) from additional 0.01°C (%)	0.30	0.38	0.28	0.28	3.3	Warming since 1900 (°C)
<i>Panel B. Tipping raises climate sensitivity to 5°C</i>						
Optimal carbon tax (\$/tCO ₂)	12	33	15	35	10.1	Emissions (Gt C y ⁻¹)
Tipping probability: i) that year (%)	0.56	0.72	5.4	25	573	CO ₂ concentration (ppm)
ii) from additional 0.01°C (%)	0.30	0.37	0.28	0.28	2.9	Warming since 1900 (°C)
Bge consumption loss if tipping (%)	0.45	0.82	0.054	0.057	1.7	Bge loss (% , as at left)
<i>Panel C. Tipping weakens carbon sinks by 50%</i>						
Optimal carbon tax (\$/tCO ₂)	12	29	14	29	10.5	Emissions (Gt C y ⁻¹)
Tipping probability: i) that year (%)	0.56	0.73	5.4	25	602	CO ₂ concentration (ppm)
ii) from additional 0.01°C (%)	0.30	0.37	0.28	0.28	3.1	Warming since 1900 (°C)
Bge consumption loss if tipping (%)	0.62	0.68	0.16	0.073	0.70	Bge loss (% , as at left)

Notes: For the policymaker who is unaware of a tipping possibility, we calculate the hazard that would be faced along that same policy path in a model with tipping points. All calculations assume an initial expected threshold of 2.53°C. Bge stands for balanced growth equivalent.

Tippoint Points: Lemoine and Traeger (2014, AEJ:P)

- ▶ Benchmark case: Tipping points increase 2015 carbon tax by 25%
 - ▶ Decreases optimal warming 5-15%
- ▶ Anticipated *learning* decreases 2015 carbon tax impact, but increases future mitigation
 - ▶ Policy maker grows more cautious as she understands tipping hazard increases if threshold not yet crossed
- ▶ Some assumptions likely bias policy impacts upwards, e.g., immediate 1-yr tipping
- ▶ Others likely bias policy impacts downwards, e.g., known and smooth tipping impacts

Catastrophic Climate Change: The "Dismal Theorem"

- ▶ Weitzman (2009) "On Modeling and Interpreting the Economics of Catastrophic Climate Change" (ReStat)

Intuition:

- ▶ Standard IAMs assume that we know the (distribution) of key system parameters (e.g., equilibrium climate sensitivity)
 - ▶ In reality, face deep structural uncertainty + finite opportunities to learn
- ⇒ Risk of catastrophic (annihilate civilization as we know it) climate change may be small but (posterior) is "fat-tailed"
- ⇒ Infinite willingness-to-pay to avoid risk! (with CRRA utility)
- ⇒ Raises questions about (appropriate) applicability of conventional cost-benefit analysis (CBA)

Weitzman (2009): The Dismal Theorem

- ▶ Two-period model: Present and future (2200+)
- ▶ Present consumption normalized $C_0 = 1$
- ▶ Future consumption *growth* $Y \equiv \ln(C)$ is a random variable
 - ▶ Reduced-form for climate change uncertainty
 - ▶ In background, temperature change ΔT is random variable which affects consumption through some damage function (e.g., $C = e^{g - \gamma \Delta T}$)
- ▶ Assume CRRA Utility:

$$U(C) = \frac{C^{1-\eta}}{1-\eta}$$

→ *Stochastic discount factor* (WTP for extra future cons.)

$$E[M] \equiv \beta E \left[\frac{U'(C)}{U'(1)} \right] = \beta E[e^{-\eta Y}]$$

Weitzman (2009): The Dismal Theorem

- ▶ Assume consumption growth Y has pdf $f(y)$

$$E[M] = \beta \int_{-\infty}^{\infty} e^{-\eta y} f(y) dy$$

- ▶ Assume $\mu = E[Y]$ is known, but $s^2 = V[Y]$ is *not*
 - ▶ Scale parameter controlling tail spread is unknown
- ▶ Assume society has *finite* number of *iid* observations of $\mathbf{y} = (y_1, \dots, y_n)$ to form estimate of s (e.g., scientific studies)
- ▶ Assume non-informative, scale-invariant *prior* pdf

$$p_0(s) \propto s^{-k}$$

Weitzman (2009): The Dismal Theorem

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- ▶ Assume non-informative, scale-invariant *prior* pdf

$$p_0(s) \propto s^{-k}$$

⇒ *Posterior*-predictive pdf → fat-tailed!

- ▶ Exponent $\sim$ sum of inductive plus prior knowledge $n + k$

Weitzman (2009): The Dismal Theorem

⇒ Stochastic discount factor:

$$E[M] = +\infty$$

- ▶ Infinite WTP today to increase future consumption

"The core underlying problem is the difficulty of learning limiting tail behavior inductively from finite data. Seemingly thin-tailed probability distributions (like the normal), which are actually only thin-tailed conditional on known structural parameters of the model (...), become tail-fattened (...) after integrating out the structural parameter uncertainty."

Weitzman (2009): The Dismal Theorem

- ▶ Analysis thus far assumes $U'(0) = \infty$
- ▶ However, in reality, individuals and society reveal finite WTP for mortality risk reductions
- ▶ NASA detection of dangerous (140m+) near-earth objects (NEO):
 - ▶ 2005 NASA Reauthorization Goal: Detect% of large NEOs by 2020
 - ▶ 2004 NASA NEO detection budget:...
 - ▶ 2014 NASA NEO detection budget:...
 - ▶ 2020 new NEO Mission funding:...

Weitzman (2009): The Dismal Theorem

- ▶ Analysis thus far assumes $U'(0) = \infty$
- ▶ However, in reality, individuals and society reveal finite WTP for mortality risk reductions
- ▶ NASA detection of dangerous (140m+) near-earth objects (NEO):
 - ▶ 2005 NASA Reauthorization Goal: Detect 90% of large NEOs by 2020
 - ▶ 2004 NASA NEO detection budget: \$4 million
 - ▶ 2014 NASA NEO detection budget: \$40 million
 - ▶ 2020 new NEO Mission funding: \$35.6 million

Weitzman (2009): The Dismal Theorem

- ▶ Let $\lambda \sim$ "value of statistical civilization" (VSL-like)
- ▶ Assume $\eta > 1$

- ▶ **Dismal Theorem:** For any given n and k ,

$$\lim_{\lambda \rightarrow \infty} E[M|\lambda] = +\infty$$

- ▶ Given any n and k , probability of disaster declines *polynomially* in scale s of disaster, whereas marginal utility impact of a disaster increases *exponentially* in scale s

Weitzman (2009): The Dismal Theorem

- ▶ Does this mean we should abandon cost-benefit analysis?
- ▶ Even Weitzman (2009) does not make this case:

"One does not want to abandon lightly the ideal that CBA should bring independent empirical discipline to any application by being based upon empirically reasonable parameter values. Even when DT applies, CBA based upon empirically reasonable functional forms and parameters might still reveal useful information. (...)

So a tricky balance is required between being over-awed by DT into abandoning CBA altogether and being underawed by DT into insisting that it is just another empirical issue to be sorted out by business-as-usual CBA."

DT: Responses and Critiques

► Millner (2013) classifies responses as questioning:

1. Relevance for climate policy CBA
2. Fat-tails assumption itself
3. CRRA Utility function

DT: Responses and Critiques

- ▶ Marginal vs. Total willingness to pay (WTP): Just because expected marginal utility in *no-policy world* is infinite does not imply that optimal policy is not finite and well-defined

DT: Responses and Critiques

- ▶ Marginal vs. Total willingness to pay (WTP): Just because expected marginal utility in *no-policy world* is infinite does not imply that optimal policy is not finite and well-defined
- ▶ Example (Millner, 2013): Suppose we wish to pick optimal transfer a ('abatement') from current to future consumption:

$$\max U(1 - a) + \beta EU(c + a)$$

$$\Rightarrow U'(1 - a) = \beta EU'(c + a)$$

- ▶ No proper solution at $a = 0$ as $EU'(c) = \infty$
- ▶ However, unique solution $a^* \in (0, 1)$ under very mild continuity conditions!

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- ▶ No proper solution at $a = 0$ as $EU'(c) = \infty$
- ▶ However, unique solution $a^* \in (0, 1)$ under very mild continuity conditions!
- ▶ Critique of critique: Assumes a can transfer from present to future with certainty

DT: Responses and Critiques

- ▶ Is equilibrium climate sensitivity (as) fat-tailed (as Weitzman suggests)?
- ▶ Is climate sensitivity truly something where (i) our prior is uninformed and (ii) we learn as Bayesians from observations?
Nordhaus (2009):
 - ▶ Climate scientists develop prior from application of physical principles
 - ▶ Sampling historical data not only method of inference

DT: Responses and Critiques

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 - ▶ Climate scientists develop prior from application of physical principles
 - ▶ Sampling historical data not only method of inference
- ▶ Weitzman interprets IPCC ECS distributions as roughly implying
 - ▶ $\Pr[\text{ECS} > 10^\circ\text{C}] \approx 5\%$ and $\Pr[\text{ECS} > 20^\circ\text{C}] \approx 1\%$
- ▶ Nordhaus: Incorrect to estimate 95th percentile by averaging 95th percentile across ECS studies
 - ▶ Should aggregate into meta-distribution, then take 95th percentile

Nordhaus (2009): Illustration

- ▶ Random variable $Y \sim N(0, 1)$
- ▶ Have 10,010 independent observations
 - ▶
- ▶ Group A: 10 obs
 - ▶ 95th pctile of estimated mean: 0.699
- ▶ Group B: 10,000 obs
 - ▶ 95th pctile of estimated mean: 0.01956
- ▶ Averaging 95th pctiles $\Rightarrow$ 0.359
- ▶ Combining observations first $\Rightarrow$ 95th pctile 0.01955

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- ▶ Averaging 95th pctiles $\Rightarrow$ 0.359
- ▶ Combining observations first $\Rightarrow$ 95th pctile 0.01955
- ▶ Nordhaus' read: Reduces 95th pctile of ECS from 7° C to 4.6° C

DT: Responses and Critiques

- ▶ Sensitivity to CRRA utility function intuitive
 - ▶ See Millner (2013) for detailed discussion
- ▶ At technical level, DT may be sensitive to assumptions
- ▶ Broader take-home points arguably more generally valid
 - ▶ Need to be careful about false precision
 - ▶ Importance of (arbitrary) cutoffs in model specifications
 - ▶ Monte Carlo's may want to over-sample tails appropriately (see Weitzman, 2009)
 - ▶ Think of CBA in context of its pros and cons

Appendix Slides

- ▶ Hassler and Krusell (2012) "Economics and Climate Change: Integrated Assessment in a Multi-Region World" (JEEA)
- ▶ Oil-consuming countries import oil e_t , produce output y_t via:

$$y_{it} = A_{it} k_{it}^{\alpha} e_{it}^{\nu}$$

- ▶ Oil-producing countries produce only oil (finite resource)
- ▶ Strong assumptions yield analytic solution:
 - ▶ No trade except in oil
 - ▶ Logarithmic utility in all countries
 - ▶ 100% capital depreciation

→ Oil producers extract constant fraction of stock each period

- ▶ Oil consumption adds to atmospheric carbon stock S_t
- ▶ Productivity A_{it} depends on climate S_t , other factors Z_{it}

$$A_{it} = e^{-\gamma_i S_t + Z_{it}}$$

- ▶ Consider uniform oil tax τ_t imposed *in consuming countries*
- ▶ Global equilibrium oil price p_t *declining* in this tax:

$$p_t = v \left(\sum (A_{it})^{\frac{1}{1-\nu}} (k_{it})^{\frac{\alpha}{1-\nu}} (1 + \tau_t)^{\frac{-1}{1-\nu}} \right)^{1-\nu} ((1 - \beta)R_t)^{\nu-1}$$

where $R_t \sim$ oil resource in ground at time t

$\Rightarrow$ Tax shifts some scarcity rent from producers to consumers...
...but has **zero** effect on equilibrium oil extraction, climate!

- ▶ Intuition: Logarithmic oil producer utility $\rightarrow$ Income, substitution effects of lower oil price cancel out
 $\rightarrow$ Same oil extraction path

HK 2012: Oil-Producer Taxes

- ▶ Consider uniform oil tax τ_t imposed *in/on producing countries*
- ▶ Revenues rebated to producers $\Rightarrow$ Substitution effect only
- $\Rightarrow$ Time-decreasing oil tax slows extraction (logarithmic utility)
- ▶ Calibration based on RICE Model (Nordhaus, 2007):

TABLE 1. Initial oil use relative to laissez faire.

Gross growth rates, net of tax on oil: θ	0.975	0.985	1.038	1.075	1.098
Initial oil use	115%	109%	76.9%	54%	39.7%

TABLE 2. Welfare gains and oil use relative to laissez faire.

θ	0.975	0.985	1.038	1.075	1.098
China	0.05%	0.05%	-0.33%	-0.43%	-0.61%
United States	0.01%	0.02%	-0.27%	-0.98%	-1.82%
Europe	-0.42%	-0.25%	0.51%	0.74%	0.59%
Africa	-0.61%	-0.37%	0.85%	1.51%	1.68%
Oil producers	-0.21%	-0.12%	0.14%	-0.08%	-0.55%