Essays on Spatial and Temporal Interconnections between and within Emissions Trading Systems

Simon Quemin

Paris-Dauphine University – PSL Research University
& Climate Economics Chair

Ph.D. Defense – Thursday, 12th October 2017

Emissions trading as a pivotal climate policy tool?

- Emissions trading is a well-established instrument to curb GHG emissions
  - track record of ETS implementation in 19 jurisdictions (ICAP, 2017)
  - 7 GtCO_2e or 13% of worldwide GHG emissions (World Bank, 2017)

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▶ Focus on spatial and temporal interconnections between and within ETSs

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  - restrictions as transitory and facilitative mechanisms towards full linkage
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- Contributions, Perspectives & Conclusions

CHAPTER 1

Transitional Restricted Bilateral Linkages between ETSs

In collaboration with Christian de Perthuis (Paris-Dauphine)
Submitted to *Environmental & Resource Economics*
Available as a FAERE policy paper and CEC working paper

Gradual linkage approach with trade restrictions

- A link could be approached gradually (Jaffe et al., 2009). Two options:
  - indirect linkages e.g. through the CDM: EU $\leftrightarrow$ CDM $\leftrightarrow$ NZ
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- Some bilateral linkages have been initiated through unilateral trading
  - Norway-EUETS, Aviation-EUETS, Australia-EUETS
- Effects of trade restrictions often studied with modelling exercises
  - esp. during Kyoto era (special issue in EJ), Ellerman & Sue Wing (2000), Rehdanz & Tol (2005), Burtraw et al. (2013), Gavard et al. (2016)

A unifying framework to compare linkage restrictions

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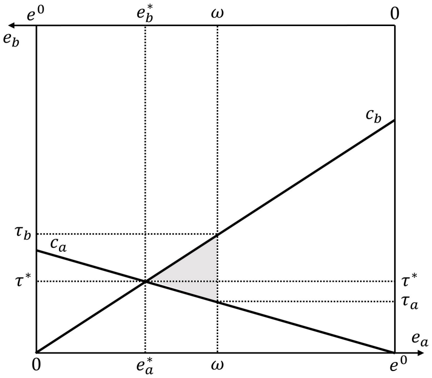
- Emission caps are exogenous and fixed once and for all
  - domestic caps result from complex negotiations (Flachsland et al., 2009)

Comparative effects of alternative link restrictions



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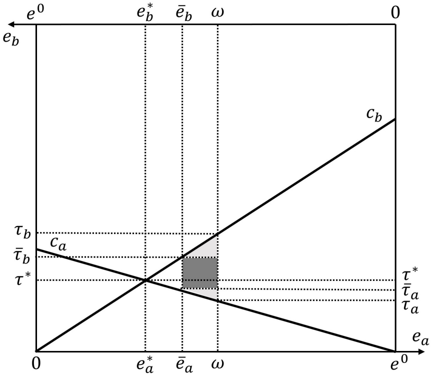

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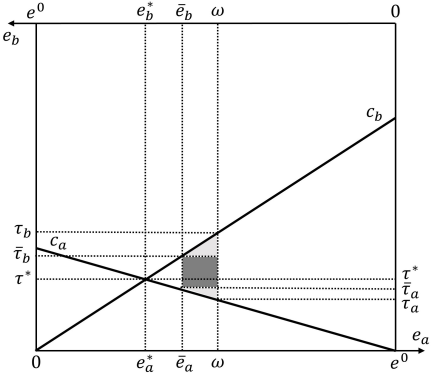

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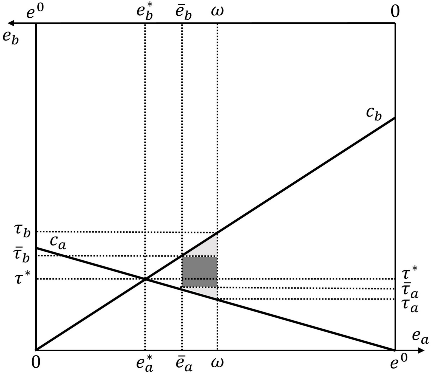

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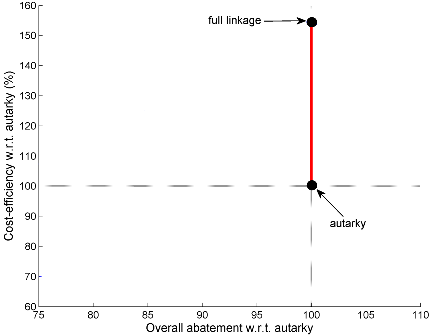

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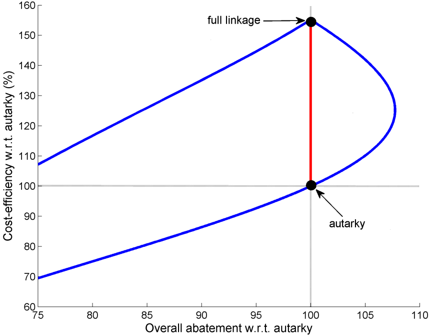

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- Effects of exchange rates are more subtle: abatements are not fungible
  - correct for relative stringency & potential to increase ambition
  - outcomes can be worse than QR&BT or autarky: challenging to select/update

CHAPTER 2

Multilateral Linkages between ETSs under Uncertainty

In collaboration with Baran Doda & Luca Taschini (LSE)
Target journal: *Journal of Public Economics*
Available as a GRI working paper and CEC working paper

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- Emission caps are exogenous and fixed once and for all
  - no strategic interactions: diverge from IEA literature, e.g. Helm (2003)

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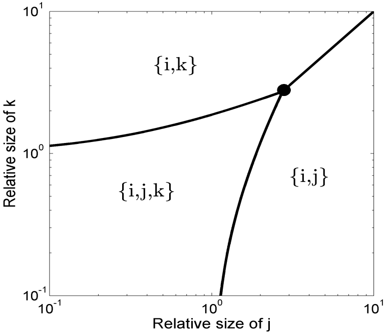
- Linkage gains arising due to uncertainty are often underappreciated
  - preferences across bilateral links: a jurisdiction prefers large partners whose permit demands are volatile and weakly correlated

Gains and preferences in multilaterally linked ETSs



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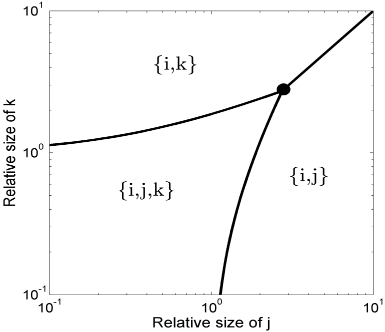

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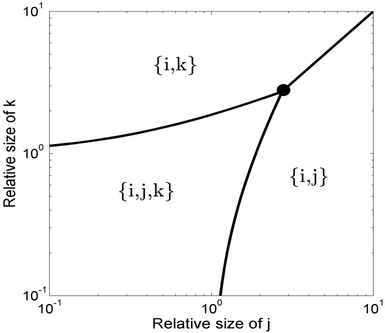

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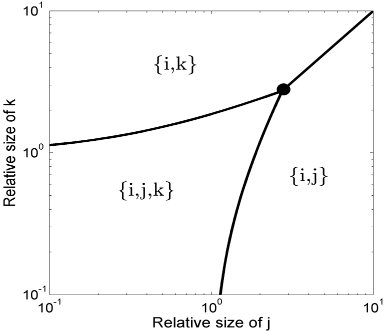

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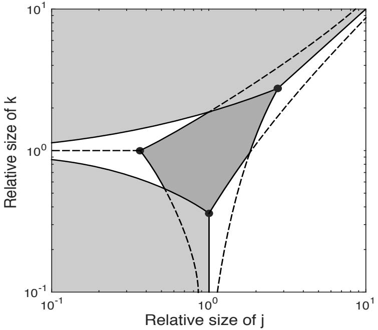

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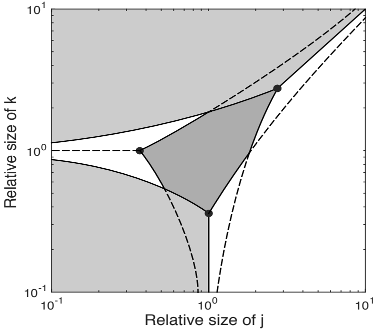

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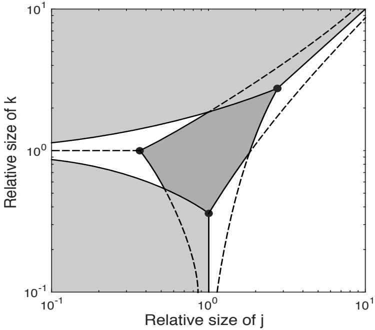

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  - without transfers, jurisdictional linkage preferences do *not* tally
- Calibration to historical emissions data provides some empirical validity
  - CHN prefers {CHN,USA,EUR} but USA/EUR prefer a bilateral link with CHN

CHAPTER 3

Intertemporal Abatement Decisions under Ambiguity Aversion

Single-authored article
Target journal: *Journal of Environmental Economics & Management*
Available as a FAERE working paper and CEC working paper

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- First attempt to introduce ambiguity aversion in ETS modelling

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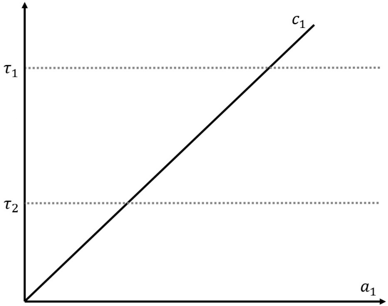
  - AN-firm abates up to the discounted expected price: intertemporal efficiency obtains with rational expectations (Samuelson, 1971; Schennach, 2000)

Effects of ambiguity aversion on early abatement decisions



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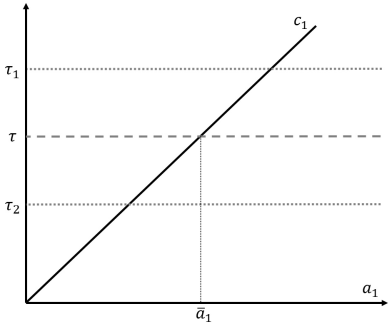

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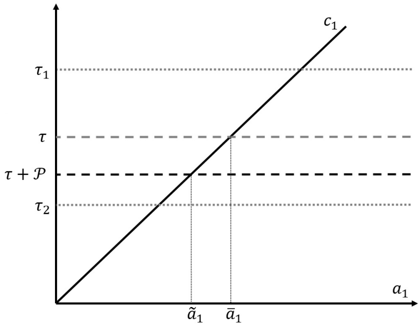

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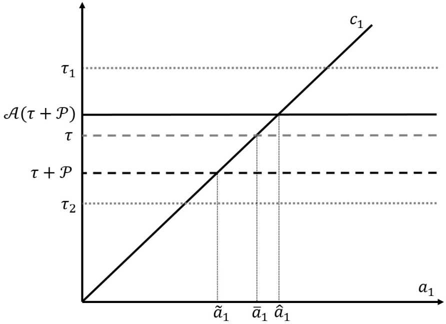

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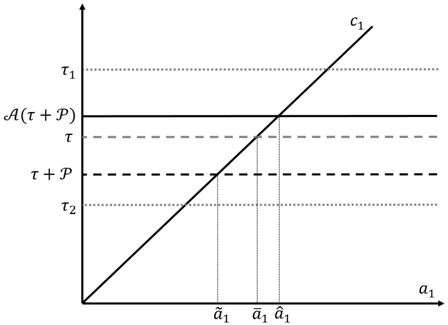

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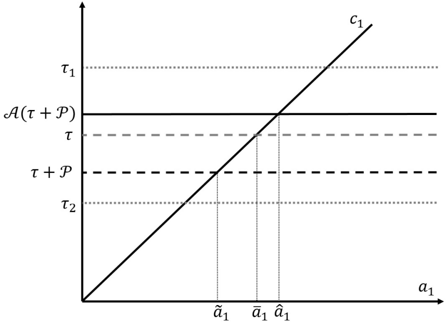

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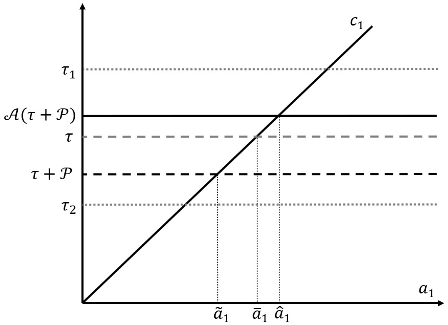

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- Forwards contracts cannot restore intertemporal efficiency

Contributions, Perspectives & Conclusions

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- Two contributions on the role of ETSs as climate policy tools

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- Effects of spatial and temporal flexibilities are intertwined
  - can linkage be an instrument to reduce regulatory uncertainty/ambiguity?
  - ETSs are never pure quantity instruments: *linkability* issues
  - significantly linked systems are a long way off: remain a distant dream?
    → political rhetoric around linkage to create an image of 'grand efforts'

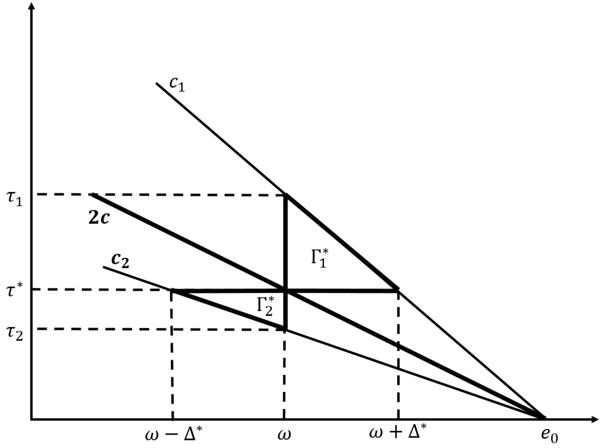
Thank you for your attention

Appendices & Discussion

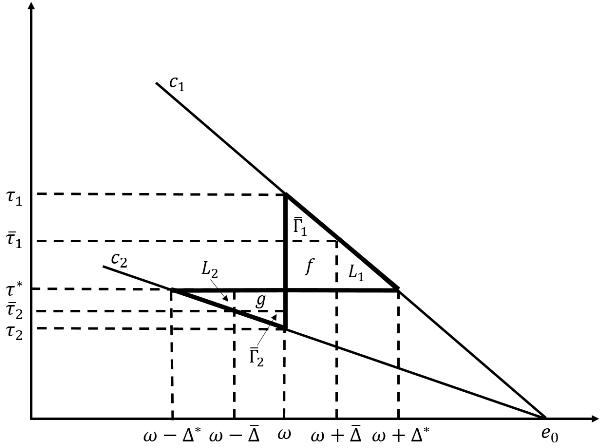
Chapter One Chapter Two Chapter Three

Appendix of Chapter 1

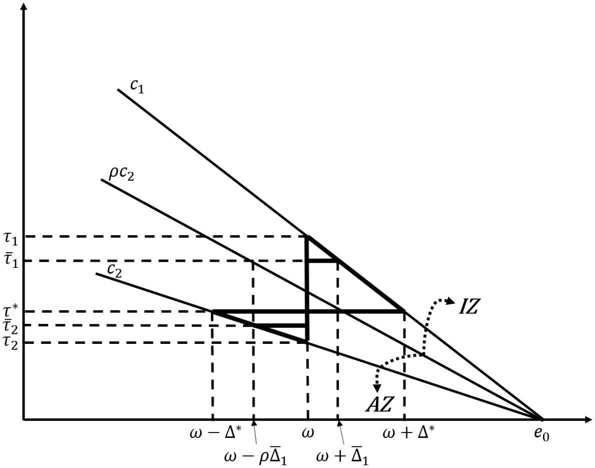
Autarky and full linkage



Quantitative restrictions and border taxes



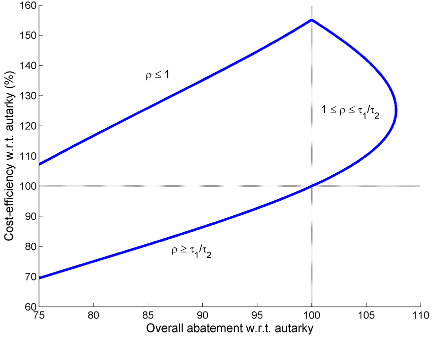
Exchange rates



Numerical simulations and indexes

$$I^A = \frac{2\bar{e} - (2\omega + (1-\rho)\Delta_1(\rho))}{2(\bar{e}-\omega)} = 1 + \frac{(\rho - 1)\Delta_1(\rho)}{2(\bar{e}-\omega)}$$

$$I^{CE} = \ln\left(\frac{C_1'(\bar{e}-\omega)}{C_2'(\bar{e}-\omega)} + 1\right) \Big/ \ln\left(\frac{\max_i C_i'(\bar{e}-\omega-\Delta_i(\rho))}{\min_i C_i'(\bar{e}-\omega-\Delta_i(\rho))} + 1\right)$$



Appendix of Chapter 2

Two sources of gains from bilateral linkage

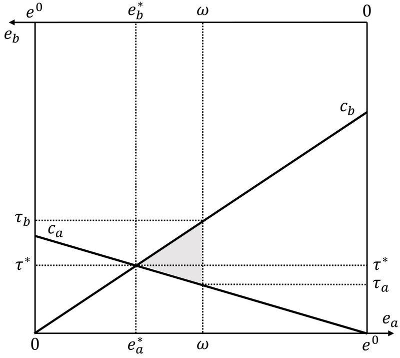


Figure: Certainty (ambition)

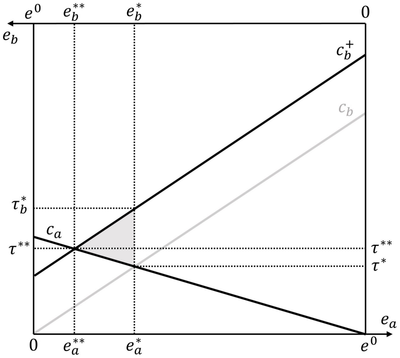


Figure: With (+) shock in country b

Modelling framework

- $\mathcal{I} = \{1, \ldots, n\}$: n jurisdictions with independent regulatory authorities
- Benefits of emissions $q_i \geq 0$ in jurisdiction $i \in \mathcal{I}$

$$B_i(q_i; \theta_i) = (b_1 + \theta_i)q_i - \frac{b_2}{2\psi_i} q_i^2, \text{ with } b_1, b_2 > 0.$$

  Size ψ_i: measures the volume of i's regulated emissions
  Shocks θ_i: business cycles, energy prices, weather, etc

$$\mathbb{E}\{\theta_i\} = 0, \ \mathbb{V}\{\theta_i\} = \sigma_i^2, \text{ and } \mathrm{Cov}\{\theta_i, \theta_j\} = \rho_{ij}\sigma_i\sigma_j.$$

- Caps are exogenous, fixed once-and-for-all, and proportional to size

$$\omega_i = A \cdot \psi_i, \text{ for all } i \in \mathcal{I}.$$

Bilateral linkage equilibria

- An $\{i, j\}$-linkage equilibrium is a triple $\left(p_{\{i,j\}}, q_{\{i,j\},i}, q_{\{i,j\},j}\right)$ where

$$p_{\{i,j\}} = \frac{\psi_i \bar{p}_i + \psi_j \bar{p}_j}{\psi_i + \psi_j}, \text{ and } q_{\{i,j\},i} - \omega_i = \frac{\psi_i}{b_2}(\bar{p}_i - p_{\{i,j\}}).$$

  - Linkage eliminates the post-shock wedge in autarkic prices
  - ...and increases/decreases effective cap in high-/low-shock jurisdiction
- The expected aggregate economic benefit from $\{i, j\}$-linkage is

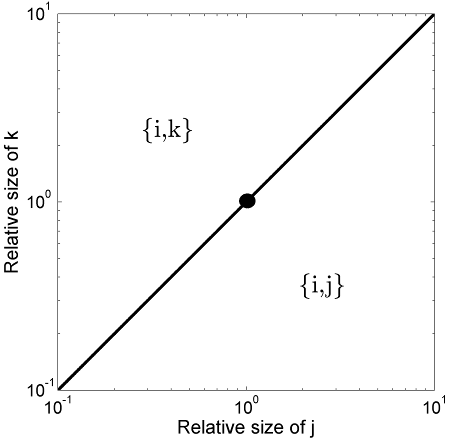
$$\mathbb{E}\{\Delta_{\{i,j\}}\} = \frac{\psi_i \psi_j}{2b_2\left(\psi_i + \psi_j\right)}\left(\sigma_i^2 + \sigma_j^2 - 2\rho_{ij}\sigma_i\sigma_j\right) \geq 0,$$

- ...and is shared in inverse to proportion to size

$$\mathbb{E}\{\delta_{\{i,j\},i}\}/\mathbb{E}\{\delta_{\{i,j\},j}\} = \psi_j/\psi_i.$$

Bilateral linkage preferences

***i*'s preferences over bilateral linkages in a 3-jurisdiction world**



- $\{i, j, k\}$
- $\psi_i = 1$
- $\sigma_i = \sigma_j = \sigma_k$
- $\rho_{ij} = \rho_{ik}$

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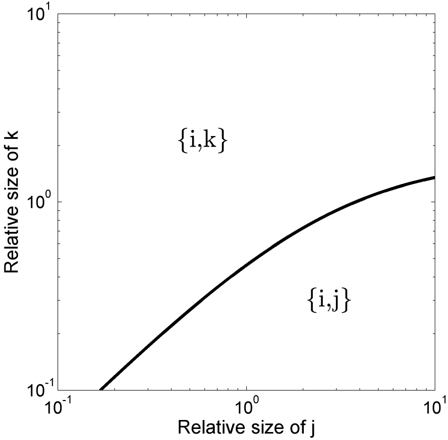

- $\{i, j, k\}$
- $\psi_i = 1$
- $2\sigma_i = 2\sigma_j = \sigma_k$
- $\rho_{ij} = \rho_{ik} = 0$

Bilateral linkage preferences

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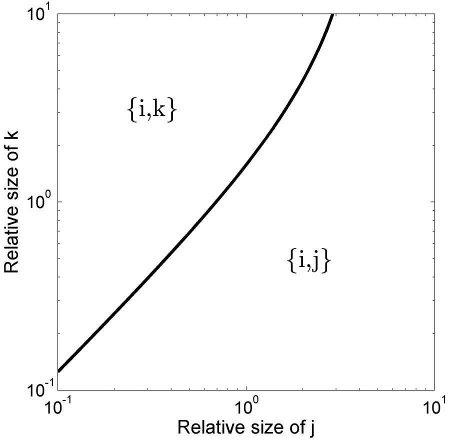
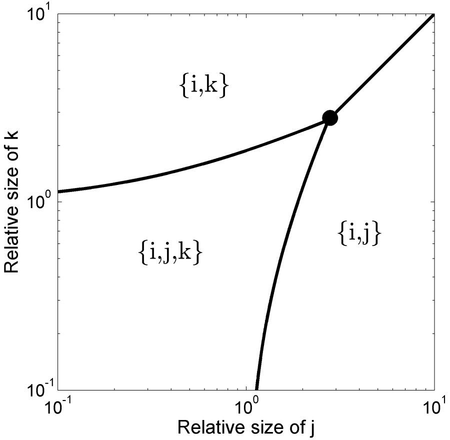


- $\{i, j, k\}$
- $\psi_i = 1$
- $\sigma_i = \sigma_j = \sigma_k$
- $\rho_{ij} = -0.5, \quad \rho_{ik} = 0$

Enter trilateral linkage

i's preferences over all linkages in a 3-jurisdiction world



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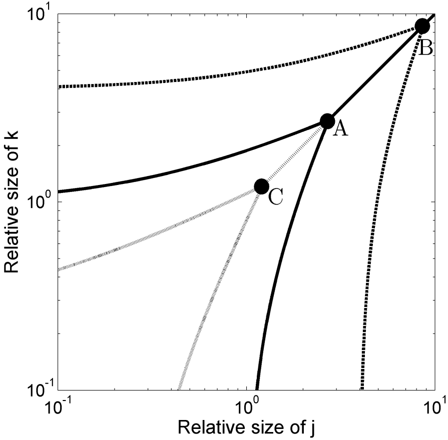
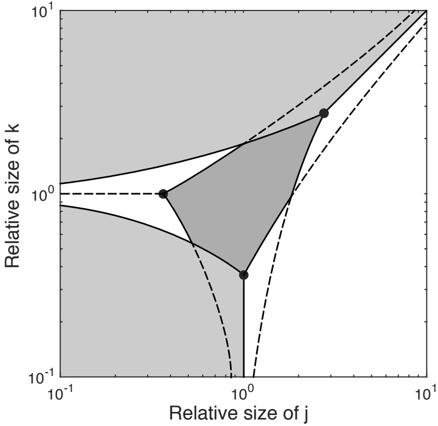


- $\{i, j, k\}$
- $\psi_i = 1$
- $\rho_{ij} = \rho_{ik} = \rho_{jk} = 0$
- **A**: $\sigma_i = \sigma_j = \sigma_k$
- **B**: $\sigma_i = 2\sigma_j = 2\sigma_k$
- **C**: $2\sigma_i = \sigma_j = \sigma_k$

Enter trilateral linkage

i, j and k's preferences under symmetry



- $\{i, j, k\}$
- $\psi_i = 1$
- $\sigma_i = \sigma_j = \sigma_k$
- $\rho_{ij} = \rho_{ik} = \rho_{jk} = 0$
- symmetry

Multilateral linkage equilibria

- A $\mathcal{C}$-linkage equilibrium is the $(|\mathcal{C}|+1)$-tuple $(p_{\mathcal{C}}, (q_{\mathcal{C},i})_{i\in\mathcal{C}})$ where

$$p_{\mathcal{C}} = \Psi_{\mathcal{C}}^{-1} \sum_{i\in\mathcal{C}} \psi_i \bar{p}_i, \text{ and } q_{\mathcal{C},i} - \omega_i = \frac{\psi_i}{b_2}(\bar{p}_i - p_{\mathcal{C}}).$$

- Under $\mathcal{C}$-linkage, the economic gain accruing to jurisdiction $i \in \mathcal{C}$ is

$$\mathbb{E}\{\delta_{\mathcal{C},i}\} \propto \psi_i \mathbb{E}\{(\bar{p}_i - p_{\mathcal{C}})^2\} = \psi_i\big((\mathbb{E}\{\bar{p}_i\} - \mathbb{E}\{p_{\mathcal{C}}\})^2 + \mathbb{V}\{\bar{p}_i - p_{\mathcal{C}}\}\big) \geq 0.$$

- Total gain in $\mathcal{C}$-linkage is decomposed into its internal bilateral linkage gains

$$\Delta_{\mathcal{C}} = \sum_{i\in\mathcal{C}} \delta_{\mathcal{C},i} = (2\Psi_{\mathcal{C}})^{-1} \sum_{(i,j)\in\mathcal{C}^2} (\psi_i + \psi_j)\Delta_{\{i,j\}}.$$

- Linking disjoint linkage coalitions is beneficial: linkage is superadditive
  - Jurisdictional linkage preferences are not aligned
  - Global market is not necessarily the most preferred link for all $i \in \mathcal{I}$.
  - Any linkage coalition different from the global market cannot be the most preferred linkage coalition for all coalition members.

Calibration methodology and results

- Assume hypothetical ETS covering all emissions of CHN, USA, EUR, KOR, EGY: sample representative of diversity present in the data
- Calibrate $\{\psi_i, \sigma_i, \rho_{ij}\}$ based on historical emissions data
- WRI: Annual country level CO_2 emissions data covering 1950-2012
- The natural logarithm of laissez-faire emissions is

$$ln\left(\tilde{q}_i\right) = ln\left(b_2/\psi_i\right) + ln\left(b_1 + \theta_i\right)$$

- We associate each component of $ln\left(\tilde{q}_i\right)$ with the trend and cyclical components of emissions obtained using the HP filter with the penalty parameter $\lambda = 6.25$ for annual data (Hodrick & Prescott, 1997)
- Congruent with assumption that shocks driven by business cycles, technology shocks, fuel prices,... See Doda (2014) for methodology and Doda & Taschini (2017) for discussion of results

Calibration methodology and results

Table: Calibration results: Size and volatility (ψ_i and σ_i)

	CHN	USA	EUR	KOR	EGY
ψ_i	100	55.038	38.699	6.645	2.356
σ_i	0.028	0.019	0.017	0.034	0.050

Table: Calibration results: Pairwise correlation coefficients (ρ_{ij})

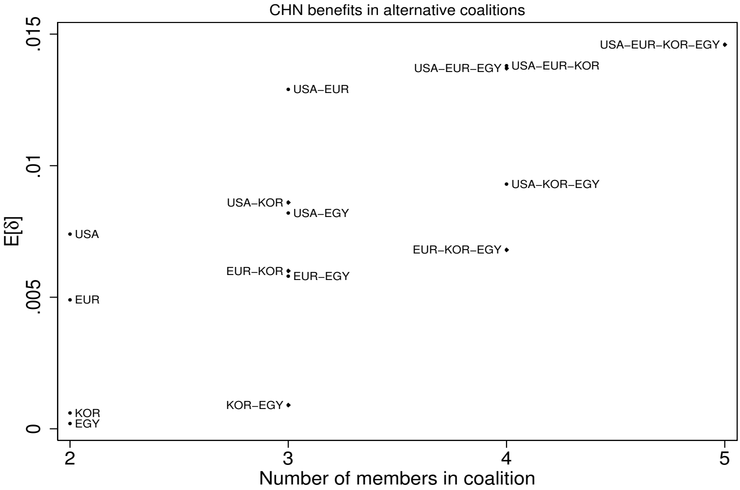
	CHN	USA	EUR	KOR	EGY
CHN	1.000				
USA	0.525	1.000			
EUR	0.460	0.652	1.000		
KOR	0.247	0.419	0.277	1.000	
EGY	-0.395	-0.186	-0.101	-0.397	1.000

Most and second preferred coalitions

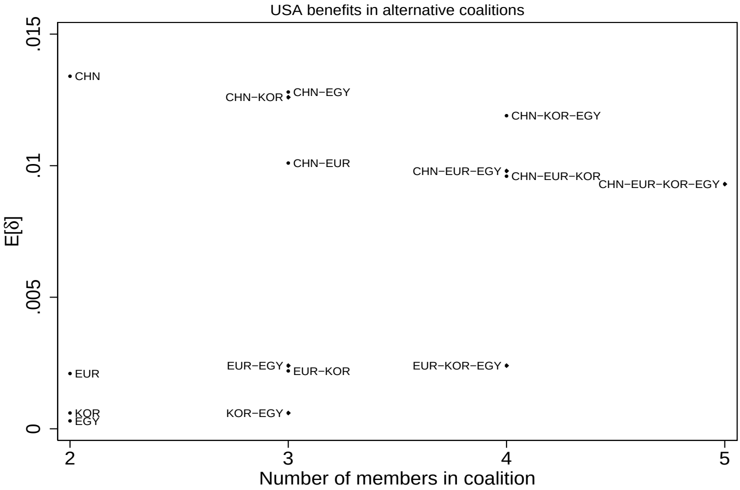
	Most preferred coalition	Second most preferred coalition
CHN	{CHN,USA,EUR,KOR,EGY}	{CHN,USA,EUR,KOR}
USA	{CHN,USA}	{CHN,USA,EGY}
EUR	{CHN,EUR}	{CHN,EUR,KOR,EGY}
KOR	{CHN,KOR}	{CHN,KOR,EGY}
EGY	{CHN,EGY}	{CHN,KOR,EGY}

- CHN ranks linkage coalitions by size
- Preferences of USA/EUR/KOR/EGY
  - Bilateral link with CHN is always top choice
  - Second preferences always include CHN but subtle otherwise
    → KOR prefers to link with EGY than with much larger USA or EUR

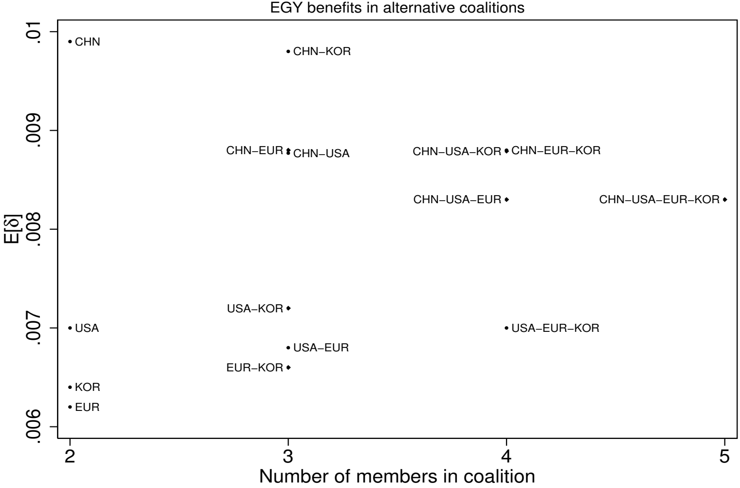
CHN linkage gains



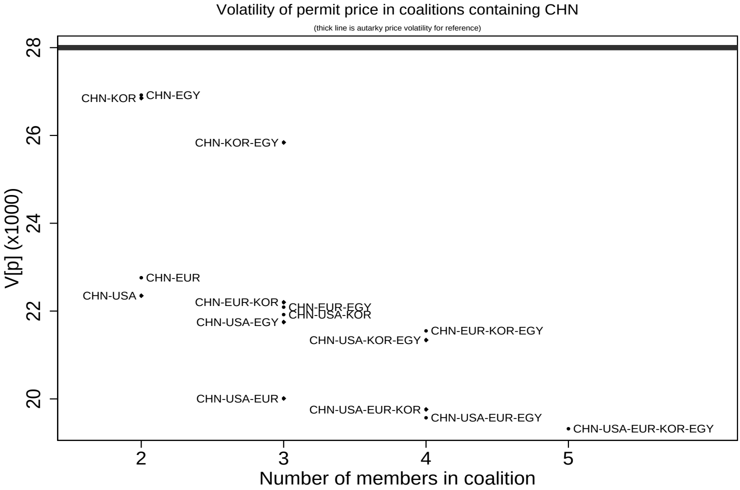
USA linkage gains



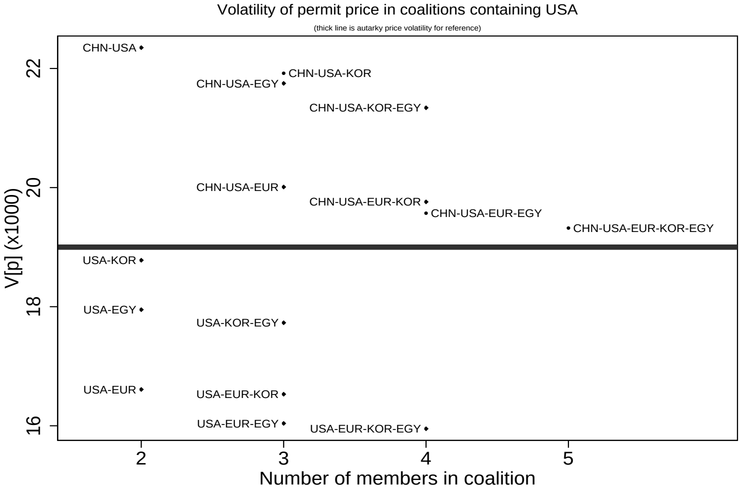
EGY linkage gains



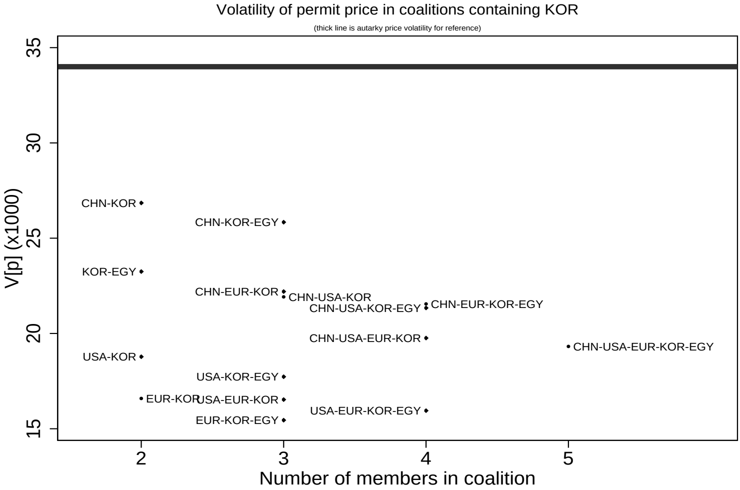
CHN price volatility



USA price volatility



KOR price volatility



Linkage costs and cost-sharing arrangements

	$\mathcal{S}^*$	$\mathbb{E}\{\tilde{\Delta}_{\mathcal{S}*}\}$	Set of blocking jurisdiction under R#
$z = 0$	{{CHN,USA,EUR},{KOR,EGY}}	0.0221	$R3$ and $R5$: ∅ $R1$, $R2$, $R4$, $R6$, $R7$, ... $R8$ and $R9$: {KOR}
$z = 0.5$	{{CHN,USA,EUR},{KOR,EGY}}	0.0137	$R1$, $R4$, $R5$ and $R7$: ∅ $R2$: {KOR} $R3$: {EUR} $R6$ and $R8$: {EUR,KOR} $R9$: {CHN}
$z = 1$	{{CHN,USA,EUR,KOR,EGY}}	0.0118	$R5$: ∅ $R1$: {KOR} $R2$ and $R4$: {CHN,USA} $R3$ and $R6$: {KOR,EGY} $R7$: {CHN} $R8$: {USA,EUR} $R9$: {EGY}

Appendix of Chapter 3

Motivation & Literature – Stylized Facts

- Under textbook assumptions: intertemporal cost efficiency
  - current price reflects NPV of last permit used (Rubin, 1996)
  - optimal price path grows at rate of interest (Hotelling, 1931)
  - focus on long-term carbon price signal
- Recurrent observations: prices lower than anticipated and formation of allowance surpluses (Tvinnereim, 2014)
  - cap erosion: crisis, offsets, CPs,... (Borenstein et al, 2016)
  - price determinants (Koch et al, 2014; Hintermann et al, 2016)
- The potential suspects are (non mutually exclusive):
  - myopia/limited foresight (Ellerman et al, 2016)
  - excessive discounting 1 (Neuhoff et al, 2012)
  - excessive discounting 2 (Bredin & Parsons, 2016)
  - excessive discounting 3 (Kollenberg & Taschini, 2016)
  - regulatory uncertainty (Salant, 2016; Koch et al, 2016)

Motivation & Literature – Regulatory Uncertainty (RU)

- RU = individual's perceived inability to predict the future state of the regulatory environment (Hoffmann et al, 2008)
  - (deep) uncertainty in the sense of Knight (1921)
  - regulatory risks are not (entirely) hedgeable
  - political nature of permits = 'ill-defined' property rights
- RU undermines long-term credibility and affects current prices (Salant, 2016; Salant & Henderson, 1978)
  - EUETS reacts to political announcements (Koch et al, 2016)
- RU increases compliance costs by delaying investments
  - option value to postpone investments (Dixit & Pindyck, 1994)
  - empirical validation based on CAIR (Dorsey, 2017)
- We use a two-period model for an ambiguity-averse firm
  - to capture the influence of RU on abatement decisions
  - to find theoretical/behavioral foundations to observed facts
  - to analyze the impact of allocation on banking decisions

Ambiguity Aversion (AA) and Representation Theorem

- Ambiguity = inability to unambiguously assign a probability measure uniquely describing the underlying risk
- Ambiguity aversion = additional aversion (w.r.t. risk aversion) to being unsure about the probabilities of outcomes
- Ample lab experiments: agents prefer gambles with known rather than unknown probabilities (and DAAA prevails)
- Firm exhibits smooth ambiguity aversion (KMM, 2005; 2009)
  - uncertain about the objective future price risk $\tilde{\tau}$
  - confronted with objective risks $\tilde{\tau}_\theta$ in scenarios $\theta \in \Theta = \left[\underline{\theta}; \overline{\theta}\right]$
  - has subjective beliefs over θ-scenarios F
  - Ambiguity = subjective risk over objective risks, i.e. two layers of uncertainty: $SEU \times \phi(EU)$ with $\phi' > 0$ and $\phi'' \leq 0$ (AA)

Firm's Objective Function & Benchmark

- Two dates 1 and 2, uncertainty resolves at date 2
- for any given observed couple (τ, ξ), temporal profits write

$$\pi_1(a_1) = \zeta_1 - C_1(a_1) \text{ and } \pi_2(a_1, a_2) = \zeta_2 - C_2(a_1, a_2) - \tau(\xi - a_1 - a_2 - \omega).$$

- The firm trades off its present abatement cost with its future certainty-equivalent benefit of banking

$$\max_{a_1 \geq 0} \ \pi_1(a_1) + \beta\phi^{-1}\left(\mathbb{E}_F\left\{\phi\left(\mathcal{V}(a_1; \tilde{\theta})\right)\right\}\right), \quad \text{where } \mathcal{V}(a_1; \theta) = \mathbb{E}\left\{\pi_2(a_1, a_2^*(a_1, \omega; \tilde{\tau}_\theta); \tilde{\tau}_\theta)|\theta\right\}. \tag{1}$$

- Program (1) is well defined for $\pi_{1,2}$ and $-\phi'/\phi''$ concave
- Benchmark = ambiguity neutrality (ϕ linear). The FOC is

$$\pi_1'(\bar{a}_1) + \beta\mathbb{E}_F\left\{\mathcal{V}_{a_1}(\bar{a}_1; \tilde{\theta})\right\} = 0 \Leftrightarrow \pi_1'(\bar{a}_1) + \beta\mathbb{E}\left\{\tilde{\tau}\right\} = 0, \tag{2}$$

i.e. cost-efficiency obtains and $\bar{a}_1$ independent of allocation ω.

Two Ambiguity Aversion Induced Effects (1/3)

- Under ambiguity aversion, FOC for Program (1) reads

$$\pi_1'(\hat{a}_1) + \beta \mathcal{A}(\hat{a}_1) \mathbb{E}_F\left\{\mathcal{D}(\hat{a}_1;\tilde{\theta}) \mathcal{V}_{a_1}(\hat{a}_1;\tilde{\theta})\right\} = 0, \text{ where} \tag{3}$$

- $\mathcal{A}$ modifies the subjective discount factor such that

$$\mathcal{A}(a_1) = \frac{\mathbb{E}_F\left\{\phi'\left(\mathcal{V}(a_1;\tilde{\theta})\right)\right\}}{\phi' \circ \phi^{-1}\left(\mathbb{E}_F\left\{\phi\left(\mathcal{V}(a_1;\tilde{\theta})\right)\right\}\right)}, \tag{4}$$

and $\mathcal{A} \geq, =, \leq 1$ i.f.f. ϕ displays DAAA, CAAA, IAAA

- $\mathcal{D}$ pessimistically distorts the subjective prior F such that

$$\forall \theta \in \Theta,\ \mathcal{D}(a_1;\theta) = \frac{\phi'\left(\mathcal{V}(\bar{a}_1;\theta)\right)}{\mathbb{E}_F\left\{\phi'\left(\mathcal{V}(\bar{a}_1;\tilde{\theta})\right)\right\}}, \tag{5}$$

and overweights bad scenarios with low-$\mathcal{V}$ values ($\phi'' \leq 0$).

Two Ambiguity Aversion Induced Effects (2/3)

- Increase in banking under AA w.r.t. AN ($\hat{a}_1 \geq \bar{a}_1$) i.f.f.

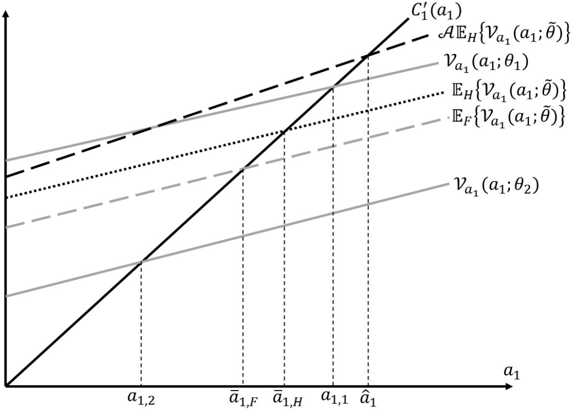
$$\mathcal{A}(\bar{a}_1)\mathbb{E}_H\{\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\} \geq \mathbb{E}_F\{\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\}, \quad (6)$$

  with H the distorted prior $H(\theta) = \int_{\underline{\theta}}^{\theta} \mathcal{D}(\bar{a}_1;X)\mathrm{d}F(X)$, i.e. the future price estimate is higher under AA than AN
- Controlling for *pessimism* ($H \equiv F$), $\mathcal{A} \geq 1$ raises banking
  - DAAA $\sim$ ambiguity prudence (Berger, 2014; Gierlinger & Gollier, 2017)
  - corresponds to an increase in firms' discount factor
  - ample evidence of DAAA in lab experiments and surveys
- Controlling for *prudence* ($\mathcal{A} \equiv 1$), pessimism raises banking only if low-$\mathcal{V}$ scenarios coincide with high-$\mathcal{V}_{a_1}$ scenarios
- The two AA effects can be aligned or countervailing

Two Ambiguity Aversion Induced Effects (3/3)

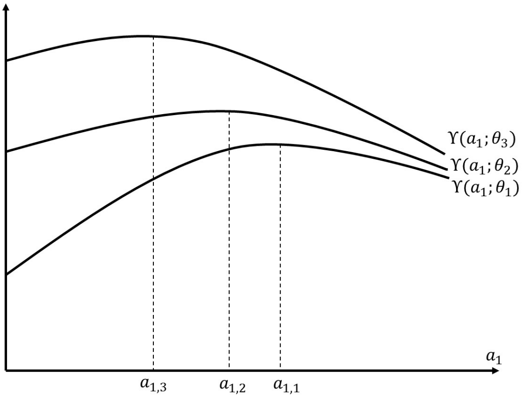
Illustration: $\Theta = \{\theta_1; \theta_2\}$, $F = \{\theta_1, .5; \theta_2, .5\}$, both $\mathcal{A}$ and $\mathcal{D}$ are constant with a_1. Joint AA-effect is decomposed into two steps

$F \rightarrow H$ is a vertical translation; $\mathcal{A}$ is rotation



Characterization of pessimism (1/3)

- Pessimism raises banking i.f.f. $\mathrm{Cov}_\theta\left\{\mathcal{V}(\bar{a}_1;\tilde{\theta});\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\right\} \leq 0$
- Illustration: $\Theta = \{\theta_1;\theta_2;\theta_3\}$. Higher banking reduces the spread across scenarios under negative correlation



Characterization of pessimism (2/3)

Proposition: Sufficient conditions for over-banking

Pessimism leads the firm to over-abate at date 1 if:
(*i*) they expect to be in a net short position at date 2 in all θ-scenarios,
(*ii*) or, their initial allocation is relatively small.

- Pessimism induces a precautionary effect
  - net buyers bank more to hedge against future price
- banking adjustment dictated by initial allocation
  - allocation is not neutral and determines bad/good scenarios

Proposition: Ambiguity on individual baselines

Consider a continuum of competitive firms, identical but for allocation. Under symmetric allocation of allowances, firms always over-bank at date 1.

Characterization of pessimism (3/3)

- Three extensions of the model:

Proposition: Introduction of forwards contracts

Under the assumption that forwards contracts are fairly priced, intertemporal efficiency (in expectations) is restored under CAAA. However, forwards cannot correct for subjective shifts in discounting.

Proposition: Market populated by both AA and AN firms

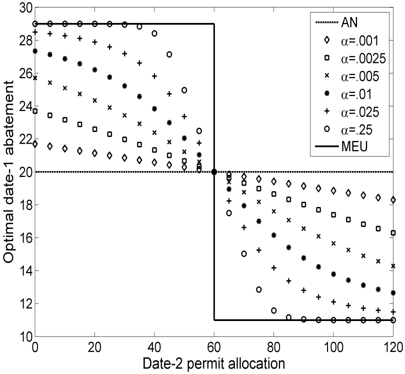
The AA-induced distortion is amplified in a market populated by a mix AA and AN firms. This also alters abatement decisions by AN firms.

Proposition: Equilibrium volume of trade (autarkic compliance)

If permits are sufficiently non-symmetrically distributed across AA firms, then the equilibrium volume of trade is lower than with AN firms.

Comparative statics and numerical simulations (1/3)

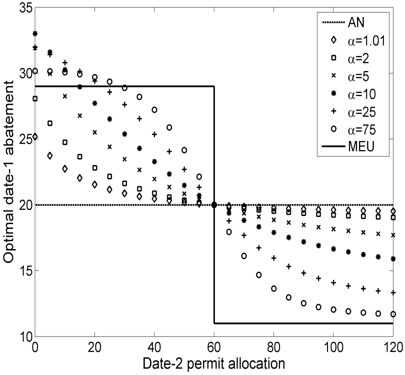
- An increase in AA ($\phi_2 = \psi \circ \phi_1$, $\psi' > 0$, $\psi'' \leq 0$) leads to
  - an increase in pessimism (MLR deterioration; Gollier, 2011)
  - when ψ is almost quadratic, an increase in prudence only if prudence is not too high relative to AA $-\phi_1''/\phi_1' \leq -\phi_1'''/\phi_1'' \leq -3\phi_1''/\phi_1'$
- With uniform measures and controlling for prudence (CAAA)



- banking decreases with ω
- unique crossing at $\omega = 60$
- magnitude of variation increases with AA degree
- continuum between AN and the MEU criterion

Comparative statics and numerical simulations (2/3)

- An increase in AA ($\phi_2 = \psi \circ \phi_1$, $\psi' > 0$, $\psi'' \leq 0$) leads to
  - an increase in pessimism (MLR deterioration; Gollier, 2011)
  - when ψ is almost quadratic, an increase in prudence only if prudence is not too high relative to AA $-\phi_1''/\phi_1' \leq -\phi_1'''/\phi_1'' \leq -3\phi_1''/\phi_1'$
- With uniform measures and accounting for prudence (DAAA)

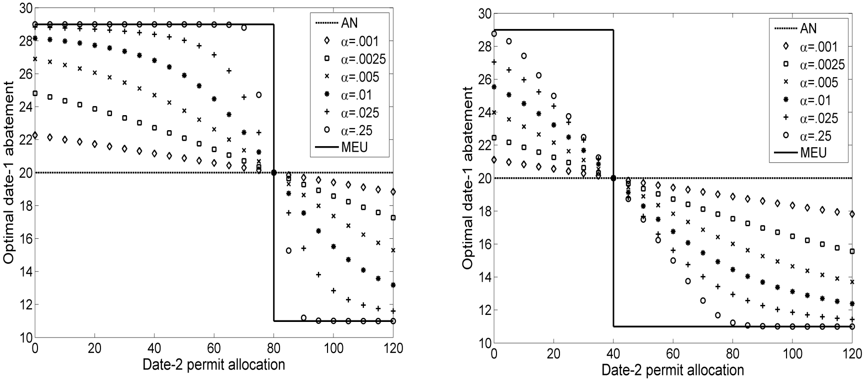


- upward offset due to $\mathcal{A}$
- weak $\mathcal{A}$-effect for medium ω
- higher $\mathcal{A}$-effect for low ω with multiple crossings
- MEU breach for low ω
- except for extreme ω, banking is driven by pessimism

Comparative statics and numerical simulations (3/3)

- Joint market price and individual baseline ambiguities
- With uniform probability measures and CAAA (G and L are first-order independent given any θ-scenario $\mathbb{E}_{\{G,L\}}\{\cdot|\theta\} \equiv \mathbb{E}_{\{G\}}\{\cdot|\theta\}\mathbb{E}_{\{L\}}\{\cdot|\theta\}$)

$\text{Cov}_\theta\{G, L\} > 0$ $\text{Cov}_\theta\{G, L\} < 0$



Overestimation of AA effects

- Marinacci (2015), Guetlein (2016), Bosetti & Berger (2017)
- Decomposition: $\phi = v \circ u^{-1}$, $u'' \leq 0$ denotes risk aversion and $v'' \leq 0$ denotes aversion towards model uncertainty
- liable firms are risk-neutral but model-uncertainty averse

$$\frac{-\phi''}{\phi'} = \frac{1}{u'}\left(\frac{-v''}{v'} - \frac{-u''}{u'}\right)$$

- AA requires v being more concave than u
- Amplification: $\frac{-\phi''}{\phi'}\Big|_{RN} \geq \frac{-\phi''}{\phi'}\Big|_{RA}$

Ambiguity premium

Proposition: Sufficient condition for over-banking

Let liable firms display CAAA. Then, it is sufficient that $(\mathcal{V}(\bar{a}_1;\theta))_\theta$ and $(\mathcal{V}_{a_1}(\bar{a}_1;\theta))_\theta$ be anticomonotonotonic for over-abatement to occur at date 1.

- For illustration, let $\partial_{a_1} C_2 \equiv 0$. Expanding the FOC gives

$$\hat{a}_1 \geq \bar{a}_1 \;\Leftrightarrow\; \begin{cases} \mathcal{A}(\bar{a}_1)\left(\langle\tilde{\tau}\rangle + \mathcal{P}(\bar{a}_1)\right) \geq \langle\tilde{\tau}\rangle\,, \\ \mathcal{P}(a_1) = \dfrac{\mathrm{Cov}\left\{\phi'\left(\mathcal{V}(a_1;\tilde{\theta})\right);\mathcal{V}_{a_1}(a_1;\tilde{\theta})\right\}}{\mathbb{E}_F\left\{\phi'\left(\mathcal{V}(a_1;\tilde{\theta})\right)\right\}} \end{cases}$$

  - $\mathcal{P}$ is an ambiguity premium demanded to compensate the exposure to ambiguity, which is positive provided that anticomonotonicity holds

Proposition: Necessary and sufficient conditions

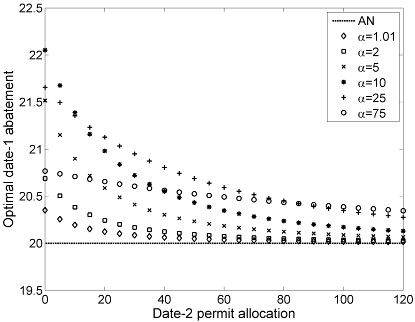
$\hat{a}_1 \geq \bar{a}_1$ i.f.f. $\mathcal{P}(\bar{a}_1) \geq 0$ under CAAA, or $\mathcal{P}(\bar{a}_1) \geq \frac{1-\mathcal{A}(\bar{a}_1)}{\mathcal{A}(\bar{a}_1)} < 0$ under DAAA.

Parametrical example (1/7)

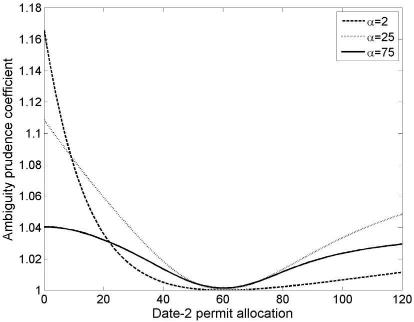
- $c_1 = c_2 = 1$, $\beta = 1$ and $\gamma = 0$
- $F \hookrightarrow \mathcal{U}(\Theta = [\![-\overline{\theta}; \overline{\theta}]\!])$, with $\overline{\theta} = 9$
- Under a cap and trade with fixed common baselines $\xi = 100$
  - $G(\cdot;\theta) \hookrightarrow \mathcal{U}([\underline{\tau} + \theta; \overline{\tau} + \theta])$, with $\underline{\tau} = 10$ and $\overline{\tau} = 30$
  - $\mathcal{V}_{a_1}(a_1;\theta) = \langle\tau\rangle + \theta$ with $\langle\tau\rangle = \frac{\underline{\tau}+\overline{\tau}}{2}$
  - $\Rightarrow$ under AN $\langle\tilde{\tau}\rangle = \langle\tau\rangle = 20$
  - AntiC holds given that $\omega \leq \omega^* = 51$ with $\omega \in [0; 120]$
- Under a tax regime with $t = 20$ for consistency
  - $G(\cdot;\theta) \hookrightarrow \mathcal{U}\left(\left[\underline{\xi} + \theta; \overline{\xi} + \theta\right]\right)$, with $\underline{\xi} = 50$ and $\overline{\xi} = 150$
  - Liability thresholds: tax charged only above $\omega \in [0; 120]$
- The ambiguity function ϕ is such that
  - CAAA: $\phi(x) = \frac{e^{-\alpha x}}{-\alpha}$ with $\alpha > 0$ the AAA degree
  - DAAA: $\phi(x) = \frac{x^{1-\alpha}}{1-\alpha}$ with $\alpha > 1$ the AAA degree

Parametrical example (2/7)

Tax only subject to $\mathcal{A}$

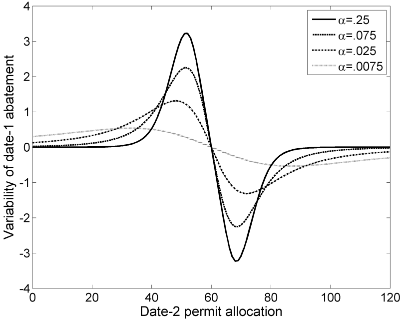


$\mathcal{A}$-effect in an ETS

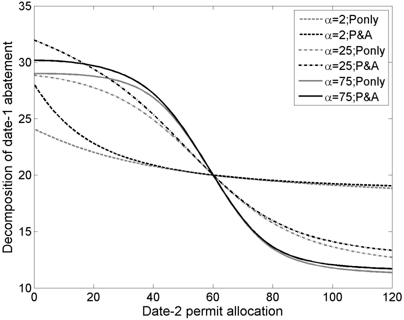


Parametrical example (3/7)

Variability under CAAA



Decomposition of $\mathcal{A}$ and $\mathcal{P}$



Parametrical example (4/7)

Illustration: Let $\Theta = \{\theta_1 = +5; \theta_2 = -5\}$, $F = \{\theta_1, .5; \theta_2, .5\}$. FOCs and the decomposition are given by

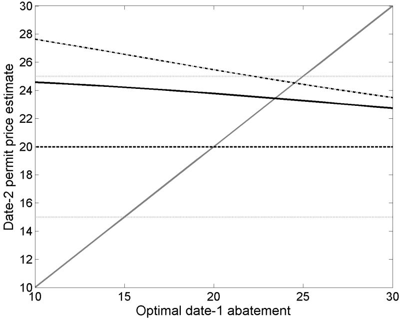
$$-C_1'(\hat{a}_1) + \beta\mathcal{A}(\hat{a}_1)\left(\langle\tau\rangle + \hat{q}_1(\hat{a}_1)\theta_1 + \hat{q}_2(\hat{a}_1)\theta_2\right) = 0 \tag{7}$$

$$H(a_1) = \begin{cases} \hat{q}_1(a_1) = & q_1 \dfrac{\phi'\left(\mathcal{V}(a_1;\theta_1)\right)}{q_1\phi'\left(\mathcal{V}(a_1;\theta_1)\right) + q_2\phi'\left(\mathcal{V}(a_1;\theta_2)\right)} \\ \hat{q}_2(a_1) = & q_2 \dfrac{\phi'\left(\mathcal{V}(a_1;\theta_2)\right)}{q_1\phi'\left(\mathcal{V}(a_1;\theta_1)\right) + q_2\phi'\left(\mathcal{V}(a_1;\theta_2)\right)} \end{cases} \tag{8}$$

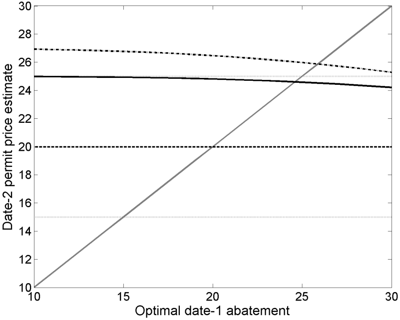
$$\mathcal{A}(a_1) = \frac{q_1\phi'\left(\mathcal{V}(a_1;\theta_1)\right) + q_2\phi'\left(\mathcal{V}(a_1;\theta_2)\right)}{\phi' \circ \phi^{-1}\left(q_1\phi\left(\mathcal{V}(a_1;\theta_1)\right) + q_2\phi\left(\mathcal{V}(a_1;\theta_2)\right)\right)} \tag{9}$$

Parametrical example (5/7)

$\alpha = 5$ & $\omega = 20$

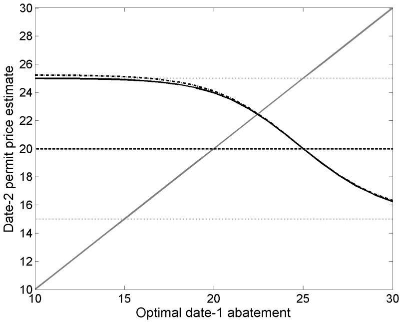


$\alpha = 10$ & $\omega = 20$

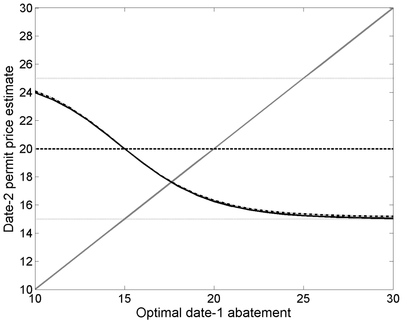


Parametrical example (6/7)

$\alpha = 75$ & $\omega = 55$

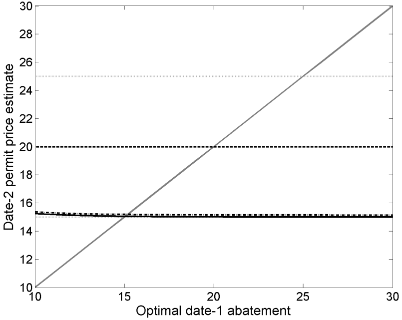


$\alpha = 75$ & $\omega = 65$



Parametrical example (7/7)

$\alpha = 75$ & $\omega = 80$



$\alpha = 5$ & $\omega = 90$