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North-South diffusion of climate-mitigation technologies: The crowding-out effect on relocation

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Abstract. The deployment of cleaner production technologies is crucial to mitigate the effect of climate change. The diffusion of technology from developed to developing countries can be done through different channels. It can be a business decision such as firms' relocation, creation of a subsidiary or the adoption of technology by southern firms, or it may be decided at government level. This paper investigates in a two-country model (North and South) the relationship between the firms' relocation and diffusion of mitigation technologies. We assume that both countries implement a carbon tax and there are two kinds of production technology used: a relatively clean technology and a dirty one. This paper theoretically shows that the diffusion technology by technology adoption, public transfer or subsidiary creation induces a decrease in relocation, while technology diffusion via purchasing dirty southern firms may increase the number of relocated firms. The paper also demonstrates that technology diffusion may have perverse effects in the long run. Indeed, total emissions may increase with technology diffusion since southern firms are more competitive.

Keywords. Technology transfer; Carbon tax; Relocation; Trade of polluting goods; Imperfect competition.

JEL codes. L13, Q53, Q58.

1. Introduction

The negotiations conducted during the COP21, which led to signing of the Paris Agreement – the most ambitious legal instrument adopted so far to fight global warming – also highlighted the role of technology diffusion in reducing emissions. In Article 10 of the Paris Agreement, countries affirm that "Parties share a long-term vision on the importance of fully realizing technology development and transfer in order to improve resilience to climate change and to reduce greenhouse gas emissions". Dechezleprêtre et al. (2011) shows that green technologies are concentrated in developed countries, while developing countries now produce the majority of the world's CO_2 emissions and will produce even more in the coming years. Thus, the deployment of cleaner production technologies seems crucial to mitigate the effect of climate change but it faces several difficulties. Being potentially beneficial for developing countries, the transfer of green technologies may have adverse effects on developed economies. Indeed, sharing innovations may enable firms located in developing countries to reduce their emissions more rapidly,

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but it may also increase their competitiveness. Moreover, technology diffusion can take a wide variety of forms, making it particularly difficult to study its effects. Technology transfers can result from governments' decisions or they can be a business choice. First of all, technologies can be purchased on the market where innovators sell their patents. However, developing countries claim that these patents are too expensive for their firms and some technologies are not sold on the market. Second, governments in developed countries have several instruments at their disposal to transfer technologies. For instance, they can implement bilateral programs, relax the intellectual property rights on green innovations[1], open the market, differentiate patent prices, or even subsidize firms to purchase patents. Finally, firms may settle in a foreign country bringing their knowledge and technologies. Relocation or opening a subsidiary in a foreign country directly affects the technology used in the host country, but it may also enhance the diffusion of technology through knowledge spillovers. The purpose of this paper is to study the different channels to diffuse technology and to determine whether technology diffusion affects the decisions to relocate according to the channel used.

While firms' relocation may induce technology diffusion, it can also be particularly detrimental for a country. Over the past 25 years, manufacturing employment, as a share of total employment, has declined significantly in most advanced economies around the world.[2] In addition to the loss of jobs and thus the resulting increase in unemployment, relocations induce the destruction of physical and human capital, leading to a loss of specific knowledge and skills. The rise in unemployment generates costs (unemployment benefits, the functioning of job search agencies and expenses induced by the social consequences of unemployment in areas such as housing and health), but also shortfalls (in taxes and social contributions). Political effects are also induced by unemployment, such as the development of a feeling of exclusion for the unemployed. Relocation also leads to lower tax revenues. Apart from these economic consequences, relocation may also be detrimental for the environment. Indeed, firms that relocate in countries implementing more lenient environmental regulations, may contribute to increasing emissions by producing more (see for instance Taylor (2015) and the literature on pollution havens). Hoel (1997) highlights the trade-off a government faces when setting its environmental regulation. On the one hand, a government wants to attract industry, but on the other hand, it wants to locate the pollution abroad if pollution is not trans-boundary pollution. Otherwise, countries prefer firms not to relocate in order to control their emissions. To reduce the risk of relocation in a context of environmental regulation, governments may use different tools, such as distributing subsidies[3] or nationalizing firms.

We develop a simple partial equilibrium model with two countries (North and South) to fathom the economics of the international diffusion of climate mitigation technologies in a world with a risk of northern firms' production relocation. In each country a carbon tax is implemented, and firms produce the same homogeneous polluting good. Firms located in one country sell in that country and also in the other country. We consider two types of production technology: a relatively clean technology and a dirty one. The cleanliness of a technology is given by its emission intensity, that is the units of emissions per unit produced. We assume that there is an innovator in the North selling the cleaner production technology in a competitive market. Cleaner firms located in both economies have already bought the technology. Moreover, we assume that in the North, all firms use a relatively clean production process, while in the South, relatively clean firms and dirty firms coexist. Furthermore, we consider that in

[1] For more details, see Maskus (2010).

[2] The destruction of jobs does not come only from relocations. For instance, Aubert and Sillard (2005) analyze the share of relocations in downsizing French industry.

[3] In a context of pollution permits, Martin et al. (2014) determine the number of free allowances that is sufficient to prevent firms from relocating. Nicolaï and Zammorano (2018) in a context of spatial competition also analyze the distribution of free allowances in order to prevent firms from relocating.

the North, the emission tax and the production costs are higher. These assumptions reflect the reality that environmental awareness increases with economic development, and that labor is usually more expensive in advanced economies. We assume that firms in the North may decide to relocate their production to the other country at a fixed and symmetric cost. By relocating a northern firm benefits from low labor cost and lenient environmental regulation, but has to pay for the transportation cost to export the good to its previous northern market.

The first contribution of this paper is to highlight the impact of technology diffusion on relocation. We show that a decrease in the dirty southern firms' emission intensity or an increase in the number of clean firms (the total number of southern firms being fixed) reduces the incentive of northern firms to relocate their production. The decrease in the dirty southern firms' emission intensity or the substitution of a dirty firm by a cleaner one reduces the technological advantage of cleaner firms and exacerbates the competition. Therefore, the developed countries' firms are less willing to relocate. As far as we know, this relationship has never been analyzed in the literature. To go further than this comparative static, it is necessary to define a time horizon but also to specify the diffusion channels of green technology. We consider the time horizon such that all the relocations take place, meaning that at equilibrium northern firms have the same profit regardless of their relocation, and we call it the long run. However, we do not take into account free entry, meaning that at equilibrium firms' profits are positive.

The second contribution of this paper is to propose a model which allows all the various channels of technology diffusion to be studied and then for the determinants of each kind of technology diffusion to be examined together with their implications in the long run. We focus on the market for technology in which firms may purchase the relatively clean technology. We consider two cases: one whereby each southern firm decides to buy a license, and another whereby the northern government decides to subsidize the license purchases. In the first case, firms only take into account their profit, while in the second case, the northern government takes northern welfare into account. Moreover, technology diffusion can also be achieved through intra-firm technology diffusion. Hence, we also consider multinational firms, which can partially relocate their production and supply each market locally. In this case, the northern firm may decide to create a subsidiary abroad from scratch, or it can buy a dirty southern firm and convert it into a clean one.

We show that in the long run the diffusion technology by technology adoption, public transfer or subsidiary creation induces a decrease in relocation, while technology diffusion via purchasing dirty southern firms may increase the number of relocated firms. Technology diffusion through the first three channels mentioned above increases competition and reduces the number of relocated firms. However, creating a subsidiary by purchasing a dirty southern firm reduces the number of competitors and may increase the number of firms that relocate. Indeed, the purchase of dirty southern firms makes the market for products more concentrated in both countries. On the northern market, there will be less dirty southern firms, while on the southern market, there will be less northern firms, the number of southern firm will be constant but the share of clean firms will be higher.

We demonstrate that technology diffusion may have perverse effects in the long run. Indeed, total emissions may increase with technology diffusion since southern firms are more competitive. These results are consistent with the previous literature on technology diffusion, which highlights the fact that transferring clean technology does not necessarily improve the environment, and that the transfer decision is highly affected by the terms of trade. The pioneering work by Stranlund (1996) assumes no trade and thus the governments' incentives to transfer are only driven by the effect on global emissions. Stephan and Muller-Furstenberger (2015) analyze the incentive to transfer energy-saving technologies when there is trade on energy, while Helm and Pichler (2015) assume trade in a global carbon market. Finally, Glachant et al. (2017) assume that there is trade in the polluting good market. The present paper is complementary in considering trade in the polluting good market, relocation and the long-run. The main differences with Glachant et al. (2017) is that this latter only consider short-run and diffusion promoted by governments.

The paper is structured as follows. Section 2 presents the modeling assumptions and describes the crowding-out effect. Section 3 studies the North-South diffusion of climate-mitigation technologies. Section 4 discusses the robustness of the results, derives some policy implications and concludes.

2. The crowding-out effect on relocation

2.1. The set-up

The model describes two countries $l = \{N, S\}$ where N and S respectively denote the North and the South. In each country there are M_l firms producing a homogeneous polluting good, and consumers purchasing the goods. The prices are given by the inverse demand function:

$$p_l = a_l - Q_l$$

where a_l is the market size in country l, and Q_l the quantity consumed in country l.

Production generates emissions and we assume that abatement technologies are not available. The production technology is characterized by an emission intensity parameter μ. We consider two technologies: a relatively-clean technology sold at a fixed price K by an innovator located in the North, and a free dirty technology. The relatively-clean technology creates μ^c units of emissions per unit produced, and the dirty one creates $\mu^d > \mu^c$ units of emissions per unit produced. We assume that in the North all M_N firms use the relatively-clean technology, while in the South both technologies are used. We denote by M_S^d, the number of dirty southern firms, and M_S^c the number of relatively-clean southern firms. The number of firms located in the South is then: $M_S = M_S^d + M_S^c$. Firms using the relatively-clean technology have purchased the technology in the past (sunk cost). For simplicity, we refer to relatively-clean firms as clean firms, even if they also pollute.

Northern and southern firms sell products on the two markets (North and South). The production of a northern firm sold in the North and in the South is respectively denoted by r_{SS_i} and r_{NS_i}. Let us also denote $r^d_{SN_i}$ and $r^d_{SS_i}$ ($r^c_{SN_i}$ and $r^c_{SS_i}$), the production of dirty southern (clean southern) firms, sold respectively in northern and southern markets. The market clearing condition implies that $Q_N = \sum_{i=1}^{M_N} r_{SS_i} + \sum_{i=1}^{M_S^c} r^c_{SN_i} + \sum_{i=1}^{M_S^d} r^d_{SN_i}$ and $Q_S = \sum_{i=1}^{M_N} r_{NS_i} + \sum_{i=1}^{M_S^c} r^c_{SS_i} + \sum_{i=1}^{M_S^d} r^d_{SS_i}$. Transport is costly and let t be the constant unit transportation cost.

Let us denote c_l the production cost in country l and $\tau_l > 0$ the carbon tax implemented in country l. In the South, clean and dirty firms have the same production costs c_S. Thus, the production costs can be interpreted as labor costs. We assume that the production cost and the emissions tax are higher in the North. Let us use the following notations for the differentials: $\Delta\tau \equiv \tau_N - \tau_S > 0$; $\Delta c \equiv c_N - c_S > 0$ and $\Delta\mu \equiv \mu_d - \mu_c > 0$.

Let us now define the equilibrium production levels.

Northern firms bought the technology in the past, and the costs of buying the clean technology no longer appear in their profit. Each northern firm solves the following problem:

$$\max_{r_{SS_i}, r_{NS_i}} \pi_{H_i}\left(M_N, M_S^c, M_S^d\right) = (p_N - c_N - \tau_N\, \mu^c)\, r_{SS_i} + (p_S - c_N - \tau_N\, \mu^c - t)\, r_{NS_i} \quad (1)$$

In the South, dirty and clean firms coexist. They respectively solve the following problems.

$$\max_{r_{SN_i}^d, r_{SS_i}^d} \pi_{F_i}^d\left(M_S^d, M_S^c, M_N\right) = (p_N - c_S - \tau_S\, \mu^d - t)\, r_{SN_i}^d + (p_S - c_S - \tau_S\, \mu^d)\, r_{SS_i}^d \quad (2)$$

$$\max_{r_{SN_i}^c, r_{SS_i}^c} \pi_{F_i}^c\left(M_S^c, M_S^d, M_N\right) = (p_N - c_S - \tau_S\, \mu^c - t)\, r_{SN_i}^c + (p_S - c_S - \tau_S\, \mu^c)\, r_{SS_i}^c \quad (3)$$

By calculating the first-order conditions and solving the system of equations, we obtain the productions:

$$r_{NN}(M_N, M_S^c, M_S^d) = \frac{a_N - c_N - \mu^c\, \tau_N - (\Delta\, c + \mu^c\, \tau_N - t)\, M_S + \left(\mu^c\, M_S^c + \mu^d\, M_S^d\right)\, \tau_S}{M_N + M_S + 1}$$

$$r_{NS}(M_N, M_S^c, M_S^d) = \frac{a_S - c_N - \mu^c \tau_N - t - (\Delta\, c + \mu^c \tau_N + t)\;M_S + \left(\mu^c\, M_S^c + \mu^d\, M_S^d\right)\, \tau_S}{M_N + M_S + 1}$$

$$r_{SS}^d(M_S^d, M_S^c, M_N) = \frac{a_S - c_S - \mu^d\, \tau_S + M_N\, (\Delta\, c + \mu^c\, \tau_N - \mu^d\, \tau_S + t) - \Delta\, \mu\, M_S^c\, \tau_S}{M_N + M_S^d + M_S^c + 1}$$

$$r_{SN}^d(M_S^d, M_S^c, M_N) = \frac{a_N - c_S - t - \mu^d\, \tau_S + \left(\Delta\, c + \mu^c\, \tau_N - \mu^d\, \tau_S - t\right)\; M_N - \Delta\, \mu\, M_S^c\, \tau_S}{M_N + M_S + 1}$$

$$r_{SS}^c(M_S^c, M_S^d, M_N) = \frac{a_S - c_S - \mu^c \tau_S + M_N\, (\Delta\, c + \mu^c\, \Delta\, \tau + t) + \Delta\, \mu\, M_S^d\, \tau_S}{M_N + M_S + 1}$$

$$r_{SN}^c(M_S^c, M_S^d, M_N) = \frac{a_N - c_S - t - (\mu^c - \Delta\, \mu\, M_S^d)\, \tau_S + (\Delta\, c + \mu^c\, \Delta\, \tau - t)\;M_N}{M_N + M_S + 1}$$

The quantity produced for the market of country l increases with its size a_l. On each market, a clean southern firm produces more than a dirty southern firm. A clean southern firm produces more than a clean northern firm on the southern market since it benefits from a low tax, a low production costs and does not pay for the transportation costs. Obviously, an increase in the northern tax or the northern production cost increase the production of southern firms, while an increase in the southern tax or in the southern production cost increase the production of northern firms.

Prices are given by:
$p_N = a_N - M_N\, r_{NN} - M_S^c\, r_{SN}^c - M_S^d\, r_{SN}^d$ and $p_S = a_S - M_N\, r_{NS} - M_S^c\, r_{SS}^c - M_S^d\, r_{SS}^d$, hence:

$$p_N = \frac{a_N + M_N\, (c_N + \mu^c\, \tau_N) + M_S\;(t + c_S) + \left(\mu^c\, M_S^c + \mu^d\, M_S^d\right)\, \tau_S}{M_N + M_S + 1}$$

$$p_S = \frac{a_S + c_S\, M_S + M_N\;(c_N + \mu^c\, \tau_N + t) + \left(\mu^c\, M_S^c + \mu^d\, M_S^d\right)\, \tau_S}{M_N + M_S + 1}$$

In each region, the price increases with the transportation cost, the taxes, the production costs, and the market size.

From the functional forms chosen, the profits are $\pi_N = r_{NN}^2 + r_{NS}^2$; $\pi_S^c = {r_{SS}^c}^2 + {r_{SN}^c}^2$; $\pi_S^d = {r_{SS}^d}^2 + {r_{SN}^d}^2$. Hence, as a firm increases its production, its profit increases as well.

The firms in the North may relocate to the South. Let us assume a constant and symmetric cost of relocation C^R. A clean firm located in the North relocates its production if, and only if, the profit realized in the South net of relocation costs is higher than the current profit in the northern country. Moreover, the firm anticipates that relocation modifies market structures. A northern firm relocates its production if, and only if, the profit realized in the South minus the relocation cost is higher than the current profit in the northern country. Stated differently, if:

$$\pi_S^c \left(M_S^c + 1, M_S^d, M_N - 1\right) - C^R > \pi_N \left(M_N, M_S^c, M_S^d\right) \tag{4}$$

Northern firms have the incentive to relocate their production in the South as long as their profit net of the relocation cost is larger than the northern profit. Hence, at equilibrium, the number of firms that relocate their production is such that clean firms obtain the same profit regardless of their location.

The remainder of this paper studies how an improvement in the technology used in the South affects the incentives to relocate. Technology improvement can take different forms and can come from different channels.

2.2. Effects of a decrease in the dirty southern firms' emission intensity

Improvement in the technology used in the South can be such that the dirty southern firms' emission intensity decreases. If so, the technology will be spread to all southern firms. By studying how a decrease in the dirty southern firms' emission intensity affects the outcome, we deduce the following lemma:

LEMMA 1. *A decrease in the dirty southern firms' emission intensity*

- *increases the consumer surplus, and decreases the profits in the North,*
- *decreases production and emissions from clean firms located in both economies,*
- *increases the production of dirty southern firms, and has an ambiguous effect on their emissions.*

Proof. Appendix A □

A decrease in μ^d reduces the productions of clean firms (r_{NN}, r_{NS}, r_{SN}^c and r_{SS}^c) since it reduces their technological advantage. This decrease is particularly significant when the carbon tax is high. However, the overall production sold in both countries increases since dirty firms become more competitive. Thus, the profit of northern firms decreases, while the consumer surplus increases. The reduction in the dirty southern firms' emission intensity decreases the emissions from clean firms in both countries, but has an ambiguous effect on the dirty southern firms' emissions. Indeed, they produce more, but emit less per unit produced. As a result, the effect on the environment is ambiguous. The reduction in the dirty southern firms' emission intensity reduces the overall emissions when M_S^c is low, τ_N is high and τ_S is low.The technological improvement decreases global emissions if:

$$a_N + a_S - t + 2\left(M_N\,(\mu^c\,\tau_N + \Delta\,c) - c_S - (\mu^c + \mu^d\,(1 + M_N))\,\tau_S - \Delta\,\mu\,M_S^c\,\tau_S\right) \geq 0$$

Indeed, lax environmental regulation in the South implies that dirty firms produce and emit a large amount before the technology improvement.

By calculating equation (4) and studying how a decrease in μ^d affects it, we deduce the following proposition.

Proposition 1. *A decrease in the dirty southern firms' emission intensity reduces the northern firms' incentive to relocate.*

Proof. Proof in Appendix B □

Our intuition is as follows. Consider for a moment that there is no trade. Since the markets for products in the two countries are independent, the decrease in the dirty southern firms' emission intensity does not affect northern profits. However, it decreases the profits of clean southern firms. Indeed, if the dirty southern firms' emission intensity decreases, northern clean firms have a lower technological advantage when they relocate. As a result, the incentives to relocate are lower.

Returning to the case where trade is bilateral, by relocating a northern firm benefits from low labor cost and lenient environmental regulation, but has to pay for the transportation cost to sell the good on the northern market. Remember that a firm's profit comprises two parts: the profits made on the northern market and the profits realized abroad. Hence, relocation increases its profit related to the southern market, especially if its technological advantage is high (high μ^d). Conversely, relocation has an ambiguous effect on the profit related to the northern market. Two cases should be then analyzed. (i) If relocation increases the northern firm's profit on the northern market, the decrease in the dirty southern firms' emission intensity reduces this gain since the technological advantage of this firm will decrease. (ii) If relocation decreases the northern firm's profit on the northern market, the decrease in the dirty southern firms' emission intensity increases this loss by inducing an increase in competition. As a result, the decrease in the dirty southern firms' emission intensity reduces the incentive to relocate.

2.3. Effects of an increase in the number of clean southern firms

Improvement in the technology used in the South can be such that the share of clean firms increases on that market. If so, technology diffusion affects the market structure, and only a share of southern firms experience a technological change. Such technology diffusion affects the share of clean firms in the South but not the total number of firms on each market. Note that relocation is also a modification of the market structure since it affects the location of clean firms. Said differently, relocation affects the number of local firms on each market, keeping the share of clean firms constant.

Keeping the number of southern firms $M_S = M_S^d + M_S^c$ constant, let us analyze the effect of an increase in M_S^c on the individual productions of the different types of firms

$$\frac{\partial r_{SN}^d}{\partial M_S^c} = \frac{\partial r_{SN}^c}{\partial M_S^c} = \frac{\partial r_{NN}}{\partial M_S^c} = \frac{\partial r_{SS}^d}{\partial M_S^c} = \frac{\partial r_{SS}^c}{\partial M_S^c} = \frac{\partial r_{NS}}{\partial M_S^c} = -\frac{\Delta\,\mu\,\tau_S}{M_N + M^c + 1} < 0$$

Thus, an increase in M_S^c decreases the production of all types of firms. Indeed, it transforms one dirty southern firm into a clean southern firm and then reduces its production cost, inducing a reduction of production for all the other firms.

The effect of an increase in M_S^c on total production is given by

$$\frac{\partial\,(Q_N + Q_S)}{\partial\,M_S^c} = -2\,(M_N + M_S)\,\frac{\Delta\,\mu\,\tau_S}{M_N + M^c + 1} + (r_{SS}^c + r_{SN}^c) - \left(r_{SS}^d + r_{SN}^d\right) > 0 \qquad (5)$$

An increase in the share of clean firms in the South increases competition. It has two effects on global production (and price). On the one hand, other firms produce less, and on the other hand, firms that were previously dirty produce more. The overall effect is such that the consumer surplus increases.

By studying how an increase in the share of clean firms on the southern market affects the incentives to relocate, we deduce the following proposition.

Proposition 2. *Keeping the number of southern firms constant, an increase in M_S^c reduces the northern firms' incentive to relocate.*

Proof. Replacing M_S^d by $M_S - M_S^c$ in (4) gives: $\frac{\partial\,(4)}{\partial\,M_S^c} = -\frac{4\,\Delta\,\mu\,(M_N+M_S)\,\tau_S\,X}{(M_N+M_S+1)^2} < 0$ □

where $X = \mu^c\,\Delta\,\tau + \Delta\,c > 0$.

The replacement of a dirty firm by a clean one decreases clean firms' individual production. However, under linear demand, it does not affect the difference between the individual northern production and the individual clean southern firm's production. We conclude then that the incentives to relocate decrease.

Keeping the number of clean firms constant, i.e. $M^c = M_N + M_S^c$, we calculate the effect of an increase in M_S^c on the individual productions of the different types of firms:

$$\frac{\partial\,r_{SS}^d}{\partial\,M_S^c} = \frac{\partial\,r_{SS}^c}{\partial\,M_S^c} = \frac{\partial\,r_{NS}}{\partial\,M_S^c} = -\frac{X+t}{M_S^d + M^c + 1} < 0$$
$$\frac{\partial\,r_{SN}^d}{\partial\,M_S^c} = \frac{\partial\,r_{SN}^c}{\partial\,M_S^c} = \frac{\partial\,r_{NN}}{\partial\,M_S^c} = -\frac{X-t}{M_S^d + M^c + 1}$$

can be interpreted as the unit gain from relocating (without taking into account the relocation cost). An increase in M_S^c decreases the individual production sold on the southern market, while it has an ambiguous effect on the individual production sold on the northern market. Indeed, it depends on the value of transportation cost. If the transportation cost is relatively low as compared with the unit gain from relocating, relocation strengthens competition and then induces a decrease in the firms' individual production. However, if the transportation cost is relatively high as compared with the unit gain from relocating, relocation softens competition and firms' individual production increases.

From the previous equations, we deduce the following lemma:

Lemma 2. *Relocations decrease the profits of the remaining northern firms if the transportation cost is relatively low as compared with the unit gain from relocating.*

Proof. $\frac{\partial\,r_{NN}}{\partial\,M_S^c} = -\frac{X-t}{M_S^d+M^c+1}$ and $\frac{\partial\,r_{NS}}{\partial\,M_S^c} = -\frac{X+t}{M_S^d+M^c+1} < 0$ □

When the transportation cost is relatively low as compared with the sum of the unit gain from relocating, relocation makes a northern firm more efficient and strengthens competition on the northern market.

3. Technology diffusion via various channels

To take things further than these previous comparative statics, let us now analyze the impact of the diffusion of climate-mitigation technologies taking into account the effect on relocation decisions and considering the different channels through which technology may be spread. We will first consider the international technology market on which agents (firms or governments) can purchase patents and second focus on the internal technology diffusion in a multinational corporate setting. In what follows, let us assume that before technology diffusion takes place, there are M_N^0 firms using the cleaner technology in the North, while in the South there are no clean firms ($M_S^{c\,0} = 0$) and $M_S^{d^0}$ dirty firms. This assumption facilitates presentation of the results without loss of generality.

3.1. First channel analyzed: international technology market and technology adoption

Consider an international technology market in which the clean technology is sold and let us assume that the northern firms have already bought the technology. southern firms can decide whether or not to adopt the technology by purchasing patents. Northern government can also purchase patents and distribute them to southern firms or subsidize their purchase of patents. Hence, technology diffusion via the international technology market can be decided either by southern firms or northern government.

3.1.1 Southern firms' decisions

We analyze here the possibility for southern firms to purchase and adopt the clean technology. We assume no adaptation cost and adoption cost is simplified to a patent price K. The timing is the following:

Stage 1. Southern firms decide whether they adopt the technology.

Stage 2. northern firms decide whether they relocate.

Stage 3. Firms produce and sell the good on the two markets for products.

Stage 3. The third stage is similar to the one defined in Section 2.1 except that at the last stage: $M_N = M_N^0 - n$; $M_S^d = M_S^{d^0} - k$; $M_S^c = n + k$ where n is the number of relocated firms if there is adoption, and k, the number of dirty southern firms adopting the technology.

Stage 2. At equilibrium a northern firm is indifferent between relocating and staying in the North. Hence, at equilibrium, the number of relocated firms n is given by the following equality.[4]

$$\pi_S^c\left(n + k, M_S^{d^0} - k, M_N^0 - n\right) - C^R = \pi_N\left(M_N^0 - n, n + k, M_S^{d^0} - k\right) \tag{6}$$

By solving (6), we define $n(k)$ given by:

$$\begin{aligned} n(k) = {} & \frac{2\,a_S\,(X+t) + 2\,a_N\,(X-t)}{4\,(X^2+t^2)} - \frac{(\mu^c\,(\tau_N+\tau_S) + t + c_N + c_S)\,X}{2\,(X^2+t^2)} \\ & - \frac{\left(k - M_S^{d^0}\right)\Delta\,\mu\,\tau_S\,X}{X^2+t^2} - \frac{C^R\left(M_N^0 + M_S^{d^0} + 1\right)}{4\,(X^2+t^2)} + \frac{M_N^0 - M_S^{d^0}}{2} \end{aligned} \tag{7}$$

The number of firms that relocate depends negatively on the relocation cost and positively on the southern market size. The more costly relocation is, the less firms relocate. Moreover, the higher the southern market size is, the more profitable for northern firms relocation is and the more firms relocate. However, the effect of northern market size on the number of relocated firms is ambiguous and depends on the transportation cost. If the transportation cost is relatively low as compared with the unit gain from relocating, the number of relocated firms increases

[4]We do not force the equilibrium number of firms to be an integer.

with the northern market size. Indeed, since it is cheap to transport goods, relocation decreases the marginal cost to produce and sell on the northern market. The greater the northern market size is, the more northern firms relocate. However, if the transportation cost is relatively high as compared with the unit gain from relocating, the relocated firm will be less efficient on the northern market. Thus, the greater the northern market size is, the less northern firms relocate.

By deriving $n(k)$ with respect to k, we obtain:

$$\frac{\partial\, n(k)}{\partial\, k} = -\frac{\Delta\, \mu\, \tau_S\, X}{X^2 + t^2} < 0$$

From the previous equation, the following corollary is deduced.

Corollary 1. *The adoption of clean technology by southern firms decreases the number of relocated firms.*

This corollary is a direct implication of Proposition 2. Adoption increases the share of clean firms on the southern market, which decreases the gains from relocation. Note that adoption highly reduces relocation when the transportation costs are low. If so, clean southern firms are highly competitive on the northern market, and northern firms have more incentive to supply this market locally.

Stage 1. Southern firms purchase the technology from the innovator anticipating the possible relocation of northern firms. A dirty southern firm adopts the cleaner technology if and only if, the profit realized when it is clean minus the adoption cost is higher than the profit it gets when it is dirty. At equilibrium, the number of adoption k is such that the profit of a southern firm is the same with the two technologies:

$$\pi_S^c\left(n(k) + k, M_S^{d^0} - k, M_N - n(k)\right) - K = \pi_S^d\left(M_S^{d^0} - k, n(k) + k, M_N - n(k)\right) \tag{8}$$

By replacing $n(k)$ and solving (8) with respect to k, we are able to define the number of firms that adopt the clean technology:

$$\begin{aligned} k^* = {} & \frac{C^R\left(M_N^0 + M_S^{d^0} + 1\right)\, X}{4\,\Delta\, \mu\, t^2\, \tau_S} + \frac{X\left(\left(M_N^0 + M_S^{d^0}\right)\, t^2 + \left(M_N^0 + M_S^{d^0} + 1\right)\, X^2\right)}{2\,\Delta\, \mu\, t^2\, \tau_S} \\ & - \frac{K\left(M_N^0 + M_S^{d^0} + 1\right)\, (t^2 + X^2)}{(2\,\Delta\, \mu\, t\, \tau_S)^2} - \frac{\left(M_N^0 + M_S^{d^0} + 1\right)\, X^2}{2\, t^2} \\ & + \frac{a_N\, (t + X) - a_S\, (X - t)}{2\,\Delta\, \mu\, t\, \tau_S} - \frac{\mu^d\, (\tau_S + \tau_S) + t + 2\, c_S}{2\,\Delta\, \mu\, \tau_S} - \frac{M_N^0 - M_S^{d^0}}{2} \end{aligned} \tag{9}$$

By studying (9), the following lemma is deduced.

Lemma 3. *A southern firm has more incentive to adopt the cleaner technology*

- *when the adoption costs are low,*
- *when the relocation costs are high,*
- *when the size of the northern market is large,*
- *when the size of the southern market is large and the transportation cost is high.*
- *when the size of the southern market is low and the transportation cost is low.*

Southern firms adopt technology to reduce the unit production cost and prevent some firms from settling on the southern market. They have more incentive to adopt technology when the profit gains on the southern market are high. This is the case when the southern market size is large and the transportation costs are relatively high since it means that the southern market is profitable and not significantly exposed to northern firms' competition. This is also the case when the size of the northern market and the relocation costs are high, since it means that only few northern firms will relocate. Therefore, using simple comparative statics, we can deduce that reducing patent prices (for instance, by allowing for pricing differentiation of patents or relaxing intellectual property rights) decreases relocation. Such policies would increase adoption, reduce relocation and may increase emissions.

3.1.2 Northern government's decision

The northern government may transfer the technology to the dirty southern firms by subsidizing purchase of the technology. It directly purchases the technology from the innovator and grants it to the dirty southern firms. We assume that the government decides to purchase licenses for all dirty southern firms or none of them and is thus unable to discriminate between firms. The northern government only purchases patents if this increases its welfare and if so all firms use the cleaner technology μ^c. Emissions generate global damage, assumed to be linear and the marginal damage is given by δ. The northern welfare is defined as the sum of the consumer surplus, the sum of the northern profits including the profit of the innovator and the tax revenue minus the environmental damage. Moreover, subsidizing southern firms $(M_S^d K)$ is considered here to be a lump-sum transfer from the government to the northern innovator. The northern welfare is thus:

$$W_N = SC_N + \Pi_N + \tau_N E_N - \delta (E_N + E_S)$$

The decision to improve southern technology is taken by the northern government while previously the southern firms were deciding whether they adopt it or not. The game is characterized by the following timing:

Stage 1. The North decides whether it subsidizes the purchase of licenses for southern firms.

Stage 2. Firms decide whether they relocate.

Stage 3. Firms produce and sell the good on the two markets for products.

We solve this problem backwards and as previously we focus on the first two stages, since the third stage is similar to the one defined in section 2.1.

Stage 2. Following the same method as in the previous section, the number of relocations n can be defined. Similarly to adoption, the subsidies affect the market structure. The number of relocated firms with subsidies is given by $n^S = n(k = M_S^{d^0})$, while the number of relocated firms without subsidies is given by $n^{WS} = n(k = 0)$. Since $n(k)$ decreases with k, we immediately deduce:

$$n^S < n(k^*) < n^{WS}$$

The number of relocations is the lowest when the northern government decides to subsidize the technology adoption for all dirty southern firms. We deduce the following corollary.

COROLLARY 2. *Subsidizing the purchase of patents for cleaner technology abroad decreases the number of relocated firms in the long run.*

This corollary is a direct implication of either Proposition 1 or Proposition 2. Indeed, subsidizing the purchase of patents may be understood as an improvement in the dirty technology, which reduces the incentive to relocate. Moreover, since an increase in the share of clean firms on the southern market decreases the incentive to relocate, implementation of a subsidy for cleaner technology also induces in the North a less concentrated market-structure in the long run. This situation is a special case whereby all firms adopt the clean technology.

Stage 1. The northern government decides whether it subsidizes the purchase of patents abroad and anticipates this will affect the firm's location. If the northern government subsidizes, the market structure is as follows: $M_S^d = 0$, $M_S^c = {M_S^c}^0 + {M_S^d}^0 + n^S$ and $M_N = {M_N}^0 - n^S$. In contrast, if the northern government does not subsidize, $M_S^d = {M_S^d}^0$, $M_S^c = {M_S^c}^0 + n^S$ and $M_N = {M_N}^0 - n^S$.

In appendix C, we determine how the subsidy affects the welfare component. Glachant et al. (2017) study in a close setting the incentive to transfer clean technology for a given market structure. Glachant et al. (2017) is a specific case of the current paper since they assume no transportation cost, no production cost and firms cannot relocate. Said differently, the timing in Glachant et al. (2017) is only composed of stage 1 and stage 3.

By studying the effect of the subsidies on the outcome, the following lemma is deduced:

LEMMA 4. *In the long run, subsidizing the purchase of patents for cleaner technology abroad*

- *increases the consumer surplus in the North,*
- *increases or decreases the sum of the northern profit,*
- *increases or decreases emissions in the North,*
- *has an ambiguous effect on emissions from initially dirty southern firms,*
- *decreases emissions from clean southern firms.*

Proof. Appendix C □

Lemma 4 extends Lemma 1 in the long-run.

On the northern market, subsidies decrease the quantity sold by clean firms from both countries, and increases the quantity sold by dirty firms. The overall effect is such that the northern consumer surplus increases since production increases. Indeed, subsidies decrease the number of inefficient firms, while keeping the total number of firms constant.

The subsidy may increase the industry profit in the North, while without relocation the subsidy always has a negative impact on northern profit (Glachant et al. (2017)). Indeed, the subsidy decreases the individual profit but increases the number of firms located in the North. Hence, the subsidy may boost the North. The crowding-out effect lowers the positive effect of the subsidy on the northern consumer surplus. Indeed, the subsidy decreases the marginal production cost, which decreases the price but also impedes relocation which lowers this price decrease when transportation costs are relatively high compared with the unit gain from relocating.

Finally, as in Glachant et al. (2017), the subsidy may increase or decrease global emissions. However, the effect is different. In Glachant et al. (2017), welfare increases with technology transfer if and only if the total emissions decrease with the transfer. However, in this paper welfare may increase despite an increase in emissions. This difference comes from the effect on relocation.

Since the government purchases patents for all the dirty southern firms from a northern innovator at a fixed price, the results can be applied to others kinds of northern government interventions such as relaxing intellectual property rights or transferring information to the southern government, this disseminating the latter to all the southern firms. These interventions would have the same effects on relocation as granting subsidies. Moreover, these actions may have the same perverse effects on emissions.

Another possible case could be that the northern government discriminates and does not give subsidies to all the dirty southern firms but only to some. Such a situation could be justified either if the innovator is not a northern firm or if there is a shadow cost of public funds. The number of firms that adopt technology would maximize welfare. This situation is nevertheless beyond the scope of this paper.

3.2. Second channel analyzed: internal transfers inside multinational companies

We have assumed that relocations are such that northern firms may decide to close their plants in the North and settle abroad. However, multinational companies may have plants in various countries and may transfer their technology to their subsidiaries. We now study how internal transfers inside multinational companies affect firms' relocation.

The timing is the following:

Stage 1. Northern firms decide whether they settle a subsidiary in the South.

Stage 2. Northern firms decide whether they relocate.

Stage 3. Firms produce and sell the good on the two markets for products.

We consider two different cases: northern firms may either create a new subsidiary from scratch, or purchase a dirty southern firm. In both cases, they automatically transfer the technology to their subsidiary. We assume as in Motta and Thisse (1994) that the northern firm and its subsidiary only supply the good locally. The northern firms that did not create a subsidiary, then decide whether or not to relocate their production. They focus on the case whereby subsidiaries are created from scratch. Let us assume that the decisions to behave or not as a multinational firm (and said differently to have two plants) are taken before the decisions to relocate in order to be consistent with the previous case. Indeed, the purpose of this paper is to study the consequences of technology diffusion on relocation.

The creation of a subsidiary does not affect either the market concentration or the share of clean firms, but only affects the share of firms supplying the good locally. Conversely, the purchase of dirty southern firms strengthens the market concentration, increases the share of clean firms on each market, and also affects the share of firms supplying the good locally.

3.2.1 Creation of a new subsidiary from scratch

Northern firms may decide to create a new subsidiary from scratch in the South, while keeping its plant in the North. Let us denote by $\hat{n}$, the number of northern firms that relocate and s, the number of northern firms that open a subsidiary abroad and whose northern plant is still active.

Stage 3. The third stage is similar to the one defined in Section 2.1 except that the market structure is different. In the third stage, the market structure is as follows: on the northern market there are $M_N = M_N^0 - \hat{n}$; $M_S^d = M_S^{d^0}$; and $M_S^c = \hat{n}$ firms operating, while on the southern market there are $M_N = M_N^0 - \hat{n} - s$; $M_S^d = M_S^{d^0}$; and $M_S^c = \hat{n} + s$ firms operating. To obtain the production level we simply replace M_N, M_S^d and M_S^c by their corresponding value.

Stage 2. Following the same method as in the previous cases, the number of relocations $\hat{n}$ is given by:

$$\begin{aligned}&\pi_{SN}^c\left(\hat{n}, M_S^{d^0}, M_N^0 - \hat{n}\right) + \pi_{SS}^c\left(\hat{n} + s, M_S^{d^0}, M_N^0 - \hat{n} - s\right) - C^R \\ =&\pi_{NN}\left(M_N^0 - \hat{n}, \hat{n}, M_S^{d^0}\right) + \pi_{NS}\left(M_N^0 - \hat{n} - s, \hat{n} + s, M_S^{d^0}\right)\end{aligned} \tag{10}$$

Relocation reduces the number of northern firms on each market, while creating new subsidiaries only reduces the number of northern firms on the southern market. In other words, relocation increases the number of local firms on the southern market and decreases the number of local firms on the northern market, while creating new subsidiaries has no effect on the number of local firms on the northernmarket and increases the number of firms supplying the market locally. Both actions have no effect on the share of clean firms operating on each market. We deduce from equation (11) the number of relocated firms, which is given by:

$$\begin{aligned}\hat{n}(s) =& -\frac{X\ (\mu^c\ (\tau_N + \tau_S) + t + c_N + c_S)}{2\,(t^2 + X^2)} + \frac{M_S^{d^0}\, X\,\Delta\,\mu\,\tau_S}{t^2 + X^2} - \frac{s\,(t+X)^2}{2\,(t^2+X^2)} + \frac{a_S\ (t+X) + a_N\ (X-t)}{2\ (t^2+X^2)} \\ & - \frac{C^R\left(M_N^0 + M_S^{d^0} + 1\right)}{4\,(t^2+X^2)} - \frac{M_S^{d^0} - M_N^0}{2}\end{aligned} \tag{11}$$

As in (7), the number of firms that relocate depends negatively on the relocation cost and positively on the southern market size. Moreover, an increase on the northern market size only increases the number of relocated firms if the transportation cost is low. Furthermore, the effect of the number of northern and southern firms on the number of relocated firms is ambiguous and depends on the relocation cost relative to the transportation cost and the unit gain from relocating. Finally, we immediately obtain the derivative of the number of relocations relative to the number of created subsidiaries.

$$\frac{\partial\,\hat{n}(s)}{\partial\,s} = -\frac{(X+t)^2}{2\,(X^2+t^2)} < 0 \tag{12}$$

The following corollary is deduced.

Corollary 3. *The number of relocated firms decreases with the number of subsidiaries created in the South.*

Corollary 3 is not a direct implication of Proposition 2 since there is a slight difference. Corollary 3 corresponds to an increase in the number of clean southern firms under the constraint that the number of firms selling on the southern market is constant, while in Proposition 2 the number of southern firms is constant.

The production of northern firms on the northern market is not affected by the subsidiary opening. However, the firm located in the North which opens the subsidiary no longer supplies the southern market. As a result, when a firm opens a subsidiary, production from the northern plant decreases. Opening of a subsidiary increases the total number of southern firms and more precisely increases the number of clean southern firms. Hence, as in the previous cases, competition on the southern market is strengthened, this reducing the number of northern firms that relocate.

Stage 1. Each firm decides to be a multinational firm or a simple firm. In other words, each northern firm decides to open a subsidiary taking into account that it will affect relocation. At equilibrium, the northern firms are indifferent between the two strategies:

$$\begin{aligned}&\pi_{NN}\left(M_N^0-\hat{n}(s),\hat{n}(s),M_S^{d^0}\right)+\pi_{SS}^c\left(\hat{n}(s)+s,M_S^{d^0},M_N^0-\hat{n}(s)-s\right)-C^o \\ &=\pi_{NN}\left(M_N^0-\hat{n}(s),\hat{n}(s),M_S^{d^0}\right)+\pi_{NS}\left(M_N^0-\hat{n}(s)-s,\hat{n}(s)+s,M_S^{d^0}\right)\end{aligned} \tag{13}$$

where C^o is the cost to create a subsidiary. The first part of the equation represents the profit made by a multinational firm creating a subsidiary while the second part is the profit made by a simple northern firm. At equilibrium, the number of subsidiaries at equilibrium is given by:

$$\begin{aligned}s=&-\frac{C^o\left(M_N^0+M_S^{d^0}+1\right)\left(t^2+X^2\right)}{(X-t)^2\,(t+X)^2}+\frac{C^R\left(M_N^0+M_S^{d^0}+1\right)}{2(X-t)^2}-\frac{a_N}{X-t}+\frac{a_S}{t+X} \\ &+\frac{t\left(\mu^c\left(\tau_N+\tau_S\right)+t+c_N+c_S\right)}{(X-t)\,(t+X)}-\frac{2\,M_S^{d^0}\,\Delta\,\mu\,t\,\tau_S}{(X-t)\,(t+X)}\end{aligned} \tag{14}$$

The following lemma is deduced.

Lemma 5. *A northern firm has more incentive to create a new subsidiary*

- *when the costs to create a subsidiary are low,*
- *when the relocation costs are high,*
- *when the size of the northernmarket is low (high) if the transportation cost is low (high),*
- *when the size of the southern market is high;*
- *when the number of northern and dirty southern firms is high only if the relocation costs are high and the opening costs are low.*

Proof. $\frac{\partial s}{\partial M_N{}^0}=\frac{C^R}{2\,(X-t)^2}-\frac{C^o\left(t^2+X^2\right)}{(X-t)^2\,(t+X)^2}$, $\frac{\partial s}{\partial M_S^{d^0}}=\frac{C^R}{2(X-t)^2}-\frac{C^o\left(t^2+X^2\right)}{(X-t)^2\,(t+X)^2}-\frac{2\,\Delta\,\mu\,t\,\tau_S}{(X-t)\,(t+X)}$ □

The number of created subsidiaries depends negatively on the costs to create a subsidiary and depends positively on the relocation costs and on the southern market size. Creating a subsidiary or relocating are two substitutable actions but they are not taken at the same stage of the timing. Moreover, the benefits of creating a subsidiary increase with the southern market size. The number of created subsidiaries depends negatively on the northern market size if the transportation cost is low for the same reason as stated above. If competition increases (i.e., an increase in $M_S^{d^0}$ and $M_N{}^0$) the number of openings only increases if the southern market is relatively concentrated (high relocation costs).

Lemma 5 extends Motta and Thisse (1994)'s results to sequential decisions and to several firms. They consider two firms, one in each country and that only the northern firm may open a subsidiary or relocate. They study how environmental dumping, that is an increase in the northern marginal cost relative to the southern one, affects location decisions. Our X captures exactly the difference between northern and southernmarginal production costs. However, in Motta and Thisse (1994), the northern firm decides at the same time either to have only a plant in the North, relocating or creating a subsidiary, while in our paper, decisions are sequential.

3.2.2 Purchase of dirty southern firms

Let us now consider that northern firms may buy a southern firm and turn it into a clean one. These purchases lead to more concentrated markets. on the northern market, there are less dirty firms since the purchased firms now only supply the market locally. On the southern market, there are less northern firms, and the dirty firms, which have been bought, are now clean. Hence the southern market is more concentrated and more competitive. Let us denote by $\tilde{n}$, the number of northern firms that relocate and by b, the number of northern firms that buy a southern dirty firm.

Stage 3. The third stage is similar to the one defined in Section 2.1 except that the market structure is different. On the northern market there are $M_N = M_N^0 - \tilde{n}$; $M_S^d = M_S^{d^0} - b$; and $M_S^c = \tilde{n}$ firms operating, while on the southern market there are $M_N = M_N^0 - \tilde{n} - b$; $M_S^d = M_S^{d^0} - b$; and $M_S^c = \tilde{n} + b$ firms operating. To obtain the production level we simply replace M_N, M_S^d and M_S^c by their corresponding values.

Stage 2. Following the same method as in the previous cases, the number of relocations $\tilde{n}$ is given by:

$$\begin{aligned} &\pi_{SN}^c\left(\hat{n}, M_S^{d^0} - b, M_N^0 - \tilde{n}\right) + \pi_{SS}^c\left(\tilde{n} + b, M_S^{d^0} - b, M_N^0 - \tilde{n} - b\right) - C^R \\ =&\pi_{NN}\left(M_N^0 - \tilde{n}, \tilde{n}, M_S^{d^0} - b\right) + \pi_{NS}\left(M_N^0 - \tilde{n} - b, \tilde{n} + b, M_S^{d^0} - b\right) \end{aligned} \tag{15}$$

Relocation reduces the number of northern firms while purchasing firms reduces the number of southern firms. We deduce from equation (16) the number of relocated firms, which is given by:

$$\begin{aligned} \tilde{n}(b) = &-\frac{X\ (\mu^c\ (\tau_N + \tau_S) + t + c_N + c_S)}{2\,(t^2 + X^2)} + \frac{\left(M_S^{d^0} - b\right)\ X\,\Delta\,\mu\,\tau_S}{t^2 + X^2} - \frac{b\,(t + X)^2}{2\,(t^2 + X^2)} \\ &+ \frac{a_S\ (t + X) + a_N\ (X - t)}{2\ (t^2 + X^2)} - \frac{C^R\ \left(M_N^0 + M_S^{d^0} - b + 1\right)}{4\,(t^2 + X^2)} + \frac{M_N^0 - M_S^{d^0} + b}{2} \end{aligned} \tag{16}$$

Note that we can get $\tilde{n}(b)$ from $\hat{n}(s)$ by replacing s by b and $M_S^{d^0}$ by $M_S^{d^0} - b$. For the same reasons as previously, the number of firms that relocate depends negatively on the relocation cost and positively on the southern market size. The effects of northern market size and the number of northern and southern firms on relocation is ambiguous and depends on the transportation cost. Finally, we immediately obtain the derivative of the number of relocation relative to the number of purchased firms.

$$\frac{\partial\,\tilde{n}(b)}{\partial\,b} = -\frac{X\ (\Delta\,\mu\,\tau_S + t)}{t^2 + X^2} + \frac{C^R}{4\,(t^2 + X^2)} \tag{17}$$

The following proposition is deduced.

PROPOSITION 3. *When the relocation costs are sufficiently high (low), the number of relocated firms increases (decreases) with the number of firms purchased in the South.*

Proposition 3 differs from Proposition 2 in many respects. Purchasing dirty southern firms and diffusing technology induces a reduction in the total number of firms selling on the southern market, a decrease in the number of dirty southern firms and an increase in the number of clean southern firms. Moreover, Proposition 3 focuses on the effect on relocation while Proposition 2 studies the effects on the incentives to relocate.

As opposed to the previous channels, the purchase of a dirty southern firm does not necessarily decrease the number of relocated firms. In fact, when the relocation costs are sufficiently high relative to the transportation cost, the unit gain from relocating, the purchase of southern firm increases the incentive to relocate. Contrary to the case whereby firms create subsidiaries, the purchase of a southern firm affects the production sold on the northern market. It softens competition on the northern market thus increasing the profit on this market for all types of firms, but also increasing the price. On the southern market, the purchase decreases the number of firms but turns a dirty firm into a clean one. Moreover, if the relocation cost is relatively great, firms do not benefit from marginal costs reduction by relocating. As a result, when relocation costs are high, few firms have an incentive to relocate and purchasing a firm softens competition and pushes northern firms to relocate.

Stage 1. Each northern firm decides to be a multinational firm or to have only one plant in the North. In other words, each northern firm decides to purchase a southern firm taking into account that it will affect relocation. It purchases a southern firm if its profit net of the purchasing costs and the costs to diffuse technology is larger than without the purchase. At equilibrium, northern firms are indifferent between the two strategies, and the number of firms purchased, i.e. b, is such that:

$$\begin{aligned}&\pi_{NN}\left(M_N^0-\tilde{n}(b),\tilde{n}(b),M_S^{d^0}-b\right)+\pi_{SS}^c\left(\tilde{n}(b)+b,M_S^{d^0}-b,M_N^0-\tilde{n}(b)-b\right)-C^p \\ &=\pi_{NN}\left(M_N^0-\tilde{n}(b),\tilde{n}(b),M_S^{d^0}-b\right)+\pi_{NS}\left(M_N^0-\tilde{n}(b)-b,\tilde{n}(b)+b,M_S^{d^0}-b\right)\end{aligned} \tag{18}$$

where C^p is the cost to purchase a firm and to diffuse technology. The first part of the equation represents the profit realized by a multinational firm purchasing a firm while the second part is the profit made by a standard northern firm which does not purchase a firm, produces in the North and sells on the southern market. Since after the purchase the multinational firm still supplies the northern market locally, the northern profit at equilibrium is the same with and without purchasing a dirty southern firm and improving its technology. Hence, b is given by:

$$\pi_{SS}^c\left(\tilde{n}(b)+b,M_S^{d^0}-b,M_N^0-\tilde{n}(b)-b\right)-C^p=\pi_{NS}\left(M_N^0-\tilde{n}(b)-b,\tilde{n}(b)+b,M_S^{d^0}-b\right)$$

At equilibrium, the number of firms purchased in the South by multinational firms is given by:

$$\begin{aligned}b=&\frac{2\,(X^2-t^2)\,\left(a_N\,(t+X)+a_S\,(t-X)-t\,\left(\mu^c\,(\tau_N+\tau_S)-2\,M_S^{d^0}\,\Delta\,\mu\,\tau_S+t+c_N+c_S\right)\right)}{2\,(X^2-t^2)\,(t\,(2\,\Delta\,\mu\,\tau_S+t)-X^2)-C^R\,(t+X)^2+2\,C^p\,(t^2+X^2)}\\&+\frac{\left(M_N^0+M_S^{d^0}+1\right)\,\left(2\,C^p\,(t^2+X^2)-C^R\,(t+X)^2\right)}{2\,(X^2-t^2)\,(t\,(2\,\Delta\,\mu\,\tau_S+t)-X^2)-C^R\,(t+X)^2+2\,C^p\,(t^2+X^2)}\end{aligned}$$

Analyzing b is not straightforward. First, it is fair to assume that the denominator is positive. Indeed, the purchasing price of dirty southern firm C^p must be high enough to ensure that b is lower than M_N^0 and $M_S^{d^0}$. This assumption implies that northern firms do not buy all southern firms. Second, under this assumption, an increase on the southern market size decreases the number of multinational firms. This counter-intuitive result can be explained as follows: northern firms anticipate that a significant southern market size leads to massive relocations, and thus, they have less incentive to buy southern firms knowing that the competition on this market will be fierce. Moreover, an increase on the northern market size only decreases the number of multinationals if the transportation cost is sufficiently high compared with the unit gain from relocating. If so, only a limited number of firms relocate, the market is highly competitive, and northern firms have less incentive to decrease competition.

4. Discussion and Concluding Remarks

This paper demonstrates that the diffusion of technology may reduce relocation by affecting competition on the northern and southern markets. Indeed, the diffusion of technology by technology adoption, public transfer or subsidiary creation induces a decrease in relocation while technology diffusion via purchasing dirty southern firms may increase the number of relocated firms.

The crowding-out effect of technology diffusion on relocation may be even more significant if there are knowledge spillovers in the South. Indeed, southern firms may imitate the climate-mitigation technologies used by southern firms that have relocated their production to their country or which have purchased the technology from the innovator. It is easier to copy and imitate a firm located in a South than a firm located in the North. By hiring employees abroad and by cooperating with local suppliers they may also generate technology spillovers. Knowledge spillovers decrease the technological advantage of relocated firms. Thus, the diffusion of technology by technology adoption, relocation or subsidy creation may generate a reduction in incentive to relocate higher than without spillovers.

If we relax the assumption of price-maker firms and assume that production costs are quadratic[5], our results still hold. Hence, the diffusion of technology (except via the purchase of a subsidiary) still decreases the production (and profit) of clean firms and increases the production (and profit) of initially dirty firms. Technology diffusion still reduces the price and the incentive to relocate.

Public transfers of technology from the North to the South reduces the number of relocation. If as in Nicolaï and Zammorano (2018), costs in terms of job losses generated by the relocation of northern firms are considered, the incentives to transfer technology are even higher. Taking into consideration the job losses induced by relocation is an additional argument in favor of technology diffusion. However, the costs of jobs cut are particularly uncertain, especially in the long run since workers can find a new job.

Policy implications may be derived from our results. The diffusion of technologies may be used to prevent firms from relocating, which is currently a hot topic. Therefore, including flexibilities to access clean technologies in the TRIPS or allowing for pricing differentiation of technology patents could accelerate the adoption of technologies, which may also prevent firms from relocating. Indeed, technology adoptions depend on the design of international technology market. Maskus (2010) details the different possible options to conceive this market in order to promote technology diffusion. The two main options are: (i) opening the technology market to all countries and (ii) the possible differentiation of patent prices according to countries. These two options non ambiguously induce an increase in technology adoption abroad. No special treatment or flexibilities for access and dissemination of clean technologies has been included in the World Trade Organization Agreement on Trade-Related Intellectual Property Rights as has been done in the field of health or nutrition. However, allowing for pricing differentiation may lower the patent prices for developed countries, induces an increase in adoption and consequently a reduction in the number of firms that relocate.

A major contribution of this paper is to propose a model that allows the different forms of diffusion of clean technologies to be studied. This theoretical framework could be used to study the extent to which dissemination by one channel affects dissemination by other channels. Glachant and Dechezleprêtre (2016) show that climate-friendly technologies spill over

[5]Quadratic costs are used to ensure that there is a closed-form solution for the production levels

limits through market mechanisms and foreign development investments. In other words, regardless of their actions, the technological advantage decreases. Hence, it would be particularly worthwhile to study whether it would be profitable to support the dissemination of technology to retain northern industries.

In addition, in our paper, it was assumed that as soon as a multinational develops a subsidiary, it transfers its technologies to the latter. However, it would be interesting to analyze to what extent multinationals might prefer not to disseminate their technology internally.

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Appendices

A. Productions, prices and profit

$r^c_{SN} - r^d_{SN} = r^c_{SS} - r^d_{SS} = \Delta\,\mu\,\tau_S > 0$, $r^d_{SS} - r_{NS} = \mu^c\,\tau_N - \mu^d\,\tau_S + \Delta\,c + t$, $r^d_{SN} - r_{NN} = \mu^c\,\tau_N - \mu^d\,\tau_S + \Delta\,c - t$, $r^c_{SS} - r_{NS} = \mu^c \Delta\,\tau + \Delta\,c + t > 0$, $r^d_{SN} - r_{NN} = \mu^c \Delta\,\tau + \Delta\,c - t$.

Proof of lemma 1:
$\frac{\partial\,p_N}{\partial\,\mu^d} = \frac{\partial\,r_{NN}}{\partial\,\mu^d} = \frac{\partial\,r_{NS}}{\partial\,\mu^d} = \frac{\partial\,r^c_{SN}}{\partial\,\mu^d} = \frac{\partial\,r^c_{SS}}{\partial\,\mu^d} = \frac{M^d_S\,\tau_S}{M_N+M_S+1} > 0$;
$\frac{\partial\,r^d_{SN}}{\partial\,\mu^d} = \frac{\partial\,r^d_{SS}}{\partial\,\mu^d} = -\frac{\left(M_N+M^c_S+1\right)\tau_S}{M_N+M_S+1} < 0$;
$\frac{\partial\,E^d}{\partial\,\mu^d} = \frac{M^d_S\left(2\left(M_N\,(\mu^c\,\tau_N+\Delta\,c)+M^c_S\,\mu^c\,\tau_S-c_S\right)-4\left(M_N+M^c_S+1\right)\mu^d\,\tau_S+a_N+a_S-t\right)}{M_N+M_S+1}$

B. Proof of Proposition 1

Since $\pi_j = r_j^2$, $\pi_1 - \pi_2 = (r_1 - r_2)\,(r_1 + r_2)$, and

$$r^c_{SS}(M^c_S+1, M^d_S, M_N-1) - r_{NS}(M_N, M^c_S, M^d_S) = \frac{(M_N+M_S)\ (X+t)}{M_N+M_S+1} > 0$$
$$r^c_{SN}(M^c_S+1, M^d_S, M_N-1) - r_{NN}(M_N, M^c_S, M^d_S) = \frac{(M_N+M_S)\ (X-t)}{M_N+M_S+1}$$

From $\frac{\partial\,r^c_{SN}(M^c_S+1,M^d_S,M_N-1)}{\partial\,\mu^d} = \frac{\partial\,r^c_{SS}(M^c_S+1,M^d_S,M_N-1)}{\partial\,\mu^d} = \frac{\partial\,r_{NN}(M_N,M^c_S,M^d_S)}{\partial\,\mu^d} = \frac{\partial\,r_{NS}(M_N,M^c_S,M^d_S)}{\partial\,\mu^d} = \frac{M^d_S\,\tau_S}{M_N+M_S+1}$, then $\frac{\partial\,(4)}{\partial\,\mu^d} = \frac{4\,M^d_S\,(M_N+M_S)\,\tau_S\,X}{(M_N+M_S+1)^2}$.

C. Proof of Lemma 4

We use the upper-script by S and WS to denote the variables with and without subsidy.
Note that $\frac{\partial\,n}{\partial\,\mu^d} = \frac{M^{d^0}_S\,X\,\tau_S}{X^2+t^2}$. The subsidy affects the individual production and the northern price

as follows:

$$r_{NN}^{WS} - r_{NN}^{S} = {r_{SN}^{c}}^{WS} - {r_{SN}^{c}}^{S} = p_N^{WS} - p_N^{S} = \frac{\Delta\,\mu\, M_S^{d^0}\, \tau_S\, t\, \left(t + X\right)}{\left(M_N^0 + M_S^{d^0} + 1\right)\, \left(t^2 + X^2\right)} > 0$$

$$r_{NS}^{WS} - r_{NS}^{S} = {r_{SS}^{c}}^{WS} - {r_{SS}^{c}}^{S} = p_S^{WS} - p_S^{S} = -\frac{\Delta\,\mu\, M_S^{d^0}\, \tau_S\, t\, \left(X - t\right)}{\left(M_N^0 + M_S^{d^0} + 1\right)\, \left(t^2 + X^2\right)}$$

$$r_N^{WS} - r_N^{S} = r_{NN}^{WS} + r_{NS}^{WS} - r_{NN}^{S} - r_{NS}^{S} = \frac{2\,\Delta\,\mu\, M_S^{d^0}\, \tau_S\, t^2}{\left(M_N^0 + M_S^{d^0} + 1\right)\, \left(t^2 + X^2\right)}$$

$$\frac{\partial\, r_{SN}^{d}}{\partial\, \mu^d} = \frac{\frac{\partial\, n}{\partial\, \mu^d}\, \left(t - X\right) - \left(M_N^0 + 1\right)\, \tau_S}{M_N^0 + M_S^{d^0} + 1}$$

$$\frac{\partial\, r_{SS}^{d}}{\partial\, \mu^d} = -\frac{\frac{\partial\, n}{\partial\, \mu^d}\, \left(t + X\right) + \left(M_N^0 + 1\right)\, \tau_S}{M_N^0 + M_S^{d^0} + 1} < 0$$

$$\frac{\partial\, r_{SN}^{d}}{\partial\, \mu^d} + \frac{\partial\, r_{SS}^{d}}{\partial\, \mu^d} = -\frac{2\,\frac{\partial\, n}{\partial\, \mu^d}\, X + 2\, \left(M_N + 1\right)\, \tau_S}{M_N^0 + M_S^{d^0} + 1} < 0$$

The subsidies decrease the individual profit in the North. Indeed,

$$\begin{aligned}
E^S - E^{WS} &= \frac{2\left(M_S^{d^0}\,\Delta\,\mu\, n^{WS} - \mu^c\, \left(n^{WS} - n^S\right)\right)\, X}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1} \\
&- \frac{M_S^{d^0}\,\Delta\,\mu\, \left(2\left({M_N}^0\, \left(\mu^c\, \tau_N - \mu^d\, \tau_S + \Delta\, c\right) + \left(-\mu^d - M_S^{c^0}\,\Delta\,\mu - \mu^c\right)\, \tau_S\right) - t - 2\, c_S + a_N + \right.}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1} \\
E_N^S - E_N^{WS} &= \frac{2\, M_S^{d^0}\, \mu^c\,\Delta\,\mu\, \left(n^S - {M_N}^0\right)\, \tau_S}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1} - \frac{2\,\mu^c\, \left(n^{WS} - n^S\right)\, \left(n^{WS} + n^S - {M_N}^0 + M_S^{c^0}\right)\, X}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1} \\
&- \frac{2\,\mu^c\, \left(n^{WS} - n^S\right)\, \left(M_S^{d^0}\, \left(\mu^c\, \tau_N - \mu^d\, \tau_S + \Delta\, c\right) + 2\mu^c\, \tau_N + t + 2\, c_N - a_N - a_S\right)}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1}
\end{aligned}$$

The subsidies increases the individual production of initially dirty firm

$$\begin{aligned}
E^S - E^{WS} &= \frac{2\left(M_S^{d^0}\,\Delta\,\mu\, n^{WS} - \mu^c\, \left(n^{WS} - n^S\right)\right)\, X}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1} \\
&- \frac{M_S^{d^0}\,\Delta\,\mu\, \left(2\left({M_N}^0\, \left(\mu^c\, \tau_N - \mu^d\, \tau_S + \Delta\, c\right) + \left(-\mu^d - M_S^{c^0}\,\Delta\,\mu - \mu^c\right)\, \tau_S\right) - t - 2\, c_S + a_N + \right.}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1} \\
E_N^S - E_N^{WS} &= \frac{2\, M_S^{d^0}\, \mu^c\,\Delta\,\mu\, \left(n^S - {M_N}^0\right)\, \tau_S}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1} - \frac{2\,\mu^c\, \left(n^{WS} - n^S\right)\, \left(n^{WS} + n^S - {M_N}^0 + M_S^{c^0}\right)\, X}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1} \\
&- \frac{2\,\mu^c\, \left(n^{WS} - n^S\right)\, \left(M_S^{d^0}\, \left(\mu^c\, \tau_N - \mu^d\, \tau_S + \Delta\, c\right) + 2\mu^c\, \tau_N + t + 2\, c_N - a_N - a_S\right)}{{M_N}^0 + M_S^{d^0} + M_S^{c^0} + 1}
\end{aligned}$$

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