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Unilateral Climate Policy and Foreign Direct Investment with Firm and Country Heterogeneity

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Keywords: Foreign Direct Investment. Carbon leakage. Climate Policy, Emissions Technologies

JEL Classification: F12, F23, Q58

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Unilateral climate policy and foreign direct investment with firm and country heterogeneity*

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May 20, 2014

Abstract

We contribute to the debate on the impact of unilateral climate policy with a two-country two-firm international oligopoly model accounting for endogenous plant location and heterogeneity in both country size and firm's emissions technology. Our results suggest that, if the carbon price differential is moderate as compared to unit transport costs and the relative size of the highly regulated country is big enough, a no relocation equilibrium may prevail also in the long run. A large market asymmetry coupled with a small technology gap emerges as the only configuration in which unilateral climate policy leads to a fall in world emissions irrespective of the optimal location choice. Thus for being effective and not leading to production relocation, unilateral climate policy should be moderate, implemented by a sufficiently large area and complemented by mechanisms for promoting the international transfer of clean technologies. Welfare implications are also discussed.

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1 Introduction

Climate policies will remain sub global in the foreseeable future, as obstacles to a global climate agreement are still substantial (Branger and Quiron, 2014; Bosetti and De Cian, 2013). It is thus important to better understand the

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impact of unilateral measures in a long term perspective, for contributing to the ongoing debate in developed countries on climate policy's design in a world with uneven commitments.[1]

The debate centres on the likelihood of *carbon leakage* and of adverse *competitiveness effects* on domestic firms in emissions-intensive sectors. Politicians worry that the more stringent national mitigation measures might lead domestic production and jobs shifting to other less regulated regions (the so called Pollution Havens).[2] Carbon leakage takes place if a policy aimed to limit emissions in a region is the direct cause of an increase in emissions outside the region itself, thus hampering its effectiveness. Two main competitiveness mechanisms may drive carbon leakage: short-term impacts mainly via trade flows and long-term responses involving also relocation decisions via foreign direct investment (FDI).[3] FDI represents a critical mechanism in assessing the threat of carbon and job leakage since it may lead to major discontinuous changes, implying considerable losses in domestic production and employment. When analysing the impact of unilateral climate policy, it is thus important to take into account that firms are internationally mobile, capturing the effect of the more stringent climate measures on the domestic firms' international location choices.

A rich theoretical and empirical literature has analysed the effectiveness of unilateral climate policy and its impact on competitiveness. A first group of theoretical studies focuses on the so-called pollution haven hypothesis (PHH) (see e.g. Copeland and Taylor, 1994, 2003), adopting a general equilibrium approach and overlooking the role of FDI.[4] Similarly, most CGE models analyze the likelihood of carbon leakage not accounting for shifts in location choices. A growing body of theoretical literature on environmental policy and FDI has appeared in recent years.[5] Some of these studies focus on optimal environmental policy within a given market structure, not considering the location choice (Bayindir-Upmann, 2003; Kayalica and Lahiri, 2005; Cole et al., 2006). Others tackle the impact of environmental policy on domestic firms location decisions (and thus on outward FDI), with models endogenizing both location and policy decisions (e.g. Petrakis and Xepapadeas, 2003, Ulph and Valentini, 2001; Abe

[1] For the debate on the new EU climate and energy package setting 2030 targets, see for instance PBL (2012), and Financial Times, "EU must improve its aim on energy", December 2, 2013.

[2] In the policy debate the key issue is the effect of tight regulation on the profitability of domestic production, more than on national firms' global profits.

[3] Reinaud (2008, p. 3) indicates that there is also a third channel (the fossil fuel price channel), but focuses on the two competitiveness-driven channels, as they can be more realistically addressed *via* national policies.

[4] These models predict that, due to the liberalisation of trade, firms active in pollution-intensive sectors, and operating in countries adopting more restrictive environmental policies, will transfer production abroad and will serve the domestic market from these new foreign plants.

[5] Early models (Markusen et al., 1993; Motta and Thisse, 1994), endogenizing the location decision but not environmental policy, give interesting insights. However these studies are concerned with symmetric countries and considered local pollution. See also Rauscher (1995) and Hoel (1997) for models where both governments and firms location decisions are treated as endogenous.

and Zhao, 2005; Ikefuji et al., 2010, 2013; Lee, Lee and Kang, 2014). In order to capture both countries' and firms' decisions, these models are based on a very stylized set-up, assuming that pollution is local, there are no transport costs and the two areas (adopting mitigation policy or not) are of the same market size. Such an approach does not allow to understand the impact of unilateral climate policy on global emissions (as in the case of greenhouse gases (GHGs)) and to fully capture its competitiveness implications.[6] Moreover, although most of these studies generally predict a major shift of domestic activities abroad, the empirical literature has shown that the evidence is mixed (Branger and Quiron, 2014).[7]

The purpose of this paper is to analyze the impact of unilateral climate policy considering internationally mobile firms which operate in a context characterized by both *country and firm heterogeneity*. We build on two new strands of literature separately addressing one or the other source of heterogeneity. Sanna-Randaccio and Sestini (2012) draw attention to the role of market size and market size asymmetry, an issue surprisingly neglected in the formal literature on unilateral climate policy and FDI.[8] Their model, allowing for endogenous plant location, shows that a larger size of the regulated area, as compared to the non-complying one, is a powerful centripetal force when transport costs are high, discouraging relocation of domestic producers in carbon intensive industries. This is a major reason why also in the long term a higher carbon tax not necessarily leads firms in the regulated area to move production abroad. A major shortcoming of Sanna-Randaccio and Sestini (2012) is the assumption that firms in the two regions have the same emissions technology. This hypothesis is contradicted by recent empirical research. In a major study on international differences in emissions intensity, Douglas and Nishioka (2012)[9] find that "emissions intensities differ systematically across countries because of differences in production techniques". Their results indicate that firms in developing countries are significantly more emissions-intensive than competitors

[6] Another strand of theoretical literature shows that restrictive unilateral climate measures may attract strategic inward FDI. This is considered as one of the mechanism explaining the lack of satisfactory evidence on the PHH (Elliot and Zhou, 2013; Dijkstra et al., 2011).

[7] Studies testing the PHH by considering inter-country FDI location choice do not find robust support for this prediction (Smarzynska Javorcik and Wei, 2004; Eskeland and Harrison, 2003; Xing and Kolstad, 2002; Wagner and Timmins, 2009; Manderson and Kneller, 2012). Mixed evidence is provided by studies on intra-country FDI location choice, analyzing whether differences in environmental stringency across sub-national units (i.e. US states, Chinese provinces) affect the spatial allocation of FDI within a country (see e.g. Keller and Levinson, 2002; Dean et al., 2005). As suggested by Mulatu et al. (2010), this last strand of literature does not really test the "pollution haven" hypothesis. However, in a recent study Aichele and Felbermayr (2014) conclude that the Kyoto protocol has been ineffective or possibly even harmful for the global climate.

[8] Market size and market asymmetry have instead been recognized as critical factors in models tackling the effectiveness of climate policy from other perspectives (Böhringer, Fisher and Rosendahl, 2011; see Branger and Quiron, 2014, for a survey). In the environment and FDI literature an exception is Zeng and Zhao (2009), who consider market asymmetry within a monopolistic competition model.

[9] Douglas and Nishioka (2012) calculate sector-specific and country-specific emissions intensity coefficients for 39 countries and 41 industrial sectors for the year 2000.

in developed nations. Similar results have been obtained by Albornoz, Cole, Elliot and Ercolani (2009) and Eskeland and Harrison (2003).[10] To account for firm heterogeneity, we draw from another strand of literature focusing on how differences in emissions technologies across firms affect the impact of new environmental taxes on aggregate emissions. Sugeta and Matsumoto (2005), although not addressing specifically the case of unilateral climate policy, offer interesting insights showing that the effectiveness of pollution taxation depends upon the technology gap across firms. As most of the analysis is undertaken in a closed economy setting, country heterogeneity and endogenous plant location choices are not captured by the model. Lahiri and Symeonidis (2007) build a two- country model where firms in different countries are characterized by asymmetry in pollution-intensity coefficients. They show that, whenever the country with the less pollution-intensive technology unilaterally increases its emissions tax, total emissions may rise if the technology gap is sufficiently high. In this model too, firms are not geographically mobile (i.e. relocation is not an option) and markets are of the same size.

We contribute to this literature providing an international oligopoly model, with endogenous plant location, in which the role of heterogeneity in *both* country size and firm emissions technology is accounted for, thus bringing the analysis closer to reality. Adopting a long term perspective (as explained in section 2), we present a model assessing under which institutional and technological scenarios unilateral climate policy may be effective and claims of domestic production and job losses may be overrated. The model catches the main features of pollution-intensive sectors,[11] allowing for transport costs, plant-specific fixed costs, accounting for *global* industrial pollution, and considering both partial and total relocation. We assume free intra-firm technology transfer across borders, but no inter-firm exchanges of technology.[12] The model thus captures the main centripetal and centrifugal forces driving the location decision when firms are confronted with unilateral climate measures (considered here as exogenous). The problem is structured as a two-stage game: in the first stage the firm based in the cooperating area determines its location, while in the second stage the two firms decide simultaneously how much to sell in each market, competing *à la* Cournot.

We find that, when the carbon price differential between the two regions (with and without stringent climate measures) is more than compensated by transport costs (the so called high transport cost case), and the size of the cooperating area is sufficiently large, an equilibrium with no relocation (henceforth

[10] The results of Eskeland and Harrison (2003) on Côte d'Ivoire, Mexico and Venezuela suggest that foreign-owned plants have lower levels of emissions than comparable domestically-owned plants. Albornoz, Cole, Elliot and Ercolani (2009) find that in Argentina foreign-owned manufacturing firms are more likely to implement Environmental Management Systems than locally-owned producers.

[11] These industries are capital intensive (and thus firms bear high fixed plant costs), generally vertically integrated, produce bulk commodities with a high weight/value ratio and are thus characterized by large transportation costs (see e.g. Reinaud, 2008; Ederington et al., 2005).

[12] On the impact of asymmetric pollution emissions standards on international location choices in the presence of inter-firm spillovers see Lee, Lee and Kand (2014).

NR) may prevail in the long run, notwithstanding the unilateral climate measures. Instead, if the carbon price differential is excessively high as compared to unit transport costs, the only feasible equilibrium location is total relocation (TR), with major losses in domestic production and jobs. The effectiveness of unilateral climate policy is shown to depend on the *joint effect* of country and firm heterogeneity. Allowing for firms' heterogeneity, in contrast with Sanna-Randaccio and Sestini (2012), we find that a no relocation equilibrium is not a sufficient condition for having a fall in global emissions when a unilateral carbon tax is implemented. A large market asymmetry coupled with a small technology gap is the only configuration in which unilateral climate policy will certainly lead to a fall in world emissions, irrespective of the optimal location choice.[13] Moreover, a small emissions technology gap plays also a crucial role in bringing about an increase in social welfare as a whole.

The paper is organized as follows. Section 2 presents the model. Section 3 analyzes the impact of unilateral climate measures on the international location choice. Section 4 addresses how heterogeneity in emission intensity influences the international location choice. Section 5 explores the effectiveness of unilateral climate measures. Section 6 presents some welfare implications and Section 7 the main conclusions.

2 The basic framework

Let us consider a partial equilibrium model with two countries (areas)[14] and two firms, 1 and 2. Also, let us define as the baseline the scenario where the two firms manufacture the same homogeneous good in country I and II respectively, and export to the other country due to "reciprocal dumping". Domestic and foreign inverse demand functions are linear and write as

$$P_K = a_K - b_K(q_{i,K} + q_{j,K}) \tag{1}$$

with $i, j = 1, 2$, $i \neq j$, $K = I, II$, where $q_{i,K}$ denotes the output sold by firm i in country K. In order to capture heterogeneity in market size as in Sanna-Randaccio and Sestini (2012) and Zeng and Zhao (2009), we assume that country I is larger than country II by setting $a_I > a_{II}$ and $b_I < b_{II}$.

The two firms face a constant marginal production cost[15] c and a fixed cost $G_{i,K}$ necessary to install a manufacturing plant (at home and/or abroad). There is also a fixed cost at the firm level F, which captures firm-specific activities such as advertising, marketing, distribution and managerial services. Firms are heterogeneous as to emissions technologies. We assume that the emissions coefficient e_i, which measures emissions per unit of output, is firm-specific with

[13] On the role of the technological gap as a driver of emissions reduction, see also Golombek and Hoel (2006).

[14] Each country may be thought of as a group of nations applying the same degree of stringency in mitigation policy.

[15] The parameter c may be influenced by country-specific and firm-specific factors. For the sake of simplicity, we assume that $c_1 = c_2 = c$.

$0 < e_1 < e_2 \leq 1$. Accordingly, the cleaner firm is based in the larger country. Finally, the attention is focused on *global* industrial pollution as in the case of GHGs emissions. In the baseline the price of emissions is the same in both areas, with $t_I = t_{II}$.

Then, we define an alternative scenario where the carbon tax in country I is higher as compared with country II (i.e. $t_I > t_{II}$). Such unilateral climate policy may have different repercussions on the local firm's location strategy. We assume that firm's 2 location choice is exogenous, as this firm may only produce in its home country and exports to the foreign market, whilst firm's 1 location choice is endogenous, with firm 1 choosing to serve the foreign market via export or FDI. Export implies an additional marginal (and unit) transport cost s, with $s > t_{II}$, whilst FDI involves plant specific fixed costs associated to the plant in the foreign market. In particular, firm 1 may choose to produce in the home country and serve the foreign market via export (i.e. no relocation (NR)). It may open a plant also in country II, serving both markets *via* local production (partial relocation (PR)). Finally, firm 1 may move *all* production abroad, and export back to the home market (total relocation (TR)). This is the case implicitly assumed in the pollution haven and carbon leakage debates. To summarize, firm 1's location strategy space is given by $S_1 = \{NR, PR, TR\}$. In what follows we set that $G_{1,I} = G_{1,II} = G_{2,II} = G$. This implies that fixed plant costs are not sunk in any country before the game starts. Thus we are considering a *long-term* perspective, as for instance in Markusen et al. (1993), due to the possible non-transitory nature of uneven abatement commitments between the two areas.

We consider a two-stage game that develops as follows: at the first stage firm 1 determines its location, while at the second stage firm 1 and firm 2 decide simultaneously how much to sell in each market. The game is solved as usual by backward induction. We start by determining the equilibrium sales by each firm in the different configurations, and then we solve for the optimal location choice of firm 1 in the first stage.[16]

3 The optimal location choice

In this section, we analyze the impact of unilateral climate policy enacted by the larger and cleaner area (country I) on the local firm optimal location choice.[17] For ease of exposition, we define as *low transport costs* the case with $s < e_1(t_I - t_{II})$, observed whenever unit transport costs are lower than the additional unit costs due to the carbon price differential; on the contrary we label *high transport cost* the case with $s > e_1(t_I - t_{II})$.

In order to identify the optimal location choice of firm 1, under the assump-

[16] As the solution of the second stage of the game is in line with the traditional literature on quantity competition *à la Cournot*, for lack of space, we do not provide details on this stage.

[17] By considering unilateral climate policy by the larger and cleaner area, we capture the fact that developed countries, which have the technology lead, implement more stringent mitigation measures than emerging and developing nations.

tion that $t_I > t_{II}$, we start considering whether there are circumstances such that relocating the whole production abroad (i.e. the TR location strategy) is preferred over producing only at home (i.e. the NR location choice).

To this aim, it suffices to compare equilibrium profits under the NR market configuration ($\hat{\Pi}_1^{NR}$) and equilibrium profits under the TR case ($\hat{\Pi}_1^{TR}$), namely:

$$\hat{\Pi}_1^{NR} - \hat{\Pi}_1^{TR} = \frac{4}{9}\left\{ s\left(\frac{A_I}{b_I} - \frac{A_{II}}{b_{II}}\right) - e_1(t_I - t_{II})\left[\frac{A_I}{b_I} + \frac{(A_{II} - s)}{b_{II}}\right] + \frac{s^2}{b_{II}}\right\} \tag{2}$$

with $A_I = [a_I - c - e_1 t_I + (e_2 - e_1)t_{II}] > 0$, $A_{II} = [a_{II} - c - e_1 t_I + (e_2 - e_1)t_{II}] > 0$ and $A_{II} - s > 0$ (see Appendix I). Unilateral climate policy has three contrasting effects on the local firm's location decision, when choosing between NR and TR. The *climate policies asymmetry* effect, captured by the second term in curly brackets in Eq. (2), represents a powerful centrifugal force. As expected, the more stringent carbon tax ($t_I > t_{II}$) induces firm 1 to move production abroad for taking advantage of the lower emission price. The effect of the carbon tax differential depends on firm 1's emission coefficient (e_1). Since the carbon tax is set on emissions, its impact on firm i's unit variable cost obviously depends on e_i, which captures firm *i's* emissions for unit of output. Nevertheless, the incentive to total relocation can be mitigated by two centripetal forces. First, we can identify a *market asymmetry effect,* captured by the first term in curly brackets: as $s > 0$, the larger the size of the home market the more profitable is the no relocation choice, since total transport costs are lower when producing in the large country and exporting to the small one (the NR case), than *viceversa* (the TR scenario). Furthermore, firm 1 can be prevented from total relocation by a *lower competition effect*, captured by the third term (i.e. $\frac{s^2}{b_{II}}$). As the intensity of competition is a function -*inter alia*- of transport costs, the higher these costs, the more difficult for the outside competitor to penetrate country I and thus the stronger the incentive for firm 1 to produce in its home country.

We prove in Appendix I that, in the low transport costs scenario ($s < e_1(t_I - t_{II})$) total relocation always dominates over no relocation as the centrifugal force always prevails over the centripetal ones. Nevertheless, in the high transport cost scenario ($s > e_1(t_I - t_{II})$), the two centripetal forces may prevail on the centrifugal one and thus no relocation may dominate total relocation.

When the total relocation choice does not belong to the equilibrium path, one needs to investigate whether there are conditions such that the incentive to keep the whole production at home, thereby getting profits $\hat{\Pi}_1^{NR}$, dominates that to partially relocate productive activities, obtaining thus $\hat{\Pi}_1^{PR}$. We obtain that:

$$\hat{\Pi}_1^{NR} - \hat{\Pi}_1^{PR} = G - \frac{4}{9}\left[s + e_1(t_I - t_{II})\right]\frac{(A_{II} - s)}{b_{II}} \tag{3}$$

Eq. (3) shows that here there are two centrifugal forces at work: the carbon price differential and unit transport costs. By choosing PR, and thus producing in both countries, firm 1 would benefit, as compared to the NR choice, not only from the lower emission prices in country II but also from saving in transport costs. On the other hand, PR is the high fixed cost option as it involves two plants. These additional plant fixed costs are a powerful centripetal force since they discourage relocating production abroad.

Moreover, when keeping the whole production at home is not the optimal location strategy, one may wonder whether a partial relocation choice (PR) can be preferred over total relocation (TR). From the comparison between equilibrium profits accruing to firm 1 under partial relocation $\hat{\Pi}_1^{PR}$ and profits observed under total relocation $\hat{\Pi}_1^{TR}$, we have:

$$\hat{\Pi}_1^{PR} - \hat{\Pi}_1^{TR} = \frac{4}{9}\left[s - e_1(t_I - t_{II})\right]\frac{A_I}{b_I} - G. \tag{4}$$

When comparing partial with total relocation, the benefits from the lower carbon tax in country II and transport costs savings go into opposite directions, the first effect discouraging partial relocation while the second favoring it. In the low transport cost case - $s < e_1(t_I - t_{II})$-, partial relocation involves not only additional fixed costs associated to the second plant but also lower variable profits. Thus, it follows that $\hat{\Pi}_1^{PR} < \hat{\Pi}^{TR}$. On the other hand, in the high transport cost scenario - with $s > e_1(t_I - t_{II})$-, the usual trade off between higher variable profits versus higher fixed costs associated with the decision to produce in both countries instead of servicing one country via export is at work.

Summarizing the above results, we can state that:

Proposition 1 *In the low transport costs scenario, under unilateral climate policy, total relocation (TR) by the local firm always prevails at equilibrium. In the high transport costs case, even no relocation (NR) or partial (PR) may occur.*

Quite interestingly, it follows from the above that a more stringent climate policy implemented by country I does not lead *a priori* to the emergence of the so-called *pollution havens*, as no relocation or partial relocation of firm 1's productive activities can be observed at equilibrium in the high transport cost scenario.

In order to illustrate under which circumstances, with high transport costs, each equilibrium prevails, we identify equilibrium areas focusing on two critical variables: the size of the foreign market[18] (a_{II}) and unit transport costs (s). Let us denote by $\breve{a}_{II}$ the size of the foreign market such that $\hat{\Pi}_1^{NR} = \hat{\Pi}_1^{TR}$ (see Appendix II, Eq. (A.II.1)). Thus, for $a_{II} < \breve{a}_{II}$, *NR* always dominates *TR*, and *viceversa*. Let us also indicate by $\bar{a}_{II}$ the size of the foreign market such that $\hat{\Pi}_1^{NR} = \hat{\Pi}_1^{PR}$ (see Appendix II, Eq. (A.II.2)). Then, the *NR* choice dominates over *PR* for any $a_{II} < \bar{a}_{II}$, and *viceversa*. We consider both $\breve{a}_{II}$ and $\bar{a}_{II}$ as functions only of s. So, the two functions $\breve{a}_{II}(s)$ and $\bar{a}_{II}(s)$ indicate (s, a_{II}) combinations for which the indifference conditions between the NR and TR choices and the NR and PR choices, respectively, hold. In particular, we prove that while $\breve{a}_{II}(s)$ is increasing in s, in the relevant range of parameters $\bar{a}_{II}(s)$ is decreasing in s. Also, $\bar{a}_{II}\mid_{s=0} > \breve{a}_{II}\mid_{s=0}$ holds (see Appendix II).

[18] This variable captures also the effect of market size asymmetry since the size of country I is given.

We may thus map these two indifference conditions ($\breve{a}_{II}(s)$ and $\bar{a}_{II}(s)$) in the (s, a_{II}) plane. In Figure 1, we can see that they cross at (s^*, $a_{II}(s^*)$), where

$$s^* = \frac{9}{4}\frac{b_I G}{A_I} + e_1(t_I - t_{II}). \tag{5}$$

Accordingly, at (s^*, $a_{II}(s^*)$) both Eq.(2) and Eq.(3) are satisfied as equality. Notice that, as $A_I > 0$, one may conclude that $s^* > 0$ and $s^* > e_1(t_I - t_{II})$, i.e. we are in the high transport cost scenario. Moreover, we find that s^* is also the value of unit transport costs for which there is indifference between partial and total relocation, and such that, for $s > s^*$, PR dominates TR and *viceversa* (see Appendix III). Thus the indifference condition $\hat{\Pi}_1^{PR} = \hat{\Pi}_1^{TR}$ can be represented in the (s, a_{II}) plane as a vertical line passing for s^*. The three indifference conditions considered above define the equilibrium areas.[19]

Insert FIGURE 1 around here

A third variable, fixed plant costs (G), affects the (s^*, $a_{II}(s^*)$) values, thus shaping the equilibrium areas. In particular, Eq.(A.II.2) shows that the position of the $\bar{a}_{II}(s)$ function depends also on G. Being $\frac{\partial \bar{a}_{II}}{\partial G} > 0$, as fixed plant costs rise, the curve defining the boundary between the NR and PR choices shifts upward. To capture the role of fixed plant costs we define with $\overline{G}$ the G value such that $a_{II}(s^*(\overline{G})) = a_I$. Thus $\overline{G}$ defines the case in which both indifference conditions $\breve{a}_{II}(s)$ and $\bar{a}_{II}(s)$ are satisfied when the two areas (with and without stringent climate policies) are of the same size. Let us define by G_M (standing for moderate fixed plant costs) any positive value of G such that $G < \overline{G}$, and by G_H any value such that $G > \overline{G}$. It follows that in the (s, a_{II}) plane, the curve $\bar{a}_{II}(s)$ defined for G_H (G_M) is located above (below) the $\bar{a}_{II}(s)$ curve defined for $\overline{G}$.

Figure 1 shows[20] that NR may be an equilibrium for a wide range of parameters also in the long run, that is when the fixed costs of the domestic plant are not sunk.

Thus we can state that:

Proposition 2 *In the high transport costs scenario, under unilateral climate policy, no relocation is an equilibrium whenever* $a_{II} < \min(\breve{a}_{II}(s), \bar{a}_{II}(s))$. *On the contrary, whenever* $a_{II} > \min(\breve{a}_{II}(s), \bar{a}_{II}(s))$, *total relocation emerges as the equilibrium if* $s < s^*$, *while partial relocation takes place if* $s > s^*$.

[19] We may also label as $a_{II,\min}$ the value of a_{II} such that the equilibrium quantity sold by firm 1 in country II under NR is nil, say $\widehat{q}_{1,II}^{NR}(a_{II,\min}) = 0$. The function $a_{II,\min}$ is increasing in s (see Figure 1). For $a_{II} < a_{II,\min}$ we are in the No Export region (NE) in which serving the foreign market is not profitable.

[20] The figure is drawn for $G \in G_M$, and thus $a_{II}(s^*) < a_I$. This is a quite relevant scenario since in the most important emissions intensive industries companies own plant in different countries, showing that partial relocation is a feasible strategy. The cement industry can be taken as an example.

The economic intuition behind this Proposition is that, with $t_I > t_{II}$, the NR equilibrium requires a sufficient degree of market asymmetry (i.e. a sufficiently small size of the foreign less regulated market). In the case when this asymmetry is not relevant enough, then the NR choice is dominated by either TR or PR, depending on the magnitude of transport costs. Furthermore,

Lemma 3 *The size of the foreign market such that $a_{II} < \min(\breve{a}_{II}(s), \bar{a}_{II}(s))$ is increasing (decreasing) in s if $s < s^*$ ($s > s^*$).*

In a range of transport costs values such that TR dominates PR (i.e. when $s < s^*$), the condition for a NR equilibrium becomes less stringent when s rises. If country I is the larger area, transport costs discourage total relocation as explained above. On the contrary, when considering transport costs values for which PR dominates TR (i.e. $s > s^*$) the condition for an NR equilibrium becomes more stringent when s rises, since transport costs promote partial relocation.

Furthermore, when focusing on moderate plant fixed costs, we find:

Proposition 4 *With G_M (and thus $a_{II}(s^*) < a_I$), when the two areas are of the same market size, the no relocation choice cannot emerge as an equilibrium, being dominated by total (for $s < s^*$) or partial relocation (for $s > s^*$).*

With moderate plant fixed costs, the incentive to partially relocate is quite strong. In this setting, the area enacting stringent mitigation measures should have a larger size with respect to the non-complying area, for unilateral climate policy leaving unchanged the domestic firm's equilibrium location choice.

Market asymmetry however plays a crucial role also in the case of very high fixed plant costs G_H (i.e. with $a_{II}(s^*) > a_I$). Here the stimulus to partial relocation is quite weak, given the high additional fixed costs. However, with market symmetry, or even more with "reverse" market asymmetry (thus with country II being larger than country I), the incentive for total relocation becomes very powerful. When the non-complying countries represent the larger area, by moving all production abroad firm 1 benefits not only from the lower price of emissions in country II but also from saving in transport costs. TR would in fact imply producing in the large area and exporting to the small one.[21]

It is worth remarking that the relative size of the area enacting the unilateral climate policy plays a major role in the different scenarios considered, although the results obtained are very industry-specific.[22] We have shown that with a sufficiently high degree of market asymmetry, the domestic firm may be willing to produce only in the home market also in the long term even in the presence of tight environmental policies. However, if the carbon tax differential is so high (with respect to unit transport costs) to move the system to the low transport cost area, market asymmetry no longer plays a role since the only feasible equilibrium becomes TR.

[21] We present in Appendix IV a condition showing that even a moderate degree of "reverse" market asymmetry is sufficient for TR to dominate always NR.

[22] The values of the technical parameters s and G have a key role in the location choice.

4 Location choice and emissions intensity heterogeneity

We now examine whether the link between country I' s unilateral climate policy and the domestic firm equilibrium location choice is affected by emission intensity heterogeneity across countries.[23]

Let us start considering the case when firm 1 chooses between NR and TR. We know from the previous section that in the low transport costs case TR is always more profitable than NR while, in the alternative scenario of high transport costs, the profitability of the choice depends on the balancing between centrifugal (carbon price differential) and centripetal (market asymmetry and lower competition) forces. On this point, it is worth remarking that a cleaner emissions technology for firm 1, and thus a lower e_1, determines a larger parameters range for which the high transport costs scenario prevails thereby making NR a feasible equilibrium. As to the dilemma between NR and TR, we prove in Appendix V that:

$$\frac{\partial(\hat{\Pi}_1^{NR} - \hat{\Pi}_1^{TR})}{\partial e_1} = -\frac{4}{9}\left\{ \begin{array}{c} s\left[(t_I + t_{II})\left(\frac{1}{b_I} - \frac{1}{b_{II}}\right)\right] \\ +(t_I - t_{II})\left[\frac{A_I - e_1(t_I + t_{II})}{b_I} + \frac{A_{II} - s - e_1(t_I + t_{II})}{b_{II}}\right] \end{array} \right\} < 0 \tag{6}$$

Eq. (6) shows that a reduction in the emissions coefficient e_1 (*ceteris paribus* an increase in the emissions technology gap between the two firms) increases the profitability of the no-relocation choice as compared with total relocation. Indeed, from the first term in curly brackets in Eq. (6) it derives that a cleaner production process for firm 1 magnifies the centripetal force originated by the market asymmetry. From the second term in Eq. (6), it emerges that a lower e_1 weakens the centrifugal effect of the carbon price differential. [24]

Therefore:

Lemma 5 *A lower value of e_1 always promotes the no relocation (NR) choice as compared to the total relocation one (TR).*

Eq. (6) implies that, when considering a cleaner emission technology for firm 1, the $\breve{a}_{II}(s)$ function, mapping the NR *vs* TR indifference condition, shifts upward in the (s, a_{II}) plane (see Figure 2). As it is found that a lower e_1 promotes the NR choice as compared with TR, a given s should be associated to a higher a_{II} (i.e. a lower degree of market asymmetry), for the neutrality condition $\hat{\Pi}_1^{NR} = \hat{\Pi}_1^{TR}$ to hold.

When comparing the NR versus the PR location choice, a lower e_1 moves the two centrifugal forces promoting partial relocation (transport cost savings

[23] A firm's environmental performance is captured by its emission coefficient, i.e. it is measured in terms of emissions per unit of output.

[24] This is the case although the cost-asymmetry due to $e_1 < e_2$ produces a market enhancing effect which increases the propensity to move abroad. See on this Sanna-Randaccio and Sestini, 2012.

and carbon price differential) in opposite directions and thus the sign of the derivative cannot be univocally determined. We find that

$$\frac{\partial(\hat{\Pi}_1^{NR} - \hat{\Pi}_1^{PR})}{\partial e_1} = \frac{4}{9}\left\{ s\frac{(t_I + t_{II})}{b_{II}} - (t_I - t_{II})\left[\frac{A_{II} - s - e_1(t_I + t_{II})}{b_{II}}\right]\right\} \quad (7)$$

The positive sign of the first term in curly brackets indicates that a fall in e_1 leads to a strengthening of the centrifugal role of s, thus promoting *PR vis-à-vis NR*. On the other hand, a lower e_1 leads to a weakening of the centrifugal role of the carbon price differential, captured by the second term in curly brackets, thus discouraging *PR vis-à-vis NR*. In order to see whether there exist conditions such that the net effect on the *NR vs PR* comparison can be univocally determined, it can be useful to analyse how a lower e_1 affects the $\bar{a}_{II}(s)$ function, which maps the NR-PR indifference condition in the (s, a_{II}) plane. To this aim, let us denote as $\widetilde{s}$ the s value for which $\frac{\partial \bar{a}_{II}(s)}{\partial e_1} = 0$ (see Appendix VI). Notice that, for $s < \widetilde{s}$ (resp. $s > \widetilde{s}$), then $\frac{\partial \bar{a}_{II}(s)}{\partial e_1} < 0$ (resp. $\frac{\partial \bar{a}_{II}(s)}{\partial e_1} > 0$). Thus, if e_1 decreases, the $\bar{a}_{II}(s)$ function rotates clockwise around the pivot point $\widetilde{s}$ (see Figure 2). Accordingly, we get that for $s < \widetilde{s}$ the *weakening* of the centrifugal role of the carbon price differential prevails, so that a more efficient emission technology for firm 1 leads to an expansion of the *NR* versus the *PR* area. On the other hand, for $s > \widetilde{s}$, the impact of the *strengthening* of the centrifugal role of transport cost savings dominates. In this case, the $\bar{a}_{II}(s)$ curve moves to the left and the *NR* area shrinks.[25]

Lemma 6 *A lower value of* e_1 *promotes (resp. discourages) the no relocation (NR) choice as compared with partial relocation (PR) whenever* $e_1(t_I - t_{II}) < s < \widetilde{s}$ *(resp.* $s > \widetilde{s} > e_1(t_I - t_{II})$*).*

Insert FIGURE 2 around here

Finally, in the dilemma between *TR* and *PR*, the role of e_1 turns out to be clear-cut. Indeed, it results that:

$$\frac{\partial(\hat{\Pi}_1^{PR} - \hat{\Pi}_1^{TR})}{\partial e_1} = -\frac{4}{9}\left\{ (t_I - t_{II})\frac{A_I}{b_I} + (t_I + t_{II})\left[\frac{s - e_1(t_I - t_{II})}{b_I}\right]\right\} < 0 \quad (8)$$

A lower emission coefficient for firm 1 increases the profitability of partial relocation with respect to total relocation, since $A_I > 0$ (see Appendix I) and the relevant scenario is that with high transport costs.[26] In particular, Eq. (8) shows that a cleaner emission technology adopted by firm 1 weakens the centrifugal effect of the carbon price differential, thus strengthening the incentive to chooses *PR* instead of *TR*.

Thus:

[25] We recall that we consider s values such that $s > e_1(t_I - t_{II})$, otherwise NR and PR would be always dominated by TR.

[26] Otherwise TR will always dominate PR (see Proposition 1).

Lemma 7 *A lower value of e_1 promotes the partial relocation (PR) choice as compared with total relocation (TR).*

The effect of a cleaner emission technology for firm 1 on the PR/TR choice may also be illustrated by evaluating its effect on s^*, namely the s value such that $\breve{a}_{II}(s) = \bar{a}_{II}(s)$. Indeed:

$$\frac{\partial s^*}{\partial e_1} = \frac{4}{9}\frac{b_I G(t_I + t_{II})}{A_I^2} + (t_I - t_{II}) > 0. \tag{9}$$

It follows that, if the production process of firm 1 is cleaner (i.e. e_1 is lower), the crossing point of the two functions $\breve{a}_{II}(s)$ and $\bar{a}_{II}(s)$ moves leftward in the $(s,\, a_{II})$ plane (see Figure 2). Accordingly, the horizontal line defining the TR *vs* PR boundary moves leftward, so that the incentive to choose partial instead of total relocation becomes stronger.

We may thus state that:

Proposition 8 *A cleaner production process of the domestic firm in the country with tighter mitigation measures reduces the parameters range for which TR is an equilibrium. Further, it promotes the NR equilibrium choice for $e_1(t_I - t_{II}) < s < \widetilde{s}$, while enhancing the PR equilibrium for $s > \widetilde{s}$.*

The findings in the above Proposition may be further qualified. Indeed, it can be proved that, within the admissible parameter range, $\widetilde{s} > s^*$ holds, being $\widetilde{s}$ thus located in the high transport cost area.[27] Moreover, it can be shown that $\widetilde{s}$ belongs to a range of s values such that an equilibrium (either PR or NR) exists. In addition, noticing that the $\widetilde{s}$ threshold increases in G, when considering the upper tail of admissible G values, $\widetilde{s}$ tends to become very high. Accordingly, it follows from the above that a lower e_1, while increasing the PR equilibrium area for very high values of s, in most cases leads to a larger NR equilibrium region as compared with the PR one.

5 Unilateral climate policy and global emissions

We assess now the impact on global emissions of a higher unilateral carbon tax, imposed by the larger and cleaner country (country I). To this aim, let us define as $\widetilde{E}_W$ the global emissions in the baseline scenario where both countries set the same pollution tax ($t_I = t_{II}$) and there is no relocation of productive activities**.** Instead $\widehat{E}_W^L$ indicates global emissions when firm 1 chooses location L, with $L \in \{NR, PR, TR\}$, as the pollution tax in country I is higher than that in country II, namely $t_I > t_{II}$. Since $\widehat{E}_W^L = e_1\widehat{Q}_1^L + e_2\widehat{Q}_2^L$,[28] we should account for the interplay of two main mechanisms: the effect of unilateral climate policy on the volume of world production, labelled as *volume effect,* and whether the

[27] See Appendix VII.

[28] Notice that $\widehat{Q}_i^L = \widehat{q}_{i,I}^L + \widehat{q}_{i,II}^L$ with $i = 1, 2$ and $\widehat{q}_{1,I}^L$ denoting equilibrium sales of producer i in country I in the market configuration L.

sales of the dirtier producer (firm 2) displace those of the cleaner firm (firm 1) in the world market, labelled as *product mix effect*.[29]

We consider first the change in global emissions when moving from the baseline scenario to the no relocation equilibrium. As to the volume effect, we can observe that:

$$\widehat{Q}_W^{NR} - \widetilde{Q}_W = -e_1(t_I - t_{II}) \left[\frac{1}{3b_I} + \frac{1}{3b_{II}} \right] < 0 \tag{10}$$

Eq.(10) shows that world production decreases, reducing *ceteris paribus* the level of global emissions. Since total sales fall in both markets, the volume effect is driven only by the magnitude of the world market (captured by the terms in square brackets), while the difference in size of the two markets has no role. On the other hand, since the higher carbon tax facing firm 1 generates a competitive advantage for its foreign rival, the dirtier producer gains market shares as compared to the cleaner one in both countries, and thus global emissions rise due to the product mix effect (See Appendix VIII, Eq.s (A.VIII.1) and (A.VIII.2)). The net impact of these two contrasting forces on global emissions turns out to be:

$$\widehat{E}_W^{NR} - \widetilde{E}_W = -e_1(t_I - t_{II}) \left[\frac{1}{3b_I} + \frac{1}{3b_{II}} \right] (2e_1 - e_2) \tag{11}$$

It follows from the above that under the NR equilibrium location choice, unilateral mitigation measures lead to a reduction in global emissions iff *the emission technology gap is small* (namely $e_1 > \frac{e_2}{2}$). Indeed, with a small technology gap, the size of the product mix effect (leading to a rise in global emissions) is not relevant and thus the the volume effect (reducing global emissions) dominates. On the contrary, with a *large emission technology gap* ($e_1 < \frac{e_2}{2}$), the product mix effect prevails on the volume effect and the unilateral climate policy turns out to be ineffective under the NR equilibrium. We can thus state the following proposition:

[29] In the trade and the environment literature using two-sector general equilibrium models (see e.g. Copeland and Taylor, 1994, 2003), it is usual to distinguish three effects of trade liberalisation on the environment, following Grossman and Krueger (1993). The *scale effect* captures the impact on the level of economic activity, with the composition of total production unchanged. The *composition effect* indicates the change in the sectoral composition of production due to the impact of trade liberalisation on the country specialization. The *technique* effect reflects that trade liberalisation may lead to a change in the technologies adopted, with a lowering in emissions for unit of output. Our model is different in various respects, since it is a partial equilibrium model and consider global instead of local pollution. The mechanisms we capture obviously present some similarities with the ones identified by the trade and environment literature. So the volume effect corresponds to the scale effect and the product mix effect captures some elements of both the composition and the technique effect. However, due to the differences in the models, there is no total comparability of these concepts. That is why we preferred adopting a different terminology.

Proposition 9 *In the case when NR is the equilibrium location choice, unilateral climate policy leads to a reduction in global pollution iff the emission technology gap is sufficiently small.*

We move now to consider the impact of a higher unilateral carbon tax on global emissions when firm 1 chooses partial relocation (PR) at equilibrium. The effect on global production is given by:

$$\widehat{Q}_W^{PR} - \widetilde{Q}_W = -\left[\frac{e_1(t_I - t_{II})}{3b_I} - \frac{s}{3b_{II}}\right]. \tag{12}$$

It emerges from Eq.(12) that the volume effect depends on the relative size of the two areas, as total sales change in opposite directions in the two countries. These sales fall in country I, due to the increase in price resulting from the higher carbon tax (first term in square brackets). Still, they rise in country II due to firm 1 producing *in loco* (instead of exporting as in the baseline), thereby saving on transport costs (second term in square brackets). Accordingly, global production falls iff $\frac{b_{II}}{b_I} > \frac{s}{e_1(t_I - t_{II})}$, namely in the case of a *large market asymmetry*.[30] An immediate by-product of the above finding is that, for the unilateral mitigation measures to reduce world production, the highly regulated area has to be sufficiently larger than the less regulated one. The product mix effect too depends on the relative size of the two areas. As compared to the baseline scenario, firm 1's sales fall in country I, due to the higher carbon tax while increasing in country II because of the strategy shift.[31] The opposite is the case for firm 2. Accordingly, for the total sales of firm 1 - $\widehat{Q}_1^{PR}$- (resp. firm 2 - $\widehat{Q}_2^{PR}$ -) to fall (resp. to rise) it is necessary that the effect in country I prevails. This is the case whenever the *market asymmetry is large,* since:

$$\widehat{Q}_1^{PR} - \widetilde{Q}_1 = -2\left[\frac{e_1(t_I - t_{II})}{3b_I} - \frac{s}{3b_{II}}\right] \tag{13}$$

and

$$\widehat{Q}_2^{PR} - \widetilde{Q}_2 = \left[\frac{e_1(t_I - t_{II})}{3b_I} - \frac{s}{3b_{II}}\right] \tag{14}$$

Notice however that, from Eq.s (13) and (14), with a large market asymmetry $\left[\frac{b_{II}}{b_I} > \frac{s}{e_1(t_I - t_{II})}\right]$, while the volume of world production contracts, the dirtier producer displaces the cleaner one in the global market. As to the net effect on global emissions, we obtain that:

$$\widehat{E}_W^{PR} - \widetilde{E}_W = -\left[\frac{e_1(t_I - t_{II})}{3b_I} - \frac{s}{3b_{II}}\right](2e_1 - e_2) \tag{15}$$

[30] We saw that PR may be an equilibrium location choice iff $\frac{s}{e_1(t_I - t_{II})} > 1$. See Proposition 1.

[31] Indeed, local production instead of exporting takes place in this country.

Eq. (15) shows that global emissions decrease iff *(i)* $\left[\frac{b_{II}}{b_I} > \frac{s}{e_1(t_I - t_{II})}\right]$ and $e_1 > \frac{e_2}{2}$ (a large market asymmetry is associated to a small technology gap), or *(ii)* $\left[\frac{b_{II}}{b_I} < \frac{s}{e_1(t_I - t_{II})}\right]$ and $e_1 < \frac{e_2}{2}$ (a small market asymmetry is coupled with a large technology gap). As far as the former condition *(i)*, the rationale is the following. We know that, with a large market asymmetry, the volume of world production decreases (leading to lower global emissions) and the dirtier producer displaces the cleaner one in the global market. The volume effect prevails, and thus global emissions fall, only if the product mix effect is weak: for this to be the case, the emission technology gap has to be rather small. A similar economic intuition holds as to condition *(ii)*. In this setting, world production rises given that market asymmetry is small $\left[\frac{b_{II}}{b_I} < \frac{s}{e_1(t_I - t_{II})}\right]$, while the cleaner producer displaces the dirtier one in the global market. Global emissions fall only if the product mix effect prevails on the volume effect, and this requires a large emission technology gap.

So, one can conclude that, when partial relocation is the equilibrium location choice, the effect of unilateral climate policy on global emissions depends on the interaction of both market and technological heterogeneities. In particular,

Proposition 10 *In the case when PR is the equilibrium location choice, global pollution decreases iff there exist (i) a large market asymmetry and a small technology gap, or (ii) a small market asymmetry and a large technology gap.*

Finally, let us consider the effect of a higher unilateral carbon tax on global emissions under total relocation. As to the volume effect, we can observe that:

$$\widehat{Q}_W^{TR} - \widetilde{Q}_W = -s\left[\frac{1}{3b_I} - \frac{1}{3b_{II}}\right] < 0 \tag{16}$$

Eq. (16) shows that, since we are assuming that the restrictive measures are introduced by the larger country, world production decreases, reducing *ceteris paribus* the level of global emissions. This change results from total sales falling in country I but expanding in country II. Thus, the sign of the change in global production is not affected by the degree of market asymmetry, which however determines the size of the effect. As in the case of no relocation, the dirtier producer gains market shares in the global market as compared to the cleaner one (see in Appendix VIII Eq.s (A.VIII.3) and (A.VIII.4)), and thus the product mix effect *ceteris paribus* leads to a rise in global emissions. The net effect of these two contrasting forces on global pollution is given by:

$$\widehat{E}_W^{TR} - \widetilde{E}_W = -s\left[\frac{1}{3b_I} - \frac{1}{3b_{II}}\right](2e_1 - e_2) \tag{17}$$

It follows that a small emission technology gap ($e_1 > \frac{e_2}{2}$) is a necessary and sufficient condition for unilateral climate policy to be effective also when total relocation is the equilibrium location choice.

We may thus state:

Proposition 11 *When TR is the equilibrium location choice, unilateral mitigation measures may lead to a reduction in global emissions iff the emissions technology gap between the domestic firm and the more pollution intensive foreign rival is sufficiently small.*

We summarize these findings in Table *1*.

Table 1: Forces affecting the equilibrium location choice in the high transport costs scenario

		STG			*LTG*		
		VE	*PME*	*TOT*	*VE*	*PME*	*TOT*
NR	*SMA*	−	+	−	−	+	+
	LMA	−	+	−	−	+	+
PR	*SMA*	+	−	+	+	−	−
	LMA	−	+	−	−	+	+
TR	*SMA*	−	+	−	−	+	+
	LMA	−	+	−	−	+	+

SMA= small market asymmetry $(b_{II}/b_I < s/e_1(t_I - t_{II}))$, LMA= large market asymmetry $(b_{II}/b_I > s/e_1(t_I - t_{II}))$, STG= small technology gap $(e_1 > e_2/2)$, LTG= large technology gap $(e_1 \leq e_2/2)$, VE= volume effect, PME= product mix effect.

It turns out that the volume effect and the product mix effect always run in opposite directions. The emission technology gap has a critical role, since with $e_1 > \frac{e_2}{2}$ (a small technology gap), the volume effect (i.e. the impact of unilateral measures on world production) always dominates the product mix effect (due to the changes in global sales of the cleaner versus the dirtier producer). The opposite holds in the case of a substantial difference in the emission coefficients of the two producers $(e_1 < \frac{e_2}{2})$.

However the extent of the technology gap *per se* does not lead necessarily to correct policy prescriptions. Lahiri and Symeonidis (2007) suggest that, with a small technology gap, unilateral mitigation measures lead to a contraction in global pollution. We show here that, when removing their assumptions on *(a)* exogenous plant location with firms producing only in the domestic market and exporting abroad and *(b)* symmetry in the size of the two areas, this finding may not hold. For instance, it comes out from Eq. (17) that, when *TR* is the equilibrium location choice and a small technology gap is associated to market size symmetry, unilateral climate policy does not lead to a contraction in global emissions. Thus, notwithstanding the stricter mitigation measures have a major effect on the location of production, inducing the local firm to move abroad the whole production, they do not affect global pollution. Furthermore, if the equilibrium location choice is PR, when the highly regulated area is not sufficiently larger than the less regulated counterpart (i.e. with small market asymmetry), the unilateral climate policy leads to a rise in world emissions if the emission technology gap is small .

Our findings can be summarized as follows:

Proposition 12 *The only configuration in which unilateral climate policy always leads to a fall in world emissions is characterized by (i) a sufficiently larger size of the regulated area as compared to the less regulated one and (ii) a sufficiently small emission technology gap.*

We see in Table *1* that in such a context a higher carbon tax unilaterally imposed by the larger area is an effective policy *whatever* the impact of the restrictive measures on the location choice of the domestic firm. A corollary of the above proposition is that, in order to assess whether unilateral climate policy reaches its intended aim of containing global pollution, one should consider *jointly* market size asymmetry and technological heterogeneity.

6 Some welfare considerations

The aim of this section is to disentangle some relevant welfare properties of the equilibrium configuration focusing mainly on the case where no relocation is preferred over the alternative (either TR or PR) location choices. To this aim, in line with the existing literature, we start by defining the social welfare function $\hat{W}_I^L$ as the sum of consumers surplus $\hat{C}s_I^L$, government revenue generated by the pollution tax $\widehat{T}_I^L$ and domestic firm's profits $\hat{\Pi}_1^L$ less the environmental damage function $\hat{D}^L$, which is strictly convex in world production $\hat{Q}_W^L$, with $L \in \{NR, PR, TR\}$. Thus, the social welfare function, when the government in country I enacts a tighter environmental policy, writes as

$$\hat{W}_I^L = \hat{C}s_I^L + \hat{\Pi}_1^L + \widehat{T}_I^L - \hat{D}^L$$

with $\hat{D}^L = \frac{\gamma}{2}(e_1\hat{Q}_1^L + e_2\hat{Q}_2^L)^2$.

As far as the component $\hat{\Pi}_1^L$, it has to be pointed out that it can include *(i) only* profits coming from domestic production (*domestic profits*) or *(ii)* profits stemming from the production taking place both in the home country *and* in the host country (*global profits)*. Of course, the definition of $\hat{\Pi}_1^L$ depends on whether firm 1 chooses zero repatriation of profits obtained from production in the host country (case *i*) or total repatriation (case *ii*). Alternatively, the focus could be placed on the objective function of the policy-maker, hypothesizing that he/she is exclusively concerned with domestic production, due to the repercussions on jobs and national income.[32] Finally, we define as consumers' aggregate welfare the sum of consumers' surplus and pollution tax revenues less the damage from

[32] It is worth remarking that, in the policy debate the focus is on the relationship between unilateral climate policy and its effects on domestic production. So, a "narrow" definition of $\hat{\Pi}_1^L$ as profits coming from the output produced in the home market could be more appropriate to deal with the issue at hand.

pollution (see Cole *et al.*, 2009, p. 1242). For the sake of simplicity, we assume that the revenue from pollution tax is 100% returned to the taxpayers.

Besides, we denote by $\tilde{W}_I$ the welfare in the baseline scenario, with $t_I = t_{II}$, namely in the case when the price of emissions in country I would be equal to that found in country II, and both firms would export from their respective home markets. Indeed, the impact of an unilateral climate policy on the country adopting the measures (country I) is evaluated by comparing welfare with and without the introduction of the stricter carbon tax, that is by evaluating the sign of $(\hat{W}_I^L - \tilde{W}_I)$. This variation captures *both* the effect of a rise in country I's pollution tax and, if this is the case, of a strategy shift as to the optimal location choice.

From the comparison -component by component- of $\hat{W}_I^{NR}$ and $\tilde{W}_I$, it emerges that there exist circumstances such that:

Proposition 13 *Whenever the equilibrium location choice is NR, a unilateral climate policy may lead to an increase in consumers' aggregate welfare, while reducing the local firm's profits.*

Proof. See Appendix IX ■

To give an intuition, let us remind here that global emissions decrease under the NR scenario provided the emission technology gap is sufficiently small,[33] namely if $e_1 > \frac{e_2}{2}$. Given the definition of consumers' aggregate welfare, the above proposition shows that the same condition on emission technology coefficients is decisive for a rise in consumers' aggregate welfare.

Rather interestingly, we find that this technology gap plays a crucial role also for social welfare as a whole. In particular:

Proposition 14 *When the equilibrium location choice is NR, the condition $e_1 < \frac{e_2}{2}$, under which unilateral climate policy increases global emissions and damage, is sufficient to have a fall in total welfare under a more stringent carbon tax.*

Proof. See Appendix X ■

So, it follows from the above Proposition that the condition on emission technology parameters determining a decrease in global emissions with respect to the baseline (i.e. $e_1 > \frac{e_2}{2}$) is necessary but not sufficient to have an increase in total welfare when unilateral mitigation measures are enacted. Indeed, it can be proved that, although firm 1's global profits decrease with respect to the baseline, the net effect on welfare as a whole may be positive. [34] For the sake of simplicity, we take into account only one source of market asymmetry (i.e. we set $a_I > a_{II}$ and $b_I = b_{II} = b$) and we set $t_{II} = 0$, $e_2 = 1$. We also focus on the most favorable scenario ensuring that a fall in global emissions occurs after an unilateral increase of the carbon tax, that is with $e_1 > \frac{e_2}{2}$. We then obtain

[33] This finding holds also in the TR scenario.

[34] If only domestic profits are considered, the results in Proposition 14 would be reinforced.

(see Appendix XI for further details) that $\widehat{W}_I^{NR} - \tilde{W}_I > 0$ iff

$$2\gamma\{[2e_1^2(\Psi+2t_I)]+[e_1(\Psi+2e_1t_I-t_I)]-[(\Psi+2e_1t_I)]\} > b(3a_I+a_{II}-4c-2s+\frac{7}{2}e_1t_I) \quad (18)$$

where $\Psi = A_I + A_{II} - s$ and γ is a measure of the value assigned by the national community to the disutility of pollution. It is worth noting that, were e_1 equal to one in (18), the term in curly brackets in the LHS would be greater than the term in brackets on the RHS.[35] This implies that, when e_1 is sufficiently high as compared with e_2, and the sensitiveness of the local community to pollution is significant (namely with a high value of γ), the unilateral climate policy has a net positive impact on welfare. On the other hand, for a very low value of γ, say $\gamma \to 0$, the unilateral policy would clearly make the society worse off, as the negative effect on firms would prevail on the positive effect on consumers' aggregate welfare.

We can also prove that under rather general conditions, unilateral climate measures make the society on the whole better off under the NR equilibrium location choice than under the alternative equilibrium location choices, either TR or PR:

Proposition 15 *In a range of parameters (namely $e_1(t_I - t_{II}) < s < s^*$) where either NR or TR may occur at equilibrium, both consumers' aggregate welfare and firm's domestic profits in country I are higher under the NR equilibrium than under the TR one, provided transport costs are sufficiently low. Further, in the range of parameters (i.e. with $s > s^*$) where either NR or PR may occur at equilibrium, both consumers' aggregate welfare and firm's domestic profits in country I are higher under the NR equilibrium than under the PR one.*

Proof. See Appendix XII. ■

It follows from the above Proposition that, there exist circumstances such that unilateral climate measures make the society on the whole better off under the NR equilibrium location choice than under the TR one. Indeed, if a more stringent climate policy is enacted, consumers in country I are better off under the NR equilibrium than under the TR one, as sales are larger under the former equilibrium location choice than in the latter. Also, it is straightforward that $\widehat{T}_I^{NR} > \widehat{T}_I^{TR}$, being $\widehat{T}_I^{TR} = 0$ and $\widehat{T}_I^{NR} > 0$. Besides, if the condition $e_1 > \frac{e_2}{2}$ holds, the environmental damage under TR can be higher than the corresponding one under NR.[36] Lastly, if the policy-maker is concerned only with profits determined by domestic production [37], profits under NR are higher than those under TR.

Even in the case when the range of parameters is such that either PR or NR can be observed at equilibrium, we find that the welfare under NR still

[35] Therefore, if $e_1 = 1$, one can easily notice that the inequality is satisfied for a sufficiently high value of γ and/or a sufficiently low value of b.

[36] In particular, this holds whenever $\frac{s}{e_1(t_I - t_{II})} < \frac{b_{II}+b_I}{b_{II}-b_I}$.

[37] It is worth remarking that the findings in Proposition 15 rely on the definition of domestic profits, as this is more appropriate in this context (see the discussion at the beginning of this Section).

dominates that under PR. Indeed, the quantity sold by both firms in country I does not change when moving from NR to PR : accordingly, there is no effect on consumers' surplus when the domestic firm chooses to partially relocate rather than to produce only in country I. Further, the Government revenue in the NR scenario is higher than that accruing under partial relocation and global emissions (and hence damage) under PR are higher than those observed in the NR case. Finally, firm 1's domestic profits decrease when moving from NR to PR.

As shown in Appendix XII, the sign of the difference $(\hat{W}_I^{PR} - \tilde{W}_I)$ on one side, and of $(\hat{W}_I^{TR} - \tilde{W}_I)$, on the other one, is not clear-cut. Nevertheless, we can get some insights on this point when taking into account the findings in Propositions 14 and 15. First, it emerges from Proposition 14 that, in the case when NR is the optimal location choice, a condition on emission technology parameters (i.e. $e_1 > \frac{e_2}{2}$) is necessary to have an increase in total welfare - with respect to the baseline - under unilateral mitigation measures. Secondly, Proposition 15 shows that total welfare under NR $(\hat{W}_I^{NR})$ can be larger than the corresponding welfare under TR $(\hat{W}_I^{TR})$ or under PR $(\hat{W}_I^{PR})$. So we can conclude that the condition(s) for global emissions to decrease is (are) *a fortiori* crucial also in order to assess the sign of the change in total welfare - with respect to the baseline - when the local firm partially or totally relocates its productive activities (that is under PR or TR).

To sum-up, evaluating the change in global emissions led by a more stringent climate policy should be a guidance for policy-makers not only on the ground of the effectiveness of climate policy itself, but also on the ground of total welfare.

7 Main Conclusions

In this paper, we analyze the impact of unilateral climate policy when firms may expand abroad also via FDI, providing a game-theoretic international duopoly model with endogenous plant location, which accounts for heterogeneity in both country size and firm emissions technology. This brings the analysis closer to reality. We address the case in which the region imposing the more stringent mitigation measures is the larger one and the domestic firm in this area is endowed with a cleaner technology than its foreign rival. We consider a long-run perspective, since climate policy is expected to remain sub-global in the foreseeable future. The model assesses how firm and country heterogeneity influence the optimal location choice and under which institutional and technological scenarios unilateral climate policy may be effective and claims of major losses in domestic production and job may be overrated.

We find that, when the carbon price differential between the two regions (with and without stringent climate measures) is more than compensated by transport costs (the high transport cost case), and the size of the cooperating area is sufficiently large, a no relocation equilibrium may prevail in the long run, notwithstanding the unilateral climate measures. Instead, if the carbon price differential is excessively high as compared to unit transport costs, the only feasible equilibrium location is total relocation, with major losses in domestic production and jobs. The effectiveness of unilateral climate policy is shown to depend on the joint effect of country and firm heterogeneity. When allowing for firms' heterogeneity, in contrast with Sanna-Randaccio and Sestini (2010, 2012), we find that a no relocation equilibrium is not a sufficient condition for having a fall in global emissions, if a unilateral carbon tax is implemented. A large market asymmetry coupled with a small emission technology gap is the only configuration in which unilateral climate policy will certainly lead to a fall in world emissions, irrespective of the optimal location choice. Besides, a small technology gap represents a crucial condition for making the society on the whole better off.

These results give rise to some policy implications. To start with, if expected to persist in the long run, unilateral climate policy should be moderate to avoid domestic production moving to the less regulated area. Furthermore, the relative size of the area with the more stringent policy is a key element in designing an effective mitigation policy. This point has already been raised in the literature tackling the effectiveness of climate policy from other perspectives, but has been surprisingly neglected by most studies on unilateral climate policy and FDI. We highlight two additional points: *(i)* the importance of considering both the direct effects of the size of the country implementing the more stringent measures and the indirect ones *via* the impact on equilibrium location choice, *(ii)* the importance of jointly considering market size and technological heterogeneity. In addition, given the crucial role of the gap in emissions efficiency, to implement an effective climate policy it might be relevant for policy-makers also to introduce complementary policies for fostering international transfer of environmentally friendly technologies to less developed (and more polluting) countries. Thus, efforts to reach a multilateral climate agreement, involving at least the major players, should be associated to initiatives favoring international transfer of clean technologies.

The literature suggests a multiplicity of channels for international technology transfer of clean technologies (Export, FDI, Licences, R&D Alliances, specific mechanisms such as CDMs). An important role is played by inter-firm technological spillovers associated to FDI (see Lee et al. 2014 on that) which are not taken into account in this paper. Other important channels are the forward and backward linkages associated to foreign production. The benefits from these different channels are highly context-dependent. The institutional and technological characteristics of host countries and the absorptive capability of local firms are a decisive determinant of whether the potential benefits associated with these mechanisms will be realized. The role of these factors also emerge from the empirical literature on CDMs (Marconi and Sanna-Randaccio, 2014). It is thus possible that specific instruments should be designed for different groups of receiving countries. An in-depth analysis of this issue is left for further research.

A Appendix

A.1 Appendix I

Proof of Proposition 1:

Let us define $A_I = [a_I - c - e_1 t_I + (e_2 - e_1)t_{II}]$ and $A_{II} = [a_{II} - c - e_1 t_I + (e_2 - e_1)t_{II}]$.

Then Eq. (2) may be written also as:

$$\hat{\Pi}_1^{NR} - \hat{\Pi}_1^{TR} = \frac{4}{9}\left\{[s - e_1(t_I - t_{II})]\frac{A_I}{b_I} - [s + e_1(t_I - t_{II})]\frac{(A_{II} - s)}{b_{II}}\right\}. \tag{A.I.1}$$

Since $A_I > 0$, because of $\hat{q}_{1,I}^{NR} + \hat{q}_{1,I}^{TR} > 0$, and $(A_{II} - s) > 0$, due to $\hat{q}_{1,II}^{NR} + \hat{q}_{1,II}^{TR} > 0$, it immediately follows that, whenever $s < e_1(t_I - t_{II})$, then $\hat{\Pi}_1^{NR} - \hat{\Pi}_1^{TR} < 0$. Moreover, it is straightforward from Eq. (4) that $\hat{\Pi}_1^{TR} > \hat{\Pi}_1^{PR}$ when $s < e_1(t_I - t_{II})$. The sign of $(\hat{\Pi}_1^{NR} - \hat{\Pi}_1^{TR})$, on one hand, and of $(\hat{\Pi}_1^{TR} - \hat{\Pi}_1^{PR})$, on the other hand, is ambiguous in the high transport costs case (i.e. with $s > e_1(t_I - t_{II})$). **Q.E.D.**

A.2 Appendix II

We prove now that: *(i)* $\breve{a}_{II}(s)$ is an increasing function of s; *(ii)* there exists a value of $G_{\min}$ s.t., for any $G \geqslant G_{\min}$, $\bar{a}_{II}(s)$ is a decreasing function of s; *(iii)* $\bar{a}_{II}\mid_{s=0} > \breve{a}_{II}\mid_{s=0}$.

To this aim, let us first consider that

$$\breve{a}_{II}(s) = \frac{b_{II}}{b_I}\frac{[(s - e_1(t_I - t_{II}))A_I]}{[s + e_1(t_I - t_{II})]} + [c + s + e_1 t_I - (e_2 - e_1)t_{II}] \tag{A.II.1}$$

$$\bar{a}_{II}(s) = \frac{9}{4}\frac{b_{II}G}{[s + e_1(t_I - t_{II})]} + [c + s + e_1 t_I - (e_2 - e_1)t_{II}] \tag{A.II.2}$$

where $A_I = [a_I - c - e_1 t_I + (e_2 - e_1)t_{II}]$.

- As far as *(i)*, the derivative of $\breve{a}_{II}(s)$ w.r.t. s writes as:

$$\frac{b_I e_1\left[2s(t_I - t_{II}) + e_1(t_I - t_{II})^2\right] + b_I s^2 + 2b_{II}e_1(t_I - t_{II})[a_I - c + e_2 t_{II} - e_1(t_I + t_{II})]}{b_I[s + e_1(t_I - t_{II})]^2}$$

In order to evaluate the sign of this ratio, we proceed as follows. As to the denominator, it is immediate to see that it is strictly positive. Concerning the numerator, when evaluated at $t_I = t_{II}$, it writes as $b_I s^2 > 0$. So, it suffices to show that the numerator is always increasing in t_I to conclude that the sign of the above ratio is strictly positive, as by assumption t_I

$> t_{II}$. The derivative of the numerator w.r.t. t_I turns out to be strictly positive, namely:

$$2e_1 b_{II}(a_I - c - 2e_1 t_I + e_2 t_{II}) + 2e_1 b_I \left[s + e_1(t_I - t_{II})\right] > 0.$$

This concludes the proof. **Q.E.D.**

- As far as *(ii)*, given that

$$\frac{\partial \bar{a}_{II}(s)}{\partial s} = 1 - \frac{9}{4} \frac{b_{II} G}{\left[s + e_1 \left(t_I - t_{II}\right)\right]^2}, \qquad \text{(A.II.3)}$$

  we obtain that $\bar{a}_{II}(s)$ is a decreasing function of s iff $G \geqslant G_{\min}$ with $G_{\min} = \frac{4}{9} \frac{[s+e_1(t_I - t_{II})]^2}{b_{II}}$. **Q.E.D.**

- Finally, concerning *(iii)*, the difference between $\bar{a}_{II} \mid_{s=0}$ and $\breve{a}_{II} \mid_{s=0}$ can be written as

$$\frac{b_{II}}{b_I} \left[\frac{e_1(t_I - t_{II})(a_I - c - e_1 t_I - e_1 t_{II} + e_2 t_{II}) + \frac{9}{4} b_I G}{e_1 \left(t_I - t_{II}\right)} \right] \qquad \text{(A.II.4)}$$

  Since the expression $(a_I - c + e_2 t_{II} - e_1 t_I - e_1 t_{II})$ is strictly positive due to $\hat{q}_{1,II}^{NR} > 0$, we can conclude that $\bar{a}_{II} \mid_{s=0} > \breve{a}_{II} \mid_{s=0}$. **Q.E.D.**

A.3 Appendix III

By simple algebra it is found that $\exists\, s : \breve{a}_{II}(s) = \bar{a}_{II}(s)$. Denote this value of s as s^*, where

$$s^* = \frac{9}{4} \frac{b_I G_{1f}}{A_I} + e_1(t_I - t_{II}).$$

Since s^* is such that $\hat{\Pi}_1^{NR}(s^*) = \hat{\Pi}_1^{TR}(s^*)$ and $\hat{\Pi}_1^{NR}(s^*) = \hat{\Pi}_1^{PR}(s^*)$, it follows that also $\hat{\Pi}_1^{PR}(s^*) = \hat{\Pi}_1^{TR}(s^*)$, with $\hat{\Pi}_1^{PR} - \hat{\Pi}_1^{TR} > (<)\ 0$ for $s > (<)\ s^*$.

A.4 Appendix IV

In a "reverse" asymmetry scenario (i.e. with $a_I < a_{II}$ and $b_I > b_{II}$) we have:

$$\hat{\Pi}_1^{NR} - \hat{\Pi}_1^{TR} = \frac{4}{9} \left\{ -s \left[\frac{A_{II}}{b_{II}} - \frac{A_I}{b_I} \right] - e_1(t_I - t_{II}) \left[\frac{A_I}{b_I} + \frac{(A_{II} - s)}{b_{II}} \right] + \frac{s^2}{b_{II}} \right\}.$$

Thus we find that TR dominates NR iff

$$s \left[\frac{A_{II}}{b_{II}} - \frac{A_I}{b_I} - \frac{s}{b_{II}} \right] + e_1(t_I - t_{II}) \left[\frac{A_I}{b_I} + \frac{(A_{II} - s)}{b_{II}} \right] > 0.$$

Accordingly, since $(A_{II} - s) > 0$ (see Appendix I), a sufficient condition for TR to be preferred over NR is given by:

$$b_I(A_{II} - s) > b_{II} A_I.$$

Q.E.D

A.5 Appendix V

In order to prove that $\frac{\partial(\hat{\Pi}_1^{NR}-\hat{\Pi}_1^{TR})}{\partial e_1}<0$, where:

$$\begin{aligned}\frac{\partial(\hat{\Pi}_1^{NR}-\hat{\Pi}_1^{TR})}{\partial e_1} &= -\frac{4}{9}\left[s(t_I+t_{II})(\frac{1}{b_I}-\frac{1}{b_{II}})\right] \\ &-\frac{4}{9}\left(t_I-t_{II}\right)\left[\frac{A_I-e_1(t_I+t_{II})}{b_I}+\frac{A_{II}-s-e_1(t_I+t_{II})}{b_{II}}\right]\end{aligned}$$

it suffices to show that $\left[\frac{A_I-e_1(t_I+t_{II})}{b_I}+\frac{A_{II}-s-e_1(t_I+t_{II})}{b_{II}}\right]>0$. Indeed, as far as the term in the first square brackets, it is immediate to see that it is strictly negative.

As to the second square bracket, let us consider first the term $\frac{A_I-e_1(t_I+t_{II})}{b_I}$. We remind that $\hat{q}_{1,II}^{NR}=\frac{(a_{II}-c-2e_1t_1-2s+e_2t_{II})}{3b_{II}}$ is assumed to be strictly positive. So, in order to get that $A_I-e_1(t_I+t_{II})>0$, it suffices that $A_I-e_1(t_I+t_{II})>(a_{II}-c-2e_1t_1-2s+e_2t_{II})>0$ for $\hat{q}_{1,II}^{NR}>0$. This is the case whenever $s>e_1t_I$, which always holds since $s>t_{II}>e_1t_{II}$.

Finally, although the sign of the second term $\frac{A_{II}-s-e_1(t_I+t_{II})}{b_{II}}$ is ambiguous, one can observe that $\left|\frac{A_I-e_1(t_I+t_{II})}{b_I}\right|>\left|\frac{A_{II}-s-e_1(t_I+t_{II})}{b_{II}}\right|$. This implies that $\left[\frac{A_I-e_1(t_I+t_{II})}{b_I}+\frac{A_{II}-s-e_1(t_I+t_{II})}{b_{II}}\right]>0$. We may thus conclude that:

$$\frac{\partial(\hat{\Pi}_1^{NR}-\hat{\Pi}_1^{TR})}{\partial e_1}<0.$$

Q.E.D.

A.6 Appendix VI

As to the behavior of the function $\bar{a}_{II}(s)$ as e_1 varies, we get that

$$\frac{\partial\bar{a}_{II}(s)}{\partial e_1}=(t_I+t_{II})-\frac{9}{4}\frac{b_{II}G(t_I-t_{II})}{\left[s+e_1\left(t_I-t_{II}\right)\right]^2}. \tag{A.VI.1}$$

The sign of this partial derivative is ambiguous and crucially depends on s, being it nil[38] when $s=\tilde{s}=\left[\frac{3\sqrt{Gb_{II}(t_I+t_{II})(t_I-t_{II})}}{2(t_I+t_{II})}-e_1(t_I-t_{II})\right]$. It can be shown that, for $e_1\left(t_I-t_{II}\right)<s<\tilde{s}$, it holds that $\frac{\partial\bar{a}_{II}(s)}{\partial e_1}<0$ - as the second term in Eq. (A.VI.1) will expand-, while, viceversa, $\frac{\partial\bar{a}_{II}(s)}{\partial e_1}>0$ for $s>\tilde{s}$.

Moreover, defining as s_{max} that value of s such that $a_{IImin}(s)=\bar{a}_{II}(s)$ (see Figure 1), we find that $s_{max}=\frac{3\sqrt{Gb_{II}}}{2}-e_1(t_I-t_{II})$, and that the difference

[38] Notice that $\frac{\partial\bar{a}_{II}(s)}{\partial e_1}$ is nil also for $s=s^2=\frac{-2e_1(t_I^2-t_{II}^2)-3\sqrt{Gb_{II}(t_I^2-t_{II}^2)}}{2(t_I+t_{II})}$. This root is disregarded as it is clearly negative.

$(s_{max} - \tilde{s})$ can be written as $\sqrt{Gb_{II}}\left[(\sqrt{t_I + t_{II}})(\sqrt{t_I + t_{II}} - \sqrt{t_I - t_{II}})\right] > 0$. Therefore $\tilde{s}$ belongs to a range of s values such that an equilibrium (either PR or NR) exists.

A.7 Appendix VII

We consider here the relationship between s^* and $\tilde{s}$. For ease of exposition, let us recall that:

$$s^* = \frac{9}{4}\frac{b_I G}{A_I} + e_1(t_I - t_{II})$$
$$\tilde{s} = \frac{3\sqrt{Gb_{II}(t_I - t_{II})(t_I + t_{II})}}{2(t_I + t_{II})} - e_1(t_I - t_{II}).$$

from which we obtain that:

$$(\tilde{s} - s^*) = \frac{\left[6A_I\sqrt{Gb_{II}(t_I + t_{II})(t_I - t_{II})} - 9b_I G(t_I + t_{II}) - 8A_I e_1(t_I - t_{II})(t_I + t_{II})\right]}{4A_I(t_I + t_{II})}.$$

As far as the denominator, it is easy to see that it is strictly positive. As far as the the numerator, we find that it has two roots in G, namely:

$$G_{1,2} = \frac{2A_I(t_I - t_{II})\left[b_{II}A_I - 4b_I e_1(t_I + t_{II}) \mp \sqrt{b_{II}A_I(b_{II}A_I - 8b_I e_1(t_I + t_{II}))}\right]}{9b_I^2(t_I + t_{II})}.$$

We find that the difference $(\tilde{s} - s^*)$ is strictly positive for $G \in]G_1, G_2[$, as confirmed also by numerical examples.

Numerical simulations[39] show that $G_1 = 0.46$ and $G_2 = 95.83$. Then $G_1 < G_{\min}$ (see Appendix II), with $G_{\min} = 17.28$. Therefore values for G such that $0 \leq G \leq G_1$ can be disregarded as they are not consistent with the hypothesis adopted in the model that $G \geqslant G_{\min}$ Defining as $G_{\max}$ the value of G such that, for any $G \geqslant G_{\max}$, we have that $\hat{\Pi}_{1II}^{PR}(G) \leqslant 0$, we find that $G_2 > G_{\max}$, with $G_{\max} = 37.06$. In addition, if one limits its attention to the case with $G < \overline{G}$, i.e. to the case with moderate fixed plant costs (see Section 3), being $\overline{G} = 26$, the values of G such that $G > G_2$ can be disregarded. We are then allowed to conclude that, for significant (and reasonable) values of the parameter G, the relationship $\tilde{s} > s^*$ holds. Having established this ranking, also $\tilde{s} > e_1(t_I - t_{II})$, i.e. $\tilde{s}$ is located in the high transport cost area. Finally notice that both threshold values, $\tilde{s}$ and s^*, increase in G, the former non-linearly and the latter linearly. Evaluating these threshold values at $G_{\min}$ and $G_{\max}$, respectively, we obtain that $s^*(G_{\min}) = 3.75$ and $\tilde{s}(G_{\min}) = 6.84$, and that $s^*(G_{\max}) = 7.14$ and $\tilde{s}(G_{\max}) = 10.38$, thus confirming the ranking stated here above.

[39] These simulations are carried out assigning to the parameters the same values as in Figures 1 and 2.

A.8 Appendix VIII

When the equilibrium location choice is NR, we find:

$$\widehat{Q}_1^{NR} - \widetilde{Q}_1 = -2e_1(t_I - t_{II})\left[\frac{1}{3b_I} + \frac{1}{3b_{II}}\right] < 0 \qquad \text{(A.VIII.1)}$$

and

$$\widehat{Q}_2^{NR} - \widetilde{Q}_2 = e_1(t_I - t_{II})\left[\frac{1}{3b_I} + \frac{1}{3b_{II}}\right] > 0 \qquad \text{(A.VIII.2)}$$

When the equilibrium location choice is TR, we find:

$$\widehat{Q}_1^{TR} - \widetilde{Q}_1 = -2s\left[\frac{1}{3b_I} - \frac{1}{3b_{II}}\right] < 0 \qquad \text{(A.VIII.3)}$$

and

$$\widehat{Q}_2^{TR} - \widetilde{Q}_2 = s\left[\frac{1}{3b_I} - \frac{1}{3b_{II}}\right] > 0. \qquad \text{(A.VIII.4)}$$

Q.E.D.

A.9 Appendix IX

As far as consumers' surplus variation under tighter environmental measures, we find that $\widehat{CS}_I^{NR} - \widetilde{CS}_I = \frac{b_I}{2}[(\hat{Q}_I^{NR} + \tilde{Q}_I)(\hat{Q}_I^{NR} - \tilde{Q}_I)]$. Accordingly, the sign of $(\widehat{CS}_I^{NR} - \widetilde{CS}_I)$ is determined by *sign* $(\hat{Q}_I^{NR} - \tilde{Q}_I^{NR}) = -\frac{1}{3b_I}(t_I - t_{II})\, e_1 < 0$. Further, in the NR case, the effect on government revenue of imposing an unilateral pollution tax in country I is given by: $\hat{T}_I^{NR} - \tilde{T}_I = t_I(e_1(\hat{q}_{1,I}^{NR} + \hat{q}_{1,II}^{NR})) - t_{II}(e_1(\tilde{q}_{1,I}^{NR} + \tilde{q}_{1,II}^{NR}))$ or $e_1(t_I - t_{II})((\hat{q}_{1,I}^{NR} - \frac{2t_{II}e_1}{3b_{II}}) + (\hat{q}_{1,II}^{NR} - \frac{2t_{II}e_1}{3b_I}))$. Even if the sign of this expression is ambiguous, one can note that, whenever $(\hat{q}_{1,II}^{NR} - \frac{2t_{II}e_1}{3b_I}) > 0$, also $(\hat{q}_{1,I}^{NR} - \frac{2t_{II}e_1}{3b_{II}}) > 0$ and thus $\hat{T}_I^{NR} - \tilde{T}_I > 0$. Assuming that $t_{II} = 0$ implies that $\hat{T}_I^{NR} - \tilde{T}_I > 0$ holds. As shown in Section 5, a higher unilateral carbon tax reduces global emissions $(\hat{E}_W^{NR})$ with respect to the baseline scenario $(\tilde{E}_W)$ iff $e_1 > \frac{e_2}{2}$. The same condition obviously applies when one examines the effect on damage. Then, let us consider the aggregate consumers' welfare. Focusing on the scenario with $e_1 > \frac{e_2}{2}$, we can evaluate the sign of the following expression: $\frac{b_I}{2}[(\hat{Q}_I^{NR} + \tilde{Q}_I)(\hat{Q}_I^{NR} - \tilde{Q}_I)] + \hat{T}_I^{NR} - \tilde{T}_I$. Under the assumption that $t_{II} = 0$, this writes as: $\frac{e_1t_I(2a_I - 2c + 8s - 11e_1t_I)}{18b_I} + \frac{e_1t_I(a_{II} - c - 2s - 2e_1t_I)}{3b_{II}}$. Since $\hat{q}_{1,II}^{NR}\ |_{t_{II}=0} = \frac{a_{II} - c - 2(s + e_1t_I)}{3b_{II}} > 0$, we get that the second term is strictly positive. Considering that $(2a_I - 2c + 8s - 11e_1t_I) > 2[a_{II} - c - 2(s + e_1t_I)] > 0$ iff $(12/7)s > e_1t_I$, and that $s > e_1t_I$, being NR

observed in the high transport cost case, also the first term is strictly positive. Thus one may conclude that the above polynomial is strictly positive. Finally, when moving to producers'surplus - evaluated in terms of global profits - we have that:

$$\hat{\Pi}_1^{NR} - \tilde{\Pi}_1^{NR} = b_I[(\hat{q}_{1,I}^{NR} + \tilde{q}_{1,I}^{NR})(\hat{q}_{1,I}^{NR} - \tilde{q}_{1,I}^{NR})] + b_{II}[(\hat{q}_{1,II}^{NR} + \tilde{q}_{1,II}^{NR})(\hat{q}_{1,II}^{NR} - \tilde{q}_{1,II}^{NR})].$$

Therefore, the sign of $\hat{\Pi}_1^{NR} - \tilde{\Pi}_1^{NR}$ is determined by $(\hat{q}_{1,I}^{NR} - \tilde{q}_{1,I}^{NR}) = -\frac{1}{3b_I}2\,(t_I - t_{II})\,e_1 < 0$ and $(\hat{q}_{1,II}^{NR} - \tilde{q}_{1,II}^{NR}) = -\frac{1}{3b_{II}}2\,(t_I - t_{II})\,e_1 < 0$. Accordingly, $\hat{\Pi}_1^{NR} - \tilde{\Pi}_1^{NR} < 0$.
Q.E.D.

A.10 Appendix X

Consider the function

$$\widehat{W}_I^{NR} = \widehat{CS}_I^{NR} + \widehat{\Pi}_1^{NR} + \widehat{T}_I^{NR} - \widehat{D}_I^{NR}.$$

In order to study the sign of $\frac{\partial \widehat{W}_I^{NR}}{\partial t_I}$, we first remind that $\widehat{CS}_I^{NR} = \frac{b_I}{2}(\hat{q}_{1,I}^{NR} + \hat{q}_{2,I}^{NR})^2$, $\widehat{\Pi}_1^{NR} = b_I(\hat{q}_{1,I}^{NR})^2 + b_{II}(\hat{q}_{1,II}^{NR})^2 - F - G$, $\widehat{T}_I^{NR} = t_I e_1(\hat{q}_{1,I}^{NR} + \hat{q}_{1,II}^{NR})$, and $\widehat{D}_I^{NR} = \frac{\gamma}{2}\left[e_1(\hat{q}_{1,I}^{NR} + \hat{q}_{1,II}^{NR}) + e_2(\hat{q}_{2,I}^{NR} + \hat{q}_{2,II}^{NR})\right]^2$. We find that:

$$\frac{\partial \widehat{CS}_I^{NR}}{\partial t_I} + \frac{\partial \widehat{\Pi}_1^{NR}}{\partial t_I} + \frac{\partial \widehat{T}_I^{NR}}{\partial t_I} = -\frac{e_1}{3}(2\hat{q}_{1,I}^{NR} + \hat{q}_{2,I}^{NR} + \hat{q}_{1,II}^{NR}) - \frac{2e_1 t_I}{3}\left(\frac{e_1}{b_I} + \frac{e_1}{b_{II}}\right) < 0.$$

Moreover,

$$sign\left(\frac{\partial \widehat{D}_I^{NR}}{\partial t_I}\right) = sign\left[e_1\left(-\frac{2e_1}{3b_I} - \frac{2e_1}{3b_{II}}\right) + e_2\left(\frac{e_1}{3b_I} + \frac{e_1}{3b_{II}}\right)\right] = \frac{e_1(e_2 - 2e_1)(b_I + b_{II})}{3b_I b_{II}}$$

so that $sign\left(\frac{\partial \widehat{D}_I^{NR}}{\partial t_I}\right) < 0$ iff $e_1 > \frac{e_2}{2}$. Accordingly, provided the inequality $e_1 > \frac{e_2}{2}$ is satisfied, it may happen that $\frac{\partial \widehat{W}_I^{NR}}{\partial t_I} > 0$. *Viceversa*, the condition $e_1 < \frac{e_2}{2}$ is sufficient for $\frac{\partial \widehat{W}_I^{NR}}{\partial t_I} < 0$. **Q.E.D.**

A.11 Appendix XI

As to the overall effect on welfare of unilateral climate policy when *NR* is the equilibrium location choice, we recall that $\widehat{W}_I^{NR} - \tilde{W}_I > 0$ iff

$$2\gamma\left\{\begin{array}{c}[2e_1^2(A_I + A_{II} - s + 2t_I)] + [e_1(A_I - t_I(1-e_1) + A_{II} - s + e_1 t_I)] \\ -[(A_I + 2e_1 t_I + A_{II} - s)]\end{array}\right\} >$$

$$b(3a_I + a_{II} - 4c - 2s + \frac{7}{2}e_1 t_I)$$

Notice that, since $A_I > 0$ and $A_{II} - s > 0$ (see Appendix I), both the first term in square brackets and the third one on the LHS are strictly positive. Also the second term is strictly positive as $e_1 > e_2/2$. The expression on the RHS is strictly positive as well, since $(3a_I + a_{II} - 4c - 2s + \frac{7}{2}e_1 t_I) > (A_I + 3e_1 t_I + A_{II} - s) > 0$.

Moreover, $[2e_1^2(A_I + A_{II} - s + 2t_I)] - [(A_I + 2e_1 t_I + A_{II} - s)]$ provided $e_1^2 > 1/2$. This last condition on e_1 represents a sufficient condition for the strict positivity of the LHS on the whole, being more easily satisfied the smaller is the gap between emission technology coefficients (i.e. with e_1 sufficiently close to $e_2 = 1$).

A.12 Appendix XII

Let us first consider the welfare properties of the TR scenario compared with the baseline. As to consumers' surplus, when applying the same methodology as in the NR case, we find that $\widehat{CS}_I^{TR} - \widetilde{CS}_I = \frac{b_I}{2}((\hat{Q}_I^{TR} + \tilde{Q}_I^{TR})(\hat{Q}_I^{TR} - \tilde{Q}_I^{TR})$, and $\hat{Q}_I^{TR} - \tilde{Q}_I = -\frac{s}{b_I} < 0$.

Concerning global emissions, we remind that a reduction in global emissions occurs, namely $e_1\left(\hat{Q}_1^{TR} - \tilde{Q}_1\right) + e_2\left(\hat{Q}_2^{TR} - \tilde{Q}_2\right) < 0$, whenever $e_1 > \frac{e_2}{2}$. Finally, both Government in country I and firm 1 are hampered when moving from the baseline scenario to TR. More specifically, the effect on Government revenue is given by $-\left(\frac{1}{3b_I}\right) t_{II}\,(2c + s) < 0$, while, as to global profits, we get that:

$$\hat{\Pi}_1^{TR} - \tilde{\Pi}_1 = \left(-\frac{4}{9b_{II}b_I}\right) s\,(b_{II}\,(a_I - c - 2e_1 t_{II} + e_2 t_{II}) - b_I\,(a_{II} - c - s - 2e_1 t_{II} + e_2 t_{II})) < 0.$$

As to the comparison between the welfare properties of equilibria under NR and under TR, let us consider first that $\widehat{CS}_I^{NR} - \widehat{CS}_I^{TR} = \frac{b_I}{2}[(\hat{Q}_I^{NR} + \hat{Q}_I^{TR})(\hat{Q}_I^{NR} - \hat{Q}_I^{TR})]$. We obtain that $\widehat{CS}_I^{NR} - \widehat{CS}_I^{TR} > 0$, as $(\hat{Q}_I^{NR} - \hat{Q}_I^{TR}) = \left[\frac{s - e_1(t_I - t_{II})}{3b_I}\right] > 0$. In fact, in order to observe either NR or TR equilibrium location choice, one should be in the high transport cost scenario. Further, it is straightforward that $\widehat{T}_I^{NR} > \widehat{T}_I^{TR}$, being $\widehat{T}_I^{TR} = 0$ and $\widehat{T}_I^{NR} > 0$. As to the difference in damage under the two equilibrium location choices, this is given by $\frac{\gamma}{2}[(\hat{E}_W^{NR})^2 - (\hat{E}_W^{TR})^2]$. Thus the sign of this difference is determined by $sign(\hat{E}_W^{NR} - \hat{E}_W^{TR})$. It comes out that $(\hat{E}_W^{NR} - \hat{E}_W^{TR}) = \frac{1}{3}(2e_1 - e_2)\left[s\left(\frac{1}{b_I} - \frac{1}{b_{II}}\right) - e_1(t_I - t_{II})\left(\frac{1}{b_I} + \frac{1}{b_{II}}\right)\right]$. If the condition $e_1 > \frac{e_2}{2}$ holds, then $\hat{E}_W^{TR} > \hat{E}_W^{NR}$ iff $\frac{s}{e_1(t_I - t_{II})} = \frac{b_{II} + b_I}{b_{II} - b_I}$ that is, if $s < \breve{s}$, where $\breve{s} = \frac{b_{II} + b_I}{b_{II} - b_I} e_1(t_I - t_{II})$.

Notice that this threshold value $\breve{s}$ is lower than s^* for sufficiently high plant fixed costs (and *viceversa*). In particular, as

$$(s^* - \breve{s}) = \frac{[9G(b_{II} - b_I) + 8e_1\,(t_I - t_{II})\,(e_1\,(t_I + t_{II}) - (a_I - c + e_2 t_{II})]b_I}{4\,(a_I - c - e_1 t_I - e_1 t_{II} + e_2 t_{II})\,(b_{II} - b_I)}$$

one finds that $(s^* - \breve{s}) > 0$ for any $G > \breve{G}$, where $\breve{G}$ is the value such that $s^*(\breve{G}) - \breve{s} = 0$. Finally, as to producer surplus, if one considers only firm $1'$s domestic profits, it comes out that $\widehat{\pi}_{1I}^{NR} > \widehat{\pi}_{1I}^{TR}$ as $\widehat{\pi}_{1I}^{TR}$ is nil.

Moving to the PR equilibrium location choice, first notice that the sign of the difference $\widehat{CS}_I^{NR} - \widehat{CS}_I^{PR}$ depends on $sign(\hat{Q}_I^{NR} - \hat{Q}_I^{PR})$. As this latter is nil, it immediately follows that consumer surplus in the NR scenario coincides with that observed in the PR one. As far as the Government revenue in the PR case, we find that $\hat{T}_I^{PR} = t_I(e_1\hat{q}_{1,I}^{PR})$, while $\hat{T}_I^{NR} = t_I[e_1(\hat{q}_{1,I}^{NR} + \hat{q}_{1,II}^{NR})]$. Since $\hat{q}_{1,I}^{PR} = \hat{q}_{1,I}^{NR}$,it immediately follows that $\hat{T}_I^{NR} > \hat{T}_I^{PR}$. Moreover, when considering global emissions, it emerges that $(\hat{E}_W^{PR} - \hat{E}_W^{NR}) = \frac{1}{3b_{II}}(2e_1 - e_2)[s + e_1(t_{II} - t_I)]$. Assuming that the condition (one of the conditions) for global emissions to decrease holds in the NR case (PR case), yields that $(\hat{E}_W^{PR} - \hat{E}_W^{NR}) > 0$. Finally, as to producer surplus, it results that $\widehat{\pi}_{1I}^{NR} > \widehat{\pi}_{1I}^{PR}$, since $\hat{q}_{1,II}^{PR}$ is not included in firm 1's domestic profits, while $\hat{q}_{1,I}^{PR} = \hat{q}_{1,I}^{NR}$. **Q.E.D.**

References

[1] Abe, K., Zhao, L., 2005. Endogenous International Joint Ventures and the Environment. *Journal of International Economics* 67, 221-240.

[2] Aichele, R., Felbermayr, G., 2013. Estimating the Effects of Kyoto on Bilateral Trade Flows Using Matching Econometrics. *World Economy* 36, 303-330.

[3] Albornoz, F., Cole, M.A., Elliot, R.J.R., Ercolani, M.G., 2009. In Search of Environmental Spillovers. *World Economy* 32, 136-163.

[4] Bayindir-Upmann, T., 2003. Strategic Environmental Policy under Free Entry of Firms. *Review of International Economics* 11, 379-396.

[5] Böhringer, C., Fischer, C., Rosendahl, K.E., 2011. Cost-Effective Unilateral Climate Policy Design: Size Matters. *Discussion Papers* dp-11-34, Resources for the Future.

[6] Bosetti, V., De Cian, E., 2013. A Good Opening: The Key to Make the Most of Unilateral Climate Action. *Environmental and Resource Economics* 56, 255-276.

[7] Branger, F., Quirion, P., 2014. Climate policy and the 'carbon haven' effect. *Wiley Interdisciplinary Reviews: Climate Change* 5, 53–71.

[8] Cole, M. A., Elliot, R.J.R., Fredriksson, G., 2006. Endogenous Pollution Havens: Does FDI Influence Environmental Regulations?, *Scandinavian Journal of Economics* 108, 157-178.

[9] Cole, M. A., Elliot, R.J.R., Fredriksson, G., 2009. Institutionalized Pollution Havens. *Ecological Economics* 68, 1239-1256.

[10] Copeland, B.R., Taylor M.R., 1994. North-South Trade and the Environment. *The Quarterly Journal of Economics* 109, 755-787.

[11] Copeland, B.R., Taylor M.R., 2003. *Trade and the Environment: Theory and Evidence*. Princeton University Press, Princeton.

[12] Dean, J.M., Lovely, M.E., Wang, H., 2005. Are Foreign Investors Attracted to Weak Environmental Regulations? Evaluating the Evidence from China. *World Bank Policy Research Working Paper* No. 3505.

[13] Dijkstra, B.R., Mathew A.J., Mukherjee, A., 2011. Environmental Regulation: An Incentive for Foreign Direct Investment. *Review of International Economics* 19, 568-578.

[14] Douglas, S., Nishioka, S., 2012. International Differences in Emissions Intensity and Emissions Content of Global Trade. *Journal of Development Economics* 99, 415-427.

[15] Ederington, J., Levinson, A., Minier, J. 2005. Footloose and Pollution-Free. *The Review of Economics and Statistics* 87, 92-99.

[16] Elliot, R., Zhou, Y., 2013. Environmental Regulation Induced Foreign Direct Investment. *Environmental & Resource Economics* 55, 141-158.

[17] Eskeland, G.S., Harrison A.E., 2003. Moving to Greener Pastures? Multinationals and the Pollution Haven Hypothesis. *Journal of Development Economics* 70, 1-23.

[18] Financial Times, 2013. "EU must improve its aim on energy", December 2, 2013.

[19] Golombek R. and Hoel M., 2006. Unilateral Emission Reductions and Cross-Country Technology Spillover. *The B.E. Journals in Economic Analysis & Policy* 4.2.

[20] Grossman, G.M., Krueger, A.B., 1993. Environmental Impacts of a North America Free Trade Agreement. In Garber, P.M., *The U.S.–Mexico free trade agreement*, Cambridge (MA). MIT Press, 13–56.

[21] Hoel, M. 1997. Environmental Policy with Endogenous Plant Locations. *Scandinavian Journal of Economics,* 99, 2, 241-59.

[22] Ikefuji, M., Itaya, J., Okamura, M., 2010. Optimal Emission Tax with Endogenous Location Choice of Duopolistic Firms, *Working Paper 2010*.6, Fondazione Eni Enrico Mattei.

[23] Ikefuji, M., Itaya, J., Okamura, M., 2013. Optimal Emission Tax with Endogenous Location Choice of Duopolistic Firms, *Discussion Paper*, Series A, 257, Hokkaido University.

[24] Javorcik, B. S., Wei, S-J., 2004. Pollution Havens and Foreign Direct Investment: Dirty Secret or Popular Myth? *Contributions to Economic Analysis and Policy* 3, 1-32.

[25] Kayalica, O., Lahiri, S., 2005. Strategic Environmental Policies in the Presence of Foreign Direct Investment. *Environmental & Resource Economics* 30, 1-21.

[26] Keller, W., Levinson A., 2002. Pollution Abatement Costs and Foreign Direct Investment Inflows to U.S. States. *The Review of Economics and Statistics* 84, 691-703.

[27] Lahiri, S., Symeonidis, G., 2007. Piecemeal Multilateral Environmental Policy Reforms under Asymmetric Oligopoly. *Journal of Public Economic Theory* 9, 885-899.

[28] Lee, K-D., Lee, W., Kang, K., 2014. Pollution Haven with Technological Externalities Arising from Foreign Direct Investment. *Environmental & Resource Economics* 57, 1-18.

[29] Manderson, E., Kneller, R., 2012. Environmental Regulation, Outward FDI and Heterogeneous Firms: Are Countries Used as Pollution Havens? *Environmental & Resource Economics* 51, 317-352.

[30] Marconi, D., Sanna-Randaccio, F., 2014. The Clean Development Mechanism and Technology Transfer to China. In Verbeke, A., van Tulder, R., Strange, R. (eds), *International Business and Sustainable Development*, Bingley, UK. Emerald Group Publishing Limited, 351-390.

[31] Markusen, J.R., Morey, E.R., Olewiler N.D., 1993. Environmental Policy when Market Structure and Plant Location are Endogenous. *Journal of Environmental Economics and Management* 24, 69-86.

[32] Motta, M., Thisse, J.F., 1994. Does Environmental Dumping Lead to Delocation? *European Economic Review* 38, 563-576.

[33] Mulatu, A., Gerlagh, R., Rigby, D., Wossnik, A., 2010. Environmental Regulation and Industry Location in Europe. *Environmental & Resource Economics* 45, 459-479.

[34] Petrakis, E., Xepapadeas, A., 2003. Location decisions of a polluting rim and the time consistency of environmental policy. *Resource and Energy Economics* 25, 197-214.

[35] PBL (Netherlands Environmental Assessment Agency), 2012. Greenhouse Gas Emission Reduction Targets for 2030. *Report n. 500114023.* PBL Netherlands Environmental Assessment Agency. The Hague, NL.

[36] Rauscher M., 1995. Environmental regulation and the location of polluting industries. International Tax and Public Finance, 2, 2, 229-244.

[37] Reinaud, J., 2008. Issues behind Competitiveness and Carbon Leakage under Uneven Climate Policies – Focus on Heavy Industry. *IEA Information Paper.*

[38] Sanna-Randaccio, F., Sestini, R., 2010. The Impact of Unilateral Climate Policies with Endogenous Plant Location and Market Size Asymmetry. *Nota di lavoro FEEM 17/2010.*

[39] Sanna-Randaccio, F., Sestini, R., 2012. The impact of Unilateral Climate Policy with Endogenous Plant Location and Market Size Asymmetry. *Review of International Economics* 20, 580-599.

[40] Sugeta, H., Matsumoto, S., 2005. Green Tax Reform in an Oligopolistic Industry, *Environmental & Resource Economics* 31, 253-274.

[41] Ulph, A., Valentini, L. 2001. Is Environmental dumping greater when plants are footloose? *The Scandinavian Journal of Economics* 103, 673-688.

[42] Wagner, U., Timmins, C., 2009. Agglomeration Effects in Foreign Direct Investment and The Pollution Haven Hypothesis. *Environmental & Resource Economics* 43, 231-256.

[43] Xing, Y., Kolstad, C., 2002. Do Lax Environmental Regulations Attract Foreign Investment? *Environmental & Resource Economics* 21, 1-22.

[44] Zeng, D-Z., Zhao, L., 2009. Pollution Havens and Industrial Agglomeration. *Journal of Environmental Economics and Management* 58, 141-154.

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