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LETTER

Potential of border tax adjustments to deter free riding in international climate agreements

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Abstract

The objective of this study is to conduct assessment of the hypothesis that trade sanctions in the form of border tax adjustments (BTAs) used by the United States against China, constitute a viable enforcement mechanism to sustain compliance with a range of emissions taxes in the context of agreements to curb global emissions of greenhouse gases (GHGs). The performance of BTAs is then compared with those of punitive tariffs on the basis of the range of emission taxes that can be successfully enforced by their implementation. Results show that BTAs are a viable enforcement mechanism for international GHG mitigation agreements. However the maximum level of carbon tax that can be enforced varies dramatically with (1) the marginal damage of pollution perceived by Chinese authorities, and (2) the legal limitations that GATT rules may impose on BTAs. Finally, while BTAs seem a promising enforcement mechanism in the context of climate agreements, punitive tariffs seem to be capable of supporting a much stricter environmental target.

1. Introduction

Unilateral implementation of policies for reduction of greenhouse gas (GHG) emissions by a given country may increase domestic prices, induce international production displacement, and result in spatial relocation instead of reduction of GHG emissions; a phenomenon known as ‘emissions leakage’. This loss of competitiveness without the corresponding environmental gain has deterred countries from implementing unilateral carbon abatement policies. Therefore policy measures that may prevent these adverse effects of unilateral abatement have been considered as an important part of climate agreements.

Two widely discussed policy instruments to address loss of competitiveness and leakage are punitive tariffs and border tax adjustments (BTAs). The former consists of a tax, decoupled from the specific carbon content of the imported good, imposed on imports from countries that do not take measures to reduce emissions. A BTA is a tax levied by emission-abating countries on imports from non-abating countries according to the emissions associated with their production process[3]. Some studies underscore the importance of these measures to reduce ‘leakage’ and, to protect competitiveness of high-tax countries (Hoerner 1998, Goh 2004, Demailly and Quirion 2008, McKibbin and Wilcoxen 2008, Winchester 2011, Jakob *et al* 2013, Jakob *et al* 2014). This strand of studies found that reduced leakage, though a likely corollary, is not a forgone conclusion of trade measures. Other studies (Babiker and Rutherford 2005, Alexeeva-Talebi *et al* 2008, Bohringer *et al* 2010, Fischer and Fox 2012) have compared emission-based BTAs to other border adjustments and domestic instruments (export rebates, full border adjustment, output-based rebating) on the basis of its effect on competitiveness and overall emissions. These studies found that the success of BTAs as instruments to protect competitiveness is also far from inexorable.

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[3] This instrument was incorporated in section 766 of the Waxman/Markey bill (H.R.2454‘The American Clean Energy and Security Act of 2009’).

A potentially important but typically overlooked benefit of implementing BTAs is their ability to encourage free riders to join a GHG mitigation agreement (Nordhaus 1998, Brack *et al* 2000, Charnovitz 2003, Hotelez 2007). Although this hypothesis has been theoretically formalized (Barrett 1997, Finus and Rundshagen 2000), its empirical assessment remains limited[4]. We focus our attention on this particular issue.

Previous studies evaluating BTAs as an enforcement mechanism (Hübler 2011, Weitzel and Peterson 2011, and Manders and Veenendaal 2008) did not consider the incentive-compatibility of a climate agreement including BTAs for the two largest emitters in the world: the United States and China. The objective of the present study is to assess the plausibility of the hypothesis that trade sanctions in the form of BTAs, used by the USA against China, can be a viable enforcement mechanism to sustain compliance with a range of carbon taxes in the context of agreements to curb global GHG emissions. The case of trade sanctions by the USA against China is particularly relevant due to: (1) the strength and magnitude of the bilateral trade flow, and (2) the emissions as well as export-intensive nature of the Chinese economy. Assessment of our hypothesis requires consideration of strategic behavior. We now proceed to formalize the game depicting strategic interactions between countries in a GHG mitigation agreement.

2. Methods

2.1. The structure of the game

The decisions to implement climate policies and trade sanctions are not taken simultaneously as each country has to go through their own legislative process. Moreover, these decisions can be observed by other countries. Therefore we model countries' strategic decisions with a dynamic game played under both complete and perfect information. Specifically, we build a four-stage sequential game played by the USA and China. A third region denominated rest of the world (ROW) is included in the model which aggregates all other countries. This region is assumed to implement a climate policy and it is passive otherwise. This is intended to capture the fact that the EU countries have already implemented a GHG mitigation policy.

The extensive form of the game is presented in figure 1. In Stage 1, the USA decides whether to implement the emissions tax imposed by ROW or not. If the USA does not implement the carbon tax, the game ends. In Stage 2 China decides whether to cooperate and impose the emissions tax or free ride. If China cooperates, the game ends. If China free rides (i.e. does not impose the carbon tax), the game proceeds to Stage 3. In Stage 3, the USA observes China's free-ridding and decides whether or not to threaten China with a BTA on all its imports coming from that country. This is captured by a continuum of BTA levels including zero (no threat). In Stage 4, China observes the global emissions tax level and the BTA threat from the USA (if any) and decides whether or not to comply with the emissions tax.

While retaliation by China would not be allowed under the General Agreement on Tariffs and Trade (GATT) by the WTO, countries typically have some leeway to increase tariffs without attributing this to 'retaliation' making de-facto retaliation possible. Although clearly an interesting dimension to examine, there is considerable uncertainty regarding China's ability to increase its tariffs within the bounds established in GATT. Moreover such retaliations by China may not be an effective deterrent of USA's tariffs as trade between both countries is clearly favorable to China (as confirmed by results in Böhringer *et al* 2013). Furthermore considering retaliation by China is computationally impractical as it requires calculation of a best response function for China and recalculation of credible and effective BTA threats by the USA subject to such best response. For these reasons we believe ruling out retaliation from China constitutes an empirically relevant yet computationally feasible modeling strategy.

Given the dynamic and perfect information nature of the game, the solution concept employed is that of a sub-game perfect Nash equilibrium. Simply stated in the context of the extensive form presented in figure 1, a sub-game begins at a decision node that is a singleton information set and it includes all the decisions and terminal nodes afterwards. A Nash equilibrium is sub-game-perfect if the players' strategies constitute a Nash equilibrium in every sub-game. The key to identifying a sub-game perfect Nash equilibrium of the game in figure 1 is computation of empirical payoffs associated with each set of strategies. We now turn our attention to this issue.

Previous numerical studies on international environmental agreements (e.g. Carbone *et al* 2009, Lessmann *et al* 2009) have explicitly modeled the choice of carbon tax (or emissions) which permits assessment of coalition stability at the 'optimal' tax. We refrain from endogenizing the carbon tax so that our results are consistent with a wide range of assumptions regarding the nature of the bargaining process within the coalition. Rather, we take a different approach which is to examine the ability of trade measures to successfully enforce 'any' carbon tax emerging from the coalition bargaining process. The disadvantage of our approach

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[4] Kemfert (2004) analyzes the influence of quantitative trade barriers on the size of stable coalitions. However Kemfert (2004) only considers banning trade and does not discuss punitive tariffs or BTAs. Additionally, stable coalitions considered in Kemfert (2004) constitute a Nash equilibrium of a one shot game, while this study refines the equilibrium concept to a sub-game perfect Nash equilibrium. The latter allows elimination of coalitions that may be stable once formed but that cannot be formed through credible threats.

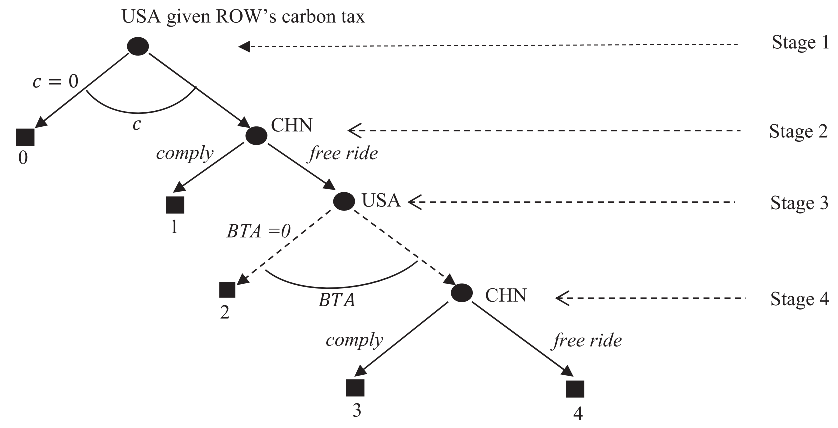

Figure 1. The game in extensive form.

is that it precludes computation of the optimal tax which seems an acceptable penalty given our objective.

2.2. Payoff functions

2.2.1. Computable general equilibrium model: the GTAP-AEZ-GHG model

Payoffs obtained by the USA and China are determined by welfare changes associated with alternative climate policy scenarios. To measure regions' welfare changes we apply the concept of equivalent variation (EV)[5]. Changes in welfare in the USA and China are determined by direct market effects of carbon taxes and emission-based BTAs but also by feedbacks from displacement of the equilibrium in interrelated markets. Quantifying the latter requires a computable general equilibrium approach. Therefore, to evaluate our hypothesis, we use the GTAP-AEZ-GHG model (Golub *et al* 2009, Hertel *et al* 2009) which is a global static computable general equilibrium model with three regions (the USA, China, and the ROW) and 24 sectors.

The model used in this analysis employs an Armington specification of international trade (Armington 1969) by which commodities produced in different regions are imperfect substitutes. Under the assumption that commodities are differentiated according to their origin, each region exerts some degree of market power[6]. Implementation of BTAs by coalition members increases their market power and hence their terms of trade. This positive terms-of-trade effect increases the welfare of the region that imposes the border tax and reduces the welfare of free-riders. However, just like in monopoly pricing, as the BTA exceeds a threshold value the benefits of BTAs to the country that imposes them vanish and their impact can become negative[7]. The econometric estimates of the Armington elasticities provided in Hertel *et al* (2007) are used in this study.

Table 1. Marginal damage of pollution for China and the US in different scenarios, \$/TCE.

	Min	Mean	Max
USA	3	4	5
China	10	20	30

Source: Nordhaus (2011)

Our model is a modified version of the standard GTAP model developed and described by Hertel (1997). First, the production and consumption structures of the model are modified to allow capital-energy and inter-fuel substitution (Burniaux and Truong 2002). Second, GHG emissions data including the carbon dioxide emissions from fossil fuel combustion (Lee 2007) and non-carbon dioxide emissions documented in Rose and Lee (2009) are introduced into the model. Within each of the 24 sectors of the model, GHG emissions are tied to primary factors, intermediate inputs, and outputs. Further technical aspects of the model are presented in appendix A.

2.2.2. Marginal damage of pollution for China and the USA

Table 1 presents estimates of marginal damage from pollution in the USA and China reported by Nordhaus (2011)[8]. Nordhaus (2011) presents estimates under six different scenarios: three for high discount rate, and three for a low discount rate. For the high discount

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[5] The procedure for EV calculation in the GTAP model is documented in McDougall (2001).

[6] Under the Armington assumption, while there is no domestic production of imported varieties there is demand for all varieties. Thus, each region has some market power for their own variety.

[7] Zhang (2006) discusses relationship between the Armington assumption and terms-of-trade effects of a tariff. Note, BTA on a good can be translated to change in power of tariff. The change will depend on the magnitude of BTA measured in \$/TCE and emissions embedded in production of the good in question.

[8] The estimates given in Nordhaus (2011) are in 2005 USD values. They are converted to our base year values which is 2001 USD.

rate, marginal damage estimates range from \$3 per tonne of carbon equivalent (TCE) to \$5/TCE for the USA, with a mean of about \$4/TCE, and from \$10/TCE to \$30/TCE for China, with a mean of \$20/TCE. The high discount rate scenario corresponds to the lower bound of the marginal damage estimates which are our values of choice in this study. The objective of this study is to identify sufficient conditions for BTAs to constitute a successful enforcement mechanism for an international environmental agreement. The lower the values of marginal damage from pollution, the smaller the potential gains from implementation of carbon taxes and BTAs. Therefore low marginal damage estimates result in the strictest conditions under which BTAs can be used to enforce the agreement. We use these lowest estimates so that we are, in effect, calculating sufficient conditions under a worst case scenario for BTAs.

2.3. Sub-game perfect Nash equilibrium

Our empirical strategy is to identify conditions under which final node 3 in figure 1 constitutes a sub-game perfect Nash equilibrium. We achieve this by backward induction. First we identify conditions under which node 3 is a Nash equilibrium of the sub-game starting at stage 2. We then proceed to identify conditions under which the USA finds optimal to impose a positive carbon tax c already implemented by ROW, provided that the agreement will be later successfully enforced and node 3 will be the final outcome. This results in sufficient conditions for BTAs to constitute a successful enforcement mechanism for an international agreement on GHG mitigation.

The optimality of strategies leading to the desired outcome is determined by their payoffs. Payoffs obtained by the USA and China are determined by welfare changes associated with alternative climate policy scenarios. Let us first denote by $\mathrm{EV}_r(c,\ \mathrm{BTA};\ a)$ the EV of region $r \in \{\mathrm{USA},\ \mathrm{CHN},\ \mathrm{ROW}\}$ when the emissions tax set by the USA and ROW is c, BTA denotes the BTA (measured in 2001 USD per tonne of carbon embedded in imports) imposed by the USA on Chinese imports if China free rides, and China's action given USA's threat is $a \in A = \{\text{free ride},\ \text{comply}\}$[9].

The expression EV_r does not include marginal damage of pollution. Marginal damage from pollution is included as a separate, linear term in countries' payoff. Specifically, a certain emissions tax c, Chinese response a, and USA's sanction BTA, will result in some level of global emissions, $EMITG(c,\ \mathrm{BTA};\ a)$. There is a region specific damage associated with such emissions level denoted by $EMITG(c,\ \mathrm{BTA};\ a)^{*}\tau$, where τ is the marginal damage of pollution which is assumed independent of emissions level. Therefore, we define the EV of the USA *adjusted* to include damage from emissions as follows:

$$\begin{aligned}&\mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\left(c,\ \mathrm{BTA};\ \mathrm{freeride};\ \tau_{\mathrm{USA}}\right)\\&\quad = \mathrm{EV}_{\mathrm{USA}}(c,\ \mathrm{BTA};\ \mathrm{freeride})\\&\qquad - \tau_{\mathrm{USA}}{}^{*}\left[EMITG(c,\ \mathrm{BTA};\ \mathrm{freeride})\right.\\&\qquad \left. - EMITG(0{,}0;\ \mathrm{freeride})\right].\end{aligned}$$

International cooperation will be a Nash equilibrium of the sub-game starting at stage 2 if and only if a threat of BTAs by the USA to China is both credible (i.e. given China's free riding, the USA is better off imposing the BTA than not imposing it) and effective (i.e. given USA's credible threat of imposing BTAs, China is better off imposing the carbon tax than free riding and facing the BTAs). The set of BTAs satisfying the credibility condition given carbon tax c established in the first stage denoted here by $\mathrm{BTA}^{\mathrm{cred}}_{c}$ is defined as:

$$\begin{aligned}&\mathrm{BTA}' \in \mathrm{BTA}^{\mathrm{cred}}_{c} \text{ if and only if } \mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\\&\quad \left(c,\ \mathrm{BTA}';\ \mathrm{freeride};\ \tau_{\mathrm{USA}}\right) \geqslant \mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\\&\quad \left(c,\ 0;\ \mathrm{freeride};\ \tau_{\mathrm{USA}}\right).\end{aligned} \tag{1}$$

Similarly, the set of BTAs that satisfy the effectiveness condition given carbon tax c established in the first stage and exogenous marginal damage τ, which is denoted by $\mathrm{BTA}^{\mathrm{eff}}_{c}$ is:

$$\begin{aligned}&\mathrm{BTA}' \in \mathrm{BTA}^{\mathrm{eff}}_{c} \text{ if and only if } \mathrm{EV}^{\mathrm{adj}}_{\mathrm{CHN}}\\&\quad \left(c,\ 0,\ \mathrm{comply};\ \tau_{\mathrm{CHN}}\right) \geqslant \mathrm{EV}^{\mathrm{adj}}_{\mathrm{CHN}}\\&\quad \left(c,\ \mathrm{BTA}',\ \mathrm{freeride};\ \tau_{\mathrm{CHN}}\right).\end{aligned} \tag{2}$$

Once the set of credible and effective BTAs has been identified for different levels of the carbon tax, we determine the set of carbon tax rates that will make the USA better off (given the subsequent enforceability of such rate with China) than not imposing a carbon tax. We denote this set by c^{*} and formally define it as follows:

$$\begin{aligned}&c' \in c^{*} \text{ if and only if } \mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\\&\quad \left(c',\ 0;\ \mathrm{comply};\ \tau_{\mathrm{USA}}\right) \geqslant \mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\\&\quad \left(0,\ 0;\ \mathrm{freeride};\ \tau_{\mathrm{USA}}\right).\end{aligned} \tag{3}$$

We now simulate the impact of strategies involved in conditions (1)–(3) which are sufficient for node 3 in figure 1 to become a sub-game perfect Nash equilibrium.

3. Results and discussion

3.1. Nash equilibrium of sub-game starting at stage 2

To assess the credibility of a BTA threat we start by assuming a certain abatement policy (carbon tax rate measured in dollars per TCE) and ask whether imposition of BTAs on Chinese imports constitutes a credible threat. We do this by calculating EV for the

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[9] The measure of equivalent variation is computed in reference to a baseline situation in which carbon taxes are not imposed and, consequently, trade sanctions are also absent from international trade.

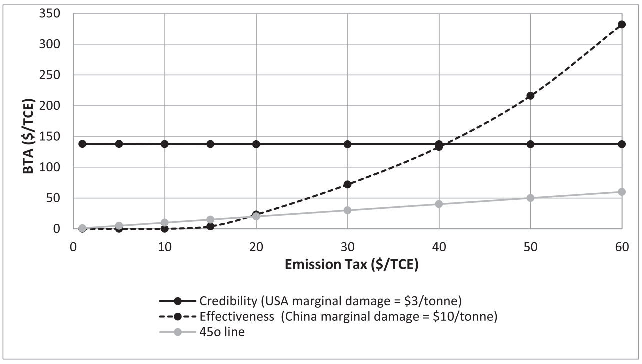

Figure 2. Credible and effective BTAs when damage of pollution is $3/TCE in the USA and $10/TCE in China over different emissions taxes.

USA at $1/TCE increments in BTAs. We repeat the procedure for different levels of the carbon tax[10]. Similarly, effective tariff threats at different carbon tax rates are identified by calculating EV for China at $1/TCE increments in BTAs for the same range of carbon taxes considered to calculate credible BTAs.

An increase in BTA will enhance terms of trade of the USA, which translates into an increase in producer surplus. On the other hand imports become more expensive which translates into a reduction in consumer surplus. An increase in BTA will then enhance USA's EV if and only if the former effect outweighs the latter. Intuition suggests that gains in producer surplus may outweigh losses in consumer surplus in a country where producers are subject to intensive competition from imports like the USA. On the other hand, while marginal gains for producers will decrease as the BTA increases, marginal losses for consumers may not diminish at higher BTA levels. Therefore, while initial increases in BTA may translate into welfare gains for the USA, they are likely to result in losses when they become sufficiently high. Consequently, the set of credible threats may include positive BTAs but may also be subject to an upper bound.

Similarly, an increase in BTA will always worsen terms of trade for the punished country. Higher carbon taxes will require higher BTAs to induce China to comply because the damage caused by the BTA has to outweigh the net (after emission reductions benefits) damage from the carbon tax. Therefore a low, though positive, BTA may not be sufficient to induce cooperation suggesting that the set of effective threats may be bounded from below and may be positively linked to the carbon tax rate.

The procedures outlined above confirm our suspicions and reveal that the set of credible BTAs is bounded from above while the set of effective BTAs is bounded from below. The upper bound of the credibility set and the lower bound of the effectiveness set are plotted in figure 2. They also confirm our expectation that the lower bound of the effectiveness set is positively linked to the carbon tax. The corollary of this is that, for a certain carbon tax rate, a credible and effective threat exists if and only if the upper bound of credible BTAs is above the lower bound of effective BTAs. The existence of a non-empty set of credible and effective threats for positive carbon tax rates can be verified in figure 2 where both sets have been graphed. These curves are constructed under the assumption that marginal damage of pollution is $3/TCE in the USA and $10/TCE in China which are the minimum values of the range reported by Nordhaus (2011).

The credibility curve represents the maximum BTA that the USA is willing to implement against China at different levels of carbon tax. The combinations of tax rates and BTAs below that line fulfill the credibility condition; i.e. the USA is better off implementing the BTA than not implementing it when China is free riding. The set of credible BTAs is insensitive to the level of the carbon tax because the marginal cost and benefit of a BTA in the USA economy are orthogonal to the level of the tax.

The effectiveness curve depicts the minimum BTA that can convince China to comply at a given emission tax. BTAs above this boundary would be effective; i.e. China is better off complying and avoiding the BTA than free riding and receiving the punishment. The effectiveness curve is convex and monotonically increasing. This is an expected result considering the fact that as the environmental policy becomes more stringent it becomes more costly for China to abate and hence the minimum BTA that can induce China to abate increases.

The area below the credibility line and above the effectiveness curve constitutes the set of BTAs that are

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[10] The specific level of a carbon tax that the USA and ROW can agree on (provided China can be subsequently induced to cooperate through trade sanctions) is unknown to us. Such tax rate will be influenced by individual countries' marginal damage from pollution and the relative bargaining strength of countries involved in the negotiation. Verifying the optimality of a range of carbon tax rates that can potentially emerge from such a bargaining process, instead of assuming a 'plausible' carbon tax rate, seems the most informative direction for this analysis.

credible and effective simultaneously. Moreover since the effectiveness line is upward sloping while the credibility line is flat, there exists a carbon tax rate above which the set of credible and effective threats is empty. Under the assumed marginal damage, figure 2 reveals that \$40/TCE is the maximum enforceable emissions tax (MET); i.e. the point at which the credibility and effectiveness curves intersect each other. This is slightly higher than the price of carbon in the EU predicted by Thompson Reuters for the period 2021–2030[11].

A legal constraint may limit the range of BTAs that the punishing country can impose[12]. As discussed by Fischer and Fox (2012) the National Treatment principle embedded in Article III of the GATT requires that imported goods be treated no less favorably than 'like' domestic products. Many scholars interpret this to mean that the BTA cannot exceed the domestic carbon tax and assume a BTA that is equal to the carbon tax (e.g. Hübler 2011, Weitzel and Peterson 2011, Fischer and Fox 2012). In order to consider a situation in which the BTA is forced to equal the domestic carbon tax, a 45 degree line is depicted in figure 2. As revealed by the intersection between the effectiveness boundary and the 45 degree line in figure 2, the maximum carbon tax that can be credibly and effectively enforced by legally constrained BTAs is reduced to \$19/TCE; not a highly stringent carbon policy by common standards. While this is a most realistic scenario, it is hardly a definitive interpretation of the rules and regulations as the general exceptions clause in Article XX may provide some leniency to punishing countries. This clause recognizes exceptions when, among other reasons, 'necessary to protect human, animal or plant life or health' and 'necessary to secure compliance with laws or regulations which are not inconsistent with the provision of this agreement'.

The credibility line in figure 2 is calculated by comparing EV with a positive BTA and EV with a zero BTA, for a given carbon tax. When the level of BTA with which the USA threatens China is low enough to be credible and high enough to be effective, the BTA is never in fact implemented and China cooperates with the agreement. However, a reasonable concern is that the USA may find it optimal to impose a BTA that is *not* high enough to induce China to cooperate and yet accrue the benefits of such protectionist measure. This can only happen when $\mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\left(c,\ \mathrm{BTA}^{*};\ \mathrm{freeride};\ \tau_{\mathrm{USA}}\right) \geqslant \mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\left(c,\ 0;\ \mathrm{comply};\ \tau_{\mathrm{USA}}\right)$, where BTA^{*} the BTAs that are not effective, the level that maximizes the USA's welfare and the rest is as before. Our results show that $\mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\left(c,\ \mathrm{BTA}^{*};\ \mathrm{freeride};\ \tau_{\mathrm{USA}}\right) < \mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}\left(c,\ 0;\ \mathrm{comply};\ \tau_{\mathrm{USA}}\right)$ for all carbon taxes that are enforceable through BTAs and, thus, the set in our results are robust to 'green protectionism' concerns.

To verify the robustness of our conclusions to the most important and controversial parametric assumption in our study, we recalculate the credibility and effectiveness lines for a range of marginal damage from emissions reported by Nordhaus (2011) for both China and the USA. Intuition suggests that an increase in USA's marginal damage from emissions should shift the credibility line upwards as marginal gains from punishing China are larger. Moreover an increase in China's marginal damage from emissions should shift the effectiveness line downwards as benefits to China from compliance with the carbon tax are larger.

Figure B1 in appendix B reveals that, while the effectiveness line is very responsive to changes in China's marginal damage from emission, the credibility line is relatively insensitive to changes in USA's marginal damage from emissions. In combination, these results reveal (as reported in table B1 in appendix B) that the maximum enforceable carbon tax rate (i.e. the rate at which the credibility and effectiveness lines intersect) is very sensitive to China's marginal damage from emissions. In fact a \$30/TCE increase in marginal damage of emission in China (from \$0 to \$30/TCE), results in a \$66/TCE increase in maximum enforceable carbon tax rate (from \$20 to \$86/TCE). In contrast, results seem to be very robust to changes in Armington elasticities which are parameters capturing the increase in market power and hence terms of trade resulting from an increase in tariffs (figure B2 and table B2, appendix B).

3.2. USA's optimal strategy at stage 1

We will now find conditions under which implementation of a carbon tax rate is an optimal policy for the USA, provided node 3 is a sub-game perfect Nash equilibrium of the game starting after the carbon tax rate has been chosen (stage 2). The key driver of the benefit/cost of imposing a carbon tax is marginal damage from emissions. Therefore, for a given carbon tax, we identify the set of marginal damage that would guarantee fulfillment of inequality (3), provided inequalities (1) and (2) hold.

The set of marginal damage that would rationalize implementation of a given carbon tax c denoted by τ^{c}_{USA}, can be formalized as follows:

$$\tau' \in \tau^{c}_{\mathrm{USA}} \text{ if and only if } \mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}$$
$$(c,\ 0;\ \mathrm{comply};\ \tau') \geqslant \mathrm{EV}^{\mathrm{adj}}_{\mathrm{USA}}(0,\ 0;\ \mathrm{freeride};\ \tau'). \qquad (4)$$

The inequality in (4) guarantees that, provided there exists a set of credible and effective BTAs to induce China to implement carbon tax c, the USA faces a marginal damage from pollution such that it is better off imposing such carbon tax than not imposing it and letting China free ride. Intuition suggests that

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[11] http://cleantechnica.com/2014/09/02/european-carbon-price-set-rise-e23t-2021–2030/.

[12] This legal constraint applies to BTAs but not, for instance, punitive tariffs.

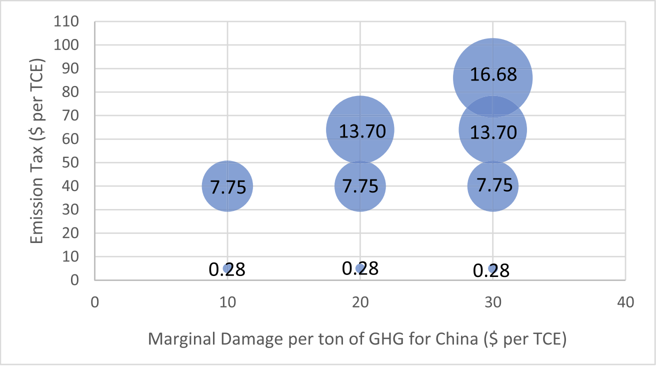

Figure 3. Marginal damage and optimal emissions tax. Note: values inside bubbles show marginal damage from GHG in USA such that USA is indifferent between imposing emission tax (y-axis) and not imposing it.

the minimum marginal damage required to justify a given carbon tax rate would raise as the tax rate increases. In other words, higher carbon tax rates are associated with an increase in the lower bound of τ^{c}_{USA}. Such relationship is quantified and reported in figure 3.

Values inside the bubbles in figure 3 depict the marginal damage from emissions to the USA for which inequality (4) holds under strict equality; i.e. values of the lower bound of τ^{c}_{USA}. Results in figure 3 indicate that if the marginal damage of emissions to China is $10/TCE, the marginal damage of emissions to the USA has to be at least $7.75/TCE to induce the USA to impose a carbon tax of $40/TCE. Combining results in figure 3 with those in figure 2 reveal that a marginal damage of $3 is not enough to induce the USA to implement the maximum enforceable carbon tax rate of $40/TCE. In other words, the carbon tax rate imposed by ROW has to be lower than $40/TCE to induce the USA to implement it in the first place. Due to the insensitivity of the credibility condition to the USA's marginal damage, the maximum enforceable carbon tax rate under a marginal damage of $7.75 in the USA is still $40/TCE. In this case it would be feasible (Nash equilibrium of the sub-game starting at stage 2) and optimal (Nash equilibrium of the whole game) to implement the maximum enforceable carbon tax rate.

3.3. Comparison of BTA and punitive tariffs

In this section we compare two types of trade sanctions widely discussed in the literature on the basis of their ability to enforce a climate agreement: punitive tariffs and BTAs. We assess such ability based on the MET that each instrument can support. While the consistency of punitive tariffs with regulations of the World Trade Organization is still unclear, implementations of such measures could be justified on the basis of their ability to 'protect human, animal or plant life or health' as allowed by the General Agreement on Tariffs and Trade (GATT, 1986), Article XX. In fact, trade sanctions have been used in the past to control ozone depleting substances, through the Montreal Protocol (UNEP 2007).

BTAs modeled in this paper fall into the category of 'specific tax'; i.e. a tax that is defined as a fixed amount for each unit of a good. A BTA per unit of an imported good depends on the carbon content of the good and the price of carbon. Punitive tariffs, on the other hand, fall into the category of 'ad valorem tax'; i.e. a charge calculated as a fixed percentage of the product's value. Though BTAs and punitive tariffs fall into two different tax categories, they can be expressed in comparable units. Changes in tariffs are measured in terms of percentage changes in the power of the tariff. BTAs are made comparable to punitive tariffs by converting them to percentage change in the power of tariffs as described in appendix C. Credibility and effectiveness sets and the resulting METs are calculated for marginal damage in table 1. Panel A of figure 4 displays credible and effective threats under punitive tariffs. Panel B presents the same set under BTAs.

Results show that threats of punitive tariffs can successfully enforce a carbon tax rate as high as $58/TCE. On the other hand, BTAs can only enforce a carbon tax rate no higher than $40/TCE. This suggests that punitive tariffs constitute a more effective enforcement mechanism than BTAs. This is not surprising as a tax on value has a much broader base than a tax on emissions as it affects 'dirty' and 'clean' goods alike. The relative ability of punitive tariffs to enforce higher tax rates is robust to the level of marginal damage assumed in the analysis (appendix D, figures D1–D3). In conclusion, while BTAs are typically considered more efficient than punitive tariffs (because they specifically tax the carbon content of goods and, thus, the source of the externality), they cannot successfully enforce relatively high emission taxes. Since successful threats are never actually carried over, an agreement using punitive tariffs could be more efficient than one using BTAs.

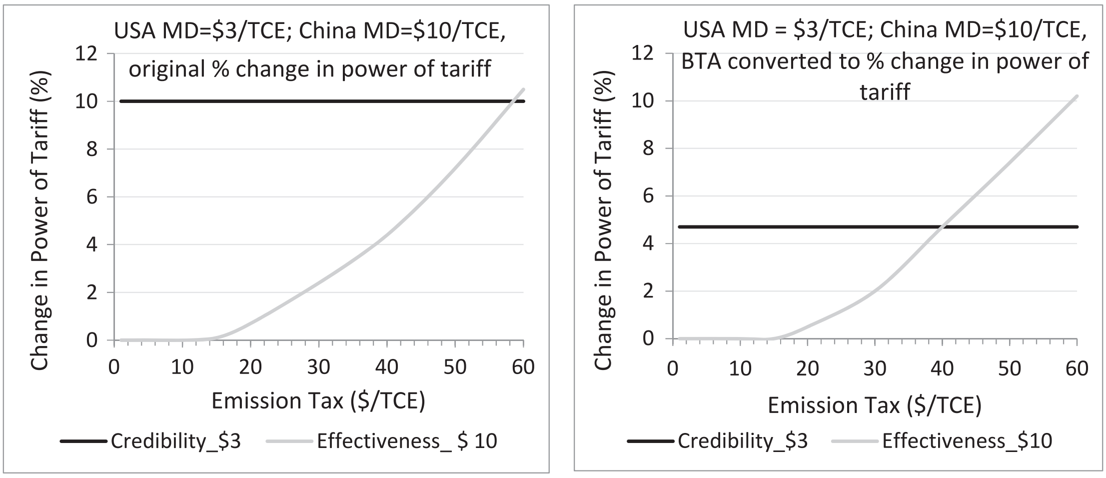

Figure 4. (A) Credible and effective changes in power of tariffs, punitive tariffs. (B) Credible and effective changes in power of tariffs, BTA.

4. Conclusions

The present study combined game theory with a computable general equilibrium model to evaluate the hypothesis that BTAs could help deter free riding and encourage the USA to implement the carbon tax rate that the ROW (in particular the European Union) has implemented. Results suggest that BTAs may in fact be used as a viable (i.e. credible and effective) enforcement mechanism for international GHG mitigation agreements. However the maximum level of carbon tax that can be enforced varies dramatically with two factors: the marginal damage of pollution perceived by Chinese authorities and the legal limitations that GATT rules may impose on BTAs. As the marginal damage from pollution perceived by the Chinese government increases, the maximum enforceable carbon tax also increases, and significantly so. On the other hand, if BTAs are legally constrained to equal domestic carbon taxes, the maximum enforceable carbon tax would be reduced substantially.

While BTAs seem a promising enforcement mechanism in the context of climate agreements (particularly if no legal constraints force BTAs to equal domestic carbon taxes) they do not seem to fare well when compared to punitive tariffs. In fact punitive tariffs seem to be capable of supporting a much larger maximum carbon tax. In particular punitive tariffs can viably (credibly and effectively) enforce a carbon tax as high as $58/TCE. However punitive tariffs may be less compatible with GATT rules than BTAs.

Our results suggest trade measures may be viable instruments to enforce climate policies and are, as such, consistent with previous analytical studies on the interactions between climate and trade policies. In particular, Barrett (1997), Turunen-Red and Woodland (2004), Kotsogiannis and Woodland (2013), Tsakiris *et al* (2014) have found potential welfare improving effects of using trade sanctions to induce free riding countries to internalize the external cost of their emissions.

An interesting situation to analyze is that in which the USA free rides and China complies and threatens the USA in the context of an international environmental agreement. Trade sanctions may not be as successful in this case as trade is favorable to China and so both the credibility and the effectiveness sets may be smaller in this situation. This case along with considerations of retaliation by the sanctioned party constitute interesting and relevant topics for further research.

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Appendix A. Methodological issues

The GTAP-AEZ-GHG computable general equilibrium model

This model represents a modified version of the standard GTAP model developed and described by Hertel (1997). The standard GTAP model introduces a regional household that collects all factor income and taxes in the economy. Regional household behavior is governed by an aggregate utility function of the Cobb–Douglas form and it is specified over three sources of final demand: (i) composite private consumption, (ii) composite government consumption, and (iii) savings. Private household derives its utility from the consumption of goods and services based on a non-homothetic constant difference of elasticity functional form. The second component of final demand is the government demand which is specified via a Cobb–Douglas functional form. Savings is the third component of final demand in regional household's utility. In the multi-region GTAP model there is a global sector called Global Bank which is assumed to be a mediatory between global savings and regional investment. One of the ways to think about the Global Bank is that it collects savings from all regions to finance regional investment. Or it can be thought of as purchasing capital goods and then selling them to regional households to meet their demand for savings.

Producers in the standard GTAP model are assumed to maximize profits subject to constant returns to scale technologies in a perfectly competitive market. Production is modeled using a constant elasticity of substitution (CES) nested function. In the top level, the output is produced as a combination of value added and intermediate demand according to Leontief technology. In the second level, value added is split into primary factors such as land, skilled and unskilled labor, capital and natural resources according to CES technology. The GTAP model assumes separability in production. The firms are assumed to first choose their optimal mix of primary factors, and then determine the optimal mix of value-added and intermediate inputs. Producers use intermediate inputs which can be domestically produced or imported.

The domestic region trades with the aggregated 'ROW' for intermediate goods demanded by producers and for final consumption goods demanded by private household and government. In the GTAP model, the Armington approach to trade is employed so that domestic products and imported products coming from different regions are imperfect substitutes.

The GTAP-AEZ-GHG model, developed in Golub *et al* (2009), introduced several modifications to the standard GTAP model. First, the production and consumption structures of the model are modified to allow capital-energy and inter-fuel substitution (Burniaux and Truong 2002). Second, GHG emissions data including the carbon dioxide (CO_2) emissions from fossil fuel combustion (Lee 2007) and non-carbon dioxide (non-CO_2) emissions (methane, nitrous oxide and F-gases) documented in Rose and Lee (2009) are introduced into the model. Within each of 24 sectors of the model, GHG emissions are tied to specific drivers such as primary factors, intermediate inputs, and output. Third, in each region land is treated as a heterogeneous endowment divided up to 18 agro-ecological zones (AEZs) (Lee *et al* 2009). Each AEZ differs in terms of its suitability for production of crops, forestry and livestock.

Fourth, the model incorporates mitigation cost curves for different sectors and regions based on data from the USEPA (USEPA 2006) by calibrating relevant parameters in the GTAP-AEZ-GHG model. The forestry component of the model is calibrated to the results of the state of the art partial equilibrium global forestry model documented in Sohngen and Mendelsohn (2007). Forest extensification and intensification decisions are modeled separately to better isolate competition for land between agriculture and timber products.

Method to calculate emissions embodied in a product

The approach used in this paper to capture the emissions embodied in a product considers both direct and indirect emissions from production processes. Using livestock sectors as an example, total emissions from primary livestock production are calculated by taking into account direct emissions from livestock farming and manure management, as well as indirect emissions from producing feed for animals, growing crops to produce the feed and so on. The total of direct and indirect GHG emissions embodied in a good are estimated by running the model as a quantity-based, global input-output model in which all prices are fixed at their baseline level and output is simply doubled. With fixed prices, no substitution will occur, and to double the production of a sector we must double input use in the sector. This will trigger increases in the production of those inputs and associated emissions. Furthermore, the input supply sectors must also expand their purchases, thereby leading to further rounds of emissions, and so on. By solving the entire model at once we are able to capture all of these direct and indirect changes in emissions. Direct and indirect emissions are calculated for all 24 sectors and three regions of the model separately by running 24×3 simulations[13].

Appendix B. Sensitivity analysis

Sensitivity analyses with respect to marginal damage from pollution

Calculation of credible and effective BTAs requires assumptions on the marginal damage from pollution faced by each region. Our analysis assumes a specific marginal damage for the USA and a specific marginal damage for China, both taken from Nordhaus (2011). The credibility threshold is built based on the USA's marginal damage of pollution and the effectiveness threshold is built based on China's marginal damage. The carbon tax set by cooperating countries depends on marginal damage faced by individual countries, but also individual players' powers and ability to negotiate. Thus, the carbon tax in the global GHG mitigation agreement is likely to differ from marginal damage from pollution faced by individual signatory countries.

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[13] Modeling is implemented using GEMPACK software. GEMPACK 11.3 (2013) can run simulations simultaneously through 'Parameter Substitution'. This new feature of the program allows one to automate simulation runs. See Horridge and Jerie (2013) for more details about how to run large number of simulations.

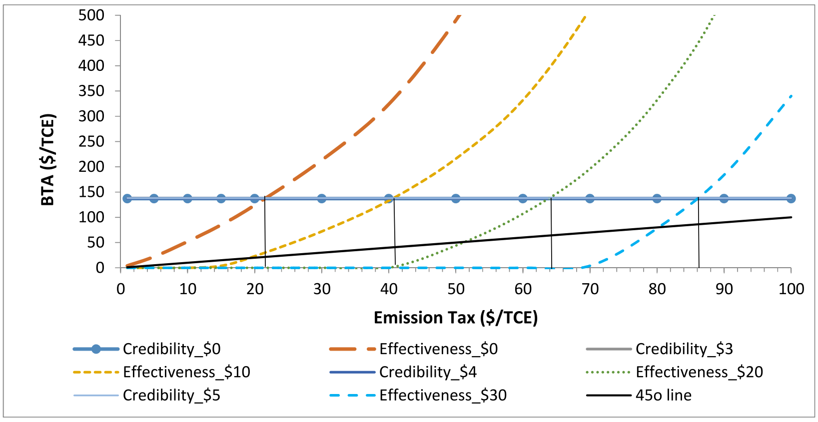

Figure B1. Credible and effective BTAs over different emissions taxes and marginal damage from pollution.

Table B1. Credibility condition and viability threshold under different marginal damage of pollution ($/TCE).

Marginal damage from pollution in USA	Marginal damage from pollution in China	Credibility condition	Maximum enforceable tax
0	0	137	21
3	10	137.4	40
4	20	137.6	64
5	30	138	86

Figure B1 illustrates the credibility and effectiveness conditions for the marginal damage from pollution listed in table 1. As revealed by this figure, the set of effective threats is highly sensitive to the marginal damage from pollution. In particular, figure B1 shows that as damage from pollution is factored in, the effectiveness curve is shifted downwards. This is because China's welfare under free riding is not only decreased due to the BTA imposed by USA against China, but also by the damage from additional pollution. The credibility line is slightly affected by the size of marginal damage (table B1).

The intersection between the credibility and effectiveness curves indicates the maximum carbon tax for which there still exist at least one level of BTA that can credibly and effectively enforce such tax rate. Let us define this intersection as the maximum enforceable (with BTAs) carbon tax, MET. As revealed by results in figure B1 the MET increases as the marginal damage from pollution increases. In other words, as the marginal damage from pollution increases, BTAs become a viable enforcement mechanism for increasingly stringent carbon policies.

Figure B1 shows that the 45 degree line is not contained in the credibility and effectiveness set when marginal damage from pollution is assumed to be zero. This is expected outcome. The punished country is better off free riding and be subject to BTAs because BTAs affect only part of the country's production that is exported. In contrast, complying and imposing a carbon tax would affect its entire production. Thus, if players follow GATT and China does not care about pollution, the set of credible and effective BTA is empty.

It is evident from figure B1 that the 45 degree line will be contained in the credible and effective set at higher damage from pollution.

Sensitivity analysis with respect to Armington parameter

Our model employs an Armington specification of international trade (Armington 1969), and commodities produced in different regions are imperfect substitutes. Under the assumption that commodities are differentiated according to their origin, each region exerts some degree of market power[14]. Implementation of BTAs by coalition members increases their market power and hence their terms of trade. This positive terms-of-trade effect increases the welfare of the region that imposes the BTA. However, just like in monopoly pricing, as the BTA exceeds a threshold value the benefits of BTAs to the country that imposes it vanish and may in fact become negative[15].

The econometric estimates of the Armington elasticities provided in Hertel *et al* (2007) are used in this modeling work. In this section, we analyze how the MET depends on Armington elasticities by

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[14] Under the Armington assumption, while there is no domestic production of imported varieties there is demand for all varieties. Thus, each region has some market power for their own variety.

[15] Zhang (2006) discusses the relationship between the Armington assumption and terms-of-trade effects of a tariff. A BTA on a good can be translated to change in the power of tariff. The change will depend on the magnitude of the BTA measured in $/TCE and emissions embedded in production of the good in question.

Table B2. Thresholds of BTA and emissions tax under varying Armington elasticities.

Trade elasticities	Maximum enforceable tax ($/TCE)
Mean	40
High	41
Low	39

systematically increasing and decreasing this parameter by two standard deviations. This reveals the robustness of our results to the value of Armington elasticities. It is found that, under our assumed values of marginal damage from pollution, the maximum enforceable carbon tax rate is quite robust to alternative values of the Armington elasticities (table B2)[16].

Figure B2 presents changes in the set of credible and effective trade threats after Armington elasticities are changed by two standard deviations. As revealed by figure B2, a decrease in Armington elasticities causes an upward shift in both the effectiveness and the credibility lines. This is to be expected since, as China's market power increases (which is associated with a lower Armington elasticity), it is harder to convince China to cooperate. Similarly, as the USA's market power increases, higher BTAs can be imposed without exhausting the benefits of gains in competitiveness and experiencing welfare losses. An increase in Armington elasticities has the opposite effect. Therefore a change in Armington elasticities has offsetting effects on the size of the set of credible and effective threats lessening the effect of such changes on the MET rate.

Appendix C. Conversion of BTAs to power of tariffs

The power of tariff, TMS, is the ratio of values at market prices to values at world prices.

$$TMS = \frac{VIMS}{VIWS}$$

where *VIMS* is the value of Chinese imports at the USA market prices, and *VIWS* is the value of Chinese imports at the world prices. A power of tariff greater than one represents a tax, while a power of tariff lower than one represents a subsidy. TMS increases with BTAs as BTAs result in higher USA market prices and lower world price on Chinese imports. The power of a tariff equals the tariff rate, RTMS, plus one.

$$TMS = 1 + \frac{RTMS}{100}$$

BTAs are converted to percentage change in the power of tariff (tms) by the following formula:

$$tms = \frac{\left[1 + RTMS_{new}/100\right] - \left[1 + RTMS_{old}/100\right]}{\left[1 + RTMS_{old}/100\right]} * 100,$$

The subscripts '*new*' and '*old*' represent the new situation with a non-zero BTA and the previous situation with a zero BTA, respectively. BTA-driven changes in power of tariffs on imports are good-specific because emissions embedded in different imported goods differ. Table C1 shows how a BTA of $137/TCE translates into percentage changes in power of tariffs for the goods most heavily traded between China and USA. To make comparison with punitive tariff instrument, these percentage changes in power of tariffs are aggregated across sectors using the value of imports in market prices (VIMS) as weights (the final column of table C1). For example, $137/TCE BTA imposed on all USA imports from China translates into 4.7% change in power of import tariff.

Appendix D. Relative power of punitive tariffs and BTAs

Figures D1–D3 compare sets of credible and effective trade threats under both instruments: (1) BTAs (converted to % change in power of tariff), and (2) % change in power of tariff rate. The purpose of this sensitivity analysis is to compare the maximum

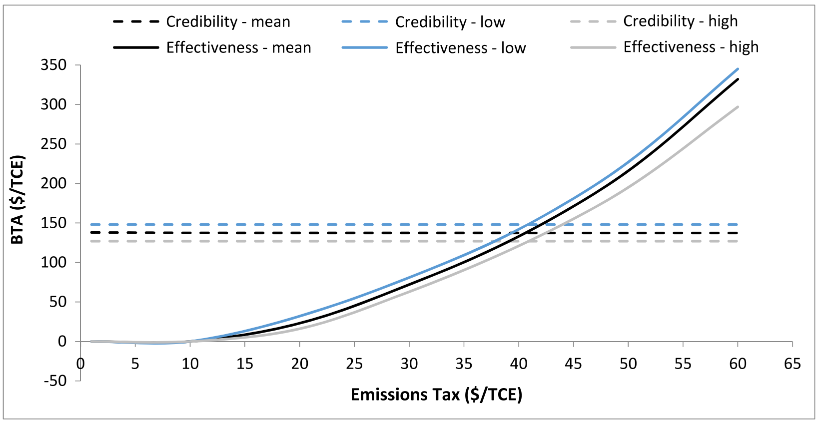

Figure B2. Sensitivity of credibility and effectiveness conditions to changes in Armington elasticities.

Table C1. $137/TCE BTA translated into percentage change in power of tariff for largest import categories of goods coming from China to USA.

	Initial power of import tariff	Power of tariff after introduction of BTA	Percent change in power of tariff	Share in total USA imports from China
Wood products	1.01	1.1	5.23	0.06
Energy intensive manufacturing	1.03	1.12	8.59	0.07
Other manufacturing	1.05	1.09	4.19	0.7

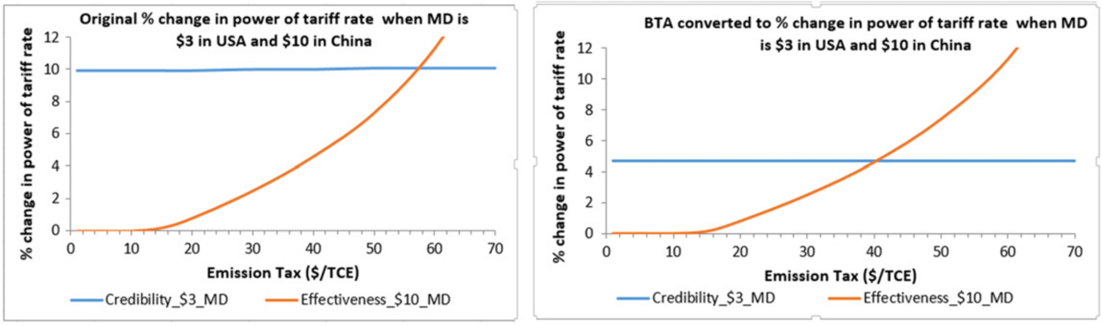

Figure D1. Credibility and effectiveness conditions under base case: MD = $3TCE in USA, and MD = $10/TCE in China.

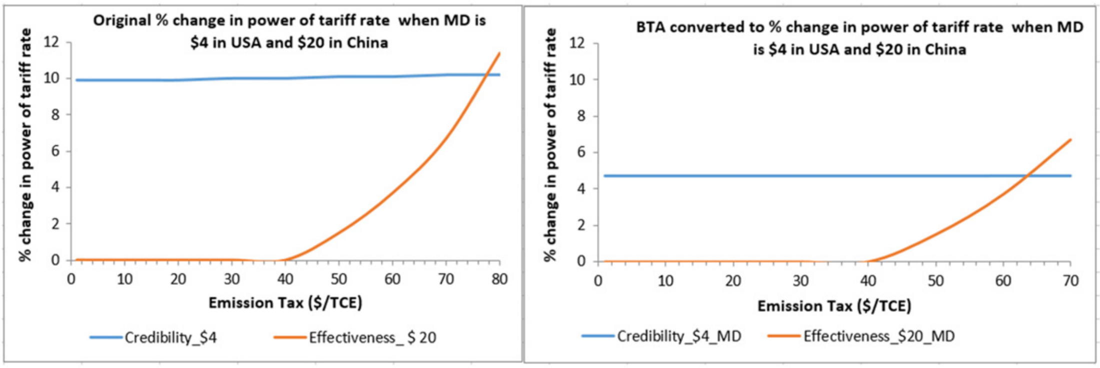

Figure D2. Credibility and effectiveness conditions under mean case: MD = $4TCE in USA, and MD = $20/TCE in China.

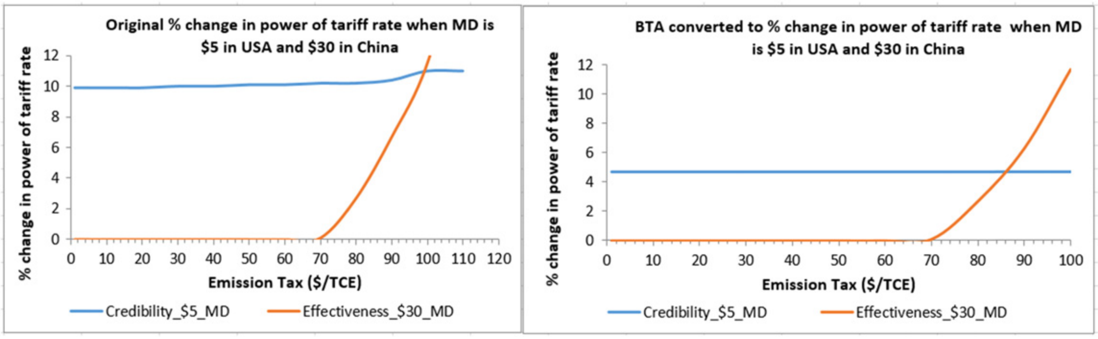

Figure D3. Credibility and effectiveness conditions under maximum case: MD = $5TCE in USA, and MD = $30/TCE in China.

enforceable carbon tax rate (intersection between credibility and effectiveness lines) attained by both instruments under different levels of marginal damage. We consider in our analysis three scenarios for marginal damage reported in Nordhaus (2011): (1) low marginal damage ($3 in USA and $10 in China) which coincides with figures 4(A) and (B), (2) mean marginal damage (($4 in USA and $20 in China), and (3) high marginal damage ($5 in USA and $30 in China). These figures reveal that punitive tariffs consistently (over all marginal damage scenarios) attain a higher maximum enforceable carbon tax rates revealing a superiority of this instrument in terms of its effectiveness to enforce stricter environmental agreements.

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