Technology Adoption, Government Policy and Tariffication

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Abstract

In this paper we integrate trade policy into an open-economy model of technology adoption to investigate the impact of alternate trade barriers on the equilibrium diffusion of technology. We show that even when ad-valorem tariffs have a neutral impact on technology adoption, non-tariff barriers such as a quota can be used to effect the speed of technology diffusion. In addition, we demonstrate how, in an open-economy setting, tariffication (i.e., the conversion of quotas to ad-valorem tariffs) can lead to faster technology adoption world-wide.

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1 Introduction

Innovation offers the potential for productivity growth. In this respect the adoption of new technologies is especially important as a superior technology confers no benefits until that technology is employed by users. Thus, evaluation of government policy should consider, not only standard issues of static efficiency, but also its dynamic impact on the incentives to adopt new technologies. In this paper, we integrate governmental trade policy into an open-economy model of technology adoption to investigate how various trade barriers impact the equilibrium diffusion of a new cost-saving innovation.

There exists an extensive literature in the field of international trade on the relative efficiency of different forms of trade barriers, specfically the relative efficiency of tariff versus quota protection.[1] This literature demonstrates that, while tariffs and quotas are equivalent under conditions of perfect competition, they can have differing impacts when the market is characterized by imperfect competition (see Bhagwati (1965) and Bhagwati (1968)). More recent contributions to this literature analyze trade policy instruments under different forms of competition (e.g., see Jorgensen and Schröder (2005)) as well as various market frictions (e.g., see Matschke (2003) and Herander (2005)).

The common thread in this literature is that the relative efficiency of different government policies is almost always analyzed in static models. However, it is also important to consider the dynamic productivity/technology effects of different trade policy instruments. Specifically, a key question addressed in this paper is how different government policies can impact firm productivity through affecting the rate at which firms adopt new technologies. In this sense, this paper is most closely related to that of Miyagiwa and Ohno (1995) which investigates the effect of different trade barriers on technology adoption.[2] However, Miyagiwa and Ohno (1995) investigates the adoption decisions of a single import-competing domestic firm engaged in Cournot competition with foreign exporters. In their model, the non-equivalence between tariffs and quotas rests on the lack of a strategic effect to technology adoption in the presence of a quota. Intuitively, under a tariff regime one of the benefits of adopting a cost-saving technology is that it reduces the exports of the foreign firm and thus increases home firm profits. This strategic benefit to adoption is absent under a quota regime and thus Miyagiwa and Ohno (1995) conclude that home firms will adopt new technology earlier under tariff protection than under an equivalent quota.

In contrast, this paper models the technology adoption decisions of an endogenous number firms engaging in monopolistic competition and thus the strategic effects of Miyagiwa and Ohno (1995) do not arise.[3] Rather, our paper focuses on trade policies that have a specific (per-unit) impact on marginal costs versus policies that have an ad valorem (percentage) impact. Specifically, we show

[1] An analogous question concerns the relative efficiency of specific vs. ad valorem tariffs (for a review see Helpman and Krugman (1989).

[2] Also see Crowley (2006).

[3] Another difference is that Miyagiwa and Ohno (1995) examine a model where both firms produce solely for the home market, while in our model, firms produce for both the home and foreign markets.

that in a dynamic model of technology diffusion a quota acts as an impediment to the adoption of cost-saving technology improvements since it has a disproportionately negative impact on high-productivity foreign firms as their relative price advantage is reduced. Basically, non-tariff barriers such as an import quota will have an effect similar to a specific price increase, thus raising the relative price of high-productivity (low-cost) firms, and impeding the desire of firms to adopt new cost-saving innovations.[4] As a result, the marginal impact of a quota will vary across time-periods, and quotas will be able to influence the technology adoption choices of both home and foreign firms, even in situations where an ad-valorem tariff has no effect. While the intuition behind these results is clear, they only becomes apparent when one analyzes policies within a dynamic framework.

As a final application of this result we consider the non-equivalence of reciprocal tariff and quota protection within a dynamic setting of technology adoption. A primary component of recent GATT/WTO negotiations has been the promotion of tariffication (i.e., the conversion of non-tariff barriers such as quotas to ad-valorem tariffs). Indeed one of the central achievements of the Uruguay Round was the widespread conversion of quantitative import restriction and other forms of protection into equivalent ad-valorem trade barriers. As was mentioned before, in standard static models of perfect competition, tariffs and quotas are perfect substitutes and thus tariffication has no impact on the overall efficiency of the trade regime. Indeed, the typical justification for tariffication in WTO agreements is the increased transparency that ad-valorem customs duties provide (thus facilitating future negotiations). In this model, we show that quotas also tend to decrease the speed of technology diffusion (relative to ad-valorem tariff barriers) since they have a disproportionately negative impact on high-productivity firms. This result has the policy-relevant implication that tariffication, in addition to increasing the visibility of trade protection, can also lead to faster technology adoption world-wide.

In the following analysis, Section 2 lays out the model of technology adoption and solves for the equilibrium rate of diffusion of a new technology within an open economy, while in Section 3 we investigate the impact of alternative trade policy instruments on technological progress. Finally, Section 4 concludes.

2 Model

To study the effects of trade barriers on cost-reducing technological improvements, we must specify the process by which firms endogenously choose to adopt new technologies. Here we employ a

[4] The intuition for this result parallels that of the classic Alchian-Allen conjecture that specific transportation costs will lead firms to export high-quality goods abroad since per-unit transportation costs lower the relative price of high quality goods. This logic is central to the literature on how quotas can lead to an increase in the average quality of imports (e.g, see Falvey (1979), Krishna (1987) and Krishna (1990)). The applicability of this result became apparent in the 1980's with the voluntary export restraint applied to Japanese auto exports by the United States. Several studies have noted that in response to this quota, Japanese auto firms shifted toward higher quality models (e.g., see Feenstra (1988)).

standard model of technology adoption in a closed economy initially proposed by Reinganum (1981) and Fudenberg and Tirole (1985) and extended to a monopolistically competitive environment by Götz (1999). This framework has the advantage of fitting the empirical evidence on technology adoption in that the cost-saving technological innovation will only gradually diffuse through the industry.[5] This model of technology adoption has been previously extended to an open economy by Ederington and McCalman (2008) and here we use a simplified version of that model to investigate the differing effects of tariffs versus quotas on the rate of technology adoption.[6]

2.1 Demand

We assume two identical countries, a home country and a foreign country. Each country has two sectors: one sector consists of a numeraire good, x_0, while the other sector is characterized by differentiated products. The preferences of a representative consumer are defined by the following intertemporal utility function:

$$U = \int_0^\infty (x_0(t) + log C(t)) e^{-rt} dt \tag{1}$$

where $x_0(t)$ is consumption of the numeraire good in time t and $C(t)$ represents an index of consumption of the differentiated product good. For $C(t)$ we adopt the CES specification which reflects tastes for variety in consumption and also imposes a constant (and equal) elasticity of substitution between every pair of goods:

$$C(t) = \left[\int_0^{\widetilde{n}} y(z,t)^\rho dz \right]^{1/\rho} \tag{2}$$

where $y(z,t)$ represents consumption of brand z at time t and $\widetilde{n}$ represents the number of available varieties in a representative country. It is straightforward to show that, with these preferences, the elasticity of substitution between any two products is $\sigma = 1/(1-\rho) > 1$ and aggregate demand in each country for good i at any point in time is given by:

$$y(i,t) = \frac{p(i,t)^{-\sigma} E}{\int_0^{\widetilde{n}} p(z,t)^{1-\sigma} dz} \tag{3}$$

where $p(i,t)$ is the price of good i in time t and E represents the total number of consumers in the country.

2.2 Production

All goods are produced using constant returns to scale technologies and a single factor of production, labor. Thus, production of any good (or brand) requires a certain amount of labor per unit of output.

[5]For a survey of the empirical evidence see Karshenas and Stoneman (1995).

[6]Ederington and McCalman (2008) was concerned with the relative impact of trade on the adoption decisions of exporting versus importing firms. However, it did not consider the relative impact of different policy instruments, the subject of this paper.

For simplicity, we assume that production of the numeraire good is defined by $l = x_0$ which ensures that the equilibrium wage is equal to unity.

We assume that varieties of the differentiated good can be produced using either of two types of technology. A low-productivity technology is always available to any firm and is purchased for F upon entering the industry. Production using the low-productivity technology is defined by $l(t) = y(t)$. A high-productivity technology is also available at time $t = 0$, but requires an additional fee of $X(t)$, which is defined in present value terms, where $X(0) = \infty$, $X(\infty) = \underline{X}$, $X' < 0$, $X'' > 0$. In particular, we assume that the adoption cost is falling faster than the interest rate, i.e. $-e^{rt}X'$ is declining over time.[7] Intuitively, this gives firms an incentive to wait to adopt even when the adoption costs are not prohibitive. With this adoption cost function, earlier adoption is more expensive; however, the decreasing costs of technology adoption implies that eventually all firms will adopt the high-tech process. Production using the high-productivity technology is defined by $l(t) = y(t)/\varphi$, where $\varphi > 1$.

2.3 Price, Profit and Ad-Valorem Tariffs

In this section, we investigate international trade between two symmetric countries. As is typical in monopolistic competition models of trade, we assume ice-berg transport costs where $b > 1$ units of a good need to be shipped for one unit to arrive. These ice-berg transport costs can reflect a combination of standard shipping costs as well as any ad-valorem tariff barriers. Thus, prices set in the domestic market are defined by:

$$p_L = \frac{\sigma}{\sigma - 1} \ , \ p_H = \frac{\sigma}{\varphi(\sigma - 1)} \tag{4}$$

Likewise prices set in the foreign market are given by:

$$p_L^F = \frac{\sigma b}{\sigma - 1} \quad , \quad p_H^F = \frac{\sigma b}{\varphi(\sigma - 1)} \tag{5}$$

Define b_h as the total shipping costs (freight costs plus any ad-valorem tariff barriers) of exporting to the home country and b_f as the total shipping costs of exporting to the foreign country. Likewise, let $[0, nq_h]$ be the range of firms that have adopted the high-productivity technology in the home country, where n is the number of home firms and q_h is between 0 and 1 and represents the fraction of home firms that have already adopted at a point in time. Let n_f and q_f have analogous interpretations as the foreign equivalents. Then the price index in the home country is given by:

$$\begin{aligned} &\textstyle\int_0^{n+n_f} p_h(i,t)^{1-\sigma} dz = \\ &\quad (\tfrac{\sigma}{\sigma-1})^{1-\sigma} [(q_h \varphi^{\sigma-1} + (1 - q_h))n + (q_f \varphi^{\sigma-1} + (1 - q_f))n_f b_h^{1-\sigma}] \end{aligned} \tag{6}$$

[7] These assumptions on the behavior of $X(t)$ are standard in the literature; see for example Fudenberg and Tirole (1985). Also see Saggi and Lin (1999) which motivates similar assumptions in an FDI setting. The assumption that adoption costs are bounded from below is made for expositional clarity so as to avoid late entry (i.e., entry after the last firm adopts).

and the price index in the foreign country is given by:

$$\begin{aligned}&\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz = \\ &(\tfrac{\sigma}{\sigma-1})^{1-\sigma}[(q_f\varphi^{\sigma-1}+(1-q_f))n_f+(q_h\varphi^{\sigma-1}+(1-q_h))nb_f^{1-\sigma}]\end{aligned} \tag{7}$$

Finally, the operating profits for home firms using the low-productivity technology (π_L) and the high-productivity technology (π_H) respectively are given by:

$$\begin{aligned}\pi_L(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz} + \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}b_f^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz} \\ \pi_H(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}\varphi^{\sigma-1}E}{\sigma\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz} + \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}\varphi^{\sigma-1}b_f^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz}\end{aligned} \tag{8}$$

Operating profits for foreign firms (π_L^F and π_H^F) are defined analogously.

2.4 Adoption Decision

In determining when to adopt the new technology, a firm takes the evolution of adoption by both home, $q_h(t)$, and foreign firms, $q_f(t)$, as given. In this situation a firm in the home country will choose its adoption date, T, to maximize the discounted value of total profits:

$$\Pi = \int_0^T e^{-rt}\pi_L(q_h(t),q_f(t))dt + \int_T^\infty e^{-rt}\pi_H(q_h(t),q_f(t))dt - X(T) - F$$

where $X(T) = e^{-rT}x(T)$. As can be seen, these profits depend on both the firm's own adoption date, T, and the adoption decisions of rival firms (which are summarized by $q_h(t)$ and $q_f(t)$). Differentiating with respect to T yields the first-order condition:

$$e^{-rT}\left[\pi_H(q_h(T),q_f(T)) - \pi_L(q_h(T),q_f(T))\right] = -X'(T) \tag{9}$$

An equivalent condition holds for adoption by foreign firms. The above first-order condition demonstrates the trade-off faced by firms in the choice of when to adopt. The left-hand side term is the gain in profits from adopting the high productivity technology while the right-hand side term is the decrease in adoption costs from delaying adoption another period. Note that the profit differential ($\pi_H - \pi_L$) is decreasing as the number of firms producing with the high-tech production process (q) increases. This is because adoption by rival firms reduces the market share of other firms and, thus, the gain to adopting a cost-saving innovation. It is this property of the model that leads to the gradual diffusion of the new technology through the industry as the initial adoption by the early-adopting firms will delay adoption by the remaining firms. By substituting the derived profit differentials into the above first-order conditions (for both home and foreign firms), one can solve for $q_h^*(t)$ and $q_f^*(t)$, the equilibrium distribution functions.

2.5 Present Value of Profits

The model can be closed by solving for the equilibrium number of firms in the industry in each country, n and n_f. Given perfect foresight, firms will enter the industry until the present value of profits are equal to zero.[8] Since the present value of profits is the same for every firm within a country, it is arbitrary which profit function is used to identify n. The following calculation is done for the last firm to adopt the technology (let T_L be the adoption date for the first adopter and T_H be the adoption date of the last adopter). The present value of profits for such a firm is given by:

$$\Pi^* = \int_0^{T_L} e^{-rt}\pi_L(q_h = q_f = 0)dt + \int_{T_L}^{T_H} e^{-rt}\pi_L(q_h(t), q_f(t))dt + \int_{T_H}^{\infty} e^{-rt}\pi_H(q_h = q_f = 1)dt - X(T_H) - F \tag{10}$$

An equivalent definition holds for foreign firms. Since entry occurs until the present value of profits is equal to zero for each type of firm, these zero-profit conditions, along with $q_h^*(t)$ and $q_f^*(t)$ characterize an equilibrium.

2.6 Free-Trade Equilibrium

As an initial benchmark, we first solve for the free-trade equilibrium (i.e., $b_h = b_f = 1$). Given free-trade, the location of firms is arbitrary in equilibrium, and thus we only need solve for the equilibrium number of world firms ($\widetilde{n}$). Likewise, given free-trade, the location of early-adopting versus late-adopting firms is arbitrary, so for notational convenience we will focus on the symmetric equilibrium where $q_h(t) = q_f(t) = q(t)$. Substituting (6) and (7) into the profit functions, and then using the first-order condition defined by (9), one can solve for $q(t)$ (i.e., the equilibrium distribution function):

$$q^*(t) = \begin{cases} 0 & \text{for } t \in [0, T_L) \\ \frac{-e^{-rt}E}{X'(t)\widetilde{n}\sigma} - \frac{1}{\varphi^{\sigma-1}-1} & \text{for } t \in [T_L, T_H] \\ 1 & \text{for } t \in (T_H, \infty) \end{cases} \tag{11}$$

The above function describes the diffusion of the new production process through the industry. Since adoption costs are initially very high, no firm will adopt earlier than T_L (resulting in per-period firm operating profits of $E/\sigma\widetilde{n}$ during this period). However, as adoption costs fall, more firms adopt the new technology so that all firms will have adopted the new technology after T_H (as before, resulting in operating profits of $E/\sigma\widetilde{n}$). Finally, for $T_L \leq t \leq T_H$ there exists a mix of low-tech and high-tech firms in equilibrium, and the distribution of firms is defined by $q^*(t)$.

The model can then be closed by solving for the equilibrium number of firms ($\widetilde{n}$). Substituting the respective profit functions into (10), one derives the zero profit condition to be:

$$\Pi^* = \left(1 - e^{-rT_L} + e^{-rT_H}\right)\frac{E}{\widetilde{n}\sigma r} + \frac{X(T_L) - X(T_H)}{\varphi^{\sigma-1} - 1} - X(T_H) - F = 0 \tag{12}$$

[8]Ederington and McCalman (2008) provides a proof that, in the context of this model, all entry will occur at $t = 0$. Intuitively, the combination of positive per-period profits and rational, forward-looking firms implies that firms have little incentive to delay entry and thus all firms enter at $t = 0$.

A straightforward application of the envelope theorem verifies that equilibrium profits are declining in $\tilde{n}$. Thus, $\tilde{n}$ is defined by where $\Pi^* = 0$. Thus, this zero-profit condition along with $q(t)^*$ (defined by 11) characterizes the free-trade equilibrium.

3 Tariffication and Technology Adoption

In this section we address the issue of tariffication (i.e., the conversion of quotas and other non-tariff barriers into ad-valorem tariffs). Tariffication was a major negotiating point in the recent Uruguay Round of GATT where the main objective was to make border protection more transparent and, hence, facilitate future negotiations. What we argue in this section, is that an unnoticed benefit of tariffication is its potential to also facilitate dynamic productivity improvements.

3.1 Ad-Valorem Tariff and Technology Adoption

First, consider the case where the home country imposes a unilateral tariff on imports from the foreign country (i.e., an increase in b_h). The direct impact of such a tariff will be to increase the market-share of home firms while decreasing the market-share of foreign firms in the home country. The expanded scale of domestic firms would increase their incentive to adopt cost-saving innovations (i.e., they are more willing to pay a fixed adoption cost in order to reduce their marginal costs of production). Thus, one would expect a unilateral tariff to increase the rate of adoption in the home country. As we show in the following proposition, if one holds the number of home firms and foreign firms constant, this is exactly what happens.[9]

PROPOSITION 1 *Holding n and n_f constant, the unilateral imposition of an ad-valorem tariff by the home country will increase the speed of technology diffusion by domestic firms (i.e., both T_L and T_H occur earlier for the home country).*
Proof: See Appendix

However, countering these direct effects is the fact that a home tariff will encourage the entry of new firms into the home market, thus endogenously increasing the number of home firms. The increase in the number of home firms would in turn decrease the market share of each individual home firm and thus tend to reduce the incentives for adoption. We refer to the ability of tariffs to impact entry/exit decisions as the indirect effect of a tariff change, and, as we show in the following proposition, for an ad-valorem tariff the indirect effect completely cancels out the direct effect (i.e., the imposition of an ad-valorem tariff by the home country will not impact the adoption decisions of home firms).

[9] A similar result to Proposition 1 can be found in Miyagiwa and Ohno (1995) and Crowley (2006). Both papers employ an oligopolistic framework in which the number of firms is automatically held constant.

PROPOSITION 2 *Allowing n and n_f to be determined endogenously, the unilateral imposition of an ad-valorem tariff by the home country will have no effect on the speed of technology diffusion by domestic firms (i.e., holding foreign adoption constant, an increase in b_h will not impact either T_L or T_H for the home country)./*
Proof: See Appendix

Proposition 2 is the result of the ad-valorem nature of our tariff which ensures that the relative price of high-tech versus low-tech firms is unchanged in both the foreign and domestic markets. Given constant relative prices, an ad-valorem tariff will only impact technology adoption through influencing the overall size of the firm. However, the zero-profit condition and the first-order condition for optimal adoption ensure that firm profits/output are constant as well and, thus, an ad-valorem tariff has no effect on the adoption decisions of home firms.

Of next concern is the impact of a unilateral tariff imposed by the home country on the adoption decisions of foreign firms. As before, the direct affect of such a tariff would be to decrease the market share of foreign firms, while the indirect affect will be to reduce the number of foreign firms in equilibrium. Once again, as we show in the following proposition, these direct and indirect effects cancel:[10]

PROPOSITION 3 *Allowing n and n_f to be determined endogenously, the unilateral imposition of an ad-valorem tariff by the home country will have no effect on the speed of technology diffusion by foreign firms (i.e., holding home adoption constant, an increase in b_h will not impact either T_L or T_H for the foreign country)*
Proof: See Appendix

Given that a unilateral tariff does not impact technology diffusion in either the home or foreign country, one would intuitively expect a similar result for the reciprocal imposition of import tariffs by both the home and foreign country (i.e., $b_h = b_f > 0$). As we derive in the following section, this intuition is correct.

3.2 Reciprocal Tariffs and Technology Adoption

Assume both countries impose a symmetric ad-valorem tariff on imports (i.e., $b_h = b_f = b > 0$). Substituting (6) and (7) into the profit functions, (8), and analyzing at the symmetric equilibrium, one derives that profits for high-tech and low-tech firms (in both countries) are given respectively by:

$$\pi_H = \frac{\varphi^{\sigma-1}}{q\varphi^{\sigma-1} + (1-q)} \frac{E}{n\sigma} \quad , \quad \pi_L = \frac{1}{q\varphi^{\sigma-1} + (1-q)} \frac{E}{n\sigma} \tag{13}$$

[10]An interesting corollary to the proposition below is that foreign firms, despite having different costs, are equal in size to home firms. This is due to the fact that it is the number of firms, n, not the size of individual firms, which adjusts to ensure that the zero-profit condition is satisfied.

Note from (13) that symmetric ad-valorem tariffs do not impact the profit functions and thus do not effect the profit differential from adopting new technologies. The invariance of profits to reciprocal ad-valorem tarrifs implies that such tariffs do not impact the equilibrium rate of technology diffusion (even when the equilibrium number of firms is held constant). This result is due to the fact that, the increase in domestic market share generated by the domestic tariff is countered by the loss of foreign market share due to the foreign tariff. Thus, we can state the following proposition:

PROPOSITION 4 *The imposition of a symmetric ad-valorem tariff by both the home and foreign country will have no effect on the speed of technology diffusion.*

We do not claim that the above Propositions are a complete description of the effects of tariffs on the diffusion of new technologies. Indeed, it should be apparent that different assumptions about the demand or cost structure of the economy could allow tariffs to have a non-negligible impact on adoption decisions.[11] However, they will serve as a useful benchmark to compare the *relative* effects of ad-valorem tariffs to quotas. Specifically, in the following sections we analyze the question of whether, given conditions where ad-valorem tariffs are an ineffective means of impacting adoption decisions, quantitative restrictions on trade, such as an import quota, could have a different effect. We analyze that question in the following sections.

3.3 Time-Invariant Quota and Relative Prices

In the following section, we examine the effect that an import quota imposed at time $t = 0$ has on the speed of technology adoption. Assume that, at time t, firm i is allocated $Q(i,t)$ number of quota licenses. Note that while the profit-maximizing price for the firm in its domestic market is still given by (4), the profit-maximizing price for the firm in the foreign market satisfies the following constrained maximization:

$$max[p(i,t) - c(i,t)]y(i,t) + \lambda_{i,t}[Q(i,t) - y(i,t)] \tag{14}$$

where $c(i,t)$ is the marginal cost of good i in year t and $\lambda_{i,t}$ represents the shadow cost of the quota constraint (i.e., the extra profit that would be generated by relaxing the quota constraint one unit). Assuming that this quota is binding, from the first-order condition of the above maximization one can derive that prices in the foreign market for low-tech and high-tech firms respectively are:

$$p^F_{L,t} = \frac{\sigma}{\sigma - 1}(b + \lambda_{L,t}) \quad , \quad p^F_{H,t} = \frac{\sigma}{(\sigma - 1)}(\frac{b}{\varphi} + \lambda_{H,t}) \tag{15}$$

Thus, the introduction of an import quota (or a voluntary export restraint) acts in the same way as a *specific* price increase, not a proportional price increase. To discuss the full implications

[11]Indeed, in Ederington and McCalman (2008) we provide a model in which the imposition of ad-valorem tariffs can effect the rate of technology adoption.

of a quota regime on the diffusion of new technologies we must make some assumptions about the allocation of quota licenses. Specifically, we assume that a perfectly competitive market for quota licenses exists in which the licenses can be traded.[12] Given the above assumptions, the price of a quota license (and thus the shadow price of the quota constraint) will be equalized over all firms at any point in time (i.e., $\lambda_{L,t} = \lambda_{H,t} = \lambda_t$).

First, consider the case where only the home country imposes a quota on foreign imports. Thus, prices of domestic firms are unchanged, and defined by (4), while prices of foreign firms in the domestic market are defined by (15) where $\lambda_{L,t} = \lambda_{H,t} = \lambda_t$. Given iceberg transport costs of $b_h = b_f = b$, the profits for a home firm are defined by (8). However, now the price index in the home country is given by:

$$\begin{aligned} &\int_0^{n+n_f} p_h(i,t)^{1-\sigma} dz = \\ &(\tfrac{\sigma}{\sigma-1})^{1-\sigma}[(q_h\varphi^{\sigma-1} + (1-q_h))n + ((\tfrac{b}{\varphi}+\lambda_t)^{1-\sigma} q_f + (1-q_f)(b+\lambda_t)^{1-\sigma})n_f] \end{aligned} \tag{16}$$

while the price index in the foreign country is given by:

$$\begin{aligned} &\int_0^{n+n_f} p_f(i,t)^{1-\sigma} dz = \\ &(\tfrac{\sigma}{\sigma-1})^{1-\sigma}[(q_f\varphi^{\sigma-1} + (1-q_f))n_f + (q_h(\tfrac{b}{\varphi})^{1-\sigma} + (1-q_h)b^{1-\sigma})n] \end{aligned} \tag{17}$$

Note that a unilateral quota by the home country will impact home firms by increasing the prices of their foreign competitors (and thus will increase the domestic market share of home firms). As with the ad-valorem tariff, this increase in market share corresponds to an increased incentive to adopt the cost-saving technology:

PROPOSITION 5 *Holding n and n_f constant, the unilateral imposition of a time-invariant import quota by the home country will increase the speed of technology diffusion by domestic firms (i.e., both T_L and T_H occur earlier for the home country).*
Proof: See Appendix

However, given endogenous entry/exit decisions, such a change in market share will result in corresponding changes in the number of home (and foreign) firms. The question is whether, as was the case for the ad-valorem tariff, these indirects effect cancel out the direct effect. As we show in the following proposition, they do not. Specifically, a unilateral quota, while it delays the date of initial adoption, will increase the rate of diffusion so that the final adoption date occurs earlier:

PROPOSITION 6 *Allowing n and n_f to be determined endogenously, the unilateral imposition of a time-invariant quota by the home country results in the initial adoption by home firms occurring*

[12]This assumption has no impact on the baseline results of the paper that quotas tend to reduce the speed of technology adoption. Indeed, as we show in the appendix (section 5.1), the rate of technology adoption is reduced even further when quota licenses are symmetrically distributed to firms and cannot be transferred. Intuitively, fixed, non-transferable quota licenses deter adoption as they prevent adopting firms from expanding the scale of their production.

later, but the last adoption occurring earlier (i.e., holding foreign adoption dates constant, T_L occurs later and T_H occurs earlier for the home country).
Proof: See Appendix.

Proposition 6 reflects the fact that the marginal cost of the quota is increasing over the diffusion phase. Specifically, recall that the aggregate number of quota licenses is held constant over time. However, as the high-productivity technology diffuses through the industry, production levels and the desired volume of trade will increase. Thus, the quota will have a greater protectionist impact at the end of the diffusion phase than at the beginning of the diffusion phase (i.e., $\lambda_{T_H} > \lambda_{T_L}$). As the direct effect of the time-invariant quota is weaker prior to diffusion and stronger following diffusion, it will reduce incentives to adopt at the beginning of the diffusion phase, while increasing incentives to adopt at the end of diffusion.

It should be apparent that the increase in the magnitude of the direct effect over time is a function of the fact that the level of quota licenses is time-invariant even while the desired volume of trade is increasing over time (as technology adoption improves the productivity of firms in the industry). However, typically in administering quota systems, the number of quota licenses is adjusted over time in response to changes in demand and supply conditions. In addition, many quota systems provide additional flexibility by allowing firms to transfer quota licenses intertemporally.[13] Thus, in the following section, we assume that the overall number of quota licenses are adjusted over time so that the marginal impact of the quota on prices remains constant (implicitly, this requires the number of licenses available to increase as technological diffusion increases aggregate supply in the industry). We make this assumption for two reasons. First, as stated previously, it mimics a realistic quota system in which the quota level is adjusted to changing market conditions. Second, it allows for a more direct comparison between a tariff system (where the marginal cost is automatically time-invariant) and the quota system.

3.4 Time-Varying Quota and Technology Adoption

In this section we consider the case where the home country imposes a quota on foreign imports, however adjusts the number of quota licenses over time so that the marginal cost of the quota remains constant. Operationally, this requires increasing the aggregate number of quota licenses over the diffusion phase. Given this assumption, the price of a quota license (and thus the shadow price of the quota constraint) will be equalized over all firms over time (i.e., $\lambda_{L,t} = \lambda_{H,t} = \lambda$). Thus, while prices of domestic firms are unchanged, and defined by (4), prices of foreign firms in the domestic market are now defined by:

[13]For example, see the European Union's quota system for imports of clothing, footwear and steel (available at http://trade.ec.europa.eu/sigl). In that system, not only are the quota levels adjusted from year to year, but there are additional flexibility provisions which allow quota licenses to be transfered intertemporally.

$$p_L^F = \frac{\sigma}{\sigma-1}(b+\lambda) \quad , \quad p_H^F = \frac{\sigma}{(\sigma-1)}(\frac{b}{\varphi}+\lambda) \tag{18}$$

Note that the presence of a binding quota affects the relative price of high-technology versus low-technology firms in the foreign market. Specifically, as the shadow price of the quota increases, the relative price of the two firms tends toward equality (i.e., the high-technology firms lose their relative price advantage overseas). It should be apparent that this reduction in the price advantage for high-technology firms will have a disproportionately negative impact on their overseas operating profits. We analyze the implications of this result in the following two sections when first we look at the unilateral imposition of a quota and then we look at the reciprocal imposition of a quota.

Given iceberg transport costs of $b_h = b_f = b$, the profits for a home firm are defined by (8). However, now the price index in the home country is given by:

$$\begin{aligned} &\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz = \\ &(\tfrac{\sigma}{\sigma-1})^{1-\sigma}[(q\varphi^{\sigma-1}+(1-q))n+((\tfrac{b}{\varphi}+\lambda)^{\sigma-1}q_f+(1-q_f)(b+\lambda)^{1-\sigma})n_f] \end{aligned} \tag{19}$$

while the price index in the foreign country is given by:

$$\begin{aligned} &\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz = \\ &(\tfrac{\sigma}{\sigma-1})^{1-\sigma}[(q_f\varphi^{\sigma-1}+(1-q_f))n_f+(q(\tfrac{b}{\varphi})^{1-\sigma}+(1-q)b^{1-\sigma})n] \end{aligned} \tag{20}$$

Note that a unilateral quota by the home country will impact home firms by increasing the prices of their foreign competitors (and thus will increase the domestic market share of home firms). However, given endogenous entry/exit decisions, such a change in market share will result in corresponding changes in the number of home (and foreign) firms. As we show in the following proposition, a unilateral time-varying quota has the same effects as the time-invariant quota: it delays the date of initial adoption but increases the rate of diffusion so that the final adoption date occurs earlier:

PROPOSITION 7 *Allowing n and n_f to be determined endogneously, the unilateral imposition of a time-varying quota by the home country results in the initial adoption by home firms occurring later, but the last adoption occurring earlier (i.e., holding foreign adoption dates constant, T_L occurs later and T_H occurs earlier for the home country).*
Proof: See Appendix.

Proposition 7 requires more discussion as it may appear counter-intuitive that a quota regime will result in faster adoption at the point in time when the number of quota licenses are the most numerous (i.e., at the end of the diffusion phase) and slower adoption at the point in time when the quota is the most restrictive (i.e., at the beginning of the diffusion phase). However, Proposition 7 simply reflects the fact that, even if the marginal cost of a quota license is being held constant over time, the overall protectionist impact of the quota system is increasing over the diffusion phase. Specifically, recall that a quota has a greater impact on high productivity firms than low productivity firms (as it reduces their cost advantage overseas). Correspondingly, a quota regime will have a greater protectionist impact at the end of the diffusion phase (when foreign firms are high-tech) than at the beginning of the diffusion phase (when foreign firms are low-tech). As a result, since the direct effect of the quota is increasing over time, it will reduce incentives to adopt at the beginning of the diffusion phase, while increasing incentives to adopt at the end of diffusion.

Of course a second question of interest is how the unilateral imposition of a quota by the home country impacts the technology adoption decisions of foreign firms. Not surprisingly, given the intuition of the model, a quota, which reduces the competitive cost advantage of high-tech firms overseas, will delay the adoption of new technologies by foreign exporting firms:

PROPOSITION 8 *Allowing n and n_f to be determined endogenously, the unilateral imposition of a quota results in delayed adoption by foreign firms (i.e., holding domestic adoption dates constant, both T_L and T_H occur later for the foreign country).*
Proof: See Appendix

Proposition 8 reflects the fact that a quota will delay the adoption of cost-saving technologies by foreign firms since the benefits of such technology adoption is diminished. In this sense, it is instructive to compare Propositions 7 and 8 (that concern the impact of a unilateral quota) with Propositions 2 and 3 (that concerns the impact of a unilateral tariff). As can be seen, allowing endogenous entry and exit decisions, governments have no ability to influence the rate of technology adoption by unilaterally imposing ad valorem tariff protection. However, one can influence the rate of technology adoption (by both domestic and foreign firms) by unilaterally imposing a comparable quota. In the next section we consider the case where both countries impose a symmetric quota on imports.

3.5 Reciprocal Quotas and Technology Adoption

In this section we consider the case where symmetric quotas are placed on trade. In such a situation, profit-functions of firms in either country are defined symmetrically. For expositional purposes we will assume the absence of transport costs (i.e., $b = 0$). The symmetric price index in the open economy equilibrium is then given by:

$$\begin{aligned}&\int_0^{n+n_f} p(i,t)^{1-\sigma} dz = \\ &\quad (\tfrac{\sigma}{\sigma-1})^{1-\sigma}[(q_h\varphi^{\sigma-1} + (1-q_h))n + (q_f\varphi^{\sigma-1}(1+\lambda\varphi)^{1-\sigma} + (1-q_f))n_f(1+\lambda)^{1-\sigma}]\end{aligned} \tag{21}$$

The symmetry of the model implies that, in equilibrium, $q_h = q_f = q$ and $n = n_f = \widetilde{n}$. Thus, imposing symmetry between the two countries and substituting (21) into the profit functions gives operating profits (from both domestic and foreign markets) as:

$$\begin{aligned}\pi_H &= \tfrac{\varphi^{\sigma-1}[1+(1+\lambda\varphi)^{1-\sigma}]}{(1+(1+\lambda\varphi)^{1-\sigma}q\varphi^{\sigma-1}+(1-q)(1+(1+\lambda)^{1-\sigma}} \tfrac{E}{\widetilde{n}\sigma} \\ \pi_L &= \tfrac{[1+(1+\lambda)^{1-\sigma}]}{(1+(1+\lambda\varphi)^{1-\sigma}q\varphi^{\sigma-1}+(1-q)(1+(1+\lambda)^{1-\sigma}} \tfrac{E}{\widetilde{n}\sigma}\end{aligned} \tag{22}$$

Substituting the above profit functions into the first-order condition for the adoption decision and solving for $q(t)$, one derives that:

$$q^*(t) = \begin{cases} 0 & \text{for } t \in [0, T_L) \\ \frac{-e^{-rt}E}{X'(t)\widetilde{n}\sigma} - \frac{[1+(1+\lambda)^{1-\sigma}]}{([1+(1+\lambda)^{1-\sigma}]-[1+(1+\lambda\varphi)^{1-\sigma}]\varphi^{\sigma-1}} & \text{for } t \in [T_L, T_H] \\ 1 & \text{for } t \in [T_H, \infty] \end{cases} \tag{23}$$

The question that we are interested in is how this rate of adoption compares to the open economy rate of diffusion with an ad-valorem tariff. First, note that when $\lambda = 0$ the equilibrium rate of diffusion is the same as that in the open economy cases. Taking the partial of $q(t)$with respect to λ gives:

$$\frac{\partial q(t)}{\partial \lambda}|_{\lambda=0} = \frac{2(1-\sigma)[\varphi^{\sigma} - \varphi^{\sigma-1}]}{4(1-\varphi^{\sigma-1})^2} < 0 \text{ for } T_L \leq t \leq T_H \tag{24}$$

So holding $\widetilde{n}$ constant, the imposition of symmetric quotas by each country will decrease the speed of technology adoption below that of the open economy case (i.e., at anytime $T_L \leq t \leq T_H$ a smaller fraction of firms will have adopted the new technology). This implies that the presence of a quota regime will slow down the rate of technology diffusion relative to an ad-valorem tariff regime. The reason for this is simple. Specific transport costs change the relative prices of the differentiated good in favor of the low technology (high cost) firms in the foreign markets, thus reducing the relative profitability of the high technology firms and the incentive to adopt the new technology. Note that this is in contrast to the reciprocal ad-valorem tariff case where, even when the number of firms was held constant, reciprocal tariffs had no impact on profit differentials and, thus, the equilbrium rate of adoption.

While the preceding analysis assumed that the number of firms in the industry is constant, the imposition of reciprocal quotas is also likely to have an impact on the number of firms in an industry. Thus, in deriving the complete impact of a quota regime on the rate of technology adoption, we must also take into account its indirect impact (i.e., how it may affect $q(t)$ indirectly through $\widetilde{n}$). However, as we verify in the following proposition, even allowing $\widetilde{n}$ to be endogenous, it is still the case that the presence of reciprocal quotas reduces the rate of technology adoption.

PROPOSITION 9 *Allowing $\widetilde{n}$ to be determined endogenously, the reciprocal introduction of a quota will delay the adoption on new cost-saving technologies (i.e., both T_H and T_L will occur later for both countries).*

Proof: See Appendix

Propositions 4 and 9 have a direct implication for the question of tariffication in international trade agreements. Assume two open economies impose symmetric quotas on each other. The above Propositions imply that a reciprocal trade agreement to convert these quota constraints into equivalent ad-valorem tariff constraints will increase the rate of technology adoption in both countries. Thus, this paper implies that the preference in GATT/WTO negotiations for the conversion on non-tariff barriers into tariff barriers actually has a potential dynamic rationale in that it tends to have a positive effect on the diffusion of new technology.

4 Conclusion

This paper has examined the linkage between policy instruments and the speed with which firms adopt a cost-saving innovation. We argue that the form of trade barriers has important implications for this question. Specifically, while ad-valorem tariffs have a neutral effect on technology adoption, non-tariff barriers such as an import quota will tend to delay adoption of new technologies. This is due to the fact that, since a quota constraint has effects similar to a specific price increase, the imposition of quota protection will also tend to delay the adoption of new, superior technologies. This result has important policy implications since it implies that the conversion of current non-tariff barriers into equivalent ad-valorem tariffs (i.e., tariffication) will have a positive impact on the worldwide diffusion of new technology.

5 Appendix

5.1 Non-transferable Quota Licenses

In this section we analyze the effects of a quota regime under the assumption that $\overline{Q}$ quota licenses are distributed to each firm and these quota licenses are non-transferable. In that case, assuming the quota binds, each firm sells $\overline{Q} = \frac{p(i,t)^{-\sigma}E}{\int_0^n p(i,t)^{1-\sigma}dz}$ units in the foreign country. From (15) this implies that in each period:

$$1 + \lambda_L = \frac{1}{\varphi} + \lambda_H \tag{25}$$

Note that (25) implies that symmetric allocated quota licenses impose greater costs on high-tech firms than they do on low-tech firms (i.e., $\lambda_H > \lambda_L$). Basically, in this framework, quotas act as a conditional tariff, where the trade tax is increased on those firms which choose to adopt the new technology. Thus, a non-transferable quota results in an even greater delay in adoption than a transferable quota (since firms which adopt the cost-saving technology cannot purchase additional licenses from the low-tech firms). Intuitively this result is is not surprising as the main benefit of adopting a productivity-improving technology is that one can sell a greater volume of goods at a lower price (i.e., a scale effect). Thus, quantity constraints (such as a quota) which prevent the expropriation of these scale effects by firms tend to deter the adoption of such technologies in a dynamic setting.

5.2 Proof of Proposition 1

From the profit functions, one can derive that the profit differential at time T_L (i.e., when $q_h = q_f = 0$) is given by:

$$\pi_H - \pi_L = \frac{(\varphi^{\sigma-1} - 1)E}{\sigma}\left[\frac{1}{n + n_f b_h^{1-\sigma}} + \frac{b_f^{1-\sigma}}{n_f + n b_f^{1-\sigma}}\right] \tag{26}$$

From (26) it is direct to derive that, at time T_L, $\frac{\partial(\pi_H - \pi_L)}{\partial b_h} > 0$. Thus, T_L occurs earlier. Similar calculations reveal that T_H occurs earlier as well. Q.E.D.

5.3 Proof of Proposition 2

The zero-profit condition is defined by:

$$\Pi = \Pi_1 + \Pi_2 + \Pi_3 - F = 0 \tag{27}$$

where $\Pi_1 = \int_0^{T_L} e^{-rt}\pi_L(q_h = q_f = 0)dt$; $\Pi_2 = \int_{T_L}^{T_H} e^{-rt}\pi_L(q_h(t), q_f(t))dt - X(T_L)$, and $\Pi_3 = \int_{T_H}^{\infty} e^{-rt}\pi_H(q_h = q_f = 1)dt$.

Totally differentiating (27) and applying the envelope theorem:[14]

[14] Note that the first-order condition for optimal adoption ensures that changes in adoption dates do not effect the present-discounted value of profits.

$$\frac{d\Pi}{db_h} = 0 = \frac{d\Pi_1}{db_h} + \frac{d\Pi_2}{db_h} + \frac{d\Pi_3}{db_h} \tag{28}$$

First, from the profit conditions, (8), one derives that the profit differential for a firm is given by:

$$\pi_H - \pi_L = (\varphi^{\sigma-1} - 1)\pi_L \tag{29}$$

Thus, during the diffusion phase, the first-order condition, (9) fixes low-tech profits at:

$$\pi_L(q^*) = \frac{1}{\varphi^{\sigma-1} - 1} \frac{-X'(T)}{e^{-rT}} \tag{30}$$

Which implies that:

$$\Pi_2 = \frac{1}{\varphi^{\sigma-1} - 1}[X(T_L) - X(T_H)] - X(T_H) \tag{31}$$

Note that profits during the diffusion phase are completely independent of b_h (i.e., $\frac{d\Pi_2}{db_h} = 0$). Since $\pi_H(q_h = q_f = 1) = \pi_L(q_h = q_f = 0)$, Π_1 and Π_3 are proportional (i.e., their derivatives with respect to policy must have the same sign). Thus, from (28):

$$\frac{d\Pi_1}{db_h} = \frac{d\Pi_3}{db_h} = 0 \tag{32}$$

Finally, note that $\frac{d\Pi_1}{db_h} = 0$ implies that $\frac{d\pi_L(q_h=q_f=0)}{db_h} = 0$ as $\Pi_1 = [1 - e^{-rT_L}]/r[\pi_L(q_h = q_f = 0)]$. Thus, from (29), $\frac{d(\pi_H(q_h=q_f=0) - \pi_L(q_h=q_f=0))}{db_h} = 0$. Since an ad-valorem tariff has no impact on the profit differential prior to the diffusion phase (i.e., before T_L), it will have no impact on the timing of T_L. The fact that ad valorem tariffs do not effect T_H is similarly established. Q.E.D.

5.4 Proof of Proposition 3

Profits for a foreign firm, given a home tariff of b_h, are given by:

$$\begin{aligned} \pi_{Lf}(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} b_h^{1-\sigma} E}{\sigma \int_0^{n+n_f} p_h(i,t)^{1-\sigma} dz} + \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} E}{\sigma \int_0^{n+n_f} p_f(i,t)^{1-\sigma} dz} \\ \pi_{Hf}(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} \varphi^{\sigma-1} b_h^{1-\sigma} E}{\sigma \int_0^{n+n_f} p_h(i,t)^{1-\sigma} dz} + \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} \varphi^{\sigma-1} E}{\sigma \int_0^{n+n_f} p_f(i,t)^{1-\sigma} dz} \end{aligned} \tag{33}$$

From these the profit differential for a foreign firm, is given by:

$$\pi_{Hf} - \pi_{Lf} = (\varphi^{\sigma-1} - 1)\pi_{Lf} \tag{34}$$

Holding home adoption dates constant and applying the envelope condition, one can derive (28). Thus, the remainder of the proof is equivalent to that of Proposition 2. Q.E.D.

5.5 Proof of Proposition 5

Let Q represent the per-period quantity of quota licenses distributed to firms. Note first that a reduction Q results in an increase in λ_t for any time period t. Let λ_{T_L} be the marginal cost of the quota constraint prior to technological diffusion (i.e., prior to T_L). From the profit functions, one can derive that the profit differential at time T_L (i.e., when $q_h = q_f = 0$) is given by:

$$\pi_H - \pi_L = \frac{(\varphi^{\sigma-1} - 1)E}{\sigma}\left[\frac{1}{n + n_f(b^{1-\sigma} + \lambda_{T_L})} + \frac{b^{1-\sigma}}{n_f + nb^{1-\sigma}}\right] \tag{35}$$

From (35) it is direct to derive that, at time T_L, $\frac{\partial(\pi_H - \pi_L)}{\partial \lambda_{T_L}} > 0$. Thus, T_L occurs earlier. Similar calculations reveal that T_H occurs earlier as well. Q.E.D.

5.6 Proof of Proposition 6

As before, the zero-profit condition is defined by (27). Totally differentiating (27) and applying the envelope theorem one derives that:

$$\frac{d\Pi}{dQ} = 0 = \frac{d\Pi_1}{dQ} + \frac{d\Pi_2}{dQ} + \frac{d\Pi_3}{dQ} \tag{36}$$

From the profit conditions, one finds that $\pi_H - \pi_L = (\varphi^{\sigma-1} - 1)\pi_L$. Thus, by similar reasoning as that in the proof to Proposition 2, one derives that profits during the diffusion phase are completely independent of Q (i.e., $\frac{d\Pi_2}{dQ} = 0$).

However, given the presence of a time-invariant quota, Π_1 and Π_3 are no longer proportional. Specifically, once again let λ_{T_L} be the marginal cost of the quota prior to diffusion and λ_{T_H} be the marginal cost of the quota following diffusion. It is direct to derive that, for the aggregative level of foreign imports to be held constant over time (since the quota is time-invariant), it must be the case that $\lambda_{T_H} > \lambda_{T_L}$. However, it can be shown that this increase in the marginal cost of the quota results in the quota increasing home firm profits following diffusion ($\pi_H(q_h = q_f = 1)$) relative to profits prior to diffusion ($\pi_L(q_h = q_f = 0)$). Thus, from (36), it must be the case that:

$$\frac{d\Pi_1}{dQ} < 0 \quad and \quad \frac{d\Pi_3}{dQ} > 0 \tag{37}$$

Finally, $\frac{d\Pi_1}{dQ} < 0$ implies that $\frac{d\pi_L(q_h=q_f=0)}{dQ} < 0$ as $\Pi_1 = [1 - e^{-rT_L}/r]\pi_L(q_h = q_f = 0)]$. Thus, $\frac{d(\pi_H - \pi_L)}{d\lambda} < 0$ in the time periods preceding diffusion, which implies that the diffusion phase will be delayed (i.e., T_L will occur later). Just like $\frac{d\Pi_1}{dQ} < 0$ implies that T_L is delayed, similar calculations show that $\frac{d\Pi_3}{dQ} > 0$ implies that T_H will occur earlier. Q.E.D.

5.7 Proof of Proposition 7

As before, the zero-profit condition is defined by (27). Totally differentiating (27) and applying the envelope theorem one derives that:

$$\frac{d\Pi}{d\lambda} = 0 = \frac{d\Pi_1}{d\lambda} + \frac{d\Pi_2}{d\lambda} + \frac{d\Pi_3}{d\lambda} \tag{38}$$

From the profit conditions, one finds that $\pi_H - \pi_L = (\varphi^{\sigma-1} - 1)\pi_L$. Thus, by similar reasoning as that in the proof to Proposition 2, one derives that profits during the diffusion phase are completely independent of λ (i.e., $\frac{d\Pi_2}{d\lambda} = 0$).

However, given the presence of a quota, $\pi_H(q_h = q_f = 1) > \pi_L(q_h = q_f = 0)$ for home firms (reflecting the increased protectionist impact of the quota over the diffusion period). Thus, Π_1 is not proportional to Π_3 and , since $\frac{d\pi_H(q_h=q_f=1)}{d\lambda}|_{\lambda=0} > \frac{d\pi_L(q_h=q_f=0)}{d\lambda}|_{\lambda=0}$, from (36) it must be the case that:

$$\frac{d\Pi_1}{d\lambda} < 0 \quad and \quad \frac{d\Pi_3}{d\lambda} > 0 \tag{39}$$

Finally, $\frac{d\Pi_1}{d\lambda} < 0$ implies that $\frac{d\pi_L(q_h=q_f=0)}{d\lambda}|_{\lambda=0} < 0$ as $\Pi_1 = [1 - e^{-rT_L}/r][\pi_L(q_h = q_f = 0)]$. Thus, $\frac{d(\pi_H - \pi_L)}{d\lambda}|_{\lambda=0} < 0$ in the time periods preceding diffusion, which implies that the diffusion phase will be delayed (i.e., T_L will occur later). Just like $\frac{d\Pi_1}{d\lambda} < 0$ implies that T_L is delayed, similar calculations show that $\frac{d\Pi_3}{d\lambda} > 0$ implies that T_H will occur earlier. Q.E.D.

5.8 Proof of Proposition 8

Note that profits for a foreign firm in both the foreign country market, π^f, and the home country market, π^h are given by:

$$\begin{aligned} \pi^h_L(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}(b+\lambda)^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz}, \quad \pi^f_L(t) = \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz} \\ \pi^h_H(t) &= \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}\varphi^{\sigma-1}(b+\lambda\varphi)^{1-\sigma}E}{\sigma\int_0^{n+n_f} p_h(i,t)^{1-\sigma}dz}, \quad \pi^f_H(t) = \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma}\varphi^{\sigma-1}E}{\sigma\int_0^{n+n_f} p_f(i,t)^{1-\sigma}dz} \end{aligned} \tag{40}$$

The zero-profit condition for foreign firms is defined by (27) when evaluated at foreign profit levels. As before, holding home adoption dates constant and applying the envelope condition, one can derive (38). From (40), the profit differential for a foreign firm, is given by:

$$\pi_H(t) - \pi_L(t) = (\varphi^{\sigma-1} - 1)\pi^f_L(t) + \frac{\varphi^{\sigma-1}(b+\lambda\varphi)^{1-\sigma} - (b+\lambda)^{1-\sigma}}{(b+\lambda)^{1-\sigma}}\pi^h_L(t) \tag{41}$$

Note that, from the first-order condition for optimal adoption, $\frac{d(\pi_H - \pi_L)}{d\lambda} = 0$, during the diffusion phase. Thus, from (41), one can derive that $\frac{d(\pi^h_L + \pi^f_L)}{d\lambda}|_{\lambda=0} > 0$ during diffusion which implies that $\frac{d\Pi_2}{d\lambda}|_{\lambda=0} > 0$. Thus, from (38) one derives that:

$$\frac{d\Pi_1}{d\lambda} + \frac{d\Pi_3}{d\lambda} < 0 \tag{42}$$

Given the presence of a quota, $\pi_H(q_h = q_f = 1) < \pi_L(q_h = q_f = 0)$ for foreign firms, and thus Π_1 is not proportional to Π_3. Since $\frac{d\pi_H(q_h=q_f=1)}{d\lambda}|_{\lambda=0} < \frac{d\pi_L(q_h=q_f=0)}{d\lambda}|_{\lambda=0}$, from (42) it must be the case that $\frac{d\Pi_3}{d\lambda} < 0$ which implies that $\frac{d\pi_H(q_h=q_f=1)}{d\lambda}|_{\lambda=0} < 0$. Thus, from (41), one can derive that $\frac{d(\pi_H(q_h=q_f=1) - \pi_L(q_h=q_f=1))}{d\lambda}|_{\lambda=0} < 0$ which implies that T_H occurs later. Finally, using (41) and the fact that $\frac{d\pi_H(q_h=q_f=1)}{d\lambda}|_{\lambda=0} < 0$, one can derive that $\frac{d(\pi_H(q_h=q_f=0)-\pi_L(q_h=q_f=0))}{d\lambda}|_{\lambda=0} < 0$ which implies that T_L occurs later as well. Q.E.D.

5.9 Proof of Proposition 9

First, from the profit conditions for reciprocal quotas, (22), one derives that the profit differential is given by:

$$\pi_H(t) - \pi_L(t) = \frac{\varphi^{\sigma-1}[1+(b+\lambda\varphi)^{1-\sigma}]}{(1+(b+\lambda)^{1-\sigma}}\pi_L(t) \tag{43}$$

Thus, during the diffusion phase, the first-order condition fixes low-tech profits at:

$$\pi_L(t) = \frac{(1+(b+\lambda)^{1-\sigma}}{\varphi^{\sigma-1}[1+(b+\lambda\varphi)^{1-\sigma}] - [(1+(b+\lambda)^{1-\sigma}]}\frac{-X'(t)}{e^{-rt}} \tag{44}$$

Which implies that:

$$\Pi_2 = \frac{(1+(b+\lambda)^{1-\sigma}}{\varphi^{\sigma-1}[1+(b+\lambda\varphi)^{1-\sigma}] - [(1+(b+\lambda)^{1-\sigma}]}[X(T_L) - X(T_H)] - X(T_H) \tag{45}$$

From the above it is direct to derive that $\frac{d\Pi_2}{d\lambda}|_{\lambda=0} > 0$. Since Π_1 and Π_3 are proportional, from (38), one derives that $\frac{d\Pi_1}{d\lambda} < 0$ and $\frac{d\Pi_3}{d\lambda} < 0$.

Finally, note that $\frac{d\Pi_1}{d\lambda} < 0$ implies that $\frac{d\pi_L(q=0)}{d\lambda}|_{\lambda=0} = 0$ as $\Pi_1 = A[\pi_L(q=0)]$ where $A = [1-e^{-rT_L}]/r$. Thus, from (43), one can derive that $\frac{d(\pi_H(q=0)-\pi_L(q=0))}{d\lambda}|_{\lambda=0} < 0$ which implies that T_L occurs later. Similar calculations show that, since $\frac{d\Pi_3}{d\lambda} < 0$, T_H will occur later as well. Q.E.D.

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