Environment and Development Economics (2020), **25**, 21–43
doi:10.1017/S1355770X19000445

RESEARCH ARTICLE

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

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(Submitted 30 September 2018; revised 05 June 2019; accepted 12 September 2019)

Abstract

The deployment of cleaner production technologies is supposed to be 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, opening of a subsidiary or the adoption of technology by southern firms, or it may be decided at the government level. This paper investigates, in a two-country model (North and South), the relationship between the diffusion of mitigation technologies, firms' relocation and the environment. 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 technology diffusion 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 become more competitive.

Keywords: technology diffusion; carbon tax; relocation; trade of polluting goods; imperfect competition; subsidiary; public transfer

JEL classification: L13; Q53; Q58

1. Introduction

The negotiations conducted during the COP21, which led to the 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, but it may also improve their competitiveness. Moreover, technology diffusion can take a wide variety of forms, making it particularly difficult to study its effects. Technology diffusion can result from governments' decisions or it 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, and how it affects the environment.

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. 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, 2005 and the literature on pollution havens). To reduce the risk of relocation, 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 where northern firms have the possibility to relocate their production to the South. In each country a carbon tax is implemented, and firms produce the same

[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.

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. Moreover, 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 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 production costs are usually higher in advanced economies. We assume that single-plant 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 provides both markets from the South, and benefits from low production cost and lenient environmental regulation. However, it has to pay for the transportation cost to export the good to the northern market.

The paper studies the determinants of various kinds of technology diffusion taking into account how they affect long-run market structures. We first 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. Then, technology diffusion can also be achieved through intra-firm technology diffusion. Hence, we also consider multi-plant 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 purchase a dirty southern firm and convert it into a clean one.

The current paper highlights the impact of technology diffusion on single-plant firms' relocation. We show that the diffusion of technology, which can take different forms such as a reduction in emissions intensity or an increase in the number of clean firms in the South, reduces single-plant firms' incentives to relocate. The intuition is as follows: the diffusion of technology improves the productivity of some or all firms in the South and thus reduces the competitive advantage that a northern single-plant firm would have to relocate. More precisely, we study how the diffusion of technology affects the number of firms that relocate according to the different diffusion channels that we mentioned above. We consider the time horizon such that all the relocations take place, meaning that at equilibrium northern single-plant firms have the same profit regardless of their relocation, and we call it the long run.[4] 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. Indeed, in the last case, competition may be reduced since the total number of firms is reduced. Finally, it is demonstrated that technology diffusion, regardless of the form taken, may have perverse effects in the long run. Indeed, total emissions may increase with technology diffusion since southern firms are more competitive. Nevertheless, we show that in the case of public transfers, the effect of technology diffusion on the northern social surplus (welfare without the environmental damage) may be positive since technology diffusion impedes relocations which have a negative effect on northern profits.

[4]We do not take into account free entry, meaning that at equilibrium firms' profits are positive.

The paper is structured as follows. Section 2 relates the paper to the literature. Section 3 presents the modeling assumptions and describes the crowding-out effect of technology diffusion on the northern firm's incentives to relocate. Section 4 studies the different channels for North-South diffusion of climate-mitigation technologies. Section 5 discusses the robustness of the results, derives some policy implications and concludes.

2. Relation to the literature

This paper is related to several strands of literature. First, this article contributes to the literature that studies the North-South technologies diffusion.[5] The literature highlights different channels through which technology can be transferred such as trade (Rivera-Batiz and Romer, 1991; Eaton and Kortum, 2002), knowledge spillovers (Aghion and Jaravel, 2015), foreign direct investment (Keller, 2010; Newman *et al.*, 2015; Sanna-Randaccio *et al.*, 2017), licensing (Kamien *et al.*, 1992; Banerjee and Poddar, 2019), or internal transfer through multinational (Ethier and Markusen, 1996; Fosfuri *et al.*, 2001). Moreover, the diffusion of technology is related to the strength of intellectual property rights (Yang and Maskus, 2001; Maskus and Yang, 2018). While many papers use growth theory or general equilibrium models (Van de Klundert and Smulders, 1996; Bretschger *et al.*, 2017), we adopt as Yang and Maskus (2009) do a partial-equilibrium approach and relate it to strategic Cournot competition. However, our paper differs from the latter in many respects. First of all, we consider that producing generates pollution. Second, we assume that the producing firms may purchase the technology to an innovator and then cannot transfer technology through licensing, while in Yang and Maskus (2009) the producing firms may license technology. Finally, Yang and Maskus (2009) consider only imitation or the purchase of licenses, while we consider that the possible channels for technology diffusion are technology adoption, public transfers, internal transfers inside multinational companies and single-plant relocation.

Second, this paper contributes to the literature which studies the effects of diffusing clean technologies to developing countries. Since the work of Stranlund (1996) that demonstrates that in the absence of trade developed countries have incentives to transfer clean technologies to developing countries when it decreases global emissions, there has been an ongoing debate regarding the effects of transferring clean technologies under the presence of trade. While Stephan and Muller-Furstenberger (2015) focus on the trade in energy and Helm and Pichler (2015) on the trade in a global carbon market, Glachant *et al.* (2017) consider the trade in the polluting good market. These three studies highlight the fact that transferring clean technology does not necessarily improve the environment, and that the effects depend on the terms of trade. The present paper is complementary to these papers since it takes into account the trade in the market of a polluting good. However, while the previous papers consider short-run effects, the current paper takes into account the relocation decisions and studies long-run effects.

Finally, this work is also related to papers studying environmental regulation under the possibility of firms to relocate, such as Markusen *et al.* (1993), Motta and Thisse (1994), Hoel (1997), Greaker (2003), Petrakis and Xepapadeas (2003) and Ikefuji *et al.* (2016). Most papers consider a partial equilibrium approach and optimal environmental regulation. Hoel (1997) defines the pollution tax maximizing the welfare when countries act non cooperatively. He highlights the tradeoff a government faces

[5] For a detailed presentation of this literature, see Keller (2004).

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 (no trans-boundary pollution). Ikefuji *et al.* (2016) also determine the optimal emission tax with endogenous plant locations but they consider a global pollution. Petrakis and Xepapadeas (2003) study the optimal emissions tax under endogenous location according to whether the regulator fixes the tax ex-ante or ex-post relocation. Greaker (2003) considers the case in which both governments implement an emission tax along with a profit tax. In the current paper, we consider that environmental policies in each country are exogenous and we study the relationship between technology diffusion, relocation and the environment.

3. The crowding-out effect on relocation

3.1. The setup

3.1.1. Assumptions

The model describes two countries $j = \{N, S\}$ where N and S denote the North and the South respectively. In country j, there are m_j firms producing a homogeneous polluting good, and consumers purchasing the goods. The prices are given by the inverse demand function: $p_j = a_j - Q_j$ where a_j is the market size in country j, and Q_j the quantity consumed in country j.

Production generates emissions that create a global damage 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, and a 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 the 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 by m_S^c the number of relatively clean southern firms. The number of firms located in the South is then $m_S = m_S^d + m_S^c$. For simplicity, we refer to relatively clean firms as clean firms, even if they also pollute.

Let us assume that there is an innovator in the North which sells the clean technology. The clean technology price is denoted by K and is assumed to be exogenous. Firms using the clean technology have already purchased the technology and, therefore, this cost represents a sunk cost to the firm. Nevertheless, dirty firms have the possibility to buy clean technology on the patent market. We consider that there is no cost of adoption.

Let us assume single-plant firms that are located in a given country but still serve both markets (North and South). In other words, they produce at home and export to foreign countries. This assumption will be relaxed in section 4.2. The production of a northern firm i sold in the North and in the South is denoted by r_{NN_i} and r_{NS_i} respectively. Let us also denote by $r_{SN_i}^d$ and $r_{SS_i}^d$ ($r_{SN_i}^c$ and $r_{SS_i}^c$) the production of a dirty southern (clean southern) firm i, sold respectively in northern and southern markets. The market clearing condition implies that $Q_N = \sum_{i=1}^{m_N} r_{NN_i} + \sum_{i=1}^{m_S^c} r_{SN_i}^c + \sum_{i=1}^{m_S^d} r_{SN_i}^d$ and $Q_S = \sum_{i=1}^{m_N} r_{NS_i} + \sum_{i=1}^{m_S^c} r_{SS_i}^c + \sum_{i=1}^{m_S^d} r_{SS_i}^d$. Transport is costly and let t be the constant unit transportation cost.

We consider that each country implements an emissions tax. Indeed, many developing countries have implemented or plan to implement environmental regulation. For instance, carbon taxes were launched in Chile and Colombia. Moreover, according to

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

the World Bank and Ecofys (2018) in Argentina and South-Africa, an Emissions Trading Scheme or carbon pricing are scheduled and these instruments are under consideration in Brazil, Côte d'Ivoire, Thailand and Vietnam. Let us denote by c_j the marginal production cost in country j and by $\tau_j > 0$ the carbon tax implemented in country j. In the South, clean and dirty firms have the same marginal production cost c_S, hence the marginal production cost is country-specific. We assume that the marginal production cost and the emissions tax are higher in the North. Let us use the following notations: $\Delta\tau \equiv \tau_N - \tau_S > 0$, $\Delta c \equiv c_N - c_S > 0$ and $\Delta\mu \equiv \mu^d - \mu^c > 0$.

3.1.2. Production and prices

Let us now determine 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:

$$\max_{r_{NN_i}, r_{NS_i}} \pi_{N_i}\left(m_N, m_S^c, m_S^d\right) = (p_N - c_N - \tau_N\mu^c)r_{NN_i} + (p_S - c_N - \tau_N\mu^c - t)r_{NS_i}.$$

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

$$\max_{r^d_{SN_i}, r^d_{SS_i},} \pi^d_{S_i}\left(m^d_S, m^c_S, m_N\right) = (p_N - c_S - \tau_S\mu^d - t)r^d_{SN_i} + (p_S - c_S - \tau_S\mu^d)r^d_{SS_i}$$

$$\max_{r^c_{SN_i}, r^c_{SS_i}} \pi^c_{S_i}\left(m^c_S, m^d_S, m_N\right) = (p_N - c_S - \tau_S\mu^c - t)r^c_{SN_i} + (p_S - c_S - \tau_S\mu^c)r^c_{SS_i}.$$

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

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

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

$$r^d_{SS}(m^d_S, m^c_S, m_N) = \frac{a_S - c_S - \mu^d\tau_S + (\Delta c + \mu^c\tau_N - \mu^d\tau_S + t)m_N - \Delta\mu m^c_S\tau_S}{m_N + m^d_S + m^c_S + 1}$$

$$r^d_{SN}(m^d_S, m^c_S, m_N) = \frac{a_N - c_S - \mu^d\tau_S + \left(\Delta c + \mu^c\tau_N - \mu^d\tau_S - t\right) m_N - \Delta\mu m^c_S\tau_S - t}{m_N + m_S + 1}$$

$$r^c_{SS}(m^c_S, m^d_S, m_N) = \frac{a_S - c_S - \mu^c\tau_S + (\Delta c + \mu^c\Delta\tau + t)m_N + \Delta\mu m^d_S\tau_S}{m_N + m_S + 1}$$

$$r^c_{SN}(m^c_S, m^d_S, m_N) = \frac{a_N - c_S - \mu^c\tau_S + (\Delta c + \mu^c\Delta\tau - t)\, m_N + \Delta\mu m^d_S\tau_S - t}{m_N + m_S + 1}.$$

In each market, a clean southern firm produces more than a dirty southern firm. Moreover, a clean southern firm produces more than a clean northern firm in the southern market since it benefits from a low tax, a low production cost and does not pay for the transportation cost. Obviously, an increase either in the northern tax or in the northern

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

production cost increases the production of southern firms, while an increase either in the southern tax or in the southern production cost increases the production of northern firms. Note that as a firm increases its production, its profit increases as well. From the functional forms chosen, the profits are equal to $\pi_N = r_{NN}^2 + r_{NS}^2$; $\pi_S^c = {r_{SS}^c}^2 + {r_{SN}^c}^2$; $\pi_S^d = {r_{SS}^d}^2 + {r_{SN}^d}^2$. At the equilibrium, prices are equal to:

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

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

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

3.1.3. Relocation

Northern firms may relocate to the South, that is, instead of serving both markets from the North, they may decide to relocate their production in the South and serve both markets from the South. In such a case, the firm will continue to produce in only one country and export its production to the other country. Let us assume a constant and symmetric cost of relocation C^R. Let $X = \mu^c \Delta\tau + \Delta c > 0$ be the unit gain from relocating (without taking into account the relocation cost).

A clean single-plant firm located in the North relocates its production if, and only if, the profit made in the South net of relocation costs is higher than the current profit in the northern country. Moreover, the single-plant firm anticipates that relocation modifies market structures. A northern single-plant 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:

$$\pi_S^c\left(m_S^c + 1, m_S^d, m_N - 1\right) - C^R > \pi_N\left(m_N, m_S^c, m_S^d\right). \tag{1}$$

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.

Let us now study how an improvement in the technology used in the South affects the incentives to relocate. We study in a complementary way how technological diffusion affects global emissions. Technology improvement can take different forms and can come from different channels. In this section, we study first the effect of a decrease in the dirty southern firms' emission intensity and second the effect of an increase in the number of clean southern firms.

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

Let us analyze the effects of a decrease in the dirty southern firms' emission intensity. Such improvement in the southern technology can be understood as a diffusion of technology to all the dirty firms. A decrease in μ^d reduces the production 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 emissions taxes are high. However, the overall production sold

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

in both countries increases since dirty firms become more competitive. Thus, the profits of northern firms decrease, while the consumer surplus increases.[6] The effect on global emissions is given by:

$$\frac{\partial E}{\partial \mu^d} = \frac{m_S^d \left(a_N + a_S - t + 2\left(m_N\left(\mu^c \tau_N + \Delta c\right) - c_S - (\mu^c + \mu^d(1+m_N))\tau_S - \Delta\mu m_S^c \tau_S\right)\right)}{m_N + m_S + 1}.$$

An improvement in the dirty technology has two effects. On the one hand, it boosts the productivity of dirty firms, which increases their production, and decreases the production and the emissions of their competitors. On the other hand, it decreases the emissions per unit produced by dirty firms. The reduction in the dirty southern firms' emission intensity increases overall emissions when the market sizes are low, the transportation cost is high, and the competitive gap between the two regions is relatively low (low τ_N and c_N and high τ_S and c_S). Indeed, in such a case, southern firms produce a low level, and the technology improvement highly boosts their production and emissions. Put differently, an improvement in the dirty technology may be detrimental for the environment.

Let us focus on the effects of a decrease in the dirty southern firms' emission intensity on the incentives to relocate. By calculating equation (1) and studying how a decrease in μ^d affects it, we deduce the following proposition (proof in online appendix A).

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

Firm's profits may be divided into two parts: profits from sales on the domestic market and profits from exports. Hence, relocation (from the North to the South) increases the profit related to the southern market, especially if the technological advantage is high (high μ^d). Conversely, relocation has an ambiguous effect on the profit related to the northern market (which was the domestic market and becomes, after relocation, the market for exports). Two cases should then be analyzed. (i) If relocation increases the northern firm's profit on the domestic 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 incentives to relocate.

3.3. *Effects of an increase in the number of clean southern firms*

Technology diffusion can also concern only a share of southern firms, and be modelled as an increase in the number of clean southern firms. Technological diffusion can take the form either of a change from dirty to clean firms or a change from clean firms located in the North to clean firms located to the South (relocation). Therefore, let us first focus on the effects of an increase in the number of clean southern firms while keeping the number of southern firms constant. Second, let us consider the effects of an increase in the number of clean southern firms while keeping the number of clean firms constant.

[6] $\partial p_N/\partial \mu^d = \partial r_{NN}/\partial \mu^d = \partial r_{NS}/\partial \mu^d = \partial r_{SN}^c/\partial \mu^d = \partial r_{SS}^c/\partial \mu^d = m_S^d \tau_S/(m_N + m_S + 1) > 0$; $\partial r_{SN}^d/\partial \mu^d = \partial r_{SS}^d/\partial \mu^d = -(m_N + m_S^c + 1)\tau_S/(m_N + m_S + 1) < 0$.

3.3.1. An increase in the share of clean firms among the firms in the South

Keeping the number of southern firms $m_S = m_S^d + m_S^c$ constant, let us first analyze the effect of an increase in m_S^c on the individual production of the different types of firms. An increase in the share of clean firms in the South 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 in production for all the other firms. An increase in the share of clean firms in the South has two effects on global production. On the one hand, each firm produces individually less, and on the other hand, the share of clean firms increases, while the share of dirty firms decreases. The second effect prevails on the first one and the overall production increases. The effect of an increase in m_S^c (keeping the number of southern firms constant) on total emissions is given by:

$$\left.\frac{\partial E}{\partial m_S^c}\right|_{m_S=m_S^d+m_S^c} = \frac{\Delta\mu}{m_N + m_S + 1}[2(\mu^d + \mu^c)\tau_S - 2m_N(\mu^c\tau_N - \mu^d\tau_S + \Delta c) + 2(m_S^c - m_S^d)\Delta\mu\tau_S + t + 2c_S - a_N - a_S].$$

An increase in the share of southern clean firms decreases the individual production and consequently emissions. The newly clean firms produce more since they are more efficient, but they pollute less per unit produced. As a result, an increase in the share of clean firms in the South has an ambiguous effect on emissions. It increases global emissions when the market sizes are low, the transportation cost is high, and when the competitive gap between the two regions is relatively low (low c_N and τ_N and high c_S). Put differently, the conditions under which emissions increase with a rise in the share of clean firms among firms in the South are close to those under which emissions increase with a decrease in μ^d. Let us focus on the effects of an increase in the share of clean firms in the southern firms on the incentives to relocate. By calculating equation (1) and studying how an increase in m_S^c affects it keeping $m_S = m_S^d + m_S^c$ constant, we deduce the following proposition (proof in online appendix B).

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

If the number of clean southern firms increases, while the number of southern firms stays constant, all firms decrease their production. Hence, the firm's profit decreases regardless of its decision (relocating or staying). Nevertheless, since the relocated single-plant firm increases its overall production when it relocates, the effect of the increase in the share of clean firms among the southern firms is all the more so as the single-plant firm has relocated. Hence, an increase in the number of clean southern firms decreases the northern firms' incentives to relocate.

3.3.2. An increase in the number of firms located in the South

Keeping the number of clean firms constant, i.e., $m^c = m_N + m_S^c$, let us first analyze the effect of an increase in m_S^c on the individual production of the different types of firms,

$$\left.\frac{\partial r_{SS}^d}{\partial m_S^c}\right|_{m^c=m_N+m_S^c} = \left.\frac{\partial r_{SS}^c}{\partial m_S^c}\right|_{m^c=m_N+m_S^c} = \left.\frac{\partial r_{NS}}{\partial m_S^c}\right|_{m^c=m_N+m_S^c} = -\frac{X+t}{m_S^d + m^c + 1} < 0$$

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

$$\left.\frac{\partial r_{SN}^d}{\partial m_S^c}\right|_{m^c=m_N+m_S^c} = \left.\frac{\partial r_{SN}^c}{\partial m_S^c}\right|_{m^c=m_N+m_S^c} = \left.\frac{\partial r_{NN}}{\partial m_S^c}\right|_{m^c=m_N+m_S^c} = -\frac{X-t}{m_S^d+m^c+1}.$$

An increase in m_S^c decreases the individual production sold on the southern market. However, the effect on the individual production sold on the northern market depends on the value of transportation cost. If the transportation cost is relatively low as compared to 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 to the unit gain from relocating, relocation softens competition and firms' individual production increases. Nevertheless, note that the total production of each firm (for sales at home and exports) decreases with the replacement of a clean firm in the North by a clean firm in the South. Indeed, by summing the production for sales at home and exports, we get:

$$\left.\frac{\partial\left(r_{SS}^d+r_{SN}^d\right)}{\partial m_S^c}\right|_{m^c=m_N+m_S^c} = \left.\frac{\partial\left(r_{SS}^c+r_{SN}^c\right)}{\partial m_S^c}\right|_{m^c=m_N+m_S^c} = \left.\frac{\partial\left(r_{NS}+r_{NN}\right)}{\partial m_S^c}\right|_{m^c=m_N+m_S^c}$$
$$= -\frac{2X}{m_S^d+m^c+1} < 0.$$

The effect of an increase in m_S^c on global emissions, keeping the number of clean firms constant, is equal to $\partial E/\partial m_S^c|_{m^c=m_N+m_S^c} = 2(\mu^c - m_S^d\Delta\mu)X/(m_S^d+m^c+1)$. Two effects are at stake. First, the newly-established clean firm in the South produces more than when it was located in the North. Second, the production and the emissions of the others firms decrease. The first effect prevails when the technological gap is relatively low, and when there are only a few dirty firms (low m_S^d).

Let us focus on the effects of an increase in the share of clean firms in the southern firms on the incentives to relocate. By calculating equation (1) and studying how an increase in m_S^c affects it, keeping $m^c = m_N + m_S^c$ constant, we deduce the following proposition (proof in online appendix C).

Proposition 3 : *Keeping the number of clean firms constant, an increase in m_S^c reduces the northern firms' incentives to relocate.*

If the number of clean southern firms increases, while the number of clean firms remains constant, the firm's profits made in the southern market decrease, but the profits made in the northern market decrease if the transportation cost is low. Hence, it affects the clean firm's profit in the same manner regardless of its decision (relocating or staying). Nevertheless, since the newly relocated firm increases its overall production when it relocates, the effect of the substitution of a northern clean firm by a southern one is all the more so as the firm has relocated. Hence, an increase in the number of clean southern firms decreases the northern firms' incentives to relocate.

4. 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 (section 4.1), and second focus on the internal technology diffusion in a multinational corporate setting (section 4.2). 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.

4.1. 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. The northern government can also purchase patents and distribute them to southern firms or directly subsidize the purchase of patents by southern firms. Hence, technology diffusion via the international technology market can be decided either by southern firms or by the northern government.

4.1.1. 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. In stage 1, southern firms decide whether to adopt the technology. In stage 2, northern firms decide whether to relocate. Finally, in 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 3.1, except that at the last stage $m_N = m_N^0 - l$, $m_S^d = m_S^{d^0} - k$ and $m_S^c = l + k$ where l is the number of relocated firms if there is adoption, and k is the number of dirty southern firms adopting the technology.

Stage 2. At equilibrium a northern single-plant firm is indifferent between relocating and remaining located in the North. Hence, at equilibrium, the number of relocated firms l is given by the following equality:[7]

$$\pi_S^c\left(l+k, m_S^{d^0}-k, m_N^0-l\right) - C^R = \pi_N\left(m_N^0-l, l+k, m_S^{d^0}-k\right). \tag{2}$$

By solving (2), we define $l(k)$ given by:

$$l(k) = \frac{a_S(X+t) + a_N(X-t)}{2\left(X^2+t^2\right)} - \frac{\left(\mu^c(\tau_N+\tau_S) + t + c_N + c_S\right)X}{2\left(X^2+t^2\right)} + \frac{\left(m_S^{d^0}-k\right)\Delta\mu\tau_S X}{X^2+t^2} - \frac{C^R\left(m_N^0+m_S^{d^0}+1\right)}{4\left(X^2+t^2\right)} + \frac{m_N^0-m_S^{d^0}}{2}. \tag{3}$$

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 fewer the firms

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

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

that 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 to the unit gain from relocating, the number of relocated firms increases 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 to the unit gain from relocating, the relocated firm will be less efficient in the northern market. Thus, the greater the northern market size is, the fewer the northern firms that relocate.

By deriving $l(k)$ with respect to k, we obtain: $\partial l(k)/\partial k = -\Delta\mu\tau_S X/(X^2 + t^2) < 0$. From this equation, the following corollary is deduced.

Corollary 1 : *The adoption of clean technology by southern firms decreases the number of single-plant firms that relocate in the South.*

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 in 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 made when it is clean minus the adoption cost is higher than the profit it gets when it is dirty. At equilibrium, the number of adoptions k is such that the profit of a southern firm is the same with the two technologies:

$$\pi_S^c\left(l(k) + k, m_S^{d^0} - k, m_N - l(k)\right) - K = \pi_S^d\left(m_S^{d^0} - k, l(k) + k, m_N - l(k)\right). \quad (4)$$

By replacing $l(k)$ and solving (4) with respect to k, we are able to define the number of firms that adopts the clean technology:

$$k^* = \frac{C^R\left(m_N^0 + m_S^{d^0} + 1\right)X}{4\Delta\mu t^2\tau_S} + \frac{X\left(\left(m_N^0 + m_S^{d^0}\right)t^2 + \left(m_N^0 + m_S^{d^0} + 1\right)X^2\right)}{2\Delta\mu t^2\tau_S}$$
$$- \frac{K\left(m_N^0 + m_S^{d^0} + 1\right)\left(X^2 + t^2\right)}{(2\Delta\mu t\tau_S)^2} - \frac{\left(m_N^0 + m_S^{d^0} + 1\right)X^2}{2t^2}$$
$$+ \frac{a_N(X + t) - a_S(X - t)}{2\Delta\mu t\tau_S} - \frac{\mu^d(\tau_S + \tau_S) + t + 2c_S}{2\Delta\mu\tau_S} - \frac{m_N^0 - m_S^{d^0}}{2}. \quad (5)$$

By studying (5), the following lemma is deduced.

Lemma 1 : *The number of southern firms that adopt the cleaner technology decreases with the adoption costs and the size of the southern market if the transportation cost is relatively low. The number of southern firms that adopt the cleaner technology increases* *with the relocation costs, the size of the northern market, and the size of southern market if the transportation cost is relatively high.*

Southern firms adopt technology to reduce the unit production cost and prevent some firms from settling in the southern market. They have more incentive to adopt technology when the 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 a few northern firms will relocate.

We can deduce from the previous results 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. Note that reducing patent prices has two effects on the innovator located in the North. On the one hand, it increases the number of southern firms that are willing to purchase the technology and consequently increases the innovator's profit, but on the other hand, it decreases the revenue of each patent sold. The effect on the innovator's profit depends on the price elasticity of demand for clean technology.

4.1.2. Northern government's decision

The northern government may transfer the technology to the dirty southern firms by subsidizing the purchase of the technology. We assume that the government directly purchases the technology from the innovator and grants it to the dirty southern firms. Moreover, the government decides to purchase licenses for all dirty southern firms or none of them and is thus unable to discriminate between firms. The goal of the northern government is to increase its welfare. Before introducing the welfare function, let us first introduce some additional assumptions. We consider that emissions generate global damage which is assumed to be linear. Let us denote by δ_N the marginal damage in the North.[8] The northern welfare is defined as the sum of the consumer surplus, the sum of the northern profits, the regulator's revenue minus the environmental damage. The northern welfare is $W_N = SC_N + \Pi_N + \Pi_I + RR_N - \delta_N(E_N + E_S)$ where Π_I is the profit of the innovator and RR_N the revenue of the northern regulator. The latter is equal to the tax revenue minus the subsidies for the southern firms. Subsidizing southern firms ($m_S^d K$) is a lump-sum transfer from the government to the northern innovator. Put differently, subsidizing southern firms is a neutral operation for the northern welfare. Indeed, the patents given to southern firms induce a profit for the northern innovator, but patents are paid for by the northern government.

The decision to improve southern technology is taken by the northern government, while previously the southern firms were deciding whether to adopt it or not. The game is characterized by the following timing: at stage 1, the North decides whether it subsidizes the purchase of licenses for southern firms. At stage 2, firms decide whether they relocate. Finally, at 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 3.1.

[8]The evaluation of damage is difficult, particularly using the monetarization method, which obviously calls for some caution regarding the value of marginal environmental damage.

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

Stage 2. Following the same method as in section 4.1.1, the number of relocations l can be defined. Similarly to adoption, the subsidies affect the market structure. The subscript referring to the case in which the northern government subsidizes the purchase of patents for dirty southern firms is denoted by G (for government), and the case in which the northern government does not subsidize the purchase of patents for dirty southern firms is now denoted by WG. The number of relocated firms with subsidies is denoted by $l^G = l(m_S^{d^0})$, while the number of relocated firms without subsidies is denoted by $l^{WG} = l(0)$. Since $l(k)$ decreases with k, we immediately deduce $l^G < l(k^*) < l^{WG}$. The number of firms that relocate 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 single-plant firms that relocate in the South.*

This corollary is a direct implication of proposition 1. Indeed, subsidizing the purchase of patents may be understood as an improvement in the dirty technology, which reduces the incentive to relocate.

Stage 1. The northern government decides whether it subsidizes the purchase of patents abroad anticipating firms' relocation. If the northern government subsidizes, the market structure will be as follows: $m_S^d = 0, m_S^c = m_S^{c\,0} + m_S^{d^0} + l^G$ and $m_N = m_N{}^0 - l^G$. In contrast, if the northern government does not subsidize, $m_S^d = m_S^{d^0}, m_S^c = m_S^{c\,0} + l^{WG}$ and $m_N = m_N{}^0 - l^{WG}$.

By studying the effect of the subsidies on the different components of the northern welfare, the following lemma is deduced (proof in online appendix D).

Lemma 2 : *In the long run, subsidizing the purchase of patents for cleaner technology abroad increases the innovator's profit and the consumer surplus in the North, increases or decreases the sum of the northern profits in the market for products, and increases or decreases emissions.*

In the northern market, subsidies decrease the quantity sold by clean firms from both countries, and increase the quantity sold by dirty firms. Nevertheless, the northern consumer surplus increases since subsidies decrease the number of inefficient firms, while keeping the total number of firms constant. The subsidy may increase the industry's profit in the North. Indeed, it decreases the individual profit but increases the number of firms located in 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 to the unit gain from relocating.

Glachant *et al.* (2017) study in a close setting the incentives to transfer clean technology. The main difference between the two papers is that in our paper, firms can relocate, while in Glachant *et al.* (2017) market structures are exogenous. As in Glachant *et al.* (2017), the subsidy may increase or decrease global emissions. Indeed, two effects are in opposition: firms in the South pollute less by production unit but since they are more competitive, they produce more. However, in Glachant *et al.* (2017), the technology transfer increases the welfare if and only if it decreases total emissions, while in this paper the technology transfer may increase welfare even if it increases global emissions. Indeed, the transfer decreases the number of relocated firms and it may increase both the consumer surplus and the northern profits.

4.2. Internal transfers inside multinational companies

Until now we have assumed single-plant firms which may decide to close their plants in the North and settle in the South. However, multinational companies may have plants in various countries and may transfer their technology to their subsidiaries. Let us now consider that some firms may decide to be multi-plant. We study how internal transfers inside multi-plant firms affect single-plant firms' relocation. Therefore, we consider the following timing: at stage 1, northern firms decide whether they settle a subsidiary in the South. At stage 2, northern single-plant firms decide whether they relocate. Finally, at stage 3, firms produce and sell the good in the two markets for products. Put differently, at stage 1, firms decide whether they will be single-plant or multi-plant. Once firms have decided to have only one plant, they may decide to relocate (stage 2). Let us introduce additional assumptions. 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 without costs 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.[9] Let us first focus on the creation of a new subsidiary from scratch.

4.2.1. Creation of a new subsidiary from scratch

Northern firms may decide to build a new subsidiary in the South, while keeping their plant in the North. Let us denote by $\hat{l}$ the number of northern single-plant firms that relocate and by s the number of northern multi-plant firms that open a subsidiary abroad and whose northern plant is still active.

Stage 3. This stage is similar to the one defined in section 3.1 except that the market structure is different. In the northern market there are $m_N = m_N^0 - \hat{l}$, $m_S^d = m_S^{d^0}$ and $m_S^c = \hat{l}$ firms operating, while in the southern market there are $m_N = m_N^0 - \hat{l} - s$, $m_S^d = m_S^{d^0}$ and $m_S^c = \hat{l} + s$ firms operating. To determine the production levels we simply replace m_N, m_S^d and m_S^c by their corresponding value.

Stage 2. At equilibrium a northern single-plant firm is indifferent between relocating and remaining located in the North. Hence, at equilibrium, the number of relocated firms $\hat{l}$ is given by the following equality:

$$\pi_{SN}^c\left(\hat{l}, m_S^{d^0}, m_N^0 - \hat{l}\right) + \pi_{SS}^c\left(\hat{l} + s, m_S^{d^0}, m_N^0 - \hat{l} - s\right) - C^R$$
$$= \pi_{NN}\left(m_N^0 - \hat{l}, \hat{l}, m_S^{d^0}\right) + \pi_{NS}\left(m_N^0 - \hat{l} - s, \hat{l} + s, m_S^{d^0}\right). \qquad (6)$$

Relocation corresponds to the transformation of a clean firm in the North into a clean firm in the South. Put differently, the total number of firms selling on each market is unchanged by a relocation. However, the creation of a subsidiary in the South corresponds to the transformation of a clean exporter from the North to the South into a clean firm from the South selling only in its domestic market. We deduce from equation (6)

[9] They focus on the case whereby subsidiaries are created from scratch.

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

the number of single-plant firms that relocate, which is:

$$\hat{l}(s) = \frac{a_S(X+t) + a_N(X-t)}{2\left(X^2+t^2\right)} - \frac{\left(\mu^c\left(\tau_N+\tau_S\right)+t+c_N+c_S\right)X}{2\left(X^2+t^2\right)}$$
$$+\frac{m_S^{d0}\Delta\mu\tau_S X}{X^2+t^2} - \frac{C^R\left(m_N^0+m_S^{d0}+1\right)}{4\left(X^2+t^2\right)} + \frac{m_N^0-m_S^{d0}}{2} - \frac{s(X+t)^2}{2\left(X^2+t^2\right)}.$$

As in equation (3), the number of firms that relocate depends negatively on the relocation cost and positively on the southern market size. As usual, the number of single-plant firms that relocate increases with the northern market size when the transportation cost is relatively low. We immediately obtain the derivative of the number of single-plant firms that relocate relative to the number of created subsidiaries $\partial\hat{l}(s)/\partial s = -(X+t)^2/2(X^2+t^2) < 0$. From this inequation, the following corollary is deduced.

Corollary 3 : *The number of single-plant firms that relocate decreases with the number of multi-plant firms.*

The firm that creates a subsidiary in the South becomes more competitive than before. This effect induces a reduction in the number of northern single-plant firms that relocate. The production of northern firms in 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, which reduces the number of northern firms that relocate.

Stage 1. Each firm decides to be a multi-plant firm or single-plant. Each northern firm decides to open a subsidiary taking into account that it also has the possibility to relocate. At equilibrium, the northern single-plant firms are indifferent between the two strategies:

$$\pi_{NN}\left(m_N^0-\hat{l}(s),\hat{l}(s),m_S^{d0}\right)+\pi_{SS}^c\left(\hat{l}(s)+s,m_S^{d0},m_N^0-\hat{l}(s)-s\right)-C^o$$
$$=\pi_{NN}\left(m_N^0-\hat{l}(s),\hat{l}(s),m_S^{d0}\right)+\pi_{NS}\left(m_N^0-\hat{l}(s)-s,\hat{l}(s)+s,m_S^{d0}\right),$$

where C^o is the cost to create a subsidiary from scratch. The first part of the equation represents the profit made by a multi-plant firm, while the second part is the profit made by a northern single-plant firm. At equilibrium, the number of subsidiaries at equilibrium is given by:

$$s = -\frac{C^o\left(m_N^0+m_S^{d0}+1\right)\left(X^2+t^2\right)}{(X-t)^2(X+t)^2} + \frac{C^R\left(m_N^0+m_S^{d0}+1\right)}{2(X-t)^2} - \frac{a_N}{X-t} + \frac{a_S}{X+t}$$
$$+\frac{t\left(\mu^c\left(\tau_N+\tau_S\right)+t+c_N+c_S\right)}{(X-t)(X+t)} - \frac{2m_S^{d0}\Delta\mu t\tau_S}{(X-t)(X+t)}.$$

We immediately deduce the following lemma.

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Lemma 3 : *The number of northern firms that create a subsidiary in the South increases with the relocation costs and the southern market size, and decreases with the costs to create a subsidiary. It increases (decreases) with the northern market size if the transportation cost is relatively high (low). Finally, it increases with the number of northern and dirty southern firms if and only if the relocation costs are high and the opening costs are low.*

Proof :

$$\frac{\partial s}{\partial {m_N}^0} = \frac{C^R}{2(X-t)^2} - \frac{C^o(t^2+X^2)}{(X-t)^2(X+t)^2},$$
$$\frac{\partial s}{\partial m_S^{d^0}} = \frac{C^R}{2(X-t)^2} - \frac{C^o(t^2+X^2)}{(X-t)^2(t+X)^2} - \frac{2\Delta\mu t\tau_S}{(X-t)(X+t)}.$$

The creation of a subsidiary and relocation are two substitutable actions, but they are not taken at the same time. Thus, strategic effects can be generated by the creation of a subsidiary. The number of multi-plant firms depends negatively on the costs to build a subsidiary and depends positively on the relocation costs and on the southern market size. The number of created subsidiaries increases with the northern market size if the transportation cost is high. Indeed, in this case, it is expensive to provide the northern market from abroad, and firms are more willing to become multi-plant. A particularly interesting result is that an increase in $m_S^{d^0}$ and ${m_N}^0$ leads to an increase in the number of subsidiaries if and only if the relocation costs are high. If relocation costs are low, firms anticipate that an increase in the number of firms will lead to a large number of firms that relocate and therefore have fewer incentives to open a subsidiary.

4.2.2. Purchase of dirty southern firms

Let us now consider that northern firms may purchase a southern firm and turn it into a clean one. Let us denote by $\tilde{l}$ the number of northern single-plant firms that relocate and by b the number of northern firms that purchase a southern dirty firm.

Stage 3. The third stage is similar to the one defined in section 3.1 except that the market structure is different. In the northern market there are $m_N = m_N^0 - \tilde{l}$, $m_S^d = m_S^{d^0} - b$ and $m_S^c = \tilde{l}$ firms operating, while in the southern market there are $m_N = m_N^0 - \tilde{l} - b$, $m_S^d = m_S^{d^0} - b$ and $m_S^c = \tilde{l} + b$ firms operating. To determine the production levels we simply replace m_N, m_S^d and m_S^c by their corresponding value.

Stage 2. At equilibrium a northern single-plant firm is indifferent between relocating and remaining located in the North. Hence, at equilibrium, the number of relocated firms $\tilde{l}$ is given by the following equality:

$$\pi_{SN}^c\left(\hat{l}, m_S^{d^0} - b, m_N^0 - \tilde{l}\right) + \pi_{SS}^c\left(\tilde{l} + b, m_S^{d^0} - b, m_N^0 - \tilde{l} - b\right) - C^R$$
$$= \pi_{NN}\left(m_N^0 - \tilde{l}, \tilde{l}, m_S^{d^0} - b\right) + \pi_{NS}\left(m_N^0 - \tilde{l} - b, \tilde{l} + b, m_S^{d^0} - b\right). \quad (7)$$

The purchase of a dirty firm in the South to transform it into a subsidiary has two effects. First, it transforms a clean exporter from the North to the South into a clean southern

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firm selling only in its domestic market. Second, it also removes from both markets a dirty southern firm. We deduce from equation (7) the number of single-plant firms that relocate, which is given by:[10]

$$\begin{aligned}\tilde{l}(b) = {} & \frac{a_S\left(X+t\right)+a_N\left(X-t\right)}{2\left(X^2+t^2\right)} - \frac{\left(\mu^c\left(\tau_N+\tau_S\right)+t+c_N+c_S\right)X}{2\left(X^2+t^2\right)} \\ & + \frac{(m_S^{d0}-b)\Delta\mu\tau_S X}{X^2+t^2} - \frac{C^R\left(m_N^0+m_S^{d0}-b+1\right)}{4\left(X^2+t^2\right)} \\ & + \frac{m_N^0-m_S^{d0}+b}{2} - \frac{b(X+t)^2}{2\left(X^2+t^2\right)}.\end{aligned}$$

The number of single-plant 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 are ambiguous and depend on the transportation cost. Finally, we immediately obtain the derivative of the number of single-plant firms that relocate relative to the number of multi-plant firms,

$$\frac{\partial\tilde{l}(b)}{\partial b} = \frac{C^R}{4\left(X^2+t^2\right)} - \frac{X\left(\Delta\mu\tau_S+t\right)}{X^2+t^2}.$$

The following proposition is deduced.

Proposition 4 : *When the relocation costs are sufficiently high (low), the number of relocated firms increases (decreases) with the number of firms purchased in the South.*

As opposed to the previous channels of technology diffusion (technology adoption, public transfer and subsidiary creation), 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 sum of the transportation cost and the unit gain from relocating, the purchase of a southern firm increases the incentives 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 in the northern market thus increasing the profit made by all types of firms in the northern market. In the southern market, the purchase decreases the number of firms but turns a dirty firm into a clean one. The results depend on the value of the relocation costs. Consider for a moment high relocation costs. In such a case, few firms have an interest in relocating. However, if the number of dirty firms purchased increases, competition in the southern market is reduced and more northern firms have incentives to relocate.

Stage 1. Each northern firm decides either to be a multi-plant or to have only one plant in the North. Put differently, each northern firm decides to open a subsidiary taking into account that it will have the possibility to relocate later in the game. It purchases a southern firm if its profit net of the purchasing costs is larger than without the purchase. At equilibrium, northern firms are indifferent between the two strategies, and the

[10]Note that we can get $\tilde{l}(b)$ from $\hat{l}(s)$ by replacing s by b and m_S^{d0} by $m_S^{d0}-b$.

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

number of firms purchased, i.e., b, is such that:

$$\pi_{NN}\left(m_N^0-\tilde{l}(b),\tilde{l}(b),m_S^{d^0}-b\right)+\pi_{SS}^c\left(\tilde{l}(b)+b,m_S^{d^0}-b,m_N^0-\tilde{l}(b)-b\right)-C^p$$
$$=\pi_{NN}\left(m_N^0-\tilde{l}(b),\tilde{l}(b),m_S^{d^0}-b\right)+\pi_{NS}\left(m_N^0-\tilde{l}(b)-b,\tilde{l}(b)+b,m_S^{d^0}-b\right),$$

where C^p is the cost to purchase a firm. The first part of the equation represents the profit made by a multi-plant firm purchasing a firm, while the second part is the profit made by a northern single-plant firm. Since after the purchase the multi-plant firm still supplies the northern market locally, the profit made in the northern market at equilibrium is the same with and without purchasing a dirty southern firm. Hence, b is:

$$\pi_{SS}^c\left(\tilde{l}(b)+b,m_S^{d^0}-b,m_N^0-\tilde{l}(b)-b\right)-C^p$$
$$=\pi_{NS}\left(m_N^0-\tilde{l}(b)-b,\tilde{l}(b)+b,m_S^{d^0}-b\right).$$

At equilibrium, the number of firms purchased in the South by multi-plant firms is:

$$b=\frac{2\left(X^2-t^2\right)\left(a_N\left(t+X\right)-a_S\left(X-t\right)-t\left(\mu^c(\tau_N+\tau_S)-2m_S^{d^0}\Delta\mu\tau_S+t+c_N+c_S\right)\right)}{2\left(X^2-t^2\right)\left(t\left(2\Delta\mu\tau_S+t\right)-X^2\right)-C^R(t+X)^2+2C^p\left(t^2+X^2\right)}$$
$$+\frac{\left(m_N^0+m_S^{d^0}+1\right)\left(2C^p\left(t^2+X^2\right)-C^R(t+X)^2\right)}{2\left(X^2-t^2\right)\left(t\left(2\Delta\mu\tau_S+t\right)-X^2\right)-C^R(t+X)^2+2C^p\left(t^2+X^2\right)}.$$

Analyzing b is not straightforward. First, it is fair to assume that the denominator is positive. Indeed, the cost to purchase a 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 purchase all southern firms. Second, under this assumption, an increase in the southern market size decreases the number of multi-plant 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 fewer incentives to purchase southern firms anticipating that the competition in this market will be fierce. Moreover, an increase in the northern market size only decreases the number of multi-plant firms if the transportation cost is sufficiently high compared to the unit gain from relocating.

5. Discussion and concluding remarks

This paper demonstrates that the diffusion of technology may reduce the number of firms that relocate by affecting competition in 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

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

imitate clean technologies used by southern firms that have relocated, that have purchased the technology from an innovator, or that are subsidiaries of northern firms. It is easier to copy and imitate a firm located in the South than a firm located in the North. By hiring employees in the South and by cooperating with local suppliers, clean firms may generate technology spillovers. Knowledge spillovers amplify the technology diffusion and decrease the technological advantage of relocated firms. Thus, knowledge spillovers may enhance the crowding-out effect of technology diffusion on relocation.

In this paper, we assume that the marginal production cost is country specific. Hence, technology diffusion always decreases the total marginal cost. However, it could be the case that technology diffusion increases the marginal production cost but diminishes the emissions intensity. However, no firm would be interested in adopting technology that would reduce its competitiveness. In other words, a firm would not adopt a technology whose total marginal cost (marginal cost of production plus emissions tax times emissions intensity) would be higher than the one before the adoption. Even in the case of public transfer, a firm in the South would have no interest in accepting a technology that would reduce its competitiveness. Put differently, even if adopting the clean technology increases its marginal production cost, a firm will only adopt the new technology if its competitiveness improves, that which always generates the crowding-out effect.

Until now, we have assumed that the innovator developing clean technologies does not produce the final good. However, companies producing final goods can also develop production technologies, and sell them on the technology market. Let us now consider the case where firms are simultaneously sellers in both the product and technology markets. In such a case, the firm would benefit in the technology market from the adoption of the technology by southern firms, but its profits in the market for products would decrease. Hence, the firm will only sell its technology if the loss in the market for products is offset by the gains in the market for technology. This gain obviously depends on the contract used to license the technology. For instance, a firm may use a royalty or a fixed fee contract (see Kamien and Tauman, 1986 or Kim and Lee, 2014). If a firm is active in both markets, its profits may increase with the diffusion of technology as a result of an increase in innovation revenues. We propose to discuss whether the crowding-out effect is affected in the following two cases. If the price of the patent is exogenous, the crowding-out effect will still hold. Indeed, the firm's relocation decision will only depend on the profits made in the product market since profits made in the technology market are not affected by relocation. If the price of the patent is endogenous and decisions to sell the technology are made before relocation decisions, again the crowding-out effect holds. Indeed, the number of relocated firms will still be decreasing with the number of adopting firms.

While several developing countries have introduced or plan to introduce a carbon tax or a market for pollution rights, many developing countries have been advocating for many years that developed countries should help them reduce emissions and do not want to implement climate policies. For instance, during the COP 21, India committed to cutting the emissions intensity of GDP by 33–35 per cent of 2005 levels by 2030, conditional on finance being made available by developed countries. The Common But Differentiated Responsibility rule implies that developing countries should be helped to reduce their emissions by the developed countries. It is therefore interesting to study the incentives to transfer technology and the robustness of the crowding-out effect when developing countries do not implement environmental regulation. When the South does not implement any environmental policies, dirty and clean firms produce the same

https://doi.org/10.1017/S1355770X19000445 Published online by Cambridge University Press

level. The diffusion of technology does not affect the production level, the profit or the consumer surplus, but it decreases emissions. Hence, the incentives to relocate are not affected by the technology diffusion and technology diffusion will increase the northern welfare. Technology diffusion will also increase the southern welfare. The North has strict incentives to transfer technology to the South. In such a case, the crowding-out effect does not hold anymore.

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 agreement on Trade-Related Aspects of Intellectual Property Rights 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 the 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 nonambiguously 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, and 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 (2017) show that climate-friendly technologies spill over 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.

Supplementary Material. The supplementary material for this article can be found at https://doi.org/10.1017/S1355770X19000445

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Cite this article: Ing J, Nicolaï JP (2020). North-South diffusion of climate-mitigation technologies: the crowding-out effect on relocation. *Environment and Development Economics* **25**, 21–43. https://doi.org/10.1017/S1355770X19000445