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Transitional Restricted Linkage between Emissions Trading Schemes*

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Abstract

Linkages between Emissions Trading Systems are deemed an important element of the future climate policy landscape. They are, however, difficult to agree and remain few and far between. Temporary restrictions on permit trading have potential to facilitate and gradually approach unrestricted, full linkage. We compare the relative merits of several link restrictions in this respect, namely quantitative restrictions, border permit taxes, exchange and discount rates, and unilateral linkage. To this end, we develop a simple model to have a unifying, comparative framework which, in conjunction with lessons from real-world experiences, serves a basis for a broader, policy-oriented discussion.

Keywords: Climate change; Climate policy; Emissions trading; Linkage; Restrictions on permit trading.
JEL Classification codes: Q58; H23.

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1 Introduction

Linkages between Emissions Trading Systems (ETSs) are deemed a key element of the future climate policy landscape (Bodansky et al., 2016). They are, however, difficult to agree and to date, few and far between (ICAP, 2017). Indeed, the multi-faceted nature of linkage as well as growing heterogeneity in market designs and governance frameworks pose many challenges to prospective partners (Ranson & Stavins, 2016). First and foremost, discrepancies in autarky prices reflect different ambition levels or views about the desirable price signal, which impede on the political feasibility of linkage although this would increase attendant economic gains (Fankhauser & Hepburn, 2010). Second, a certain degree of design harmonization is required to ensure market compatibility and avoid disruptions to the linked system (Jaffe et al., 2009; Tiche et al., 2016).[1] Third, even when jurisdictions have compatible systems and are seeing eye to eye in terms of ambition and price levels, there are still risks that link outcomes do not unfold as anticipated. For instance, linkage creates exposure to developments originating abroad that propagate throughout the linked system (Flachsland et al., 2009).

Therefore, forging linkage agreements that reconcile and accommodate every party's interests is proving difficult and the most suitable way for interconnection may fall short of an unrestricted link (i.e., full linkage), at least in the near term. Two types of approaches can be contemplated to palliate the acknowledged difficulties in initiating linkage. First, connections to a common hub might constitute a first step toward further market integration, e.g. indirect linkage via offsetting or networking.[2] For instance, Jaffe et al. (2009), Tuerk et al. (2009) and Fankhauser & Hepburn (2010) conceived of a progressive mechanism of market integration via unilateral connections to the Clean Development Mechanism, envisaged as a common hub in the Kyoto era.[3] Second, permit trade restrictions might be established in the perspective of full linkage. According to Mehling & Haites (2009), «a bilateral link can be approached gradually; quantity restrictions could be applied to the other scheme's units initially and can be loosened over time as the effects [associated with the link] become clear».

[1] Market designs reflect jurisdictional circumstances and have often been critical to striking an internal political deal (Flachsland et al., 2009). This complicates inter-system design alignment as one may be limited in its inclination to cede sovereign control over entrenched policy objectives and design features.

[2] The concept of networking ETSs has recently emerged as a substitute for direct multilateral linkages (Keohane et al., 2015; Mehling & Görlach, 2016), notably under the auspices of the Networked Carbon Markets initiative by the World Bank. The idea is to allow for trades of 'carbon assets' between systems that are inherently different (e.g., in terms of design, ambition, MRV standards) by placing a 'mitigation value' on assets that account for these differences and possibly using trade restrictions as analyzed herein.

[3] Such an international offsetting scheme is currently missing. The Sustainable Development Mechanism established under Article 6.4 of the Paris Agreement could allow for indirect links, but has yet to be developed.

In essence, restrictions provide levers to adjust for the reach of the link and their potential is threefold. First, they can contain some effects of the link (e.g., price variation, abatement relocation, monetary transfers) that could otherwise hinder link formation (Jaffe et al., 2009; Lazarus et al., 2015).[4] Second, they can offer leverage in linkage negotiation through induced rents or revenues (Gavard et al., 2016). Third but not least, they can help gradually overcome some obstacles to full linkage while giving a taste of it, essentially facilitating negotiations by breaking down a lengthy linking process into progressive steps in the sense of «linking by degrees» (Burtraw et al., 2013).[5] Our focus primarily lies on the latter aspect. Indeed, such a gradual approach and the various forms it may take, albeit some of which are discussed in the literature, have not been analyzed properly. Additionally, linkage has sometimes been initiated via restrictions on permit trading, as attest transitional one-way links integrating Norway and the European aviation sector to the European Union ETS.

We consider three main types of link restrictions, namely quantitative transfer limits, border taxes on permit transfers and exchange rates on permits' compliance values. We also discuss two other forms of restrictions, namely unilateral linkage and discount rates. To evaluate their effects we use a partial-equilibrium model of linkage between two ETSs in a static and deterministic framework. Our stylized model is simple enough to allow for analytical solutions and enables us to compare link restrictions in a unifying framework, which greatly enhances insight. Crucially, it has enough structure to highlight key differences between the various restrictions considered. Note that we adopt a descriptive approach in comparing restrictions. By design, therefore, we lack a normative criterion for establishing a clear ranking between them.[6] However, we take our model, along with lessons drawn from real-world experiences with ETSs and linkage, as a basis for a policy-oriented discussion of the comparative merits of each restriction in their ability to initiate linkage and gradually scale up the link.

Restrictions are distortionary and drive a wedge between jurisdictional prices.[7] Hence, they create a trade-off between eliminating some impediments to linkage and undermining a fundamental reason for linking in the first place, i.e. cost efficiency. More precisely, by fixing the maximum authorized net permit transfer, a quantitative restriction provides a direct quantity

[4] As further discussed in Jaffe et al. (2009), restrictions can be used «to reduce inter-system trading, or if there is a desire, to require that trading with other systems lead to a net reduction in emissions».

[5] Symmetrically, link restrictions may provide levers to maneuver if partners are not satisfied with the link and wish it be severed. That is, they offer additional ways to terminate the link, whose organization affects intertemporal cost effectiveness and price formation in the linked scheme (Pizer & Yates, 2015).

[6] We do not tackle the issue of why such restrictions arise and take them as exogenously given.

[7] Restrictions are always detrimental relative to full linkage in aggregate terms but they can improve upon full linkage from a jurisdiction's perspective, and we characterize jurisdictional optimal restrictions.

handle on the reach of the link but the ratio of inter-system price convergence is unknown ex ante. Symmetrically, a border tax sets the price ratio but there is uncertainty about the resulting permit transfers. In both cases, the restricted link outcomes are comprised between autarky and full linkage, and aggregate emissions are constant. Just like a border tax, an exchange rate specifies the ratio of jurisdictional marginal abatement costs in equilibrium but further alters the relative compliance value of permits. Aggregate emissions are thus allowed to vary as a result of inter-system permit trading.

On the face of it, quantitative restrictions seem to be the natural route to full linkage between two quantity instruments. As two jurisdictional prices coexist, however, inter-system transaction prices may not reflect marginal abatement costs, which can generate uncertainty about price formation and undesirable price fluctuations. Relatedly, the distribution of the scarcity rent (associated with the binding restriction) across jurisdictions and firms is not clear ex ante. Quantitative restrictions can thus lead to uncertain distributional effects and weakened price signals, which may impair the transition to a full link.

Some of these aspects can be mitigated under a border tax on permits. Indeed, distributional outcomes can be better managed as a tax raises revenues where a quantity restriction creates a scarcity rent instead. These revenues can be seen as a form of interjurisdictional transfers and might thus help spur cooperation. Additionally, because the price ratio is conveyed by the tax rate, there should be less undesirable price fluctuations and better information on jurisdictional marginal abatement costs. Border taxes, however, may be more complicated to pursue legislatively speaking, for instance at the EU level.

By altering the fungibility of jurisdictional abatement efforts, exchange rates can be employed to adjust for differences in programmes' stringencies – and potentially other economic as well as non-economic criteria. In addition, we show how exchange rates, when skillfully selected, have potential to increase ambition over time. On the flip side, however, difficulties precisely pertain to the selection and subsequent adjustment of the exchange rate, which might possibly lead to environmental and economic outcomes worse than autarky.

Therefore, this analysis allows us to pinpoint comparative advantages and weaknesses for each link restriction. Although there is no 'ideal' transitional restricted linkage, we finally show how experience suggests that unilateral linkage – whereby permits can flow in one direction but not vice versa – can be a practical way of gradually approaching a full, two-way link. By comparing all types of restrictions in a unifying framework, we complement and provide an analytical underpinning to Lazarus et al. (2015). Closer to our model, but conceptually different, are Rehdanz & Tol (2005) and Eyckmans & Kverndokk (2010) who consider link restrictions as an expedient for importing jurisdictions to both lower aggregate emissions and deter exporting jurisdictions from issuing additional permits relative to autarky.

To a large extent, the rest of the related literature resorts to quantitative illustrations. For instance, with CGE models, Bernstein et al. (1999), Bollen et al. (1999) and Criqui et al. (1999) compared the economic consequences of different emissions trading scenarios to understand the opportunity cost of trade restrictions under the Kyoto Protocol.[8] In particular, Ellerman & Sue Wing (2000) formally underlined the monopsonistic effects and rents induced by restrictions on permit imports. More recently, restrictions gained renewed attention in the context of linking. For instance, Burtraw et al. (2013) quantify the impacts of a restricted link between the California ETS and RGGI with a 3-for-1 exchange rate in comparison with full linkage (1-for-1 trading) and, with a CGE model, Gavard et al. (2016) assess the benefits of a quantity-restricted link between China and the US (or Europe).

In practice, restrictions have been used to regulate offset credits for 'supplementarity' reasons in the form of quantitative (and qualitative) limits on offset compliance usage and discount rates on offset compliance value (Trotignon, 2012; Braun et al., 2015; Gronwald & Hintermann, 2016).[9] To the best of our knowledge, the closest example of border taxes on inter-jurisdictional abatement transfers was on exports of Chinese Certified Emission Reductions, whose objective was to split the CDM rent between the government and projects owners (Liu, 2010; Zhu, 2014). So far, exchange rates have not been used to regulate uniformly-mixed pollutants, but they are usually advocated for non-uniformly mixed pollutants to account for the heterogeneity in both pollutants and reception points.[10] Accordingly, they were considered in some cap-and-trade programmes but were not implemented in the end, as in the case of the ozone-targeting RECLAIM (Tietenberg, 1995; Fromm & Hansjürgens, 1996).

The remainder proceeds as follows. Section 2 sets forth the unifying modelling framework. Section 3 describes the implications of each link restriction analytically. Section 4 provides a policy discussion on the relative merits of each restriction with a special focus on the transition to full linkage. Section 5 concludes. An Appendix contains the analytical derivations and proofs (A), numerical simulations (B) and details about domestic cap selection (C).

[8] Westskog (2002) discusses the relevance of various arguments for trading restrictions in this context.

[9] In general, quantitative limits do not exceed 15% of entities' compliance obligations and, since offset quotas usually span several compliance periods, offset usage need also be timed. To give but one example of discount rate, France applies a 10% discount on the mitigation value of Emission Reduction Units.

[10] In this case, volume efficiency requires that trading ratios be set equal to the ratio of delivery coefficients so that marginal abatement costs vary across emission sources in accordance with associated marginal damages (Montgomery, 1972; Mendelsohn, 1986) although cost efficiency can generally not be achieved (Førsund & Nævdal, 1998). For more details on optimal trading ratios and damage-differentiated policies, see e.g. Muller & Mendelsohn (2009), Holland & Yates (2015) and Fowlie & Muller (2017).

2 Modelling framework

There are two jurisdictions 1 and 2 with domestic ETSs in place to regulate uniformly-mixed pollutants.[11] Markets for permits are competitive and we abstract from market designs to single out restriction-specific effects.[12] Jurisdictions have the same unregulated emission level $\bar{e}$ and $e_i \in [0;\bar{e}]$ denotes jurisdiction i's emission level for $i \in \{1,2\}$. For clarity and without loss of generality for the purpose of our model, jurisdictions face the same binding cap on emissions $\omega < \bar{e}$ or domestic abatement target $a = \bar{e} - \omega > 0$. For comparability, we assume caps are enforced under autarky, full linkage and all other forms of restricted linkages.[13]

In each jurisdiction, we consider the representative firm, i.e. the aggregate of all emitting firms located within its geographical boundaries (Montgomery, 1972; Krupnick et al., 1983). Abatement costs, denoted C_i in jurisdiction i, are increasing and convex functions of the abatement level $a_i = \bar{e} - e_i$ with $C_i(0) = 0$. For analytical tractability and as is standard practice, these functions are equipped with a quadratic specification (Newell & Stavins, 2003). Without loss of generality and up to a translation of the results the linear term is omitted for convenience and we let c_i denote jurisdiction i's linear marginal abatement cost slope. That is, the higher c_i the less sensitive (i.e., elastic) i's emissions ($\mathrm{d}e_i$) to a shift in the permit price ($\mathrm{d}\tau$) since $\mathrm{d}\tau = c_i \mathrm{d}e_i$. In other words, jurisdictions are identical but for abatement technology and $1/c_i$ measures jurisdiction i's flexibility in abatement.

Autarky. Compliance cost minimization under autarky in jurisdiction i requires

$$\min_{e_i \in (0;\bar{e})} \Big\langle C_i(\bar{e} - e_i) \Big\rangle \text{ subject to } e_i \leq \omega. \tag{1}$$

Because abatement is costly, jurisdictions emit up to their binding caps and $\tau_i = c_i a$ denotes i's autarky permit price. When autarky prices differ across jurisdictions, cost efficiency can be improved upon by relocating some abatement from the high-price to the low-price system. Let jurisdiction 1 (resp. 2) be the high-price (resp. low-price) system, i.e. $\tau_1 > \tau_2$. Therefore, jurisdiction 1 has less flexibility in abatement than jurisdiction 2, i.e. $1/c_1 < 1/c_2$ and the natural direction of the net interjurisdictional permit flow is from 2 to 1.

[11] We limit the analysis to a bilateral link for ease of exposition but we note this is not entirely innocuous. For instance, in a multilateral linkage, permit importers may benefit from binding quantitative restrictions on imports in other jurisdictions/sectors as this reduces the permit price but not their own demands.

[12] Price containment mechanisms affect price formation (Holt & Shobe, 2016) and full price convergence need not obtain when they are divergent across systems (Jaffe et al., 2009; Grüll & Taschini, 2012).

[13] We discuss jurisdictional cap selection in more details in Appendix C. We are also silent on the strategic anticipatory effects of (different types of restricted) linkage on domestic cap selection à la Helm (2003).

Full linkage. Jurisdictional permits are fungible, i.e. mutually recognized, and can flow both ways without limitation. Abatement thus occurs where it is the least expensive. At the full-linkage equilibrium joint compliance costs with the overall emissions cap 2ω are minimized, that is

$$\min_{(e_1,e_2)\in(0;\bar{e})^2} \Big\langle C_1(\bar{e}-e_1)+C_2(\bar{e}-e_2)\Big\rangle \text{ subject to } e_1+e_2 \leq 2\omega. \tag{2}$$

We let $\Delta^* > 0$ denote the equilibrium variation in emissions in jurisdiction 1 as a result of full linkage relative to autarky. As the linked market clears, the full-link equilibrium is entirely characterized by

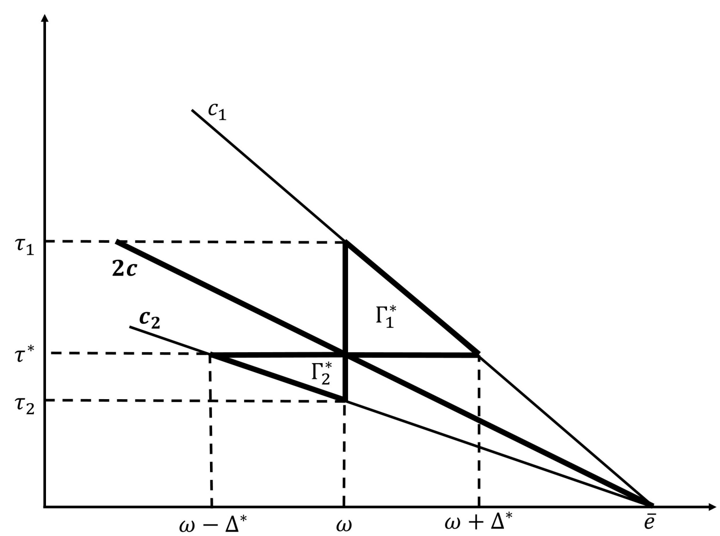
$$C_1'(a-\Delta^*) = \tau^* = C_2'(a+\Delta^*), \tag{3}$$

where τ^* is the full-link equilibrium price. With quadratic abatement costs it comes

$$\Delta^* = \frac{\tau_1-\tau_2}{c_1+c_2} = \frac{\tau_1-\tau^*}{c_1} = \frac{\tau^*-\tau_2}{c_2} \text{ and } \tau^* = 2ca, \tag{4}$$

where $1/c = 1/c_1 + 1/c_2$ denotes the flexibility in abatement of the fully linked system. Overall abatement is the same as under autarky but is now apportioned across jurisdictions

Figure 1: Autarky and full-linkage equilibria



Note: Area Γ_i^* demarcates the economic gain accruing to jurisdiction i under unrestricted permit trading.

in proportion to their flexibility in abatement, i.e. jurisdiction i abates τ^*/c_i in equilibrium. That is, cost efficiency obtains and the autarky price differential is arbitraged away. The situation is graphically depicted in Figure 1 where the thick-edged triangles demarcate the jurisdictional gains from the full link, $\Gamma_i^* = c_i\Delta^{*2}/2 = (\tau_i - \tau^*)^2/(2c_i)$.[14] Note that they are proportional to the square of the autarky-linking price wedges and that aggregate gains are distributed in inverse proportion to abatement flexibility, i.e. $\Gamma_1^*/\Gamma_2^* = c_1/c_2$.

3 Relative implications of link restrictions

3.1 Linkage with quantitative restrictions on permit transfers

Consider that jurisdiction 1 limits net imports of 2-permits as valid domestic compliance instruments, or alternatively, that jurisdiction 2 imposes a limit on the net quantity of domestic permits it is willing to export. Either way, we assume the restriction is binding and we let $\alpha \in [0;1]$ denote the allowed share of the cost-efficient, unrestricted transfer.[15] Abatement transfer is thus restricted to

$$\bar{\Delta}(\alpha) = \alpha\Delta^*, \tag{5}$$

and the level of abatement undertaken by jurisdiction 1 (resp. 2) is $a - \bar{\Delta}(\alpha)$ (resp. $a + \bar{\Delta}(\alpha)$). On the face of it, a quantitative restriction should thus limit the reach of the link and associated impacts, i.e. its implications should be comprised between autarky and full linkage. As it turns out, there are more subtle implications.

The convergence in jurisdictional shadow prices is incomplete and cost efficiency does not obtain. The restriction $\alpha \in (0;1)$ drives a wedge between these two prices denoted $\bar{\tau}_1(\alpha) = c_1(a - \bar{\Delta}(\alpha))$ and $\bar{\tau}_2(\alpha) = c_2(a + \bar{\Delta}(\alpha))$ such that $\tau_1 > \bar{\tau}_1(\alpha) > \tau^* > \bar{\tau}_2(\alpha) > \tau_2$. This generates a deadweight loss $L(\alpha) \propto (1-\alpha)^2$ that is the sum of the deadweight losses on the importer and exporter's sides of the market (triangles L_1 and L_2 in Figure 2), the magnitude of which depends on jurisdictional abatement flexibilities. Because overall abatement is maintained, cost efficiency relative to full linkage can be measured by the index

$$I(\alpha) = (\Gamma_1^* + \Gamma_2^* - L(\alpha))/(\Gamma_1^* + \Gamma_2^*) = \alpha(2-\alpha). \tag{6}$$

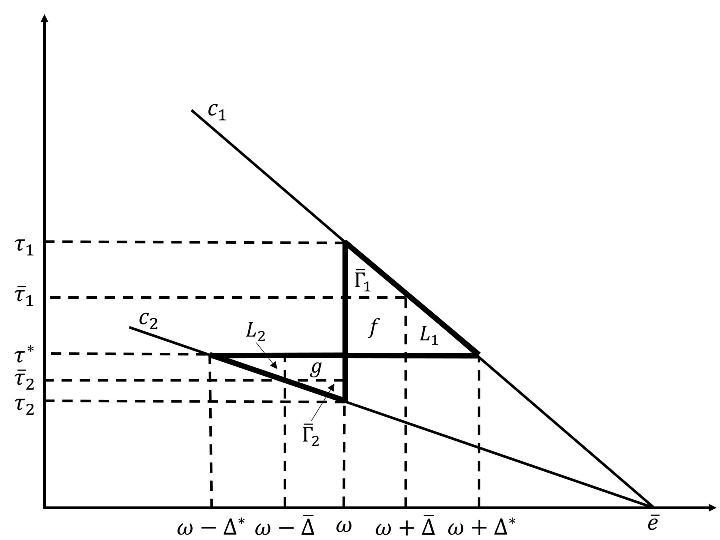
[14] Even when jurisdictions have equal autarky prices and there are no 'immediate' gains from trade due to the equalization of marginal abatement costs, linkage still brings about benefits in terms of increased market liquidity (Fankhauser & Hepburn, 2010). Indeed, jurisdictional permits are fully fungible and the linked market is 'thicker' than each system in isolation, which should reduce bid-ask spreads.

[15] In reality, quantitative restrictions are likely to be expressed in the form of concrete ceilings on the share of domestic caps that can be outsourced or exported. In practice, these restrictions could be implemented in a fashion akin to the 'gateway mechanism' proposed by Sterk et al. (2006) or by creating an additional market for licenses which must be attached to permits to allow for imports/exports as e.g. in Bernstein et al. (1999) or Gavard et al. (2016). Our notation, however, clarifies exposition because the continuum of quantity-constrained link equilibria between autarky and full linkage is described when α spans $[0;1]$.

Even a stringent limit can bring about a high share of the full-link gains, e.g. $I\,(10\%) = 19\%$ and $I\,(50\%) = 75\%$. The less stringent the restriction, the bigger the overall economic gain from the restricted link, but the lower the increase in gain at the margin (I is concave). This is so because when α increases, interjurisdictional price disparities narrow down and net gains per permit exchanged decrease accordingly. Note that the economic gains from constrained abatement relocation accruing to jurisdictions reduce to $\bar{\Gamma}_i(\alpha) = \alpha^2\Gamma_i^*$.

Crucially, there are two related implications of the interjurisdictional price wedge. First, jurisdiction 1 is willing to buy up 2-permits for a price at most as high as $\bar{\tau}_1$ while jurisdiction 2 is willing to sell off 2-permits for a price at least as high as $\bar{\tau}_2$. This means that transaction prices are undetermined in the present model (they can settle anywhere in $[\bar{\tau}_2; \bar{\tau}_1]$) and that jurisdictional permits are not fungible.[16] Second, there exists a scarcity rent $S(\alpha) \propto \alpha(1-\alpha)$ of size $f + g$ in Figure 2 whose apportionment ultimately depends on these transaction prices. Note that the scarcity rent is relatively sizeable when the restriction is close to 50% and exceeds the aggregate economic gains from trade $\bar{\Gamma}_1 + \bar{\Gamma}_2$ when $\alpha \leq 2/3$.

Figure 2: Quantity and tax restricted linkage equilibria



Note: Area $\bar{\Gamma}_i$ measures the economic gains from restricted permit trading accruing to i. Area L_i is the deadweight loss associated with the restriction on i's side of the market. Area $f + g$ alternatively measures the scarcity rent under quantity restriction or the tax revenues collected by jurisdiction 1.

To pin down both the rent extraction and transaction prices we must specify something about bargaining. The market structure we consider is a bilateral monopoly and we assume a Nash bargaining game for the rent extraction (Nash, 1950) with zero-value outside options where

[16] We note that this could reduce the gains in liquidity as compared to unrestricted linkage.

$\theta \in [0;1]$ (resp. $1-\theta$) denotes the bargaining power of jurisdiction 1 (resp. 2).[17] In this case jurisdictions capture a share of the rent that is proportional to their respective bargaining power

$$S_1(\alpha;\theta) = \theta S(\alpha), \text{ and } S_2(\alpha;\theta) = (1-\theta)S(\alpha), \tag{7}$$

which also determines the permit transaction price

$$\bar{\tau}(\alpha;\theta) = \theta\bar{\tau}_2(\alpha) + (1-\theta)\bar{\tau}_1(\alpha). \tag{8}$$

By contrast, the literature generally considers that the apportionment of the rent ultimately depends on the way the restriction is set. Typically, it is assumed that a restriction on imports, i.e. on demand for 2-permits in jurisdiction 1, grants monopsony power ($\theta = 1$) to jurisdiction 1 which captures the entire rent. Symmetrically, a restriction on exports, i.e. on supply of 2-permits for jurisdiction 1, grants monopoly power ($\theta = 0$) to jurisdiction 2 which pockets the entire rent. For instance, Ellerman & Sue Wing (2000) consider the case of a competitive supply with restricted demand and Forner & Jotzo (2002) that of a competitive demand with restricted supply. There is, however, no reason to postulate the existence of a link between the definition of the restriction and the market structure itself.[18]

It is noteworthy that one jurisdiction may be better off from the restricted link relative to full linkage. To see this, fix $\theta = 1$, i.e. jurisdiction 1 has monopsony power and makes the price. We reason around the full-link equilibrium to analyze the effects of a restriction on jurisdictions' total compliance costs, denoted TC_i in jurisdiction i. Consider a restriction that is binding by a slightly enough margin. This leads to an infinitesimally small increase in abatement in jurisdiction 1 ($\mathrm{d}\varepsilon > 0$) and decrease in the permit price ($\mathrm{d}\tau < 0$). Any such active restriction changes the total costs of compliance in both jurisdictions. In particular for jurisdiction 1,

$$\mathrm{d}TC_1 = \Big(C_1'(a - \Delta^* + \mathrm{d}\varepsilon) - \tau^*\Big)\mathrm{d}\varepsilon + \Delta^*\mathrm{d}\tau. \tag{9}$$

The first term on the right-hand side of Equation (9) is positive and corresponds to the incremental increase in domestic abatement costs due to more expensive domestic abatement being substituted for imported permits. The second term is negative and measures the

[17] Following the seminal contribution of Hahn (1984) the literature on permit markets generally focuses on the potential exercise of market power in view of permit price manipulation in relation with the initial allocation of permits. An exception is Ellerman & Sue Wing (2000).

[18] For instance, when demand is restricted, the standard argument is that the linked market is a pure buyers' market (buyers' cartel) in which acquiescent sellers are compelled to compete to sell off their permits (and vice versa for a restricted supply). But one could as well conceive of the situation where sellers collude and/or buyers compete so that the model is underspecified without further assumptions on bargaining.

incremental cost savings on remaining imports. The sign of $\mathrm{d}TC_1$ is thus ambiguous and depends on the relative magnitude of these two countervailing effects. When the restriction is lax (i.e., α close to 1), the import price effect dominates the domestic abatement effect and jurisdiction 1 is better off under the restriction than unrestricted linkage. The converse holds when the restriction is stringent (i.e., α close to 0). By a continuity argument there exists an optimal restriction from the perspective of the monopsonistic jurisdiction. Note that the price effect is absent in the case of price-taking jurisdiction 2 and the sign of $\mathrm{d}TC_2$ is unambiguous

$$\mathrm{d}TC_2 = -\Delta^* \mathrm{d}\tau > 0. \tag{10}$$

This corresponds to a direct income transfer to jurisdiction 1. By the same token, we can define jurisdictions' optimal restrictions in the general case.

Proposition 3.1. *Given $\theta \in [0;1]$ jurisdictional optimal quantitative restrictions read*

$$\alpha_1^*(\theta) = \begin{cases} \dfrac{(c_1+c_2)\theta}{2(c_1+c_2)\theta - c_1} & \text{if } \theta \geq \bar{\theta} \doteq \dfrac{c_1}{c_1+c_2}, \\ 1 & \text{otherwise}, \end{cases} \tag{11a}$$

$$\text{and, } \alpha_2^*(\theta) = \begin{cases} \dfrac{(c_1+c_2)(1-\theta)}{2(c_1+c_2)(1-\theta) - c_2} & \text{if } \theta \leq \bar{\theta}, \\ 1 & \text{otherwise}. \end{cases} \tag{11b}$$

In the relevant ranges, α_1^* (resp. α_2^*) is a decreasing (resp. increasing), convex function of θ with $\alpha_1^*(1) > \alpha_2^*(0)$, $\inf\{\alpha_1^*\} = \lim_{c_1 \to c_2^+} \alpha_1^*(1) = 2/3$ and $\inf\{\alpha_2^*\} = \lim_{c_2 \to 0^+} \alpha_2^*(0) = 1/2$.

Proof. Relegated to Appendix A.1. □

First, because α_1^* and α_2^* intersect once at $\theta = \bar{\theta}$, the two jurisdictions can never prefer a quantity-restricted linkage simultaneously (relative to full linkage). Second, the range of relative bargaining powers over which the high-cost jurisdiction prefers a quantity-restricted link over full linkage is smaller than for the low-cost jurisdiction. This is so because the former gains relatively more from the full link than the latter. Third, optimal restrictions always authorize at least 50% of the full-link volume of transfers and that under monopoly power is more stringent than under monopsony power ($\alpha_2^*(0) < \alpha_1^*(1)$).

3.2 Linkage with border taxes on permit transfers

A border tax on interjurisdictional permit transfers corresponds to the dual link restriction of a quantitative limit. That is, to each tax rate there corresponds a unique authorized share of permit transfers and vice versa. While both instruments are formally equivalent in our deterministic framework (i.e., in terms of equilibrium characterization) they will nonetheless differ in their distributional aspects as well as political and linkage implications. In particular, the effects of a tax on permit imports (resp. exports) levied by jurisdiction 1 (resp. 2) can be assimilated to those of an equivalent quantitative restriction with $\theta = 1$ (resp. $\theta = 0$). Without loss of generality, consider that jurisdiction 1 imposes a proportional tax μ on 2-permit imports.[19] This tariff only concerns interjurisdictional transfers and there is no levy on domestic transactions.[20] The restricted equilibrium is defined by the triplet $(\bar{\tau}_1, \bar{\tau}_2, \bar{\Delta})$ and, depending on the dispersion in autarky prices, satisfies

$$(\bar{\tau}_1, \bar{\tau}_2, \bar{\Delta}) = \begin{cases} \left(\tau_1 - c_1\bar{\Delta}, (1-\mu)\bar{\tau}_1, \dfrac{(1-\mu)\tau_1 - \tau_2}{(1-\mu)c_1 + c_2}\right) & \text{if } \mu \in [0; 1 - \tau_2/\tau_1], \\ (\tau_1, \tau_2, 0) & \text{otherwise.} \end{cases} \tag{12}$$

Again, the situation is depicted in Figure 2. Equilibrium (12) is constrained to autarky if the tax rate is set at too high a level for given autarky prices. For instance, when $\tau_1 = 2\tau_2$ then the tax rate on permit imports should not exceed 50% for some transfers to occur. The border tax thus locates the restricted link outcome between autarky ($\mu \geq 1 - \tau_2/\tau_1$) and full linkage ($\mu = 0$). Cost efficiency does not obtain as the border tax is distortionary and the spread in jurisdictional prices is linearly proportional to the tax rate. Overall abatement is constant but some mutually beneficial transfers absent the tax do not take place ($\bar{\Delta} \leq \Delta^*$, where $\bar{\Delta}$ is decreasing with the tax rate). Relative to full linkage the increase in the permit price in 1 is less than the tax because part of it is passed on to 2 where the permit price declines. The magnitude of these price variations depends on relative jurisdictional abatement flexibilities.

However, there are two key crucial differences from quantitative restrictions. First, a border tax allows for trading of permits whose jurisdictional prices differ as jurisdiction 1 pays a markup on each 2-permit it imports. That is, jurisdictional permits are fungible. Second, a border tax raises revenues where a quantitative restriction generates a scarcity rent instead.

[19]The alternative situation where jurisdiction 2 imposes a tax μ on permit exports would also satisfy the tax restricted-linkage equilibrium in Equation (12) but with symmetric distributional aspects.

[20]Heindl et al. (2014) consider a bilateral link where one jurisdiction levies a domestic tax on intrajurisdictional emissions on top of the linked market price. Some abatement undertaken in this jurisdiction is thus attributable to this tax system, which undermines the price signal in the linked permit system.

Distributional aspects of the restriction are thus clearer. Relative to full linkage the imposition of a border tax by jurisdiction 1 is unambiguously detrimental to jurisdiction 2. This is attributable to impeded interjurisdictional trade (L_2) and diminished terms of trade (g). Although its economic gains from trade are reduced, jurisdiction 1 also raises tax revenues equal to $f + g$. That is, jurisdiction 1 is better off with the tax than under full linkage provided that $g > L_1$. This holds true for small tax rates and highlights the standard trade-off between the level of the tax rate (μ) and the width of the tax base ($\bar{\Delta}$).

Corollary 3.2. *The optimal tax rate on imports is $\mu^* = (c_1 - c_2)/(3c_1)$ and jurisdiction 1 is better off from the border tax regime than full linkage if $\mu \in [0; \bar{\mu}]$ where $\bar{\mu} > \mu^*$.*

Proof. Special case of Proposition 3.1 with $\theta = 1$. See also Appendix A.2. □

3.3 Linkage with exchange rates on relative permit values

We let $\rho > 0$ denote the rate at which emission reductions occurring in 1 are converted into emission reductions occurring in 2 through interjurisdictional exchange of permits. That is, one unit of abatement in 1 is worth ρ unit of abatement in 2. We define the linked market ρ-equilibrium by the following joint compliance cost minimization programme

$$\min_{(e_1,e_2)\in(0;\bar{e})^2} \Big\langle C_1(\bar{e} - e_1) + C_2(\bar{e} - e_2) \Big\rangle \text{ subject to } \rho e_1 + e_2 \leq (1+\rho)\omega. \tag{13}$$

We assume the aggregate constraint on emissions binds and let $\bar{\Delta}_i(\rho)$ denote the variation in emissions in jurisdiction i at the ρ-equilibrium relative to autarky. Market closure yields $\bar{\Delta}_2(\rho) = -\rho\bar{\Delta}_1(\rho)$ and the interior ρ-equilibrium is characterized by the necessary first-order condition

$$C_1'(\bar{e} - \omega - \bar{\Delta}_1(\rho)) = \rho C_2'(\bar{e} - \omega + \rho\bar{\Delta}_1(\rho)). \tag{14}$$

With quadratic abatement cost functions, abatement unit transfers from 2 to 1 satisfy

$$\bar{\Delta}_1(\rho) = \frac{\tau_1 - \rho\tau_2}{c_1 + \rho^2 c_2} \geq 0 \;\Leftrightarrow\; \rho \leq \tau_1/\tau_2. \tag{15}$$

There are two effects consecutive to the introduction of an exchange rate, namely fungibility of jurisdictional abatement units does not hold (emission conversion, or EC effect) and jurisdictional marginal abatement costs are adjusted for the exchange rate in equilibrium (MAC effect). First, for a given volume of interjurisdictional permit transfer, an exchange rate specifies a rate of conversion between emission reductions in 1 and 2, thereby changing overall abatement. Accounting for the sole EC effect, more or less overall abatement occurs in equilibrium relative to the benchmark. Second, the ratio of jurisdictional marginal abatement costs in equilibrium is determined by the exchange rate. Accounting for the sole MAC effect, an exchange rate induces a deadweight loss and modifies incentives for interjurisdictional abatement transfers in a fashion akin to a border tax.

Proposition 3.3. *Relative to full linkage, in any interior linked market ρ-equilibrium,*
(i) jurisdiction 1 raises emissions i.f.f. $\rho < 1$;
(ii) jurisdiction 2 reduces emissions i.f.f. $(\rho - 1)(\rho - \bar{\rho}) < 0$ with $\bar{\rho} \doteq \frac{c_1(\tau_1 - \tau_2)}{c_1\tau_2 + c_2\tau_1} \in (0; \tau_1/\tau_2)$;
(iii) the additional aggregate level of abatement satisfies $\gamma(\rho) \doteq (\rho - 1)\bar{\Delta}_1(\rho)$, which is positive i.f.f. $\rho \in (1; \tau_1/\tau_2)$ and maximal at $\rho = \hat{\rho} \doteq \sqrt{\tau_1/\tau_2}$ where $\gamma(\hat{\rho}) = \frac{a(\sqrt{c_1} - \sqrt{c_2})^2}{2\sqrt{c_1 c_2}}$.

Proof. Relegated to Appendix A.3. □

When parity does not hold, jurisdictional abatements are not equivalent and aggregate emissions vary as a result of interjurisdictional permit trading. We see from Equation (15) that permits flow in the natural direction provided that the exchange rate is smaller than the ratio of autarky prices. We also note from Equation (14) that cost efficiency obtains only under parity ($\rho = 1$) and that the (τ_1/τ_2)-equilibrium replicates autarky. Indeed, this exchange rate makes up for the autarky price wedge and there is no incentive to trade. These observations delineate three trading regimes depending on the value of the exchange rate w.r.t. parity (full linkage) and τ_1/τ_2 (autarky), whose relative properties are listed in Table 1.[21]

Table 1: Relative properties of the three trading regimes

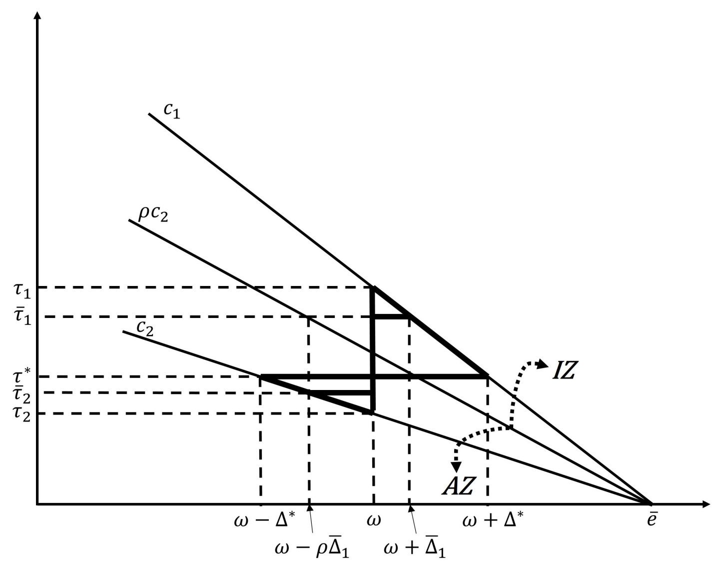
	Reduction zone	Amplification zone	Inversion zone
Relative permit value	J1>J2	J2>J1	J1≫J2
Permit flow	J1→J2	J1→J2	J2→J1
Overall abatement	higher than A/FL	lower than A/FL	lower than A/FL
Cost efficiency	higher than A lower than FL	higher than A† lower than FL	lower than A lower than FL
Emissions w.r.t. FL	J1: lower J2: higher i.f.f. $\rho > \bar{\rho}$	J1: higher J2: higher i.f.f. $\rho < \bar{\rho}$	J1: lower J2: higher
Permit prices	$\tau^* < \bar{\tau}_1 < \tau_1$; $\bar{\tau}_2 > \tau_2$ $\bar{\tau}_2 < \tau^*$ i.f.f. $\rho > \bar{\rho}$	$\bar{\tau}_1 < \tau^*$; $\bar{\tau}_2 > \tau_2$ $\bar{\tau}_2 < \tau^*$ i.f.f. $\rho < \bar{\rho}$	$\bar{\tau}_1 > \tau_1$ $\bar{\tau}_2 < \tau_2$
Gains from trade‡	$\bar{\Gamma}_1 > \bar{\Gamma}_2$ i.f.f. $\rho < \hat{\rho}$	$\bar{\Gamma}_1 > \bar{\Gamma}_2$	$\bar{\Gamma}_2 > \bar{\Gamma}_1$

Note: Ji: jurisdiction i; FL: full linkage; A: autarky; †: except for very small rates; ‡: not a welfare measure (only account for economic gains from permit trade and ignore shifts in overall emission levels).

[21] Lazarus et al. (2015) identify the three same trading zones but name them differently.

Reduction zone ($1 \leq \rho \leq \tau_1/\tau_2$). The dispersion in jurisdictional marginal abatement costs adjusted for the exchange rate is *reduced* and the conversion rate is favorable to jurisdiction 1. The linked market ρ-equilibrium is depicted in Figure 3. Controlling for the EC effect, this is conducive to less abatement transfers than is mutually beneficial under full linkage. Controlling for the MAC effect, the 1-permit value is inflated, i.e. the exchange rate reduces the demand for 2-permits in jurisdiction 1 while increasing the demand for 1-permits in both jurisdictions (but jurisdiction 2 remains the net permit exporter). Consequently, holding 2-permit imports constant, less emissions are allowed into jurisdiction 1 than under full linkage. In other words, holding abatement transfers constant, jurisdiction 2 undertakes more abatement (ρ-as-many). These two effects combined yield higher overall abatement relative to the benchmark. Relative to full linkage, jurisdiction 1 emits less while jurisdiction 2 may emit more ($\rho > \bar{\rho}$) or less ($\rho < \bar{\rho}$) but overall, total abatement increases.

Figure 3: Restricted linkage equilibrium in the reduction zone (with $\rho > \bar{\rho} > 1$)



Note: The two curved dotted arrows rotate the line of slope ρc_2 to the amplification zone (AZ) and the inversion zone (IZ) and point outside of the reduction zone represented by the hull $\langle \bar{e}c_2, \bar{e}c_1 \rangle$.

Amplification zone ($\rho \leq 1$). The dispersion in jurisdictional marginal abatement costs adjusted for the exchange rate is *amplified* and the conversion rate is favorable to jurisdiction 2. Controlling for the EC effect, this leads to more exchanges of abatement than under full linkage. Controlling for the MAC effect, the 1-permit value is deflated. Permits keep on flowing in the natural direction but since one 2-permit is worth ρ-as-many 1-permit more emissions occur overall. These two effects combined yield less aggregate abatement than in the benchmark. Relative to full linkage, jurisdiction 1 emits more while jurisdiction 2 may emit more ($\rho < \bar{\rho}$) or less ($\bar{\rho} < \rho$) but overall, total abatement decreases.

Inversion zone ($\rho > \tau_1/\tau_2$). The dispersion in jurisdictional marginal abatement costs adjusted for the exchange rate is *inverted* and the conversion rate is favorable to jurisdiction 1 (even more so than in the reduction zone). The exchange rate sufficiently reduces the demand for 2-permits in jurisdiction 1 and increases the demand for 1-permits in both jurisdictions for jurisdiction 1 to become the net permit exporter. This regime is less cost efficient than autarky since abatement occurs where it is most expensive. Relative to autarky, jurisdiction 1 (resp. 2) abates (resp. emits) more. Since the exchange rate inflates the 1-permit value, this results in aggregate emissions higher than in the benchmark.

Note that aggregate gains from trade no longer reflect gains in cost efficiency since overall abatement varies with the exchange rate. Loosely speaking, the more distant ρ from parity, the bigger the dispersion in jurisdictional marginal abatement costs at the ρ-equilibrium and the lower the degree of cost efficiency.[22] An exchange rate affects both the size of the aggregate gains from trade and its repartition across jurisdictions in the following manner

$$\bar{\Gamma}_1(\rho) + \bar{\Gamma}_2(\rho) = \frac{(\tau_1 - \rho\tau_2)^2}{2\,(c_1 + \rho^2 c_2)} \text{ with } \bar{\Gamma}_1(\rho)/\bar{\Gamma}_2(\rho) = c_1/(c_2\rho^2). \tag{16}$$

Aggregate gains from trade decrease with ρ as long as $\rho \leq \tau_1/\tau_2$, are nil at $\rho = \tau_1/\tau_2$ and increase with ρ thereafter. In addition, jurisdiction 1 (resp. 2) gets a higher share of these gains when $\rho \leq$ (resp. $\geq$)$\hat{\rho}$, i.e. jurisdiction 1 (resp. 2) wants the exchange rate to be as low (resp. high) as possible. This line of reasoning, however, does not account for the attendant variation in aggregate emissions. In Appendix C we show that factoring in this shift in emissions mitigates jurisdictions preferences for too high or too low rates. Here, we illustrate the flexibility in overall emissions with the following special case.

Corollary 3.4. *The two jurisdictions are better off under full linkage with adjusted caps* $(\omega_1, \omega_2) = (\omega, \omega - \gamma(\hat{\rho}))$ *than under* $\hat{\rho}$*-equilibrium with initial caps* $(\omega_1, \omega_2) = (\omega, \omega)$.

Proof. Relegated to Appendix A.3. □

A possible interpretation is that exchange rates have potential to increase environmental ambition over time. Consider that jurisdictions initiate linkage with an exchange rate that triggers additional abatement relative to autarky. All else equal, both jurisdictions then have an incentive to transition to full linkage with domestic caps adjusted so as to generate overall abatement commensurate with that under the exchange rate.

[22] Gains in liquidity should be similar to those under full linkage because permits are fungible.

4 Policy discussion and comparative analysis

We take our modelling exercise as a basis for a policy discussion on the comparative merits and political feasibility of each type of link restriction. We further draw on real-world experiences with emissions trading, linking and trade restrictions. In order to both accommodate these and enrich the discussion, we will, at times, slightly deviate from the simple modelling framework of Section 3. For starters, Figure 4 is helpful in displaying the comparative effects of link restrictions in the overall-abatement−cost-efficiency space relative to autarky. Details on the calibration and additional numerical illustrations can be found in Appendix B.

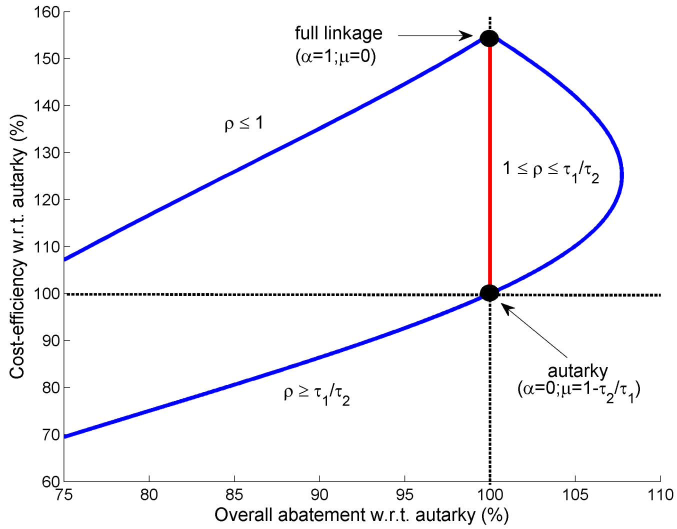
In Figure 4 the red line describes the economic (and fixed environmental) outcomes along the continuum of quantitative restrictions and border taxes. The blue curve depicts relative cost efficiency as a function of relative overall abatement along the continuum of exchange rates. It delineates the reduction zone in the upper-right quadrant, the amplification zone in the upper-left quadrant and the inversion zone in the lower-left quadrant. In essence, Figure 4 clearly shows that both quantitative restrictions and border taxes affect cost efficiency but preserve overall abatement while exchange rates have an impact along these two dimensions. We now enhance the comparison and consider each restriction in turn.

4.1 Quantitative transfer restrictions

Under a quantitative restriction transfers are restricted up to the authorized limit if binding; if not, full linkage should obtain. Thus, because transfers are confined within a predefined range a quantitative restriction is an attractive instrument if jurisdictions seek to have a direct handle on the quantity-side consequences of a link and retain a certain degree of oversight over their domestic systems. On the one hand, a high-price environmentally-inclined jurisdiction may wish to limit imports to avoid those link-induced consequences potentially pitting the economic gains from linkage against broader environmental or equity concerns. This would ensure that a certain volume of abatement occurs domestically (e.g., ancillary benefits, reputational aspects) or assuage fears about over-allocation in exporting jurisdictions that could dilute domestic ambition. On the other hand, a low-price jurisdiction may desire to limit exports in a bid to contain the link-induced price rise.

That said, some implications of quantitative restrictions are not as straightforward as they seem to be on the face of it. This is attributable to the coexistence of different price signals and undetermined transaction prices. Since one permit may have two distinct prices whether

Figure 4: Comparative effects of the three link restrictions relative to autarky



it is sold domestically ($\bar{\tau}_i(\alpha)$) or abroad ($\bar{\tau}(\alpha;\theta)$) quantitative restrictions may create perverse incentives for firms to make profits on secondary markets that are disconnected from abatement-related fundamentals. This might lead to purely speculative trades and contribute to the financialization of the market. A related issue is the existence of a scarcity rent whose apportionment among firms is not clear ex ante.

Some mechanisms may be devised to allocate the rent between firms, thereby mitigating these uncertain distributional effects. For instance, restrictions could be formulated at the firm level, e.g. as a percentage of firms' individual compliance obligations. Alternatively, authorities could issue a certain number of trade licenses and require that firms attach, say, one license to each foreign permit they surrender for domestic compliance. Because the rent distribution may serve as a negotiation lever, linkage can be facilitated if jurisdictions are able to agree on how to allocate these licenses among them. While this parallel license market may offer a better management of the distributional aspects of the restricted link it does not determine how transaction license prices are fixed and, ultimately, the share of the total rent one can extract.[23] Additionally, administrative and transaction costs associated with setting up and running this parallel market might shrink the gross benefits of linkage. However, finally note that hybrid approaches where licenses are auctioned off may limit these costs and redirect the rent from the firms to the regulatory authorities.[24]

[23]Indeed, when the restriction is binding, the license price is also determined by Equation (8).

[24]Like a border tax, note that fixed-price licenses may solve the issue of undetermined transaction prices.

Under conditions of uncertainty, note that a restriction that turns out to be non-binding ex post might still affect permit trading and price formation. For instance, Gronwald & Hintermann (2016) provide evidence that the probability of non-bindingness of the usage quota on Kyoto credits affects the offset-permit price spread in the EUETS. In this respect, a relatively stringent restriction has joint potential to bring about an important share of the full-link aggregate economic gains, effectively contain the reach of the link as well as reduce uncertainty about its bindingness and related impact on price formation. However they may maintain a relatively wide price wedge and thus a wide range over which prices can vary. By contrast, a relatively lax restriction reduces this wedge but would risk sustaining uncertainty relative to its bindingness and not protecting from the full-link effects.

As a transitory linkage mechanism, quantity restrictions seem to be the natural route to gradually allow for unlimited trading between two quantity instruments. However, the ratio of jurisdictional shadow prices is undetermined ex ante, hard to infer ex post and transaction prices may fluctuate independently of abatement-related fundamentals. Permit prices may thus no longer reflect jurisdictional marginal abatement costs, which is essential information in both assessing and transitioning to a full link.

4.2 Border taxes on permit transfers

Although there is a bijection between price and quantity restrictions in terms of equilibrium characterization, distributional and other link-related effects of the two restrictions differ. Because the ratio of jurisdictional prices is fixed by the tax rate, price signals better reflect marginal abatement costs, which is key information in the perspective of a full link. Moreover, a border tax raises revenues. That is, authorities have a better handle on the distributional effects of their policy as compared to quantitative restrictions which generate scarcity rents whose distribution is unclear a priori.[25] Controlling for the deadweight loss, a border tax operates an interjurisdictional surplus transfer. In other words, taxes have a redistributive potential that may serve as leverage to foster and spur linkage negotiations.[26]

Under conditions of uncertainty, the dual property between price and quantity restrictions would vanish (Weitzman, 1974). In practice, this relates to the comparative advantage of having a fixed level of permit transfers with a variable ratio of jurisdictional prices versus a fixed price ratio and variable permit transfers. Note that because a border tax concerns

[25] Note that unless tax revenues are redistributed to firms, they will always be worse off as a result of the tax-restricted link relative to full linkage and might thus voice opposition.

[26] They can be seen as surrogates for otherwise politically unpalatable lump-sum transfers (Victor, 2015).

permit prices the link equilibrium will always be affected and potentially brought to autarky if the rate is set at too high a level. By contrast, quantitative restrictions may turn out to be non-binding (even though this would still bear on price formation).

As a transitory linkage mechanism, border taxes may be more seamless than quantitative restrictions both in informing a full-link scaling-up and managing associated distributional aspects. Note that small tax rates generate a sizeable share of the full-link gains but do not reduce much of its effects. Conversely, too high a tax rate risks turning out to be detrimental (w.r.t. full linkage) even for the jurisdiction that collects revenues. Finally note a border tax is a fiscal policy and might thus be relatively more complicated to pursue legislatively speaking than a quantity-based approach, for instance in the EU.[27]

4.3 Linkage with exchange rates

As with a border tax an exchange rate sets the ratio of jurisdictional marginal abatement costs (MAC effect). Additionally, it also modifies the one-for-one compliance value of jurisdictional permits, i.e. jurisdictional abatement efforts are not equivalent (EC effect). As noted by Burtraw et al. (2013), exchange rates thus have potential to adjust for programmes' stringencies even though cost-efficiency is reduced.[28] Note that taking this line of reasoning to its logical extreme (i.e., $\rho \sim \tau_1/\tau_2$) would conduce the link to resemble autarky. Additionally, an exchange rate may also serve as a means to accommodate other economic criteria or types of political and environmental preferences.[29]

Cost efficiency may be higher or lower than under autarky but is always be lower than under full linkage. Moreover, aggregate emissions vary as a result of interjurisdictional trading due to the EC effect. In particular, the volume of unit transfers can increase, decrease or even be reversed relative to full linkage. As compared to autarky, the aggregate implications of an exchange rate in both economic and environmental terms could therefore happen to be beneficial (reduction zone) as well detrimental (inversion zone). In loose terms, the reduction zone is likely to be targeted by regulators. In particular, if they prioritize environmental

[27] Indeed, pursuant to Article 192 §2 of the Lisbon Treaty (2007), policies that are deemed to be 'primarily of a fiscal nature' require unanimity between Member States to be enacted. Additionally, we note the indirect but related concern about WTO-compatibility voiced in the broader case of border (tax) adjustments.

[28] Burtraw et al. (2013) implement a 3-for-1 rate in linking California and RGGI (one CCA is worth three RGAs) arguing that this «provides a rough adjustment for the relative stringencies of the two programmes but reduces the opportunities for cost savings from shifting CO_2 emissions from RGGI to California». Note that this reverses the natural direction of abatement flows, i.e. the 3-for-1 rate belongs to the inversion zone.

[29] Exchange rates could adjust for discrepancies in permits' mitigation value. In this respect, see the documentation provided under the auspices of the World Bank's Globally Networked Carbon Markets Initiative.

outcomes they should aim for a rate close to $\hat{\rho}$. If, instead, they wish to increase liquidity without bearing much of the other effects of a full link, they should set ρ close to τ_1/τ_2.

Under conditions of uncertainty, however, selecting an exchange rate is likely to prove difficult and can have unintended, possibly detrimental, consequences. The difficulty is indeed twofold. First, due to ex-ante uncertainty about programmes' actual stringencies (hence autarky prices) it is complicated to select the rate right in the first place.[30] Second, it is also challenging to duly adjust the rate ex post since autarky prices that would have prevailed absent the link restriction are not directly observable. Although counterfactual autarky prices could be constructed, it could only be so with a lag of one compliance period at best. The risk of error and detrimental outcomes (e.g., associated with the inversion zone) in selecting the policy handle is higher than for the other two restrictions, whose associated outcomes are always confined within autarky and full linkage.

As a transitory linkage mechanism, an exchange rate has potential to increase environmental ambition over time when emissions cap diminution is not directly feasible. Indeed, penalized schemes have an incentive to raise domestic ambition provided that their abatement units become (gradually) traded with parity. In fact, Corollary 3.4 shows that it is in the interest of each party. We also note that since an exchange rate does not induce explicit rents, the transition to a full link may be easier than for the other two restrictions.

4.4 Two special cases of link restrictions

We now dicuss two additional restrictions, namely unilateral linkage and discount rates, as special cases of quantitative restrictions and exchange rates, respectively.

Unilateral (or conditional) linkage. Unilateral linkage is a special case of quantitative restrictions whereby entities in one jurisdiction can surrender foreign permits for domestic compliance but not the other way around. Should the unilateral link be established in the natural direction of trade its implications would closely resemble those of a full link save for the non-fungibility of permits. Conversely, it may also be that the unilateral link is not active, i.e. an autarky-like situation persists, as attests the so far inactive unilateral integration of the European aviation sector into the EUETS as of 2012. Unilateral linkage is thus of a conditional nature, which may incite jurisdictions to increase ambition.[31] Additionally, uni-

[30] This issue is somewhat mitigated if markets to be linked are already in operation as historical price levels can help guide the selection of the exchange rate.

[31] Imagine a unilateral link between a 'high-ambition' system A and a 'low-ambition' system B whereby only A can purchase B-units. In this sense, full linkage is conditional on B increasing ambition. Also note

lateral linkage can mitigate price uncertainty and distributional aspects (there is no scarcity rent) associated with quantitative restrictions.

Both the Norway-EU and aborted Australia-EU unilateral links were envisaged as initial, transitory steps toward fully-fledged links. During Phase I of the EUETS and until the extension of the EUETS to EEA-EFTA countries by late 2007, Norwegian firms could surrender European permits (EUAs) domestically but not vice versa.[32] This one-way link originated in a unilateral decision on the part of Norway to help prepare for full integration to the EUETS, e.g. gradual market design alignment. In mid-2012 Australia and the EU Commission agreed to link up their domestic ETSs following a two-step process whereby Australia would first be unilaterally linked to the EU (EUAs recognized in Australia, but not vice versa) before the link would become two-way 3 years later. For compatibility with the EUETS, each of these two steps were to contingent upon gradual design adjustments in Australia.[33]

These two experiences indicate that unilateral links (*i*) can be established pursuant to unilateral or joint decisions; (*ii*) do not require market designs to be as much aligned as for bilateral links; (*iii*) may help initiate linkage while giving more time to bring schemes into sufficient alignment deemed necessary for bilateral links to be established seamlessly.

The elaboration of the RECLAIM programme also underlines the practical merits of unilateral linkage.[34] To take spatial factors into account the Los Angeles air basin was initially divided into 38 zones without interzonal permit trading. This would have massively reduced gains from using a market-based policy relative to command-and-control approaches. One alternative was to create a single market with trading ratios accounting for spatial discrepancies but quantification of these ratios proved complicated and the resulting scheme altogether would have been cumbersome and unworkable. The final programme solely comprised two geographical zones (upwind sources, located near the coast and contributing more to elevated ozone levels and downwind sources, located inland) with interzonal trading allowed only from upwind to downwind sources (Tietenberg, 1995; Fromm & Hansjürgens, 1996).

that the unilateral link constitutes a soft price floor for system A.

[32]Only one EUA transaction was recorded and the price for Norwegian permits was well below the price of CERs (Mehling & Haites, 2009) and the unilateral link can be seen as a de facto soft price ceiling.

[33]For instance, Australia committed to gradually scrap its price floor and ceiling. See Jotzo & Betz (2009) for more details on the compatibility between the EUETS and Australia Carbon Pricing Mechanism (CPM). Although linkage negotiations were conducted pursuant to Article 25 of the EUETS Directive concessions pertaining to design alignment were exclusively envisaged on the Australian side of the link because Europe had more political weight and thus 'design pull'. The project of an intercontinental link between Australia and Europe stalled when the CPM was officially repealed in mid-2014.

[34]The REgional CLean Air Incentives Market was launched in 1994 to regulate ozone (a non-uniformly mixed pollutant) levels in the Los Angeles basin. Environmental objectives were reached (without hot spots) and compliance costs were reduced w.r.t. command-and-control approaches (Fowlie et al., 2012).

Discount rates. Discount rates are the unilateral version of exchange rates. That is, when jurisdiction A applies a given conversion ratio to B-permits, B need not impose a conversion ratio to A-permits that is equal to the inverse of the former. Therefore, discount rates may be asymmetrical, i.e. of different magnitudes depending on the direction of trade. When the differential in autarky prices surpasses the discount rate its implications are similar to those of an equivalent exchange rate (same EC and MAC effects) but full permit fungibility does not obtain. As noted by Lazarus et al. (2015) this asymmetry may have potential to overcome some challenges inherent to exchanges rates. First, discount rates need not be mutually agreed upon so that jurisdictions can maintain relatively more flexibility in selecting and adjusting the discount rates they use. Second, if both jurisdictions were to implement discount rates higher than unity on inflowing foreign permits, then, whatever the realized direction of the permit flow, overall abatement and cost efficiency would increase relative to autarky, which is congruent with the 'desirable' characteristics of the reduction zone.

5 Conclusion

We compare various restrictions on permit trading in the context of a bilateral link between ETSs in gradually approaching unrestricted, full linkage. Restricted linkage creates a trade-off between eliminating some impediments to full linkage and undermining a fundamental reason for linking in the first place (i.e., cost efficiency) which justifies a temporary use of restrictions moving toward unrestricted linkage. This trial phase may allow to test the effects of the link and, by limiting its reach, assuage some of the induced effects and perceived risks. This also gives more time and flexibility for partners to reconcile their policy differences and bring their respective schemes further into alignment for a full link to be established seamlessly. A few years down the road, partners may decide to scale up the link. Otherwise, should trial not be conclusive the link may need to be severed.[35]

We tried to keep the model as simple as possible to have a clear, unifying framework which, in conjunction with lessons from real-world experiences, served as a basis for a less formal, policy-oriented discussion of comparative advantages and weaknesses of link restrictions. On the face of it, quantitative restrictions seem to be the most implementation-friendly route to a full link between quantity instruments. In particular, they provide a direct quantity handle on the reach of the link. However, there is uncertainty about price formation and the distribution

[35] Restriction-induced rents may not incentivize recipients for a full-link rollout. It should thus be clear on both sides (or ideally spelt out in the linkage agreement) that the use of restrictions is only temporary.

of the scarcity rent, which may impair the transition to a full link. These aspects are mitigated with a border a tax, which should ensure a better management of distributional outcomes, less undesirable price fluctuations and better information on jurisdictional marginal abatement costs. Exchange rates can be used to correct for discrepancies in programmes' stringencies and have potential to increase ambition over time. However, they can be challenging to select and adjust, which might lead detrimental outcomes.

In order to hammer out a linkage agreement as workable and wieldy as possible, regulators can pick the instrument (or combination thereof) that best assuages dominant link-related risks and fits the negotiation and domestic contexts. As experience corroborates, transitory unilateral linkage may well strike a good balance between the 'ideal' and the 'practical' in translating economic theory into specific policy design elements.[36] In addition, the insights gained in this simple framework can help evaluate the effects of trade restrictions as proposed in the context of networked ETSs. An recent example is the ICAR Platform proposed by Füssler et al. (2016), which provides a structure to which ETSs may dock on a voluntary basis contingent upon their meeting a set of predefined requirements. Docked ETSs retain some discretion in the form of unilateral imposition of both quantitative restrictions on permit outflows and inflows as well as qualitative restrictions (e.g., discount rates) de facto assigning relative compliance values assigned to foreign permits.

Finally, we offer two alleys for future research. First, although we treat jurisdictions as monolithic entities and abstract from intrajurisdictional distributional issues, we stress that this deserves more attention.[37] Relatedly, the way restricted linkage affects firms and other jurisdictional constituencies will certainly shape regulators' room for maneuver in selecting and implementing restrictions. Note also that different regimes of revenue recycling can have important implications in assessing link restrictions as is the case with first-best instrument selection (Pezzey & Jotzo, 2012). Second, while our model is static, we note that each link restriction should distort firms' intertemporal decisions differently. For instance, Pizer & Yates (2015) compare how different rules for the treatment of banked permits in the context of a (possible) future delinking alter present price formation and cost effectiveness. Relatedly, in a strategic framework, letting jurisdictions bargain over future linking rules (e.g., restrictions) rather than domestic caps may spur cooperation through linkage.[38]

[36] This echoes the words of Tietenberg (2006) that «in practice, one common approach to resolving spatial concerns involves a system of directional trading».

[37] Moreover, recent contributions underline that taking regulators to act as single, social welfare maximizing entities may constitute an oversimplification (Habla & Winkler, 2017; Marchiori et al., 2017).

[38] Similarly, Açıkgöz & Benchekroun (2017) analyze the anticipatory non-cooperative responses of signatories to various exogenously-given types of climate agreements to be implemented in the future.

References

Açıkgöz, Ö. T. & Benchekroun, H. (2017). Anticipated International Environmental Agreements. *European Economic Review*, **92**, 306–36.

Bernstein, P. M., Montgomery, W. D., Rutherford, T. F. & Yang, G.-F. (1999). Effects of Restrictions on International Permit Trading: The MS-MRT Model. *The Energy Journal*, **20**, 221–56.

Bodansky, D. M., Hoedl, S. A., Metcalf, G. E. & Stavins, R. N. (2016). Facilitating Linkage of Climate Policies Through the Paris Outcome. *Climate Policy*, **16**(8), 956–72.

Bollen, J., Gielen, A. & Timmer, H. (1999). Clubs, Ceilings and CDM: Macroeconomics of Compliance with the Kyoto Protocol. *The Energy Journal*, **20**, 177–206.

Bovenberg, A. L. & Goulder, L. H. (1996). Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses. *American Economic Review*, **86**(4), 985–1000.

Braun, N., Fitzgerald, T. & Pearcy, J. (2015). Tradable Emissions Permits with Offsets. In B. Hintermann & M. Gronwald (eds.) *Emissions Trading as a Policy Instrument: Evaluation and Prospects*, chapter 10, (pp. 239–66). MIT Press.

Burtraw, D., Palmer, K. L., Munnings, C., Weber, P. & Woerman, M. (2013). *Linking by Degrees: Incremental Alignment of Cap-and-Trade Markets*. Discussion Paper 13-04, Resources for the Future.

Carbone, J. C., Helm, C. & Rutherford, T. F. (2009). The Case for International Emission Trade in the Absence of Cooperative Climate Policy. *Journal of Environmental Economics & Management*, **58**(3), 266–80.

Criqui, P., Mima, S. & Viguier, L. (1999). Marginal Abatement Costs of CO_2 Emission Reductions, Geographical Flexibility and Concrete Ceilings: An Assessment using the POLES Model. *Energy Policy*, **27**(10), 585–601.

Ellerman, A. D. & Sue Wing, I. (2000). Supplementarity: An Invitation to Monopsony? *The Energy Journal*, **21**(4), 29–59.

Eyckmans, J. & Kverndokk, S. (2010). Moral Concerns on Tradable Pollution Permits in International Environmental Agreements. *Ecological Economics*, **69**(9), 1814–23.

Fankhauser, S. & Hepburn, C. (2010). Designing Carbon Markets, Part II: Carbon Markets in Space. *Energy Policy*, **38**(8), 4381–7.

Feng, H. & Zhao, J. (2006). Alternative Intertemporal Permit Trading Regimes with Stochastic Abatement Costs. *Resource & Energy Economics*, **28**(1), 24–40.

Flachsland, C., Marschinski, R. & Edenhofer, O. (2009). To Link or Not To Link: Benefits and Disadvantages of Linking Cap-and-Trade Systems. *Climate Policy*, **9**(4), 358–72.

Forner, C. & Jotzo, F. (2002). Future Restrictions for Sinks in the CDM: How about a Cap on Supply? *Climate Policy*, **2**(4), 353–65.

Førsund, F. R. & Nævdal, E. (1998). Efficiency Gains under Exchange-Rate Emission Trading. *Environmental & Resource Economics*, **12**(4), 403–23.

Fowlie, M., Holland, S. P. & Mansur, E. T. (2012). What Do Emissions Markets Deliver and to Whom? Evidence from Southern California's NOx Trading Program. *American Economic Review*, **102**(2), 965–93.

Fowlie, M. & Muller, N. (2017). *Market-Based Emissions Regulation when Damages Vary across Sources: What are the Gains from Differentiation?* Working Paper 18801, National Bureau of Economic Research.

Fromm, O. & Hansjürgens, B. (1996). Emission Trading in Theory and Practice: An Analysis of RECLAIM in Southern California. *Environment & Planning C: Government & Policy*, **14**(3), 367–84.

Füssler, J., Wunderlich, A. & Taschini, L. (2016). *International Carbon Asset Reserve: Prototyping for Instruments Reducing Risks and Linking Carbon Markets*. Final Report, The World Bank Group − Networked Carbon Markets, INFRAS: Zürich/London.

Gavard, C., Winchester, N. & Paltsev, S. (2016). Limited Trading of Emissions Permits as a Climate Cooperation Mechanism? US-China and EU-China Examples. *Energy Economics*, **58**, 95–104.

Gronwald, M. & Hintermann, B. (2016). *Explaining the EUA-CER Spread*. Working Paper 5795, CESifo.

Grüll, G. & Taschini, L. (2012). Linking Emission Trading Schemes: A Short Note. *Economics of Energy* & *Environmental Policy*, **1**(3), 31–8.

Habla, W. & Winkler, R. (2017). *Strategic Delegation and International Permit Markets: Why Linking May Fail*. Working Paper 6515-2017, CESifo.

Hahn, R. W. (1984). Market Power and Transferable Property Rights. *Quarterly Journal of Economics*, **99**(4), 753–65.

Heindl, P., Wood, P. J. & Jotzo, F. (2014). *Combining International Cap-and-Trade with National Carbon Taxes*. CCEP Working Paper 1418, Crawford School of Public Policy, The Australian National University.

Helm, C. (2003). International Emissions Trading with Endogenous Allowance Choices. *Journal of Public Economics*, **87**(12), 2737–47.

Holland, S. P. & Yates, A. J. (2015). Optimal Trading Ratios for Pollution Permit Markets. *Journal of Public Economics*, **125**, 16–27.

Holt, C. A. & Shobe, W. M. (2016). Price and Quantity Collars for Stabilizing Emission Allowance Prices: Laboratory Experiments on the EUETS Market Stability Reserve. *Journal of Environmental Economics & Management*, **80**, 69–86.

ICAP (2017). *Status Report 2017*. Berlin: International Carbon Action Partnership.

Innes, R. (2003). Stochastic Pollution, Costly Sanctions, and Optimality of Emission Permit Banking. *Journal of Environmental Economics & Management*, **45**(3), 546–68.

Jaffe, J., Ranson, M. & Stavins, R. N. (2009). Linking Tradable Permit Systems: A Key Element of Emerging International Climate Change Architecture. *Ecology Law Quarterly*, **36**(4), 789–809.

Jotzo, F. & Betz, R. (2009). Australia's Emissions Trading Scheme: Opportunities and Obstacles for Linking. *Climate Policy*, **9**(4), 402–14.

Keohane, N., Petsonk, A. & Hanafi, A. (2015). Toward a Club of Carbon Markets. *Climatic Change*, 1–15.

Krupnick, A. J., Oates, W. E. & Verg, E. V. D. (1983). On Marketable Air-Pollution Permits: The Case for a System of Pollution Offsets. *Journal of Environmental Economics & Management*, **10**(3), 233–47.

Lazarus, M., Schneider, L., Lee, C. & van Asselt, H. (2015). *Options and Issues for Restricted Linking of Emissions Trading Systems*. Prepared by the Stockholm Environment Institute, International Carbon Action Partnership, Berlin, Germany.

Leiby, P. & Rubin, J. (2001). Intertemporal Permit Trading for the Control of Greenhouse Gas Emissions. *Environmental & Resource Economics*, **19**(3), 229–56.

Lipsey, R. G. & Lancaster, K. (1956). The General Theory of Second Best. *Review of Economic Studies*, **24**(1), 11–32.

Liu, X. (2010). Extracting the Resource Rent from the CDM Projects: Can the Chinese Government Do Better? *Energy Policy*, **38**(2), 1004–9.

Marchiori, C., Dietz, S. & Tavoni, A. (2017). Domestic Politics and the Formation of International Environmental Agreements. *Journal of Environmental Economics & Management*, **81**, 115–31.

Marschinski, R., Flachsland, C. & Jakob, M. (2012). Sectoral Linking of Carbon Markets: A Trade-Theory Analysis. *Resource & Energy Economics*, **34**(4), 585–606.

Mehling, M. A. & Görlach, B. (2016). *Multilateral Linking of Emissions Trading Systems*. Working Paper 2016-009, MIT Center for Energy and Environmental Policy Research.

Mehling, M. A. & Haites, E. (2009). Mechanisms for Linking Emissions Trading Schemes. *Climate Policy*, **9**(2), 169–84.

Mendelsohn, R. (1986). Regulating Heterogeneous Emissions. *Journal of Environmental Economics & Management*, **13**(4), 301–12.

Montgomery, W. D. (1972). Markets in Licenses and Efficient Pollution Control Programs. *Journal of Economic Theory*, **5**(3), 395–418.

Muller, N. Z. & Mendelsohn, R. (2009). Efficient Pollution Regulation: Getting the Prices Right. *American Economic Review*, **99**(5), 1714–39.

Naegele, H. (2015). *Offset Credits in the EUETS: A Quantile Estimation of Firm-Level Transaction Costs*. Discussion Paper 1513, DIW Berlin.

Nash, J. F. J. (1950). The Bargaining Problem. *Econometrica*, **18**(2), 155–62.

Newell, R. G. & Stavins, R. N. (2003). Cost Heterogeneity and the Potential Savings from Market-Based Policies. *Journal of Regulatory Economics*, **23**(1), 43–59.

Pezzey, J. C. & Jotzo, F. (2012). Tax-versus-Trading and Efficient Revenue Recycling as Issues for Greenhouse Gas Abatement. *Journal of Environmental Economics & Management*, **64**(2), 230–6.

Pizer, W. A. & Yates, A. J. (2015). Terminating Links Between Emission Trading Programs. *Journal of Environmental Economics & Management*, **71**, 142–59.

Ranson, M. & Stavins, R. N. (2016). Linkage of Greenhouse Gas Emissions Trading Systems:

Learning from Experience. *Climate Policy*, **16**(3), 284–300.

Rehdanz, K. & Tol, R. S. (2005). Unilateral Regulation of Bilateral Trade in Greenhouse Gas Emission Permits. *Ecological Economics*, **54**(4), 397–416.

Sterk, W., Braun, M., Haug, C., Korytarova, K. & Scholten, A. (2006). *Ready to Link Up? Implications of Design Differences for Linking Emissions Trading Schemes*. Working Paper 1-06, Wuppertal Institute for Climate, Environment and Energy.

Tiche, F. G., Weishaar, S. E. & Couwenberg, O. (2016). *Carbon Market Stabilisation Measures: Implications for Linking*. Working Paper 2016-011, MIT Center for Energy and Environmental Policy Research.

Tietenberg, T. (1995). Tradeable Permits for Pollution Control when Emission Location Matters: What Have We Learned? *Environmental & Resource Economics*, **5**(2), 95–113.

Tietenberg, T. (2006). *Emissions Trading: Principles & Practice*. Washington, DC: Resources for the Future Press, second edition.

Trotignon, R. (2012). Combining Cap-and-Trade with Offsets: Lessons from the EUETS. *Climate Policy*, **12**(3), 273–87.

Tuerk, A., Mehling, M., Flachsland, C. & Sterk, W. (2009). Linking Carbon Markets: Concepts, Case Studies and Pathways. *Climate Policy*, **9**(4), 341–57.

Victor, D. G. (2015). *The Case for Climate Clubs*. Policy paper, E15Initiative (International Centre for Trade and Sustainable Development & World Economic Forum).

Weitzman, M. L. (1974). Prices *vs.* Quantities. *Review of Economic Studies*, **41**(4), 477–91.

Westskog, H. (2002). Why should Emissions Trading be Restricted? *Climate Policy*, **2**(1), 97–103.

Yates, A. J. & Cronshaw, M. B. (2001). Pollution Permit Markets with Intertemporal Trading and Asymmetric Information. *Journal of Environmental Economics & Management*, **42**(1), 104–18.

Zhu, J. (2014). Assessing China's Discriminative Tax on Clean Development Mechanism Projects: Does China's Tax Have so Many Functions? *Journal of Environmental Planning & Management*, **57**(3), 447–66.

Appendices & Supplemental Material

A Analytical derivations and collected proofs

A.1 Quantity-restricted linkage

Let $\alpha \in [0;1]$ be the authorized share of interjurisdictional abatement transfers relative to full linkage. In the constrained link, jurisdiction 1 (resp. 2) abates $a - \alpha\Delta^*$ (resp. $a + \alpha\Delta^*$) and the equilibrium marginal abatement cost is $\bar{\tau}_1(\alpha) = c_1(a - \alpha\Delta^*)$ (resp. $\bar{\tau}_2(\alpha) = c_2(a + \alpha\Delta^*)$). Note also that $\bar{\tau}_1(\alpha) - \bar{\tau}_2(\alpha) = (1-\alpha)(\tau_1 - \tau_2)$ and that $|\tau_i - \bar{\tau}_i(\alpha)| = c_i\alpha\Delta^*$, for $i = \{1, 2\}$. The scarcity rent S, the deadweight loss L and jurisdictional economic gains from trade $\bar{\Gamma}_i$ then obtain from simple area computations (e.g., from Figure 2), that is

$$S(\alpha) = \alpha\Delta^*(\bar{\tau}_1(\alpha) - \bar{\tau}_2(\alpha)) = \Delta^*(\tau_1 - \tau_2)\alpha(1-\alpha), \tag{A.1a}$$

$$2L(\alpha) = (1-\alpha)\Delta^*(\bar{\tau}_1(\alpha) - \bar{\tau}_2(\alpha)) = \Delta^*(\tau_1 - \tau_2)(1-\alpha)^2, \tag{A.1b}$$

$$2\bar{\Gamma}_i(\alpha) = \alpha\Delta^*|\tau_i - \bar{\tau}_i(\alpha)| = c_i\Delta^{*2}\alpha^2. \tag{A.1c}$$

The scarcity rent S is increasing (resp. decreasing) in α for $\alpha \leq$(resp. $\geq$)1/2. The deadweight loss L is decreasing in α at a decreasing rate. Jurisdictional economic gains $\bar{\Gamma}_i$ are increasing in α less than linearly but at an increasing rate. Addintionally, note that

$$S(\alpha) \geq \bar{\Gamma}_1(\alpha) + \bar{\Gamma}_2(\alpha) \Leftrightarrow \tau_1 - \tau_2 \leq 3(\bar{\tau}_1(\alpha) - \bar{\tau}_2(\alpha)) \Leftrightarrow \alpha \leq 2/3. \tag{A.2}$$

That is, the size of the scarcity rent relative to that of the economic gains from trade accruing to jurisdictions is significant for a wide range of quantitative restrictions. The way the rent is apportioned among jurisdictions is thus of political importance in terms of linkage design. Finally note that since overall abatement is constant the degree of cost-efficiency relative to full linkage can be measured by the ratio of the total surplus under the restriction α to the total surplus under full linkage, which is given by the index

$$I(\alpha) \doteq \frac{\Gamma_1^* + \Gamma_2^* - L(\alpha)}{\Gamma_1^* + \Gamma_2^*} = \frac{\alpha\Delta^*(\tau_1 + \bar{\tau}_1(\alpha) - (\tau_2 + \bar{\tau}_2(\alpha)))}{\Delta^*(\tau_1 - \tau_2)} = \alpha(2-\alpha). \tag{A.3}$$

Although any binding quantitative restriction is detrimental in aggregate terms, this is not necessarily so from a jurisdictional perspective, as shown below.

Proof of Proposition 3.1. Fix $\theta \in [0;1]$. The surplus accruing to jurisdiction 1 under the restriction α consists of gains from trade and a share of the scarcity rent, that is

$$\Gamma_1(\alpha;\theta) \doteq \bar{\Gamma}_1(\alpha) + S_1(\alpha;\theta) = \Gamma_1^* \alpha^2 + \theta S(\alpha). \tag{A.4}$$

The optimal restriction from jurisdiction 1's perspective thus satisfies

$$\alpha_1^*(\theta) \doteq \arg \max_{\alpha\in[0;1]} \left\langle \Gamma_1(\alpha;\theta) \right\rangle, \tag{A.5}$$

for which the first-order condition simplifies to

$$(c_1 + c_2)\theta = (2(c_1 + c_2)\theta - c_1)\alpha_1^*, \tag{A.6}$$

provided that α_1^* belongs to $[0;1]$; otherwise, full linkage is preferred, i.e. $\alpha_1^* = 1$. Note that $\alpha_1^* \geq 0$ and $\alpha_1^* \leq 1$ require $\theta \geq \bar{\theta}/2$ and $\theta \geq \bar{\theta}$ where $\bar{\theta} \doteq c_1/(c_1 + c_2) \geq 1/2$, respectively. Equation (A.6) thus holds for $\theta \geq \bar{\theta}$, which is congruent with Equation (11a). The proof proceeds similarly for jurisdiction 2 where $\alpha_2^*(\theta) \doteq \arg\max_{\alpha\in[0;1]} \langle \Gamma_2(\alpha;\theta) \doteq \Gamma_2^*\alpha^2 + (1-\theta)S(\alpha)\rangle$.

A.2 Border tax-restricted linkage

Consider that jurisdiction 1 unilaterally taxes imports of 2-permits at a proportional rate μ and does not share any of the revenues it collects. In the admissible tax range $[1; 1 - \tau_2/\tau_1]$, net permit imports are limited to a volume of $\bar{\Delta}(\mu)$ such that

$$0 \leq \bar{\Delta}(\mu) = \frac{(1-\mu)\tau_1 - \tau_2}{(1-\mu)c_1 + c_2} \leq \Delta^*,\ \bar{\Delta}'(\mu) = -\frac{c_1\tau_2 + c_2\tau_1}{((1-\mu)c_1 + c_2)^2} < 0,\ \text{and}\ \bar{\Delta}''(\mu) < 0. \tag{A.7}$$

Jurisdictional economic gains from trade are reduced to $\bar{\Gamma}_i(\mu) = c_i(\bar{\Delta}(\mu))^2/2$ and decreasing in the tax rate. The total surplus accruing to jurisdiction 1 is $\Gamma_{1,t}(\mu) = \bar{\Gamma}_1(\mu) + \mu\bar{\tau}_1(\mu)\bar{\Delta}(\mu) = c_1(\bar{\Delta}(\mu))^2/2 + \mu\bar{\Delta}(\mu)(\tau_1 - c_1\bar{\Delta}(\mu))$ where the second term corresponds to tax revenues. Therefore, jurisdiction 2 is always worse off w.r.t. full linkage but still better off w.r.t. autarky ($\Gamma_2^* = \bar{\Gamma}_2(0) \geq \bar{\Gamma}_2(\mu) \geq 0$) while jurisdiction 1 can be better or worse off w.r.t. full linkage (but always better off w.r.t. autarky) as the diminution in economic gains from trade can be more or less than offset by tax revenues. Indeed, it holds that

$$\Gamma_{1,t}'(\mu) = \bar{\Delta}'(\mu)\left[c_1\bar{\Delta}(\mu) + \mu(\tau_1 - 2c_1\bar{\Delta}(\mu))\right] + \bar{\Delta}(\mu)\left[\tau_1 - c_1\bar{\Delta}(\mu)\right], \tag{A.8}$$

where the two bracketed terms are positive for all admissible rate μ. The sign of $\Gamma'_{1,t}$ is thus ambiguous. However, by continuity of both $\Gamma_{1,t}$ and $\Gamma'_{1,t}$ and by noting that

$$\Gamma'_{1,t}(0) = \frac{c_2(c_2\tau_1 + c_1\tau_2)}{(c_1+c_2)^3}(\tau_1 - \tau_2) > 0 \text{ and } \Gamma'_{1,t}\Big(1 - \frac{\tau_2}{\tau_1}\Big) = \bar{\Delta}'\Big(1 - \frac{\tau_2}{\tau_1}\Big)(\tau_1 - \tau_2) < 0, \quad \text{(A.9)}$$

along with $\Gamma_{1,t}\left(1 - \frac{\tau_2}{\tau_1}\right) = 0 < \Gamma_{1,t}(0)$, there exist $\mu_1^* \leq \bar{\mu}_1$ both admissible such that jurisdiction 1's surplus is maximized at μ_1^* ($\bar{\Gamma}'_1(\mu_1^*) = 0$) and jurisdiction 1 is indifferent between a tax on imports at a rate $\bar{\mu}_1 > \mu_1^*$ and no tax at all ($\Gamma_{1,t}(\bar{\mu}_1) = \Gamma_{1,t}(0) = \Gamma_1^*$). In aggregate, the tax on 2-permit imports results in a deadweight loss of

$$L(\mu) = (\Delta^* - \bar{\Delta}(\mu))(\bar{\tau}_1(\mu) - \bar{\tau}_2(\mu)) = \mu(\Delta^* - \bar{\Delta}(\mu))(\tau_1 - c_1\bar{\Delta}(\mu)), \quad \text{(A.10)}$$

and taking the derivative gives

$$L'(\mu) = (\Delta^* - \bar{\Delta}(\mu))(\tau_1 - c_1\bar{\Delta}(\mu)) - \bar{\Delta}'(\mu)\mu(\tau_1 - c_1\bar{\Delta}(\mu)) - c_1\bar{\Delta}'(\mu)\mu(\Delta^* - \bar{\Delta}(\mu)) > 0, \quad \text{(A.11)}$$

which is the sum of three positive terms. The deadweight loss is hence increasing in the tax rate or, equivalently, the aggregate surplus from the link is decreasing in the tax rate.

Notice the bijection between binding quantitative restrictions and admissible tax rates that exists in the deterministic, partial-equilibrium framework we consider. In particular, the tax rate that restricts net permit transfers up to an authorized share $\alpha \in [0; 1]$ is such that

$$\bar{\Delta}(\mu) = \alpha\Delta^* \Leftrightarrow \mu = \frac{(1-\alpha)(c_1^2 - c_2^2)}{c_1(c_1(1-\alpha) + c_2(1+\alpha))}, \quad \text{(A.12)}$$

with $\mu = 0 \Leftrightarrow \alpha = 1$ and $\mu = 1 - c_2/c_1 \Leftrightarrow \alpha = 0$. However, a limit and a tax rate linked via Equation (A.12) are not equivalent in terms of distributional aspects (e.g., for a scarcity rent and tax revenues of identical sizes, the rent apportionment depends on relative bargaining powers) or market functioning (e.g., transaction price formation). Finally, notice that the optimal tax rate on permit imports obtains as a special case of Equation (11a) with $\theta = 1$, that is

$$\bar{\Delta}(\mu_1^*) = \alpha_1^*(1)\Delta^* \Leftrightarrow \mu_1^* = (c_1 - c_2)/3c_1. \quad \text{(A.13)}$$

There is no particular interest in determining an analytical value for $\bar{\mu}_1$. In the symmetric case where jurisdiction 2 unilaterally imposes a tax μ_2 on 2-permit exports and keeps all the revenues to itself the optimal tax rate would satisfy $\bar{\Delta}(\mu_2^*) = \alpha_2^*(0)\Delta^* \Leftrightarrow \mu_2^* = \frac{c_1 - c_2}{c_1 + 2c_2} > \mu_1^*$.

A.3 Linkage with exchange rates

Proof of Proposition 3.3. From Equation (14) and market closure, any interior linked market ρ-equilibrium is characterized by

$$\Delta_1(\rho) = \frac{\tau_1 - \rho\tau_2}{c_1 + \rho^2 c_2} \geq 0 \Leftrightarrow \rho \leq \frac{\tau_1}{\tau_2}, \text{ and } \Delta_2(\rho) = -\rho\Delta_1(\rho) \geq 0 \Leftrightarrow \rho \geq \frac{\tau_1}{\tau_2}. \tag{A.14}$$

Since $\Delta_1(\rho) \sim_{0^+} \frac{\tau_1}{c_1}$ and $\Delta_1(\rho) \sim_{+\infty} \frac{-\tau_2}{\rho c_2} \rightarrow_{+\infty} 0^-$, it holds that $\lim_{0^+} e_1(\rho) = \bar{e}$ and $\lim_{+\infty} e_1(\rho) = \omega$. The only relevant (positive) root of $\Delta_1'(\rho) = 0$ is $\rho^+ = \frac{\tau_1}{\tau_2} + \sqrt{\frac{\tau_1^2}{\tau_2^2} + \frac{c_1}{c_2}}$. Similarly, $\Delta_2(\rho) \sim_{+\infty} \frac{\tau_2}{c_2}$ and $\Delta_2(\rho) \sim_{0^+} \frac{\rho^2\tau_2}{c_1} \rightarrow_{0^+} 0$ so that $\lim_{+\infty} e_2(\rho) = \bar{e}$ and $\lim_{0^+} e_2(\rho) = \omega$. The only relevant (positive) root of $\Delta_2'(\rho) = 0$ is $\rho^{++} = \frac{c_1\tau_2}{c_2\tau_1}\left(\sqrt{1 + \frac{c_2\tau_1}{c_1\tau_2}} - 1\right)$. Noting that $\rho = 1$ is an obvious root of $\Delta_i(\rho) = \Delta^*$ for $i = \{1, 2\}$, it follows that

$$\Delta_1(\rho) \geq \Delta^* \Leftrightarrow (\rho - 1)(\rho + \bar{\rho}_1) \leq 0, \tag{A.15a}$$

$$\rho\Delta_1(\rho) \geq \Delta^* \Leftrightarrow (\rho - 1)(\rho - \bar{\rho}_2) \leq 0, \tag{A.15b}$$

where $\bar{\rho}_1 \doteq \frac{c_1\tau_2 + c_2\tau_1}{c_2(\tau_1 - \tau_2)} > 0$ and $\bar{\rho}_2 \doteq \frac{c_1(\tau_1 - \tau_2)}{c_1\tau_2 + c_2\tau_1} \in (0; \tau_1/\tau_2)$. Statements (i) and (ii) thus follow immediately: Jurisdiction 1 increases its emissions relative to full linkage provided that the exchange rate is less than unitary; jurisdiction 2 decreases its emissions relative to full linkage provided that $(\rho - 1)(\rho - \bar{\rho}_2) < 0$. Note that the threshold $\bar{\rho}_2$ satisfies

$$\bar{\rho}_2 \leq 1 \Leftrightarrow \frac{\tau_1}{\tau_2} \leq \frac{2c_1}{c_1 - c_2} \Leftrightarrow \frac{c_1}{c_2} \leq \frac{2(\bar{e} - \omega_2) + (\bar{e} - \omega_1)}{\bar{e} - \omega_1} = 1 + 2\frac{\bar{e} - \omega_2}{\bar{e} - \omega_1}. \tag{A.16}$$

In our special case where $\omega_1 = \omega_2$, $\bar{\rho}_2 = 1 \Leftrightarrow \tau_1 = 3\tau_2 \Leftrightarrow c_1 = 3c_2$. Note that when $\bar{\rho} = 1$ emissions in jurisdiction 2 never pass below their full-linkage level.

Relative to the benchmark, additional aggregate abatement $\gamma(\rho)$ obtains as the difference between aggregate emissions in the benchmark and in the ρ-equilibrium, that is

$$\gamma(\rho) \doteq 2\omega - \left(\omega + \bar{\Delta}_1(\rho) + \omega - \rho\bar{\Delta}_1(\rho)\right) = (\rho - 1)\bar{\Delta}_1(\rho). \tag{A.17}$$

Recall that $\bar{\Delta}_1(\rho) \geq 0$ i.f.f. $\rho \in [0; \tau_1/\tau_2]$. Hence $\gamma(\rho) \geq 0$ i.f.f. $\rho \in [1; \tau_1/\tau_2]$. We then solve for

$$\gamma'(\rho) = 0 \Leftrightarrow \rho^2 c_2(\tau_1 + \tau_2) - 2\rho(c_2\tau_1 - c_1\tau_2) - c_1(\tau_1 + \tau_2) = 0. \tag{A.18}$$

Noting that by assumption $\tau_i = c_i a$, $i = \{1, 2\}$, then $c_2\tau_1 = c_1\tau_2$ and additional aggregate abatement is maximized at $\rho = \hat{\rho} \doteq (\tau_1/\tau_2)^{1/2}$. Computing $\gamma(\hat{\rho})$ establishes Statement (iii).

Proof of Corollary 3.4. In the linked market $\hat{\rho}$-equilibrium variations in jurisdictional emission levels as compared to autarky read

$$\hat{\Delta}_1 = \frac{\sqrt{c_1} - \sqrt{c_2}}{2\sqrt{c_1}}a, \text{ and } \hat{\Delta}_2 = -\sqrt{\frac{c_1}{c_2}}\hat{\Delta}_1 = \frac{\sqrt{c_2} - \sqrt{c_1}}{2\sqrt{c_2}}a. \tag{A.19}$$

In total, aggregate abatement increases by

$$\gamma(\hat{\rho}) \doteq \hat{\Delta}_1 - \hat{\Delta}_2 = (\hat{\rho} - 1)\Delta_1(\hat{\rho}) = a(\sqrt{c_1} - \sqrt{c_2})^2/(2\sqrt{c_1 c_2}). \tag{A.20}$$

Assume that in lieu of implementing the exchange rate regime $\hat{\rho}$ jurisdictions were to agree upon a full link where jurisdiction 2 would reduce its domestic cap in such a fashion that aggregate abatement would be equal to that in the $\hat{\rho}$-equilibrium. That is, jurisdictional caps would be such that $\hat{\omega}_1 = \omega$ and $\hat{\omega}_2 = \omega - \gamma(\hat{\rho})$. Under full linkage with jurisdictional caps $(\hat{\omega}_1, \hat{\omega}_2)$ permits continue to flow in the natural direction and unit transfers amount to

$$\hat{\Delta} = \Delta^* - c_2\gamma(\hat{\rho})/(c_1 + c_2). \tag{A.21}$$

These two linkage regimes can be compared in terms of sole economic gains from trade because they are generative of the same aggregate level of emissions. In particular, jurisdiction i prefers the full link with domestic caps $(\hat{\omega}_1, \hat{\omega}_2)$ over the $\hat{\rho}$-equilibrium with domestic caps (ω, ω) i.f.f. $\hat{\Delta} \geq |\hat{\Delta}_i|$, which holds for $i = \{1, 2\}$ since

$$\hat{\Delta}_1 - \hat{\Delta} = \frac{c_2 - c_1}{2(c_1 + c_2)}a < 0, \text{ and } |\hat{\Delta}_2| - \hat{\Delta} = \frac{c_2 - c_1 - 3\sqrt{c_1 c_2}}{2\sqrt{c_1 c_2}}a < 0. \tag{A.22}$$

Another interpretation than that proposed in the body of the paper is that, if the two jurisdictions were to establish a link with an exchange rate aimed at correcting for too low an ambition level in jurisdiction 2, then they would both be better off from a full link with an equivalent downward-adjusted cap in jurisdiction 2.

B Numerical simulations

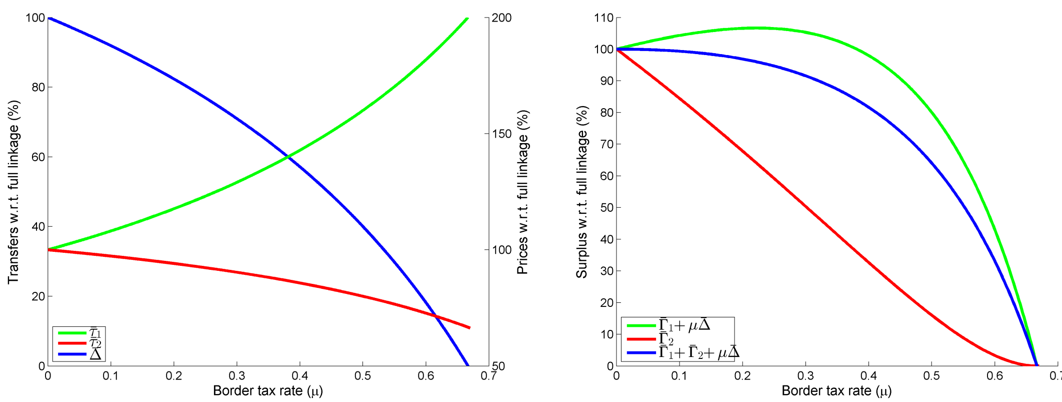
Jurisdictions have the same domestic abatement objective, thus $c_1/c_2 = \tau_1/\tau_2$. Equating this ratio to 3 ensures that $\bar{\rho}_2 = 1$ and provides clear-cut results in terms of emission variations for jurisdiction 2 (see Equation (A.15b)). The numerical results are presented in relative values (with full linkage or autarky taken as benchmarks) and hold irrespective of the stringency of the common domestic abatement objective. In the following and without loss of generality we set $\bar{e} = 1000$, $\omega = 900$ and $c_1 = 3c_2 = 0.3$, which gives $\tau_1 = 3\tau_2 = 30$.

Border taxes on permit transfers. Relative to full linkage, the implications of a border tax on permit imports in the admissible tax range $[0; 2/3]$ are displayed in Figure B.1. This also depicts the effects of a quantitative transfer restriction when jurisdiction 1 has monopsony power ($\theta = 1$). As the tax rate rises, Figure B.1a shows that trade decreases while the price

Figure B.1: Effects of a border tax set by jurisdiction 1 on 2-permit imports

(a) Permit prices and transfers

(b) Gains from trade + tax revenues

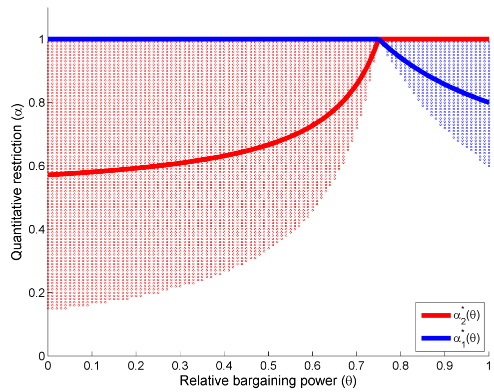


wedge increases, i.e. cost-efficiency decreases. In particular, $\mu = 0$ corresponds to full linkage and for $\mu \geq 2/3$ the tax regime replicates autarky. Figure B.1b shows that jurisdiction 1's surplus (gains from trade + tax revenues) is increasing with μ as long as $\mu < \mu^* \simeq .22$ and at that $\bar{\mu} \simeq .40$ it is indifferent between a tax $\bar{\mu}$ and full linkage. Both aggregate and jurisdiction 2's surpluses decrease with the tax rate and remain positive. However, note that jurisdiction 2's surplus is quasi linearly decreasing while the aggregate surplus is concave and relatively flat for small tax rates. For instance, when the tax rate is $\mu \simeq .3$ jurisdiction 2 loses about half of its full-link gains while the deadweight loss remains small (∼10%).

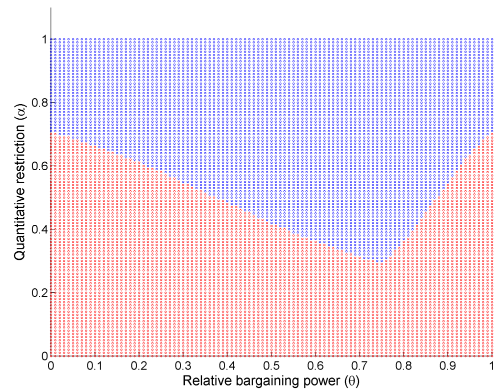
Quantitative transfer restrictions. Figure B.2a depicts the optimal quantitative restrictions for jurisdiction 1 (blue line) and 2 (red line) as a function of relative bargaining power. The blue and red circles denote restrictions that constitute an improvement w.r.t. full linkage for jurisdictions 1 and 2, respectively. Note that the range of such quantity-restricted linkages is wider for the lower-cost jurisdiction. Although both jurisdictions cannot simultaneously be better off under a quantitative restriction w.r.t. full linkage, one jurisdiction may accept to lose out a share of its full-link gains if this is necessary for the other jurisdiction to initiate linking. As an illustration, the blue circles in Figure B.2b indicate quantitative restrictions

Figure B.2: Jurisdictional preferences for quantitative linkage restrictions

(a) Optimal & better-than-autarky restrictions



(b) Potential agreement on restrictions



Note: Fig. B.2a: thick blue and red lines are optimal quantitative restrictions for jurisdiction 1 and 2, respectively, and intersect at $\theta = \bar{\theta} = .75$; blue and red circles indicate volume-restricted linkages better than full linkage for jurisdiction 1 and 2, respectively. Fig. B.2b: blue (red) bullets denote restrictions that are (not) *potentially acceptable* at a 50% level of full-linkage gains from trade by both jurisdictions.

that are *potentially acceptable* in the sense that jurisdictions are willing to give up on (at most) half of their full-linkage gains in the restricted link. In this case, $\alpha \simeq .7$ (resp. $\alpha \simeq .3$) is the most stringent limit to be potentially acceptable when $\theta = \{0; 1\}$ (resp. $\theta = \bar{\theta}$).

Linkage with exchange rates. We first define three indexes measuring overall abatement (B.1a), average abatement cost (B.1b) and cost-efficiency (B.1c) relative to autarky.

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

$$I^{AC} = \frac{1}{I^A} \times \frac{C_1(\bar{e}-\omega-\Delta_1(\rho)) + C_2(\bar{e}-\omega+\rho\Delta_1(\rho))}{C_1(\bar{e}-\omega)+C_2(\bar{e}-\omega)} \tag{B.1b}$$

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

Note that I^{CE} merely gives an indication (and not a proper measure) of the degree of cost-efficiency. The kink at $\rho = 1$ is due to the max operator: at this point there is a discontinuity since the higher marginal abatement cost jurisdiction switches ($\bar{\tau}_1 \geq \bar{\tau}_2 \Leftrightarrow \rho \geq 1$).

Figure B.4 describes both the economic and environmental outcomes along the continuum of ρ-equilibria. The green curve in Figure B.4a shows that the degree of cost-efficiency is the lower the farther away the exchange rate from parity, where it is maximal. The blue curve in Figure B.4a shows that overall abatement is higher than in the benchmark provided

Figure B.3: Overall abatement, average abatement cost and cost-efficiency w.r.t. autarky

(a) $I^{AC} = f\left(I^{A}\right)$ (b) $I^{CE} = f\left(I^{A}\right)$

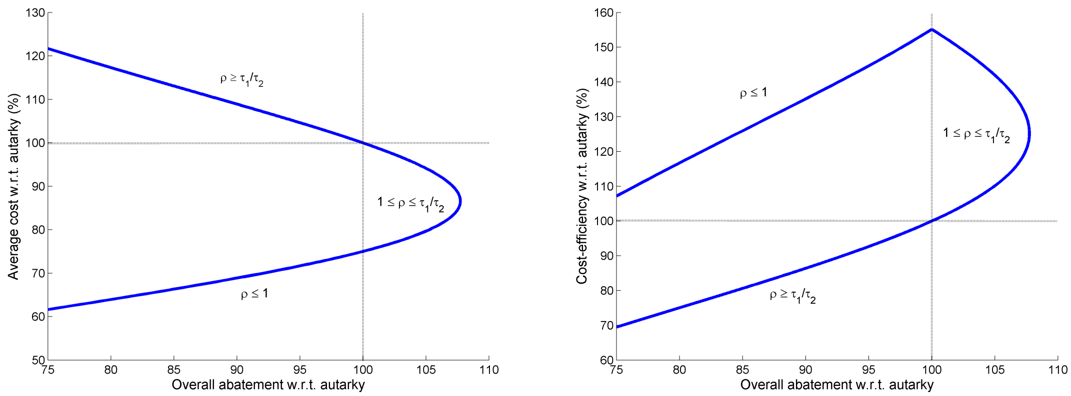
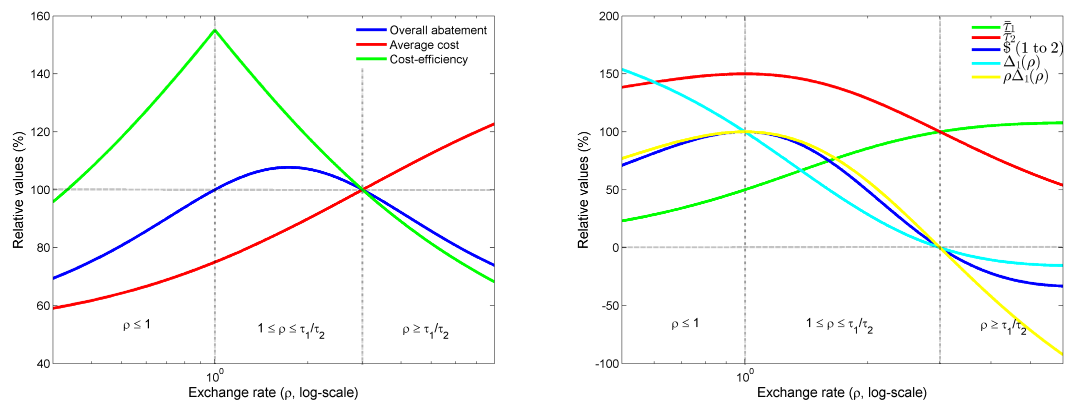


Figure B.4: Relative implications of an exchange rate (with $\bar{\rho} = 1$)

(a) Overall abatement and cost-efficiency (b) Prices and abatement transfers



Note: All values relative to autarky except transfers in Fig. B.4b that are measured w.r.t. full linkage. Due to the abatement cost quadratic specification, jurisdictional abatements and prices have identical variations.

that the exchange rate lies in $[1; \tau_1/\tau_2]$ and is maximal at $\rho = \hat{\rho}$. Another way to see this is to consider Figure B.4b. In the reduction zone, overall abatement is higher than in the benchmark since the volume of abatement undertaken in jurisdiction 2 is higher than the corresponding increase in emissions occurring in jurisdiction 1 (the yellow line is above the cyan one and the spread between them is maximal at $\rho = \hat{\rho}$). The converse holds outside of this zone. Note also that as the exchange rate runs from autarky to parity both abatement and permit flows from 2 to 1 increase. In the amplification zone the wedge in jurisdictional prices (relative to autarky) widens out as compared to full linkage while it is reversed in the inversion zone. In the latter zone, the negative values associated with the blue, cyan and yellow lines indicate that permit trading occurs opposite to the natural direction.

C Cap selection and environmental damages

We assume that damage functions are linear and let $d_i > 0$ denote jurisdiction i's constant marginal damage from aggregate emissions. This ensures jurisdictional cap reaction functions are orthogonal, i.e. jurisdictions select the same domestic cap whatever the other jurisdiction's choice. Note that this is a mild assumption as there is evidence that marginal benefits from mitigation are much flatter than marginal abatement costs over the range of annual emissions (Newell & Stavins, 2003). For instance, when cap selection is non-cooperative, the Cournot-Nash jurisdictional caps satisfy

$$\omega_i \doteq \arg \min_{\omega \in [0;\bar{e}]} \left\langle C_i(\bar{e} - \omega) + d_i(\omega + \omega_{-i}) \right\rangle = \bar{e} - d_i/c_i, \text{ for } i = \{1, 2\}. \tag{C.1}$$

Note that each domestic cap is strictly binding ($\omega_i < \bar{e}$) and independent of the cap-setting decision in the other jurisdiction (ω_{-i}). We abstract from corners by assuming that $d_i < c_i\bar{e}$, i.e. $\omega_i > 0$ for $i = \{1, 2\}$. Note that our assumption of identical caps in the main text obtains if we assume that $c_1/c_2 = d_1/d_2$. Note also that jurisdictions do not internalize the negative externality generated by their emissions on the other jurisdiction. By contrast, cooperative caps are socially efficient and satisfy $\omega_i^* = \bar{e} - (d_i + d_{-i})/c_i < \omega_i$.

The optimal exchange rate ρ_i^* for jurisdiction i maximizes the difference in compliance costs between autarky and ρ_i^*-equilibrium, knowing how both jurisdictions react to a rate ρ, that is

$$\rho_i^* \doteq \arg \max_{\rho > 0} \left\langle C_i(\bar{e} - \omega) - C_i(\bar{e} - \omega - \bar{\Delta}_i(\rho)) + d_i(\rho - 1)\bar{\Delta}_1(\rho) \right\rangle. \tag{C.2}$$

This mitigates jurisdictional preferences for too high or too low rates as mentioned in the main text. We do not provide an analytical solution to Programme (C.2) and refer the reader to the literature on optimal intertemporal trading ratios, e.g. Leiby & Rubin (2001), Yates & Cronshaw (2001), Innes (2003) and Feng & Zhao (2006), for similar analytical problems.

Note that the socially efficient level of emissions $2\bar{e} - (d_1 + d_2)/c$ need not coincide with that triggered under $\hat{\rho}$-linkage. In particular, we numerically show that when d_i/c_i is relatively small (resp. big) then the two jurisdictions overabate (resp. underabate) at the $\hat{\rho}$-equilibrium as compared to the social optimum. Additionally, we numerically show that jurisdictionally-preferred exchange rates defined in Programme (C.2) that are *potentially acceptable* at a 50% level of full-link gains are centred around parity within the range $[0.61; 1.44]$.