COORDINATING CLIMATE AND TRADE POLICIES: PARETO EFFICIENCY AND THE ROLE OF BORDER TAX ADJUSTMENTS

by

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First version: July 3, 2013
This version: March 3, 2014

Abstract: This paper explores the role of trade instruments in globally efficient climate policies, focusing on whether or not some form of border tax adjustment (BTA) is warranted when carbon prices differ internationally. The analysis shows that, while there is no case for BTA when all instruments can be freely deployed, Pareto-efficiency does require a form of BTA when carbon taxes in some countries are constrained: its purpose then is to partly counteract the impact on emissions of inappropriate carbon pricing there, or, equivalently, to undo the trade distortions such pricing creates. The required form of BTA is generally complex, but a special case is identified in which it optimally has the simple structure envisaged in practical policy discussions. It is also shown that the efficiency case for BTA depends critically on whether climate policies are pursued by carbon taxation or by cap-and-trade.

Keywords: Environmental taxation; cap- and-trade; international trade; Pareto efficiency; border tax adjustments.

JEL classification: H20; F18.

Acknowledgements: We thank two anonymous referees and the Editor, Brian Copeland, James Markusen, Donald MacLaren, Jon Strand, Jean-Francois Tremblay, John Whalley, Alan Woodland and many seminar participants for helpful comments and suggestions. Kotsogiannis acknowledges support from the Leverhulme Trust. Much of this work was completed while Kotsogiannis was a Visiting Scholar in the Fiscal Affairs Department of the IMF. Views expressed here should not be attributed to the International Monetary Fund, its Executive Board, or its management, or to the Leverhulme Trust. Any remaining errors are ours alone.

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1 Introduction

A key concern in countries contemplating reasonably aggressive carbon pricing—and one that has become still more prominent since the crisis, as they struggle to restore growth—is the fear that their competitive position in world markets would be jeopardized by 'carbon leakage' as production shifts elsewhere.[1] The likelihood that any mitigation measures will be strongly asymmetric, at least for coming years, amplifies this concern, which is reflected in the inclusion in climate change legislation both in the EU[2] and in proposals elsewhere (such as the Waxman-Markey climate and energy bill in the U.S.) of provisions, for exposed emissions-intensive sectors, for various forms of 'border tax adjustment' (BTA)[3]—meaning the levying of some charge on imports, and remission of charge on exports, to the extent that carbon prices are higher domestically than elsewhere. Unsurprisingly, the appropriateness or not of such adjustments has been the focus of heated debate. But that debate has been largely uninformed by close analysis. Against that background, the purpose of this paper is to provide a firmer analytical basis for these discussions, in particular by giving a better sense of whether—or not—some form of BTA might have a useful role to play in addressing climate challenges.

The theoretical literature has begun to address the linkages between climate (environmental, more generally) and trade policies that are at the heart of this question. Most of it has focused on non-cooperative policy formation, characterizing nationally trade and environmental policies and the interplay between them (as in, for instance, Markusen (1975), Baumol and Oates (1988), Copeland (1996), Panagariya *et al.* (2004), Copeland (2011) and Ishikawa and Kiyono (2006)) or desirable directions of reform—whether for small or large economies—when one or other instrument, environment or trade, is for some reason constrained away from optimal (as in Copeland (1994), Hoel (1996), Turunen-Red and Woodland (2004) and Neary (2006)). The key result in this literature, which will be a useful benchmark below, is that the pursuit of simple national interest requires, when both instruments can be freely deployed, that the domestic carbon tax be set to reflect only the national damage from carbon emissions, while tariffs are set with an eye to both reducing emissions abroad (because that reduces damage at home) and securing standard terms of trade gains. And there is nothing in this policy that looks like a border tax adjustment, the presence of any carbon tax abroad then having no direct relevance to

[1] Instructive discussions of these issues are in Copeland and Taylor (2004) and Sheldon (2006). Levinson and Taylor (2008) provide empirical evidence that more stringent environmental regulation reduces exports.

[2] Adjustments of this kind, in the context of the EU Emissions Trading System, are provided for in Directive 2009/29/EC amending Directive 2003/87/EC.

[3] This has also been advocated by, for instance, Stiglitz (2006).

policy formation at home.

While this non-cooperative perspective is clearly an important one, an understanding of the requirements of cooperative policy is also valuable. It would certainly be naive to imagine that actual climate policies are entirely shaped to the collective good. But nor are they always easily explained in terms of narrowly defined self-interest. The adoption of carbon pricing in British Columbia, for instance, and the Regional Greenhouse Gas Initiative (capping emissions in several U.S. states) do almost nothing for global emissions, and hence for climate damage, but do impose some local costs. And the EU is undertaking relatively aggressive mitigation policies even though the costs to its members of adapting to climate change appear quite low (and for some quite possibly negative).[4] The motives behind these policies are no doubt complex, including perhaps a concern (and some sense of historic guilt) for the harm that might be suffered elsewhere and a desire to prod others into action (maybe all overlain with a fear that delaying action to avert catastrophic effects could be still more costly). But they certainly seem to reflect more than immediate and narrowly-defined self-interest. Even without delving into motives, in any event, the implications of cooperative design in relation to climate policies must be a central benchmark both given the commonplace rhetoric of cooperation in this area—do policies rationalized from that perspective really make sense?—and perhaps above all for assessing the appropriateness of whatever policy structures do emerge. One would at least like to know if policies adopted could be improved in such a way that all countries can benefit.

This collective perspective has, however, received very little attention in the literature (the sole exception of which we are aware being the partial equilibrium treatment in Gros (2009)). The aim in this paper is therefore to explore the interaction between climate and trade policies in a cooperative setting, with a particular eye to whether or not—and why—this calls for something recognizable as BTA. It does so by characterizing Pareto-efficient allocations within a standard general equilibrium model of competitive trade in many goods, augmented by a climate-like production externality, in which potentially three sets of policy instruments may be deployed: international lump-sum transfers, carbon pricing, and tariffs. The first of these are naturally directed to equity concerns, moving the world around its utility possibly frontier; the second are naturally targeted to controlling emissions; and the third would have no role if the other two instruments were optimally deployed. Attention thus focuses on the implications of various constraints on these instruments for the setting of the others to achieve what we will refer to as constrained

[4]The results in Obsterghaus and Reif (2010), for example, suggest that the fiscal costs of adaptation in the EU would be around 16 billion euros per annum (in 2005 prices) by mid-century, though such figures are subject to considerable uncertainty.

Pareto-efficient outcomes.

Within this broad class of issues, attention here focusses especially on the question of whether there are circumstances in which some form of BTA is part of a globally efficient response to climate change (or to any other environmental problem with broadly the same border-crossing structure). By 'border tax adjustment' we shall mean, in the most general interpretation, tariff structures that in some direct way reflect differences in national carbon prices. And of particular interest is the possibility that this adjustment will take the very simple form commonly envisaged in policy discussions—which is likely the only one conceivably practicable—of setting a charge on imports equal to some notion of the carbon charge 'not paid' abroad on imports, and remitting tax on exports in similar fashion.

There are of course many other issues, not addressed here, raised by the possibility of BTA for carbon prices. These include the questions of whether or not such adjustment is WTO-consistent (see, for instance, Chapter 5 of OECD (2004), and McLure (2011)),[5] very significant issues of implementability (Moore, 2010); and, not least, the (perhaps limited) empirical significance of the relative producer price effects of carbon pricing that might be adjusted for (Houser *et al.* 2008). Nor does the analysis here consider the potential merit of BTA as a credible device by which countries implementing carbon pricing can encourage participation by others.[6] Important though these issues are, they are not the concern here—which is with the pure efficiency case for climate-motivated border tax adjustment.

To anticipate the results that follow, what emerges, loosely speaking, is that when carbon taxes and other policies are for some reason constrained in a subset of countries, global Pareto efficiency requires that other countries not only set their own carbon taxes to reflect global rather than national damage, but—and more to the point here—that they set tariffs which embody a form of BTA in the broad sense above. There are here key differences from the case of nationally-motivated policies. Most straightforwardly, the unconstrained carbon taxes look to global rather than national harm, and there is of course no self-interested terms of trade motive. And, at the root of the BTA, the case for manipulating emissions abroad (now to global rather than national good, of course) through tariff policy arises from the collective perspective only to the extent that carbon taxes abroad are constrained at levels different from the collectively efficient level set in

[5]There are precedents, notably in the U.S Superfund tax and, of particular relevance in the climate context, for ozone-depleting chemicals.

[6]Participants themselves presumably gain from the BTAs, and non-participants would then benefit by imposing a carbon price themselves, at least to the extent that by doing so they would capture revenues otherwise accruing to others (though terms of trade effects would also play a role).

the unconstrained country (or countries). The form of the required BTA is generally complex, but in one special case—inelastic demand and fixed coefficients in emitting and producing—does indeed reduce to the simple form of practical policy discussions. There is no collective case for BTA, however, if the constrained countries use cap-and-trade rather than carbon taxation—because then policy in the unconstrained country cannot affect emissions there.

The plan of the paper is as follows. Section 2 sets out the model, which takes carbon taxation to be the instrument of climate policy, and Section 3 then derives benchmark results for collectively efficient carbon tax and tariff policies when both these instruments can be freely set—these results in themselves add little that is not evident from the previous literature, but provide a reference for the more novel results. These begin in Section 4, which considers Pareto-efficient policies when carbon taxes and tariffs are constrained in some countries, establishing that, as just noted, there is then indeed a case for some form of BTA, both (under weak conditions) in the general sense above and (under strict ones) in the more precise sense of practical policy discussions. Section 5 then compares these results with those of Markusen (1975) for non-cooperative policy-making, and considers their applicability when carbon pricing is by cap-and-trade rather than carbon taxation. Section 6 concludes.

2 Modeling climate and trade policies

The framework is that of Keen and Wildasin (2004), modified to deal with pollution as a by-product of production. We consider a perfectly competitive general equilibrium model of international trade in which there are J countries indexed by the superscript j. In each country there is a representative consumer and a private sector that produces (only) N tradeable commodities.[7] The N-vector of international commodity prices is denoted by $\mathbf{w}$.[8] (All vectors are column vectors, and a prime indicates transposition). Trade is subject to trade taxes or subsidies, denoted by the vector $\boldsymbol{\tau}^j$ in country j; consistent with most-favored nation rules, each country is assumed to apply the same tariff rates to all others.[9] The commodity price vector in country j is then given by the N-vector

[7]The inclusion of non-tradeable commodities provides no additional insights. See Vlassis (2013).

[8]Though world prices are something of a fiction, in the sense that no private agent may trade at them, they do matter for the revenues that national governments collect.

[9]As usual, the model is very general in allowing for all types of trade taxes and subsidies. If $\tau_i^j > 0$ ($\tau_i^j < 0$) and commodity i is imported by country j, then τ_i^j is an import tariff (import subsidy); if i is exported by country j then $\tau_i^j > 0$ ($\tau_i^j < 0$) is an export subsidy (export tax).

$\mathbf{p}^j = \mathbf{w} + \boldsymbol{\tau}^j$.[10]

The production of each commodity generates some pollutant—we of course have in mind carbon emissions, though there are many other possible interpretations[11]—with the N-vector $\mathbf{z}^j$ denoting sectoral emissions in country j. Total emissions in country j are thus given by $\boldsymbol{\iota}'\mathbf{z}^j$ where $\boldsymbol{\iota}$ is the N-vector of 1s; and global emissions, on which—as with the concentration of greenhouse gases in the global atmosphere—damage in each country depends, are

$$k = \sum_{l=1}^{J} \boldsymbol{\iota}'\mathbf{z}^l \, . \tag{1}$$

This damage is assumed to arise (only) directly in consumer welfare, not through production possibilities; though perhaps not the most realistic assumption in the climate context, this helps relate our results to other analyses and results in the literature.[12]

The representative consumer of country j has preferences represented by the expenditure function

$$e^j(u^j, \mathbf{p}^j, k) = \min_{\mathbf{x}^j} \{\mathbf{p}^{j\prime}\mathbf{x}^j \ : \ U^j\left(\mathbf{x}^j, k\right) \geq u^j\} \, , \tag{2}$$

with (derivatives being denoted by subscripts) $\mathbf{e}^j_{\mathbf{p}}$ the vector of compensated demands and e^j_k, assumed strictly positive in all countries, being the compensation required for a marginal increase in global emissions.

Emissions $\mathbf{z}^j$ are subject to pollution taxes, given by the N-vector $\mathbf{s}^j$; these, note, may be sector-specific.[13] Production in country j is competitive and characterized by the revenue function

$$r^j(\mathbf{p}^j, \mathbf{s}^j) = \max_{\mathbf{y}^j, \mathbf{z}^j} \{\mathbf{p}^{j\prime}\mathbf{y}^j - \mathbf{s}^{j\prime}\mathbf{z}^j \ : \ \left(\mathbf{y}^j, \mathbf{z}^j\right) \in T^j\} \, , \tag{3}$$

where T^j is the technology set and $\mathbf{y}^j$ is the (net) output of tradeable goods (the dependence on underlying endowments being omitted for brevity). The revenue function in (3) is convex, linearly homogeneous in $(\mathbf{p}^j, \mathbf{s}^j)$ and assumed to be twice continuously differentiable; it is further assumed throughout that $\mathbf{r}^j_{\mathbf{ss}}$ is non-singular for all $\mathbf{p}^j, \mathbf{s}^j$.[14] (The

[10]Consumption taxes are excluded from the analysis as they would be irrelevant for countries that are unconstrained in their use of tariffs and carbon taxes; and would complicate the formalities, with little additional insight, for those that are constrained.

[11]And extensions too. The analysis and main results are readily generalized to allow for M-types of pollutants, and much the same analysis would also apply to pollutants whose emissions do not disperse uniformly in the atmosphere.

[12]Kotsogiannis and Woodland (2013) show that allowing for emissions to instead enter production does not change the essence of the results that follow.

[13]As in, among others, Copeland (1994), Hoel (1996) and Turunen-Red and Woodland (2004).

[14]For the properties of the revenue function see Dixit and Normal (1980) and Woodland (1982). See also Turunen-Red and Woodland (2004).

fossil fuels from whose use carbon emissions arise are not explicitly identified, though they can be thought of as being amongst the N commodities, since our interest here is not in their pricing). Hotelling's lemma implies that $\mathbf{r}^j_{\mathbf{p}}(\mathbf{p}^j, \mathbf{s}^j) = \mathbf{y}^j$ is the vector of net supply functions; it also follows from (3) that $\mathbf{r}^j_{\mathbf{s}}(\mathbf{p}^j, \mathbf{s}^j) = -\mathbf{z}^j$: emissions are given by (minus) the derivative of the revenue function with respect to the sectoral carbon tax rates.

Tax revenues from all sources are assumed to be returned to the domestic consumer as lump sum. At some points, unrequited commodity transfers between countries will be allowed; denoting by the $\boldsymbol{\alpha}^j$ the N-vector of such transfers received by j, these must satisfy

$$\sum_{j=1}^{J} \boldsymbol{\alpha}^j = \mathbf{0}_{N\times 1}\,, \tag{4}$$

where $\mathbf{0}_c$ denotes the c-vector of zeroes. The consumer's budget constraint in country j is thus

$$e^j(u^j, \mathbf{p}^j, k) = r^j(\mathbf{p}^j, \mathbf{s}^j) - \mathbf{s}^{j\prime}\mathbf{r}^j_{\mathbf{s}}\left(\mathbf{p}^j, \mathbf{s}^j\right) + \boldsymbol{\tau}^{j\prime}\left(\mathbf{e}^j_{\mathbf{p}}(u^j, \mathbf{p}^j, k) - \mathbf{r}^j_{\mathbf{p}}\left(\mathbf{p}^j, \mathbf{s}^j\right)\right) + \mathbf{w}'\boldsymbol{\alpha}^j\,. \tag{5}$$

This simply says that expenditure $e^j(u^j, \mathbf{p}^j, k)$ must equal GDP, given by $r^j(\mathbf{p}^j, \mathbf{s}^j)$, plus carbon tax revenues $(\mathbf{s}^{j\prime}\mathbf{z}^j)$, tariff revenue $(\boldsymbol{\tau}^{j\prime}\left(\mathbf{e}^j_{\mathbf{p}}(u^j, \mathbf{p}^j, k) - \mathbf{r}^j_{\mathbf{p}}(\mathbf{p}^j, \mathbf{s}^j)\right)$; recall that, for instance, $\tau^j_i > 0$ means an import tariff if j is imported and a subsidy if it is exported) and the value at world prices of transfers received by country j $(\mathbf{w}'\boldsymbol{\alpha}^j)$.

Defining

$$\mathbf{m}^j \equiv \mathbf{e}^j_{\mathbf{p}}(u^j, \mathbf{p}^j, k) - \mathbf{r}^j_{\mathbf{p}}\left(\mathbf{p}^j, \mathbf{s}^j\right)\,, \tag{6}$$

to be the vector of j's net imports, market clearing requires that

$$\sum_{j=1}^{J} \mathbf{m}^j = \mathbf{0}_{(N-1)\times 1}\,, \tag{7}$$

where, by Walras' Law, the market-clearing equation for the first commodity is dropped. The same commodity is taken as numeraire, and, without loss of generality, to be untaxed in all countries: so $\tau^j_1 = 0$ and $p^j_1 = 1 = w_1$, for $j = 1, \ldots, J$; it is also assumed throughout that, for all j, $\mathbf{m}^j_{\mathbf{p}}$ is non-singular.

Given tariffs $\boldsymbol{\tau}^j$ and carbon taxes $\mathbf{s}^j$, for $j = 1, \ldots, J$, a vector of international transfers $\boldsymbol{\alpha}^j$ satisfying (4), the market equilibrium conditions (7), and the national budget constraints (5), the system may be solved for the equilibrium world price vector $\mathbf{w}$ and the vector of national utilities $\mathbf{u} = (u^1, \ldots, u^J)'$.[15]

[15]Differentiability of all functions at the initial equilibrium is assumed. Standard assumptions hold, so an equilibrium exists (Woodland (1982)).

The analysis that follows proceeds by characterizing the set of Pareto-efficient allocations under a range of assumptions on the instruments available. In general there are of course an infinite number of such allocations. While it would be possible to focus on just one by appealing to some specific social welfare function—and as will be seen the results can indeed be so interpreted—or bargaining solution, the approach here has the merit of identifying features (including the potential use of BTAs) that are generic to any process that leads to a Pareto-efficient outcome.

Formally, we proceed by using Motzkin's Theorem of the Alternative to characterize Pareto-efficient carbon tax and tariff structures. The necessary conditions for this are derived in Appendix A. These involve J country-specific variables σ^j that pick out the particular point on the utility possibility frontier being characterized. In effect, σ^j can—but need not—be thought of as the implicit social marginal value, evaluated at the Pareto-efficient allocation being characterized, of the utility of country j:[16] if, for instance, $\sigma^i > \sigma^j$ then country i is in this sense implicitly more 'income-needy' at the allocation being described than country j. While the formal role of the σ^j is thus no more than mechanical, the discussion and intuition can then proceed as if the problem were one of simply maximizing some social welfare function, having marginal welfare weights σ^j, with the assurance that, behind the scenes, whatever instruments are available can be used to translate what is then expressed as an increase in social welfare into a Pareto improvement.

3 The benchmark: Unconstrained carbon tax and tariff policies

To fix ideas, this section considers briefly the relatively straightforward case in which there are no constraints on the carbon taxes and tariffs that can be set in any country. In doing so it combines the results of Chichilnisky and Heal (1984) and Sandmo (2005, 2006), on optimal environmental taxation in the absence of tariffs and international transfers, with those of Keen and Wildasin (2004), on efficient tariff structures in the absence of environmental concerns. While the results in this section are thus as previous work would lead one to expect, they provide a useful reference point for later and more interesting

[16] This interpretation follows from the formalities in the Appendix A on noting that the conditions in (A.15)-(A.16) are equivalent to those of maximizing a social welfare function $\Omega(\mathbf{u})$ with marginal welfare weights $\Omega'_{\mathbf{u}} = \mathbf{y}'\boldsymbol{\Lambda}_{\mathbf{u}}$, the typical element of which is $\sigma^j(e^j_u - \boldsymbol{\tau}^{j\prime}\mathbf{e}^j_{\mathbf{p}u}) + \mathbf{v}'\mathbf{e}^j_{\mathbf{p}u}$, where $\mathbf{v}$ is a vector of shadow values that emerges in the application of Motzkin's theorem in Appendix A. When tariffs and carbon taxes are unconstrained, (B.4) then implies that $\sigma^j = \Omega_{u^j}/e^j_u$, so that the σ^j is the social marginal utility of income of country j; more precisely, σ^i/σ^j is the social marginal value of income in country i relative to that in country j.

cases.

Starting with the case in which carbon taxes and tariffs can be freely deployed in all countries:

Proposition 1 *At any Pareto-efficient allocation, constrained only by an inability to make explicit international lump sum transfers, there exists a vector*[17] $\boldsymbol{\sigma} \gg \mathbf{0}_J$ *such that:*

(a) The vector of carbon taxes in country j is given by

$$\sigma^j \mathbf{s}^j = \left(\sum_{i=1}^{J} \sigma^i e_k^i \right) \boldsymbol{\iota} \gg \mathbf{0}_{N \times 1} \, , \tag{8}$$

so that for all j, $\mathbf{s}^j = \left(\sum_{i=1}^{J} \theta^{ij} e_k^i \right) \boldsymbol{\iota}$, where $\theta^{ij} = \sigma^i / \sigma^j$, $j = 1, \ldots J$.

(b) The tariff vectors of any pair of countries j and i are collinear:

$$\boldsymbol{\tau}^j = \theta^{ij} \boldsymbol{\tau}^i, \;\; j, i = 1, \ldots, J \; . \tag{9}$$

Proof: See Appendix B. □

Part (a) is straightforward: Pareto efficiency requires that each country sets its carbon tax in each sector n to equate the implicit social value of the revenue it would lose from a small cut in its own emissions, $\sigma^j s_n^j$, to the sum of the marginal environmental benefits conveyed to all countries, $\sum_{i=1}^{J} \sigma^i e_k^i$. An immediate implication, since the marginal damage from emissions is the same whichever sector they originate in, is that each country should apply the same carbon tax to all activities: within each country, carbon taxes are optimally uniform across sectors. But while each country sets a single carbon tax rate, part (a) also shows that the level of that tax generally differs across countries. Recalling the informal interpretation of σ^j above, Pareto efficiency requires that more 'income-needy' countries impose lower carbon taxes. This is intuitively natural, and to the same effect as the results of Chichilnisky and Heal (1994) and Sandmo (2005, 2006)—and consistent too with much of the policy debate, which has emphasized the lesser ability of lower income countries to cope with aggressive carbon pricing.

Part (b), requiring collinear tariff vectors, is as in Keen and Wildasin (2004). The implication is that production efficiency—in the narrow sense of it being impossible to increase global output of any good without reducing the global output of some other—is generally not part of the solution. And there is generally production inefficiency in a broader sense too, when account is also taken of environmental concerns. Maximizing the net output of some good without either reducing the net output of another or increasing

[17]The notation $\mathbf{q} \gg \mathbf{0}$ means that all elements of the vector $\mathbf{q}$ are strictly positive.

global emissions requires that both producer prices $\mathbf{p}$ and carbon taxes $\mathbf{s}$ be equalized across countries. Proposition 1 points to violations on both of these margins (or neither): in each case, relative (implicit) 'welfare weights' shape the proportionality factor between the (sectorally uniform) carbon taxes and tariffs applied by each country. Keen and Wildasin (2004) discuss the potential rationale for production inefficiency at some length.[18] Broadly, production inefficiency may be called for when distributional concerns across countries cannot be pursued by direct transfers between them. Tariff policy can be used to similar end: combining an export subsidy in a less income-needy country A, for instance, with an import tariff in a more income-needy country B serves to transfer revenue from the former to the latter. Ensuring that such implicit transfers are well-targeted, however, may require differentiating those tariffs across countries (with perhaps an even larger import tariff in some even more income-needy country C—which implies production inefficiency.

Proposition 1 applies whether or not international transfers between countries can be deployed. If they can be then, of course, Pareto-efficiency requires equalizing the σ^j across all countries. The same may be true, however, even without international transfers: if there are more goods on which the tariff rates may be varied than there are countries (and sufficient rank in the corresponding matrix of net exports), then—as just described—offsetting tariffs can be designed so as to achieve any desired reallocation of tariff revenue between countries, with no need to distort production decisions (Keen and Wildasin (2004) and Turunen-Red and Woodland (2004)). These circumstances give the familiar textbook results: carbon taxes are then set at first best Pigovian levels, tariff policy has no role, and there is full production efficiency:

Proposition 2 *If there are no constraints on lump transfers between countries, or there are at least as many goods as countries (and an appropriate rank condition on the matrix of net exports is satisfied), then, at any Pareto-efficient allocation:*

(a) The vector of carbon taxes in every country j is given by

$$\mathbf{s}^j = \mathbf{s} = \left(\sum\nolimits_{i=1}^{J} e_k^i\right) \boldsymbol{\iota} \gg \mathbf{0}_{N\times 1},\ j = 1, \ldots, J\,, \tag{10}$$

and

(b) tariffs are zero in every country

$$\boldsymbol{\tau}^j = \mathbf{0}_{(N-1)\times 1},\ j = 1, \ldots, J\,. \tag{11}$$

Proof: See Appendix C. □

[18]While there are no environmental issues in their setting, the same general intuition applies here.

In the relatively unconstrained world of Propositions 1 and 2, there is thus an alignment of instruments with objectives that is straightforward and as expected: with international transfers dealing with distributional concerns, carbon taxes are addressed to the climate externality and are optimally uniform across both sectors and countries,[19] while tariffs—except in so far as they may be needed to substitute for explicit transfers—are redundant. Importantly for present purposes, there is nothing in Propositions 1 and 2 that is in the nature of a border tax adjustment: no sign, that is, of the efficient tariff in any country reflecting the difference between its own carbon tax and those of the other countries.[20] A case for BTA can thus arise only in more constrained circumstances. It is to this possibility that we now turn.

4 Pareto efficiency and the role of border tax adjustments

Suppose now—going to something of the opposite extreme to the circumstances of the previous section—that carbon taxes and tariffs can be freely set in some country h $(= 1$, in the two country case, referred to as 'unconstrained', and sometimes as 'home'), but everywhere else (in 'constrained' countries, abroad) are fixed at arbitrary levels. Specifically, we will have in mind in the informal discussion that carbon taxes in the latter—which may be sector-specific—are 'too low' (relative to the first-best Pigovian carbon-tax).

This is of course in itself an arbitrary restriction on the set of available instruments. But it is not without some resonance of the current climate debate. In particular, the accepted UNFCCC principle of 'common but differentiated responsibility',[21] has largely manifested itself in the view that advanced economies are to undertake much more significant mitigation measures than are emerging and developing countries. And the EU, for instance, has committed to undertake significant mitigation measures irrespective of action elsewhere. With the wider good at least cited as a rationale for such unilateral action, it is useful to know what such a policy might look like—and whether it would include a role for BTAs.

For clarity, it is useful to approach this question in two steps. Subsection 4.1 deals first with the case in which distributional issues can be dealt with by international lump-sum

[19] The same outcome would of course be achieved under a global cap-and-trade scheme, establishing a single global carbon price.

[20] In the latter case, of course, there is simply no difference in carbon taxes.

[21] United Nations Framework Convention on Climate Change; the reference is to Principle 1 of Article 3.

transfers. This, together with further standard simplifying assumptions, gives rise to some sharp results. Subsection 4.2 then turns to the more general and complex case.

4.1 Border tax adjustments in the absence of distributional concerns

It is useful to start with the relatively simple case, which gives a crisp result upon which some intuition can be built.

Proposition 3 *Suppose there are only two countries, 1 and 2, with carbon taxes and tariffs fixed at arbitrary levels in country 2 but unconstrained in country 1, that lump sum transfers between the two countries are unconstrained and that compensated demands for the non-numeraire commodities* $n = 2, ..., N$ *are independent of emissions (so that* $\mathbf{e}^{j}_{\mathbf{p}k} = \mathbf{0}_{(N-1)\times 1}$*). Then constrained Pareto efficiency requires that:*

(a) Carbon taxes in the unconstrained country 1 satisfy

$$\mathbf{s}^{1\prime} = \left(\sum\nolimits_{j=1}^{2} e^{j}_{k}\right)\boldsymbol{\iota}' \ , \tag{12}$$

and

(b) tariffs in country 1 satisfy

$$\boldsymbol{\tau}^{1\prime} = \boldsymbol{\tau}^{2\prime} + \left(\mathbf{s}^{1} - \mathbf{s}^{2}\right)'\mathbf{r}^{2}_{\mathbf{sp}}\left(\mathbf{e}^{2}_{\mathbf{pp}} - \mathbf{r}^{2}_{\mathbf{pp}}\right)^{-1} \ . \tag{13}$$

The proof of this will be seen to emerge as a special case of Proposition 5 below.

Now, and in the absence of emission effects through compensated demands (something we return to shortly below), the unconstrained carbon tax is set at its first-best Pigovian level. The unconstrained tariff $\boldsymbol{\tau}^{1}$ in (13), meanwhile, is doing two things. First, it is neutralizing the potential production inefficiency induced by the constrained tariff abroad: setting $\boldsymbol{\tau}^{1} = \boldsymbol{\tau}^{2}$ would ensure that producer prices in the two countries coincide. Second—and of most interest here—it is reflecting the difference in carbon taxes between the two countries, differing from zero only to the extent that the carbon tax abroad is not set at its first best level. This latter element of the Pareto efficient tariff is thus a form of border tax adjustment.

The nature of the BTA called for in Proposition 3 is though somewhat complex, reflecting the structure of the matrix[22] $\mathbf{r}^{2}_{\mathbf{sp}}$ and the price elasticity of net imports in the constrained

[22]This is Copeland's (1994) indicator of sectoral pollution intensity. The point here is also closely related to the observation of Lockwood and Whalley (2010) that a case for BTA can arise only when

country. The critical role played by $\mathbf{r}^2_{\mathbf{sp}}$ indicates that the essential rationale for the BTA is to manipulate producer prices $\mathbf{p}^2$ in the constrained country so as to affect emissions $-\mathbf{r}^2_s$ there: if $\mathbf{r}^2_{\mathbf{sp}} = \mathbf{0}_{N\times(N-1)}$, there is no possibility of doing so, and there is simply no collective case for a purposive tariff policy. This result, incidentally, provides an answer to one question that has lingered in the literature: whether the border tax adjustment should reflect technology in the adjusting country, abroad, or some mixture of the two: Proposition 3 shows that constrained Pareto efficiency requires that adjustment (both the tariff on imports and the refund on exports) be made by reference to the technology abroad (in the constrained country). The reason is straightforward: since it is inefficiency in emissions abroad that policy is intended to address, it is technology there which should shape that policy.

This enables the intuition underlying Proposition 3 to be developed more precisely in two ways, reflecting the dual interpretation of $\mathbf{r}^2_{\mathbf{sp}}$: as $\mathbf{r}^2_{\mathbf{sp}} = -\mathbf{z}^2_{\mathbf{p}}$, the interpretation just used, reflecting the impact of producer prices on emissions; and as $\mathbf{r}^2_{\mathbf{sp}} = \mathbf{y}^2_{\mathbf{s}}$, the impact of carbon prices on production.

For an interpretation along the first of these lines, suppose, for simplicity, that (in addition to the assumptions of the proposition) all carbon taxes and tariffs are zero in the constrained country, 2. Recalling that optimality requires that any conceivable marginal changes in policy have zero impact (given the availability of international transfers) on the sum of utilities, consider the particular policy of combining a change in world prices, and hence of producer prices in the constrained country, of $\mathbf{dw} = \mathbf{dp}^2$, with an offsetting change in the unconstrained tariff, $\mathbf{d}\boldsymbol{\tau}^1 = -\mathbf{dw}$. It can then be shown[23] (assuming for simplicity that $\mathbf{e}^2_{\mathbf{p}u} = \mathbf{e}^2_{\mathbf{p}k} = \mathbf{0}_{(N-1)\times 1}$) that the consequent change in global welfare is

$$e^1_u du^1 + e^2_u du^2 = -(e^1_k + e^2_k)dk - \boldsymbol{\tau}^{1\prime}\left(\mathbf{e}^2_{\mathbf{pp}} - \mathbf{r}^2_{\mathbf{pp}}\right)\mathbf{dp}^2 . \tag{14}$$

The first effect in (14) is simply the global social benefit of any reduction in country 2's emissions induced by the change in producer prices there. The second term is $-\boldsymbol{\tau}^{1\prime}\left(\mathbf{e}^2_{\mathbf{pp}} - \mathbf{r}^2_{\mathbf{pp}}\right) = -\boldsymbol{\tau}^{1\prime}\mathbf{dm}^2$, which in turn is equal, in equilibrium, to $\boldsymbol{\tau}^{1\prime}\mathbf{dm}^1$; this effect, reflecting the impact of the reform on the distortion of trade implied by the initial tariff structure, is thus harmful to the extent that it decreases 1's imports of goods that are subject to a positive tariff. Optimal policy implies balancing these two effects; which,

differential carbon taxes affect relative producer prices: otherwise the exchange rate (or domestic price level) will accommodate such differences automatically.

[23]By summing the two equations in (5), perturbing the result using (7) and holding both $\boldsymbol{\tau}^2$ and $\mathbf{s}^2$ constant at zero.

since $dk = \boldsymbol{\iota}'\mathbf{z}^2_{\mathbf{p}}\mathbf{dp}^2 = -\boldsymbol{\iota}'\mathbf{r}^2_{\mathbf{sp}}\mathbf{dp}^2$, requires

$$\boldsymbol{\tau}^{1\prime} = \left(e^1_k + e^2_k\right)\boldsymbol{\iota}'\mathbf{r}^2_{\mathbf{sp}}\left(\mathbf{e}^2_{\mathbf{pp}} - \mathbf{r}^2_{\mathbf{pp}}\right)^{-1} \quad . \tag{15}$$

And this, recalling part (a) of Proposition 3, is precisely as part (b) implies in this case. The kind of policy thus called for is a reduction in the producer price of 'dirty' goods in the constrained country, to discourage their production there, combined with a tariff that offsets the tendency for the unconstrained country to consequently import more of those dirty goods.

For the second interpretation, continue with the assumptions of the previous paragraph but suppose that country 2 now raises its carbon tax from zero to the Pigovian level, $e^1_k + e^2_k$, while holding its tariff unchanged at zero. If, in response, tariffs in country 1 are eliminated—as part (b) of Proposition 3 requires—and world prices adjusted to leave prices $\mathbf{p}^1$ unchanged, then the change in country 2's exports (to a linear approximation) is[24]

$$\mathbf{dm}^{2\prime} = \boldsymbol{\tau}^{1\prime}\left(\mathbf{e}^2_{\mathbf{pp}} - \mathbf{r}^2_{\mathbf{pp}}\right) - \left(e^1_k + e^2_k\right)\boldsymbol{\iota}'\mathbf{r}^2_{\mathbf{sp}} \, . \tag{16}$$

But then (15) implies that $\mathbf{dm}^2 = \mathbf{0}_{(N-1)\times 1}$. That is, a collective policy response consistent with Proposition 3 leaves country 2's exports (roughly) unaffected. Turning the point the other way: the collectively efficient tariff policy undoes (to a first approximation) the trade impact of any country setting its carbon taxes away from the Pigovian level.

While Proposition 3 calls for what is recognizably a form of BTA—conditioning the unconstrained tariff directly on the difference in carbon tax rates between the two countries—it is substantially more complex than the type of BTA envisaged in practical discussions. As noted above, in principle it is necessary to adjust the difference in carbon taxes to reflect the elasticities of output with respect to carbon taxes abroad and the price elasticities of foreign net imports. In practice, what is commonly in mind is a more mechanical calculation (perhaps the only type with any hope of verifiability) of charging imports (and refunding on exports) an amount equal to the shortfall of the carbon tax actually paid abroad, directly and indirectly, relative to that which would have been paid had the home country carbon tax been applied. To express this in the present notation, denote by $\mathbf{B}^2\left(\mathbf{p}^2, \mathbf{s}^2\right)$ the $N \times (N-1)$ matrix whose typical element b_{nl} denotes the production of good n required, in country 2, per unit of output of non-numeraire good l, and by $\boldsymbol{\Phi}^2$ the $N \times N$ diagonal matrix whose element ϕ_n gives carbon emissions per unit of gross output (assumed constant). Then the mechanical BTA just described corresponds to the

[24] This follows from $\mathbf{dp}^1 = \mathbf{dw} = -\,\mathbf{d}\boldsymbol{\tau}^1 = \boldsymbol{\tau}^1$, and $\mathbf{ds}^2 = \left(e^1_k + e^2_k\right)\boldsymbol{\iota}$ (as well as the temporary assumption that $\mathbf{e}^2_{\mathbf{p}u} = \mathbf{e}^2_{\mathbf{p}k} = \mathbf{0}_{(N-1)\times 1}$).

vector

$$\boldsymbol{\gamma}' = \left(\mathbf{s}^1 - \mathbf{s}^2\right)' \boldsymbol{\Phi}^2 \mathbf{B}^2 \left(\mathbf{p}^2, \mathbf{s}^2\right) \ , \tag{17}$$

whose elements give the amount by which the carbon tax paid per unit of output in country 2 falls short of that which would have been paid, given the production techniques used in country 2, had the carbon tax rates of country 1 been applied.

To relate this to the more complex form of BTA called for by Proposition 3, write emissions in country 2 as

$$\mathbf{z}^2 = -\mathbf{r}_s^2 \left(\mathbf{p}^2, \mathbf{s}^2\right) = \boldsymbol{\Phi}^2 \mathbf{B}^2 \left(\mathbf{p}^2, \mathbf{s}^2\right) \mathbf{r}_{\mathbf{p}}^2 \left(\mathbf{p}^2, \mathbf{s}^2\right) \ . \tag{18}$$

Assuming emissions per unit of output to be constant, differentiating (18), using Proposition 93 of Dhyrmes (1978), gives

$$-\mathbf{r}_{\mathbf{sp}}^2 = \boldsymbol{\Phi}^2 \left[\mathbf{B}^2 \, \mathbf{r}_{\mathbf{pp}}^2 + \boldsymbol{\Delta}^2 \, \mathbf{B}_{\mathbf{p}}^2\right] \ , \tag{19}$$

where $\boldsymbol{\Delta}^2 \equiv \mathbf{r}_{\mathbf{p}}^{2\prime} \otimes \mathbf{I}_N$ and $\mathbf{B}_{\mathbf{p}}^2 = \partial \text{vec}(\mathbf{B}^2) / \partial \mathbf{p}^2$. Substituting (19) into (13) and recalling (17), the BTA of Proposition 3 can then also be written as[25]

$$\boldsymbol{\tau}^{1\prime} = \boldsymbol{\tau}^{2\prime} + \boldsymbol{\gamma}' - \left(\mathbf{s}^1 - \mathbf{s}^2\right)' \boldsymbol{\Phi}^2 \left[\mathbf{B}^2 \mathbf{e}_{\mathbf{pp}}^2 + \boldsymbol{\Delta}^2 \mathbf{B}_{\mathbf{p}}^2\right] \left(\mathbf{e}_{\mathbf{pp}}^2 - \mathbf{r}_{\mathbf{pp}}^2\right)^{-1} \ . \tag{20}$$

The constrained Pareto-efficient BTA thus requires two adjustments to the mechanical form of BTA in (17) based on technology abroad, to allow for the impact on emissions that a change in prices abroad may have through changes in both patterns of input use (through $\mathbf{B}_{\mathbf{p}}^2$) and/or demand (through $\mathbf{e}_{\mathbf{pp}}^2$).

It follows immediately from (20) that:

Proposition 4 *In the circumstances of Proposition 3, if emissions per unit of output are constant, there are no substitution effects in demand between non-numeraire commodities ($\mathbf{e}_{\mathbf{pp}}^2 = \mathbf{0}_{(N-1)\times(N-1)}$), and required inputs of goods per unit of output are fixed ($\mathbf{B}_{\mathbf{p}}^2 = \mathbf{0}_{N(N-1)\times(N-1)}$) then constrained Pareto efficiency requires that:*

$$\boldsymbol{\tau}^1 = \boldsymbol{\tau}^2 + \gamma \, . \tag{21}$$

Here then is a case in which collectively efficient policy has a remarkably simple form. The unconstrained carbon tax should be set at the first-best Pigovian level and the border tax adjustment should take the form of a countervailing charge on imports (and refund on exports) corresponding mechanically to the tax 'under-paid' in the foreign country.

[25] Making also use of the fact that $\left(\mathbf{e}_{\mathbf{pp}}^2 - \mathbf{r}_{\mathbf{pp}}^2\right)\left(\mathbf{e}_{\mathbf{pp}}^2 - \mathbf{r}_{\mathbf{pp}}^2\right)^{-1} = \mathbf{I}_{N-1}$ implies $-\mathbf{r}_{\mathbf{pp}}^2 \left(\mathbf{e}_{\mathbf{pp}}^2 - \mathbf{r}_{\mathbf{pp}}^2\right)^{-1} = \mathbf{I}_{N-1} - \mathbf{e}_{\mathbf{pp}}^2 \left(\mathbf{e}_{\mathbf{pp}}^2 - \mathbf{r}_{\mathbf{pp}}^2\right)$.

One important difference from common proposals, however, is that, to the extent that technologies differ between the two countries, the rebate on exports will generally not equal the carbon tax paid at home.

Proposition 4 rests on simplifying assumptions. It does suggest, nevertheless, that—conceptually at least—proposals for border adjusting carbon taxes commonly encountered in policy discussion are not wholly misplaced, from the perspective of global efficiency at least. While that broad truth remains, its precise form becomes much more complicated under more general conditions, as is taken up next.

4.2 Border tax adjustments in the general case

Reverting to the general case in which explicit international transfers cannot be deployed, there are many countries and pollution may affect commodity demands, efficient carbon tax and tariff structures are substantially more complex:

Proposition 5 *Suppose that carbon taxes and tariffs are freely variable in country h but are taken as fixed elsewhere. Then at any constrained Pareto efficient allocation there exists a vector $\boldsymbol{\sigma} \gg \mathbf{0}_J$ such that:*

(a) Carbon taxes in h are given by

$$\sigma^h \mathbf{s}^{h\prime} = \left\{ \sum\nolimits_{j=1}^{J} \sigma^j e_k^j + \sum\nolimits_{j \neq h}^{J} \left(\sigma^h \boldsymbol{\tau}^h - \sigma^j \boldsymbol{\tau}^j \right)' \mathbf{e}_{\mathbf{p}k}^j \right\} \boldsymbol{\iota}', \tag{22}$$

and

(b) tariffs in h are such that

$$\begin{aligned} \sigma^h \boldsymbol{\tau}^{h\prime} \;&=\; -\sum\nolimits_{j=1}^{J} \sigma^j \mathbf{m}^{j\prime} \left(\mathbf{Q}^h \right)^{-1} + \sum\nolimits_{j \neq h}^{J} \sigma^j \boldsymbol{\tau}^{j\prime} \mathbf{m}_{\mathbf{p}}^j \left(\mathbf{Q}^h \right)^{-1} \\ &\quad + \sum\nolimits_{j \neq h}^{J} \left(\sigma^h \mathbf{s}^h - \sigma^j \mathbf{s}^j \right)' \mathbf{r}_{\mathbf{sp}}^j \left(\mathbf{Q}^h \right)^{-1}, \end{aligned} \tag{23}$$

where $\mathbf{Q}^h \equiv \sum_{j \neq h}^{J} \mathbf{m}_{\mathbf{p}}^j$.

Proof: See Appendix D. □

As anticipated earlier, the simpler Proposition 3 above emerges as a special case of this on setting $\sigma^j = \sigma$, $\mathbf{e}_{\mathbf{p}k}^j = \mathbf{0}_{(N-1)\times 1}$ for all j, and, recalling (7), noting that with only two countries the first two terms on the right of (23) reduce to $\boldsymbol{\tau}^j$.

For the interpretation of Proposition 5 itself, consider first part (a). As one might expect (and in line with Proposition 1), with distributional concerns again present the carbon tax to be set in any unconstrained country reflects the welfare-weighted rather than the simple sum of the marginal climate damages suffered by others. But a new consideration also now arises (the last term in (22)), with efficiency requiring a recognition the carbon tax set in h, by affecting emissions and hence demand structures in the constrained countries, impacts distortions associated with the tariffs set there. To the extent, for instance, that the fall in emissions implied by increasing the carbon tax in h increases demand in some constrained country j for goods that tariff distortions imply are under-imported there (the tariff imposed by country j being lower than any export subsidy imposed by country h—both adjusted by the corresponding implicit welfare weights), so that $\left(\sigma^h \boldsymbol{\tau}^h - \sigma^j \boldsymbol{\tau}^j\right)' e^j_{\mathbf{p}k} \boldsymbol{\iota}' > \mathbf{0}'_{1\times N}$, this calls for $\mathbf{s}^h$ to be set higher than would otherwise be the case. In this way, the unconstrained carbon tax is used to reduce the distortions associated with imperfections of collective tariff policies. If, for example, a warming in climate leads in country j to increase demand for heating equipment that is subject to a large import tariff, this becomes an argument for a lower carbon tax in country h.

One other aspect of part (a) bears emphasis: since it implies that $\mathbf{s}^h$ is collinear with $\boldsymbol{\iota}$, the carbon tax in the unconstrained country h should be uniform across sectors, whether or not it is uniform in the constrained countries. The best way to respond, if need be, to sectoral differentiation abroad, is through the tariff structure. The proper task of the carbon tax is to address inefficiencies in the aggregate level of emissions.

For the characterization of efficient tariff policies in part (b), the novelties relative to Proposition 3 all come from the presence of distributional concerns. The first term on the right of (23) relates to the distributional impact of terms of trade effects associated with varying tariffs in country h (vanishing if international lump sum transfers can be deployed) and the second to the interaction with tariff distortions abroad. Of most interest here is the final term, $\sum_{j\neq h}^{J} \left(\sigma^h \mathbf{s}^h - \sigma^j \mathbf{s}^j\right)' \mathbf{r}^j_{\mathbf{sp}} \left(\mathbf{Q}^h\right)^{-1}$. This is a BTA in the broad sense defined in the introduction and discussed after Proposition 3, but now with carbon taxes weighted by implicit income neediness, σ^j. Loosely speaking, in the absence of international transfers, more weight is attached to the real income loss that carbon taxation causes in more income-needy countries, so that constrained Pareto efficiency requires border tax adjusting in a way which pretends that poorer countries have higher carbon taxes than is actually the case.

There is no entirely sharp targeting of instruments to objectives in Proposition 5: when international transfers cannot be made, tariff and carbon tax policies become closely intertwined. There are, nevertheless fairly clearly-defined rules for the two. Carbon taxes are addressed to global climate change and an interaction, through demand effects, with tariff distortions; and tariffs are set with an eye partly to BTA, along the lines discussed above, and partly to engineering distributionally-judicious movements in terms of trade.

5 Further discussion

This section compares the results above to those of Markusen (1975) for the non-cooperative case and asks how the case for BTA is affected when countries use not carbon taxes but cap-and-trade systems.

5.1 Comparison with non-cooperative policies

While the focus of this paper is on cooperative policy-making, the framework is sufficiently general to encompass the (much more studied) case in which the choice of carbon tax and tariff policies of country h are motivated by national interest (as in, for example, Markusen (1975) and Panagariya *et al.* (2004)). This can be done—taking again country h to be the unconstrained country—simply by setting $\sigma^j = 0$ for all $j \neq h$ in Proposition 5 (as a simple device for attaching no weight to welfare in countries other than h). Proceeding in this way, Proposition 5 implies that carbon taxes satisfy

$$\mathbf{s}^{h\prime} = e_k^h \boldsymbol{\iota}' + \boldsymbol{\tau}^{h\prime} \sum\nolimits_{l \neq h}^{J} \mathbf{e}_{\mathbf{p}k}^{l} \boldsymbol{\iota}', \tag{24}$$

and tariff policies are set such that

$$\boldsymbol{\tau}^{h\prime} = \left[-\mathbf{m}^{h\prime} + e_k^h \sum\nolimits_{l \neq h}^{J} \left(\boldsymbol{\iota}' \mathbf{r}_{\mathbf{sp}}^{l} \right) \right] \left(\mathbf{Q}^h \right)^{-1} . \tag{25}$$

Equations (24) and (25) are the many-country counterparts of Markusen (1975)—see, in particular, his equation (15). The unilateral response of country h (to carbon pricing and tariff policies in other countries) in other countries thus has some common features with the cooperative one in Proposition 5. In each case, the carbon tax is set with a view to the impact of the induced change in global emissions on demand patterns abroad, and hence on domestic trade distortions, and in each case tariff policy reflects terms of trade impacts. The two main differences are as one would expect: in the cooperative case, the carbon tax reflects global damage from emissions, not simply national; and terms of trade impacts, along with interactions with existing tariff structures, are assessed not by the interests of the national economy alone but by the implicit welfare weights of all countries.

5.2 Border tax adjustment and cap-and-trade

It has been assumed so far that the climate instruments deployed, if any, are carbon taxes. An alternative, however, is cap-and-trade: not levying a charge directly on emissions, but instead issuing a fixed number of tradable emission rights. This alternative is of considerable practical importance, perhaps even more so than carbon taxation: it is schemes of this kind that have been adopted by the EU and which have made most headway in the U.S. The question is whether the conclusions above continue to apply when the instrument of climate policy is not a carbon tax, but national-level cap-and-trade.[26]

The essence of the results in Section 3—when instrument choice is unconstrained—clearly apply essentially unchanged. This is a simple consequence of the familiar equivalence, under perfect certainty[27] (as assumed here) of carbon taxation and cap-and-trade,[28] and of the result above that sectoral differentiation of carbon taxation (which could not be replicated by permits tradable between sectors) cannot be part of a Pareto-efficient allocation: analogues of Propositions 1 and 2 thus hold with the characterizations of carbon taxes reinterpreted as characterizing emissions caps in terms of the associated shadow value of emissions. (Whether the pollution permits are auctioned or allocated free of charge, critical in practice, is immaterial here, given the lump sum return of any revenues raised).

What though if, as in the earlier discussion, the instrument choice is constrained in some country? For brevity, again assume, as in Subsection 4.1, just two countries, with lump-sum transfers between them available.[29]

If the constrained country uses carbon taxation, Propositions 3-5 continue to apply even if the unconstrained uses cap-and-trade, since any allocation that can be achieved when it uses carbon taxation—as above—can be replicated by instead fixing the corresponding level of domestic emissions as the cap in a trading scheme.

Matters are very different, however, if the constrained country uses cap-and-trade. For then policies adopted in the unconstrained country can have no impact on emissions in the constrained country.[30] Since the sole rationale of BTA in the cooperative case is to

[26] A global cap-and-trade scheme would of course imply a globally uniform emissions price, obviating any question of border tax adjustment.

[27] There is large literature on the choice between taxation and cap-and-trade under uncertainty: see, for instance, Pizer (2002) and Aldy *et al.* (2010).

[28] More precisely, the important point for present purposes is that any allocation which can be supported with a uniform carbon tax in some country can also be supported as an equilibrium in which that country adopts a cap-and-trade scheme. To see this, note that a uniform carbon tax at rate $\mathbf{s}^h$ in country h generates total emissions there of $z^h = -\boldsymbol{\iota}'\mathbf{r}^h_{\mathbf{s}}\left(\mathbf{p}^h, \mathbf{s}^h\right)$. Reinterpreting this as the market-clearing condition for the trading of emission rights in a cap-and-trade scheme, the assumed non-singularity of $\mathbf{r}^h_{\mathbf{ss}}$ implies that setting any level of emissions generated by a uniform carbon tax as the cap in an emissions trading scheme (and maintaining all tariffs and carbon prices elsewhere unchanged) will generate an equilibrium carbon price exactly equal to that carbon tax; and it is clear that the equilibrium condition (5) and (7) will also be satisfied at unchanged tariffs.

[29] We omit proofs of the claims that follow: these are straightforward once the structure of Section 2 is reformulated in terms of emission levels rather than carbon taxes.

[30] So long, that is, as the emission cap there is binding. It could in principle be that in some efficient

manipulate emissions in the constrained country, it can in this case serve no purpose. The point that quantity restrictions in one country powerfully affect the implications of trade reform in others is a familiar one: see for instance Copeland and Taylor (2005, pp. 123), Falvey (1988) and, closest to the present context, Copeland (1994). The implications do not seem to have been recognized, however, in the context of BTAs: the collective case for such adjustment depends not only on the level of carbon prices abroad but also on the way in which any carbon pricing there is implemented.

6 Concluding remarks

This paper has explored the interplay between climate- and trade-related instruments in forming globally efficient responses to climate change. An inability to make lump sum transfers, as Sandmo (2004, 2005) has shown, generally makes non-uniform (across countries) carbon pricing Pareto efficient. One role that then emerges for tariff policies is in easing these constraints by serving as a surrogate transfer device. A second potential role, much closer to the terms of the current policy debate, and on which most of the analysis has focused, is in mitigating the distortions that arise from these cross-country differences in carbon prices. The results here have identified circumstances in which global efficiency does indeed require some form of BTA—as well as others in which it does not—and has characterized the form of adjustment needed.

The first role emerges most clearly when there are no constraints on the rates at which carbon taxes (or emission levels under cap-and-trade schemes) and tariffs can be set, but international transfers are ruled out. The implications of Pareto-efficiency are then straightforward: carbon prices should be uniform across sectors within countries (or permits tradable across them), but constrained Pareto efficiency generally requires that they differ across countries: broadly speaking, they are lower in countries for which the implicit equity welfare weights associated with the allocation being described are higher. This is a quite different role from that of responding to distortions arising from the differences in carbon prices.

The second purposive role for tariff policy, including an element of BTA, emerges when climate policies are constrained in some countries that undertake their mitigation through carbon taxes (perhaps of zero). It then remains optimal to set those carbon prices that can be deployed freely—whether explicitly by taxation or implicitly by cap-and-trade—in line with (a simple modification of) the Pigou rule. Tariffs in such countries should now

allocations the unconstrained country sets its tariffs so as to drive emissions abroad below the cap. In that case, the situation in the constrained country is the same, at the margin, as if it set a carbon tax of zero; and so the earlier results for that case apply.

reflect the cross-country differences in carbon prices this implies, the purpose being to induce changes in the producer prices faced by firms abroad that go some way towards offsetting the impact of inadequacies (from the collective perspective) of carbon pricing there; or, equivalently, to undo the impact of those inadequacies on trade flows. The results here fully characterize the BTA required. This, in general, requires weighting the shortfall in carbon taxes in the constrained country (relative to the modified-Pigovian price charged in the unconstrained) by the carbon-price responsiveness of outputs and the price elasticity of exports in the former and, when international transfers cannot be deployed, treating poorer—more exactly, those with a high implicit welfare weight at the particular constrained Pareto efficient allocation being characterized—as if they had higher carbon taxes than is in fact the case. The analysis has also identified, however, one special but instructive case in which the required BTA takes precisely the simple form—as envisaged in practical policy debate and proposals—of a charge on imports (and rebate on exports) equal to the carbon tax 'not paid' abroad.

A case for BTA thus emerges only in terms of cooperative policy making—as previous results have shown, and as noted above, there being no such case when climate and tariff policies are set in terms of national self-interest—and, even then, only given restrictions on the ability to freely deploy climate and trade policies in some countries. Views may differ on the importance of such circumstances, though they do to some degree echo the realities that UNFCCC principles mean that strong mitigation actions are most expected of advanced countries, and that many countries invoke the rhetoric of the collective good in rationalizing their actions and proposals.

It has also been seen, however, that collective efficiency does not call for any form of BTA if it is (binding) cap-and-trade policies, not carbon taxation, that is the constrained instrument—a point of some importance as cap-and-trade seems, increasingly, to be the preferred instrument in practice. The reason is straightforward: emissions in countries using such schemes cannot be affected by policies elsewhere. While there has been some discussion of the practical differences between implementing BTAs under carbon taxes and cap-and-trade, the wider point that the underlying economic case for adjustment is entirely different in the two cases—and, in terms of collective efficiency, much weaker under cap-and-trade—seems not to have been recognized.

The analysis here is of course severely limited in several respects. Factors have been assumed immobile, for example, precluding the possibility of carbon leakage through location choices that is a major concern in policy debates. And assessing the quantitative significance of the results above—the likely magnitude (and distribution) of the welfare gains from the constrained efficient BTA of Proposition 4, for instance, and the extent to which they can be realized by the simpler form of BTA found in practical proposals—is left to future work. What the analysis here does establish, however, is that while practical proposals are no doubt ultimately driven primarily by some notion of national (or sectoral) self-interest, an inability to deploy a full set of instruments in all countries can create a conceptual case for the use of BTAs along broadly the lines often proposed—in relation to carbon taxes, but not cap-and-trade—in the more appealing terms of global efficiency.

Appendices

Appendix A: Necessary conditions for Pareto efficiency

Perturbing (5), using (1), $\mathbf{p}^j = \mathbf{w} + \boldsymbol{\tau}^j$ and recalling that $\mathbf{r}_{\mathbf{s}}^j = -\mathbf{z}^j$, gives

$$\lambda_u^j du^j - \boldsymbol{\lambda}_{\mathbf{w}}^{j\prime}\,\mathbf{dw} - \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{j\prime}\mathbf{d}\boldsymbol{\tau}^j - \sum\nolimits_{i \neq j}^{J} \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{j/i\prime} \boldsymbol{d\tau}^i - \boldsymbol{\lambda}_{\mathbf{s}}^{j\prime}\mathbf{ds}^j - \sum\nolimits_{i \neq j}^{J} \boldsymbol{\lambda}_{\mathbf{s}}^{j/i\prime}\mathbf{ds}^i = 0 \quad j = 1, ..., J, \quad \text{(A.1)}$$

where

$$\begin{aligned}
\lambda_u^j &\equiv e_u^j - \boldsymbol{\tau}^{j\prime}\mathbf{e}_{\mathbf{p}u}^j \,, && \text{(A.2)}\\
-\lambda_{\mathbf{w}}^{j\prime} &\equiv \mathbf{m}^{j\prime} + \lambda_k^j \sum\nolimits_{l=1}^{J}\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^l\right) + \mathbf{s}^{j\prime}\mathbf{r}_{\mathbf{sp}}^j - \boldsymbol{\tau}^{j\prime}\mathbf{m}_{\mathbf{p}}^j \,, && \text{(A.3)}\\
-\lambda_{\boldsymbol{\tau}}^{j\prime} &\equiv \lambda_k^j\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^j\right) + \mathbf{s}^{j\prime}\mathbf{r}_{\mathbf{sp}}^j - \boldsymbol{\tau}^{j\prime}\mathbf{m}_{\mathbf{p}}^j, && \text{(A.4)}\\
-\lambda_{\boldsymbol{\tau}}^{j/i\prime} &\equiv \lambda_k^j\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^i\right) \,, && \text{(A.5)}\\
-\lambda_{\mathbf{s}}^{j\prime} &\equiv \lambda_k^j\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{ss}}^j\right) + \mathbf{s}^{j\prime}\mathbf{r}_{\mathbf{ss}}^j + \boldsymbol{\tau}^{j\prime}\mathbf{r}_{\mathbf{ps}}^j \,, && \text{(A.6)}\\
-\lambda_{\mathbf{s}}^{j/i\prime} &\equiv \lambda_k^j\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{ss}}^i\right) \,, && \text{(A.7)}\\
\lambda_k^j &= e_k^j - \boldsymbol{\tau}^{j\prime}\mathbf{e}_{\mathbf{p}k}^j \,, && \text{(A.8)}
\end{aligned}$$

with (A.5) and (A.7) referring to the effects on country j of changes in carbon taxes and tariffs in all other countries.

Perturbing equations (7) gives

$$\sum\nolimits_{j=1}^{J} \mathbf{e}_{\mathbf{p}u}^j du^j = \boldsymbol{\pi}_{\mathbf{pp}}\mathbf{dw} + \sum\nolimits_{j=1}^{J} \boldsymbol{\pi}_{\mathbf{pp}}^j \boldsymbol{d\tau}^j + \sum\nolimits_{j=1}^{J} \boldsymbol{\pi}_{\mathbf{ps}}^j \mathbf{ds}^j \,, \quad \text{(A.9)}$$

where

$$\begin{aligned}
-\boldsymbol{\pi}_{\mathbf{pp}} &\equiv \sum\nolimits_{j=1}^{J}\left\{\mathbf{m}_{\mathbf{p}}^j + \mathbf{e}_{\mathbf{p}k}^j \sum\nolimits_{l=1}^{J}\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^l\right)\right\} \,, && \text{(A.10)}\\
-\boldsymbol{\pi}_{\mathbf{pp}}^j &\equiv \mathbf{m}_{\mathbf{p}}^j + \sum\nolimits_{l=1}^{J} \mathbf{e}_{\mathbf{p}k}^l\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^j\right) \,, && \text{(A.11)}\\
-\boldsymbol{\pi}_{\mathbf{ps}}^j &\equiv -\mathbf{r}_{\mathbf{ps}}^j + \sum\nolimits_{l=1}^{J} \mathbf{e}_{\mathbf{p}k}^l\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{ss}}^j\right) \,. && \text{(A.12)}
\end{aligned}$$

Perturbing also (4) and stacking the results along with (A.1) for all countries j and (A.9) gives the system

$$\boldsymbol{\Lambda}_{\mathbf{u}}\mathbf{du} - \boldsymbol{\Lambda}_{\mathbf{w}}\mathbf{dw} - \boldsymbol{\Lambda}_{\boldsymbol{\tau}}\mathbf{d}\boldsymbol{\tau} - \boldsymbol{\Lambda}_{\mathbf{s}}\mathbf{ds} - \boldsymbol{\Lambda}_{\alpha}\mathbf{d}\alpha = \mathbf{0}_{(J+2N-1)\times 1} \,, \quad \text{(A.13)}$$

where the matrices $\mathbf{\Lambda_u}, \mathbf{\Lambda_w}, \mathbf{\Lambda_\tau}, \mathbf{\Lambda_s}$ are given by

$$\mathbf{\Lambda_u} = \begin{bmatrix} \lambda_u^1 & 0 & \cdots & 0 \\ 0 & \lambda_u^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_u^J \\ \mathbf{e}_{\mathbf{p}u}^1 & \mathbf{e}_{\mathbf{p}u}^2 & \cdots & \mathbf{e}_{\mathbf{p}u}^J \\ & \mathbf{0}_{N\times J} & & \end{bmatrix} \mathbf{du} = \begin{bmatrix} du^1 \\ du^2 \\ \vdots \\ du^J \end{bmatrix}$$

$$\mathbf{\Lambda_w} \equiv \begin{bmatrix} \boldsymbol{\lambda}_{\mathbf{w}}^{1\prime} \\ \vdots \\ \boldsymbol{\lambda}_{\mathbf{w}}^{J\prime} \\ \boldsymbol{\pi}_{\mathbf{pp}} \\ \mathbf{0}_{N\times(N-1)} \end{bmatrix} \mathbf{dw} \equiv \begin{bmatrix} dw_2 \\ dw_3 \\ \vdots \\ dw_N \end{bmatrix}$$

$$\mathbf{\Lambda_\tau} \equiv \begin{bmatrix} \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{1\prime} & \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{1/2\prime} & \cdots & \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{1/J\prime} \\ \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{2/1\prime} & \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{2\prime} & \cdots & \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{2/J\prime} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{J/1\prime} & \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{J/2\prime} & \cdots & \boldsymbol{\lambda}_{\boldsymbol{\tau}}^{J\prime} \\ \boldsymbol{\pi}_{\mathbf{pp}}^1 & \boldsymbol{\pi}_{\mathbf{pp}}^2 & \cdots & \boldsymbol{\pi}_{\mathbf{pp}}^J \\ & \mathbf{0}_{N\times J(N-1)} & & \end{bmatrix} \mathbf{d}\boldsymbol{\tau} = \begin{bmatrix} \mathbf{d}\boldsymbol{\tau}^1 \\ \mathbf{d}\boldsymbol{\tau}^2 \\ \vdots \\ \mathbf{d}\boldsymbol{\tau}^J \end{bmatrix}$$

$$\mathbf{\Lambda_s} \equiv \begin{bmatrix} \boldsymbol{\lambda}_{\mathbf{s}}^{1\prime} & \boldsymbol{\lambda}_{\mathbf{s}}^{1/2\prime} & \cdots & \boldsymbol{\lambda}_{\mathbf{s}}^{1/J\prime} \\ \boldsymbol{\lambda}_{\mathbf{s}}^{2/1\prime} & \boldsymbol{\lambda}_{\mathbf{s}}^{2\prime} & \cdots & \boldsymbol{\lambda}_{\mathbf{s}}^{2/J\prime} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{\lambda}_{\mathbf{s}}^{J/1\prime} & \boldsymbol{\lambda}_{\mathbf{s}}^{J/2\prime} & \cdots & \boldsymbol{\lambda}_{\mathbf{s}}^{J\prime} \\ \boldsymbol{\pi}_{\mathbf{ps}}^1 & \boldsymbol{\pi}_{\mathbf{ps}}^2 & \cdots & \boldsymbol{\pi}_{\mathbf{ps}}^J \\ & \mathbf{0}_{N\times JN} & & \end{bmatrix} \mathbf{ds} \equiv \begin{bmatrix} \mathbf{ds}^1 \\ \mathbf{ds}^2 \\ \vdots \\ \mathbf{ds}^J \end{bmatrix}$$

$$\mathbf{\Lambda}_{\boldsymbol{\alpha}} \equiv \begin{bmatrix} -\mathbf{w}' & \mathbf{0}' & \cdots & \mathbf{0}' \\ \mathbf{0}' & -\mathbf{w}' & \cdots & \mathbf{0}' \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0}' & \mathbf{0}' & \cdots & -\mathbf{w}' \\ \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{0}} \\ \mathbf{I}_N & \mathbf{I}_N & \cdots & \mathbf{I}_N \end{bmatrix} \mathbf{d}\boldsymbol{\alpha} \equiv \begin{bmatrix} \mathbf{d}\boldsymbol{\alpha}^1 \\ \mathbf{d}\boldsymbol{\alpha}^2 \\ \vdots \\ \mathbf{d}\boldsymbol{\alpha}^J \end{bmatrix} . \tag{A.14}$$

Notice that $\mathbf{\Lambda_u}$ is of dimension $(J+2N-1)\times J$, $\mathbf{\Lambda_w}$ of dimension $(J+2N-1)\times(N-1)$, $\mathbf{\Lambda_\tau}$ of $(J+2N-1)\times J(N-1)$, $\mathbf{\Lambda_s}$ of dimension $(J+2N-1)\times JN$ and $\mathbf{\Lambda}_\alpha$ of dimension $(J+2N-1)\times JN$.

The analysis that follows uses Motzkin's theorem of the Alternative, which states (Mangasarian (1969), p.29) that for a system of the form in (A.13) either there exists $\mathbf{du} \geq \mathbf{0}_{J\times 1}$ and $\mathbf{dw}$ such that $\mathbf{\Lambda_u du} + \mathbf{Ddx} = \mathbf{0}$ or there exists $\mathbf{y}$ such that

$$\mathbf{y}'\mathbf{\Lambda_u} \gg \mathbf{0}'_{1\times J} , \tag{A.15}$$
$$\mathbf{y}'\mathbf{D} = \mathbf{0}' . \tag{A.16}$$

The focus is thus on solutions to necessary conditions for Pareto-efficiency of the form $\mathbf{y}'\mathbf{D}^* = \mathbf{0}'$ where $\mathbf{D}^*$ is the submatrix of $\mathbf{D}$ corresponding to whichever of the instruments in $\mathbf{dx}$ may be deployed. For this is helpful to partition the vector $\mathbf{y}' = (\boldsymbol{\sigma}', \mathbf{v}', \omega')$ conformably with the block structure of the matrices in (A.13). Starting from a tight equilibrium, it is required that $\boldsymbol{\sigma} \gg \mathbf{0}_{J\times 1}$. □

Appendix B: Proof of Proposition 1

With $\mathbf{w}, \boldsymbol{\tau}$ and $\mathbf{s}$ freely available, the conditions $\mathbf{y}'\boldsymbol{\Lambda}_{\mathbf{w}} = \mathbf{0}'$, $\mathbf{y}'\boldsymbol{\Lambda}_{\boldsymbol{\tau}} = \mathbf{0}'$ and $\mathbf{y}'\boldsymbol{\Lambda}_{\mathbf{s}} = \mathbf{0}'$ imply, respectively, that

$$\sum\nolimits_{j=1}^{J} \sigma^j \left\{\mathbf{m}^{j\prime} + \lambda_k^j \sum\nolimits_{l=1}^{J} \left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^l\right) + \mathbf{s}^{j\prime}\mathbf{r}_{\mathbf{sp}}^j - \boldsymbol{\tau}^{j\prime}\mathbf{m}_{\mathbf{p}}^j\right\} + \mathbf{v}'\left\{\sum\nolimits_{j=1}^{J}\left[\mathbf{m}_{\mathbf{p}}^j + \mathbf{e}_{\mathbf{p}k}^j \sum\nolimits_{l=1}^{J}\left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^l\right)\right]\right\} = \mathbf{0}'_{1\times(N-1)} \,, \tag{B.1}$$

$$\sigma^j \left\{\lambda_k^j \left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^j\right) + \mathbf{s}^{j\prime}\mathbf{r}_{\mathbf{sp}}^j - \boldsymbol{\tau}^{j\prime}\mathbf{m}_{\mathbf{p}}^j\right\} + \sum\nolimits_{l\neq j}^{J} \sigma^l \lambda_k^l \left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^j\right) + \mathbf{v}'\left\{\mathbf{m}_{\mathbf{p}}^j + \sum\nolimits_{l=1}^{J} \mathbf{e}_{\mathbf{p}k}^l \left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{sp}}^j\right)\right\} = \mathbf{0}'_{1\times(N-1)} \,, \quad j = 1, \dots J \,, \tag{B.2}$$

$$\sigma^j \left\{\lambda_k^j \left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{ss}}^j\right) + \mathbf{s}^{j\prime}\mathbf{r}_{\mathbf{ss}}^j + \boldsymbol{\tau}^{j\prime}\mathbf{r}_{\mathbf{ps}}^j\right\} + \sum\nolimits_{l\neq j}^{J} \sigma^l \lambda_k^l \left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{ss}}^j\right) + \mathbf{v}'\left\{-\mathbf{r}_{\mathbf{ps}}^j + \sum\nolimits_{l=1}^{J} \mathbf{e}_{\mathbf{p}k}^l \left(-\boldsymbol{\iota}'\mathbf{r}_{\mathbf{ss}}^j\right)\right\} = \mathbf{0}'_{1\times N} \,, \quad j = 1, \dots J \,. \tag{B.3}$$

Post-multiplying (B.3) by $\left(\mathbf{r}_{\mathbf{ss}}^j\right)^{-1}\mathbf{r}_{\mathbf{sp}}^j$ and comparing the result with left-hand-side of (B.2), using also the definitions in (A.4)-(A.7), non-singularity of $\mathbf{m}_{\mathbf{p}}^j$ implies that

$$\sigma^j \boldsymbol{\tau}^j = \mathbf{v}, \quad j = 1, \dots J \,, \tag{B.4}$$

from which part (b) of the proposition follows. Part (a) follows on using (B.4) and (A.8) in (B.3). Finally, (A.15) implies, recalling (A.2), that

$$\sigma^j \left(e_u^j - \boldsymbol{\tau}^{j\prime}\mathbf{e}_{\mathbf{p}u}^j\right) + \mathbf{v}'\mathbf{e}_{\mathbf{p}u}^j > 0 \,, \quad j = 1, \dots J \,, \tag{B.5}$$

and hence, from (B.4), $\sigma^j > 0$, $j = 1, \dots J$. □

Appendix C: Proof of Proposition 2

It suffices to show that in either of the circumstances envisaged in the proposition

$$\sigma^j = \sigma \,, \quad j = 1, \dots J \,. \tag{C.1}$$

Starting with the case in which explicit lump-sum transfers are available, the condition $\mathbf{y}'\boldsymbol{\Lambda}_{\boldsymbol{\alpha}} = \mathbf{0}'_{1\times J(N-1)}$ implies (C.1). Part (a) then follows directly from part (a) of Proposition

1, and part (b) from noting that (again from part (b) of Proposition 1) with $\boldsymbol{\tau}^j = \boldsymbol{\tau}$, $j = 1, \ldots J$, the common tariff vector can be normalized to zero.

When explicit transfers are unavailable, using (B.4) and (A.2) in the condition $\mathbf{y}'\boldsymbol{\Lambda}_\mathbf{w} = \mathbf{0}'_{1\times(N-1)}$ gives

$$\sum\nolimits_{j=1}^{J} \sigma^j \left\{ \mathbf{m}^{j\prime} + e_k^j \sum\nolimits_{l=1}^{J} \left(-\boldsymbol{\iota}'\mathbf{r}_\mathbf{sp}^l \right) + \mathbf{s}^{j\prime}\mathbf{r}_\mathbf{sp}^j \right\} = \mathbf{0}'_{1\times(N-1)} \,, \tag{C.2}$$

which, using part (a) of the proposition, becomes

$$\mathbf{M}'\boldsymbol{\sigma} = \mathbf{0}_{(N-1)\times 1} \,, \tag{C.3}$$

where

$$\mathbf{M}' = \left[\begin{array}{cccc} \mathbf{m}^1 & \mathbf{m}^2 & \cdots & \mathbf{m}^J \end{array} \right]_{(N-1)\times J} \,. \tag{C.4}$$

Recall, from (7), that market clearing implies $\mathbf{M}'\boldsymbol{\iota}_{J\times 1} = \mathbf{0}_{(N-1)\times 1}$, so that $\mathbf{M}'$ has column rank of no more that $J-1$. If it has precisely this rank, then $\boldsymbol{\sigma}_{J\times 1}$ must be collinear with $\boldsymbol{\iota}_{J\times 1}$ implying again that $\sigma^j = \sigma$, for $j = 1, \ldots, J$. □

Appendix D: Proof of Proposition 5

In this case, with countries other than h constrained, conditions (B.2) and (B.3) can be assumed to hold only for $j = h$. Proceeding as in the proof of Proposition 1 gives

$$\sigma^h \boldsymbol{\tau}^h = \mathbf{v} \,. \tag{D.1}$$

Using this and (A.2) in (B.3) for $j = h$, part (a) follows. Using part (a) and (A.2) in (B.1) gives part (b). □

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