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Productivity growth, trade and FDI nexus: evidence from the Canadian manufacturing sector

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Abstract Using the confined exponential and logistic models of technology diffusion, this paper investigates the roles played by international trade and FDI in explaining productivity growth through both technology transfer and domestic innovation, with the technology transfer also occurring independently. Using panel data on Canadian manufacturing industries, we first find a robust role for the autonomous and international trade embodied technology transfer in explaining TFP growth. Second, international trade and FDI (as well as research and development) all contribute to productivity growth through the rate of innovation. Finally, we find that the exponential and logistic models of technology diffusion may have different implications for the growth dynamics in a technologically lagging country.

Keywords Economic growth · TFP · Technology transfer · International trade · FDI

JEL Classification O30 · O47 · O570

1 Introduction

It has been argued that the transfer of new technologies (or knowledge) from the leading country, and the capacity to assimilate them, is an important source of productivity growth in follower countries—at least as important as domestic inventiveness itself. For example, Keller (2004) points out that the major sources of productivity growth, which originated from technological change in OECD countries, are not domestic; instead, they come from abroad. For most countries, he reports that foreign sources of technology account for 90 % or more of domestic productivity growth. Similarly, Eaton and Kortum (1999) estimate that in 1988 around 85 % of productivity growth in France, Germany and the UK was due to foreign research and development (R&D). However, according to Nadiri and Kim

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(1996), the importance of research spillovers (across countries) varies with the country: domestic research seems important in explaining productivity in the U.S., but the contribution of foreign research is more important for countries like Canada and Italy.[1]

As a result, improving our understanding of the role of foreign technology (in enhancing domestic productivity) and how it diffuses across borders is important in order to identify what governments can do through policies to stimulate international technology diffusion and its absorption in their economies. According to Hoekman and Javorcik (2006), the ‘correct’ policy intervention in this area, if any, depends critically on the channels through which technology diffuses internationally and the quantitative effects of the various diffusion processes on allocative efficiency and productivity growth. In addition, as many other authors, they argue that the major channels for technology diffusion across countries include international trade and foreign direct investment (FDI).

Thus, in light of Canada’s lagging productivity performance relative to the U.S. (and other OECD countries), particularly in the manufacturing sector, this paper aims to investigate the role of technology transfer (*through international trade* and *FDI*, e.g.,) in explaining productivity growth in Canadian manufacturing industries over the period 1987–2004. To this end, we develop an empirical framework in which domestic innovation and technology transfer provide two potential sources of productivity growth for a country behind the technological frontier. Within this framework, we examine the roles played by international trade, FDI, as well as other factors in stimulating each source of productivity growth, while also allowing technology transfer to occur independently of the above economic variables.[2] In other words, we investigate whether a number of variables proposed as determinants of productivity growth (such as international trade, FDI, and R&D) affect productivity growth directly through the rate of innovation or indirectly through the speed of technology diffusion, which is also allowed to proceeds autonomously. We look at these issues across alternative models of technology diffusion, namely the confined exponential and logistic diffusion models, in which the difference in levels of total factor productivity (TFP) between Canada and a frontier country (the U.S.) is used to measure the potential for technology transfer.

This paper improves over the existing literature in three important respects, which are discussed in turn. First, it has often been a common assumption in the literature to gauge international technology spillovers by using international R&D spillover regressions. For example, if a country’s R&D activity measure is positively correlated with TFP in another country, all else equal, this is consistent with international technology spillovers from the former to the latter country. A drawback of this approach is that it allows for knowledge spillovers from *only* formal R&D, and thereby ignores the informal activities (*not captured in R&D statistics*) which most empirical evidence suggests are important for productivity growth—(see, e.g., Luh and Stefanou (1993); Bahk and Gort 1993) for evidence on learning by doing. Thus, our use of the technology gap as a direct measure of the potential for technology transfer allows for knowledge spillovers from both formal R&D investments and informal sources of productivity growth.

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[1] The diffusion of technology typically involves both market transactions and externalities. However, many economists believe that most international technology diffusion occurs not through market transactions (such as patenting, licensing and copyrights) but instead through externalities (spillovers). Thus, in this paper we use the terms technology/knowledge transfers and spillovers interchangeably.

[2] Xu (2000) stresses that there exist significant cross-country knowledge spillovers in both *disembodied* and *embodied* forms, and that international trade and FDI are considered to be two major channels for embodied knowledge spillovers. Disembodied (or autonomous) spillovers include knowledge and technology flows that do not relate directly to the flow of goods and services between economic agents (Griliches 1992).

Second, another drawback of most previous studies, particularly existing work on R&D knowledge spillovers, is that they often assume a specific channel (such as international trade) for international technology diffusion. Unlike those studies, which looked at technology diffusion channels (e.g., international trade vs. FDI) in isolation, we investigate whether foreign technology diffuses through international trade against the alternatives that its pace is determined by FDI and other factors, or that it proceeds independently. This is in line with Hoekman and Javorcik (2006)'s claim that a more systematic approach requires the simultaneous consideration of the effects of various technology transmission channels on firm or industry productivity. Given the complementarities (and indivisibilities) of various international activities that transmit technology, econometric models that threat any one of them as the unique source of foreign technology run a considerable risk of misattribution.[3] To our knowledge, this is one of the few empirical studies that attempt to ascertain simultaneously the relative importance of alternative diffusion channels within the same framework.

Third, some few existing empirical studies have appropriately measured the potential for technology transfer by using the technology gap (difference in levels of TFP between a technologically lagging country and the frontier country)—(see, e.g., Khan 2006; Cameron et al. 2005). Nonetheless, these studies not only overlook the role of FDI, but also consider *only* one type of technology diffusion processes, i.e., the confined exponential model. However, as mentioned earlier there exists an alternative technology diffusion process, namely the logistic model of technology diffusion. This latter diffusion process has been neglected in existing empirical literature, although a priori, there appears to be no reason to favor one of these technology diffusion processes over the other (see, e.g., Benhabib and Spiegel 2003). More importantly, as will be seen shortly, the two models may have different implications (both qualitatively and quantitatively) for the growth dynamics in a technologically lagging country. Consequently, the present paper contributes to the literature by applying for the first time (in the context of trade, FDI and R&D driving productivity growth) these two aforementioned processes of technology diffusion.

To preview our main results, we first find evidence of a robust role for the autonomous and international trade embodied technology transfer in explaining TFP growth in the Canadian manufacturing sector. Second, international trade, FDI, and R&D all contribute to productivity growth through the rate of innovation. Finally, we find that the exponential and logistic models of technology diffusion may have different implications for the growth dynamics of a technologically lagging country.

The remaining of the paper is organized as follows. The next section briefly reviews the empirical evidence on the international technology diffusion through international trade and FDI. Section 3 outlines the theoretical framework underlying our empirical model. Section 4 presents the evolution of relative levels of TFP across manufacturing industries in Canada and the U.S. It also discusses the construction of other variables and data sources. Section 5 introduces the econometric specification and presents estimation results. Finally, Sect. 6 provides summary and some concluding remarks.

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[3] Thus, previous studies that specify one channel (such as international trade) may suffer from omitted variable biases and thereby overestimate the importance of this channel in international technology diffusion. For example, Coe and Helpman (1995) estimate an equation with international trade as the sole channel of international R&D spillovers. Keller (1998) finds, however, that the international R&D spillovers identified in Coe and Helpman (1995) are not related to international trade per se, but are a result of various unspecified spillover channels.

2 International technology diffusion through trade and FDI: evidence from empirical research

As mentioned earlier, cross-country technology or knowledge spillovers may take place in both disembodied and embodied forms, and international trade and FDI are considered to be the most important channels for embodied knowledge spillovers. In this section, we review some widely quoted papers that have empirically investigated the diffusion of technology through international trade and/or FDI.[4]

Coe and Helpman (1995) (henceforth, CH) are the first to examine the R&D spillovers among (22) OECD countries through international trade. Using cumulative R&D expenditures as a proxy for stock of knowledge, they study the effects of the domestic R&D as well as the R&D stocks of a country's trading partners on domestic TFP. Using pooled data, they find that trade is an important channel of transferring technology and trade-weighted foreign R&D stock has a positive and statistically significant impact on domestic country's TFP. Their estimates also suggest domestic R&D has a positive effect on TFP, but foreign R&D capital stock seems to have a stronger effect than domestic R&D, and the greater the effect of foreign R&D, the more open the economy is. Moreover, domestic R&D may be more important in larger countries than in smaller countries. CH's paper inspired a number of studies on international R&D spillovers. Coe et al. (1997) extend their sample and investigate the importance of trade as a vehicle for R&D spillovers from industrialized countries to less developed countries (LDCs). Their findings show that TFP in LDCs is positively and significantly related to the R&D of their industrial trade partners. The spillovers from the U.S. prove to be the largest as the U.S. is the leading trade-partner for many LDCs. Keller (1998) challenges CH's results by generating simulated and randomly selected trade partners and estimating the international R&D spillover effects. He finds that these 'counterfactual' (import-shares) estimations give rise to larger positive international R&D spillovers and explain more of the variation in productivity across countries. Thus, he argues these results imply that the R&D spillovers might occur through channels other than international trade.

Although Keller's (1998) findings have led some to doubt the importance of trade for international technology diffusion, subsequent work seems to strengthen the evidence for import-related international technology diffusion. Xu and Wang (1999) decompose total imports into capital and non-capital goods imports and find that R&D spillovers embodied in trade flows are mainly carried by capital goods due to their higher content of technology. They also suggest that substantial R&D spillovers in the OECD countries are transmitted through other unknown channels. Lumenga-Neso et al. (2005) revisit the results of Coe and Helpman (1995) and Keller (1998). Instead of computing the foreign knowledge variable as a bilateral-import share weighted sum of foreign R&D, they construct an alternative variable to capture the effect of the previous rounds of imports as well.[5] Using this variable, they confirm that trade contributes to the technology spillovers. Acharya and Keller (2009) examine international technology transfer through R&D spillovers in sixteen OECD countries' manufacturing industries. Their analysis shows that the productivity

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[4] It is worth mentioning that this review does not cover all studies addressing trade and/or FDI and productivity linkages, but only those that have *explicitly* used trade and/or FDI (as a channel of transmission) in constructing measures of foreign technology transfer.

[5] This captures the case that even if some country *i* imports only from some other country *h*, for instance, the former might still gain access to technology from countries other than *h*—if country *h* has in turn imported from those other countries before.

impact of international technology transfer often exceeds that of domestic R&D, more so in high-technology industries. Moreover, technology transfer is found to be strongly varying across country-pairs and tends to decline in geographic distance, pointing to goods trade as the transfer channel. Evaluating directly this hypothesis, they find that trade (as measured by imports) is crucial for technology transfer from Germany, France, and the UK, while for the U.S., Japan, and Canada non-trade channels are more important.

Compared to the use of international trade as weights in the construction of foreign R&D variable, FDI as a channel of knowledge spillovers has received relatively little attention. Lichtenberg and van Pottelsberghe (1996, 2001) extend CH's analysis by incorporating both inward and outward FDI flows in addition to the trade flow as conduits of technology diffusion. Owing to limited bilateral FDI data, they test only 13 out of 22 OECD countries covered in CH's study. They find that outward FDI flows and imports flows are two simultaneous channels through which technology is internationally diffused. Surprisingly, inward FDI flows are not a significant channel of technology diffusion. Thus, they argue that the hypothesis of technology sourcing associated with MNEs activities abroad is confirmed while the widespread belief that inward FDI is a major channel of technology transfer is rejected.

Hejazi and Safarian (1999) measure international spillovers through trade and FDI outflow from six of the G-7 countries to all OECD countries and Israel. They find that the R&D spillovers through FDI are greater than those through trade. The importance of trade as a spillover channel is reduced and the overall spillovers increase significantly with the inclusion of FDI. However, the small number of countries and limited FDI data make it difficult to compare their results with those from previous research. A counterintuitive result emerges when they interact openness to FDI with FDI-weighted foreign R&D stock. It shows that the impact of FDI as a channel for technology diffusion becomes insignificant. In other words, they find that technology transfer through FDI has no correlation to a country's overall openness to FDI.

Xu and Wang (2000) examine international trade and FDI as channels for technology diffusion (measured by R&D diffusion) among industrialized countries. They find strong empirical support for capital goods trade as a channel for international technology diffusion and some evidence that multinational enterprises (outward FDI) transmit foreign technology back to the home country. However, they find no evidence that inward FDI is a significant channel for international technology diffusion among industrialized countries. Moreover, their results also show that technology diffuses in disembodied forms (as measured by technology gap using TFP levels), with countries that are farther from the world technology frontier benefiting more.

In a developed and developing cross-country study, Ciruelos and Wang (2005) investigate international R&D diffusion through both inward FDI and trade and find that both FDI and trade serve as important channels for cross-country technology diffusion. However, trade has a stronger effect on TFP than FDI. In addition, they also find that there exist heterogeneous effects of FDI in developed and developing countries. For inward FDI to promote technology diffusion in developing countries, a certain threshold of human capital has to be reached.

Using a panel of OECD countries, Zhu and Jeon (2007) investigate how international R&D spillovers transmit through different channels (trade, FDI, and information technology) and enhance TFP across national borders. They find that international trade remains an important conduit for R&D spillovers. Although inward FDI is positively related to international R&D spillovers from the source country to the host country, its impact on technology transfer turns out to be much smaller. Outward FDI has a positive impact on R&D spillovers, but it is only marginally significant. Further, they also find that the development of information technology has played a more important role in international technology diffusion and productivity growth in recent years.

Using micro-level data, Keller and Yeaple (2009) estimate international technology spillovers to U.S. manufacturing firms via imports and FDI. Their results suggest that FDI leads to substantial productivity gains for domestic firms. The size of FDI spillovers is economically important, accounting for about 14 % of productivity growth in U.S. firms between 1987 and 1996. FDI spillovers are particularly strong in high-tech sectors, whereas they are largely absent in low-tech sectors. Small firms with low productivity benefit more from FDI spillovers than larger productivity firms with more productivity do. The evidence for import spillovers is much weaker. Another micro-level study, by Kraay et al. (2006), uses plant-level panel data from Colombia, Mexico, and Morocco to examine the simultaneous effects of various international transactions on firm productivity. Their findings suggest that past international activities (such as importing, exporting, and FDI) do not help much in predicting current firm performance, once past realizations on quality and marginal costs are controlled for. That is, activities do not typically Granger-cause performance. Interestingly, in the minority of cases where significant associations emerge, international activities appear to move costs and product quality in the same direction. Thus the net effect on profits in these cases is not immediately apparent.

To sum up this review of literature, it emerges that although a few recent studies have considered several channels of technology diffusion simultaneously, the majority of existing studies have examined only one channel in isolation. Moreover, while trade has received strong empirical support as a channel for international technology diffusion, evidence on the FDI channel is mixed. One important reason for the mixed results on FDI is that FDI data are of poor quality. For example, Xu and Wang (2000) and Xu (2000) underline that even within the OECD, countries define FDI differently. Thus, Xu (2000) contends that results from multi-country studies using FDI data should be considered with cautions, and thereby advocates for country-specific studies.

Finally, as mentioned earlier the present paper extends the framework developed by Bernard and Jones (1996a, b). Similar extended framework has also been used by Khan (2006) and Cameron et al. (2005), which employ French and the UK manufacturing sector data, respectively. However, this paper differs from the latter studies in two important respects. First, they overlook the role of FDI and focus on international trade and R&D as factors influencing the transmission of technology. Second, they ignore the logistic model of technology diffusion and consider only the confined exponential model—recall that the drawbacks associated with these two omissions have been discussed above. Nonetheless, Khan (2006) finds that spending on R&D and trade with technologically advanced economies positively influence TFP growth via innovation, but not the speed of technology transfer. Cameron et al. (2005) report that while R&D raises TFP growth through innovation, international trade enhances growth via the speed of technology diffusion. Besides, both studies report strong evidence for productivity convergence within manufacturing between the non-frontier country (France or UK) and the frontier (the U.S.). However, in examining the role of sectors in aggregate convergence for 14 OECD countries (including France and UK), Bernard and Jones (1996a, b) find that manufacturing sector shows no or little evidence of either labor productivity or TFP convergence, while other sectors, especially services, are driving the aggregate convergence to the U.S. Interestingly, as will be seen in the next section, this discrepancy in findings may be an implication of the type of technology diffusion and catch-up processes used in Khan (2006) and Cameron et al. (2005), i.e., the exponential model of technology diffusion.

3 Theoretical framework

This section outlines the theoretical framework underlying our modeling strategy. The framework provides a tractable and intuitive approach to understanding productivity dynamics across Canadian manufacturing industries. Consider a two-country model where $i \in \{B, F\}$ denotes countries, and $j = 1, \ldots, J$ representing manufacturing industries. Value added (Y) in each industry at time t is produced with labor (L) and physical capital (K) according to a standard neoclassical production technology,

$$Y_{ijt} = A_{ijt} F_j(L_{ijt}, K_{ijt}) \tag{1}$$

where $F_j(.,.)$ satisfies the assumptions of the constant returns to scale and diminishing marginal returns to each input factor. A_{ijt} is an index of technical efficiency (or TFP) and varies across countries, industries, and time. Henceforth, the country at the technological frontier (i.e., the one with the highest level of TFP) is indexed by F while i denotes the country that lies behind the frontier. In the empirical analysis that follows, the U.S. and Canada are denoted as the frontier and non-frontier economies, respectively. As Fig. 1 shows, TFP levels in most Canadian manufacturing industries have tended to be relatively lower than those in the U.S. for the period under study.[6]

Following Bernard and Jones (1996a, b), we assume two sources of productivity growth for a country-industry behind the technological frontier: domestic innovation and technology transfer from the frontier country. However, as underlined earlier, there are two types of technology diffusion and catch-up processes, namely the exponential and logistic models of technology diffusion. Let's discuss in turn the functional forms of these diffusion processes.

The confined exponential diffusion process, which has received most attention in the empirical literature, is expressed as follows:

$$\Delta \ln A_{ijt} = \gamma_{ij} + \lambda_{ij}\left(\frac{A_{Fjt-1}}{A_{ijt-1}} - 1\right), \quad \gamma_{ij}, \lambda_{ij} \geq 0 \tag{2}$$

where γ_{ij} is the rate of growth due to sector-specific domestic innovation, while $((A_{Fjt-1}/A_{ijt-1}) - 1)$ is the sector-specific TFP gap between the frontier economy (F) and the non-frontier country (i). The latter term is used as an indicator of the potential for technology transfer from F to i with λ_{ij} denoting the speed of technological transfer or catch-up.[7] Equation (2) therefore neatly summarizes the notion that productivity growth in sector j of country i stems from either domestic innovation or technology transfer from the frontier to the non-frontier economy.[8] Thus, as shown in Eq. (2), the exponential technology diffusion or catch-up process stipulates that the further country i lies behind the frontier in sector j, the larger the second term on the right-hand side of Eq. (2) and the greater the potential for productivity growth through technology transfer. As a result,

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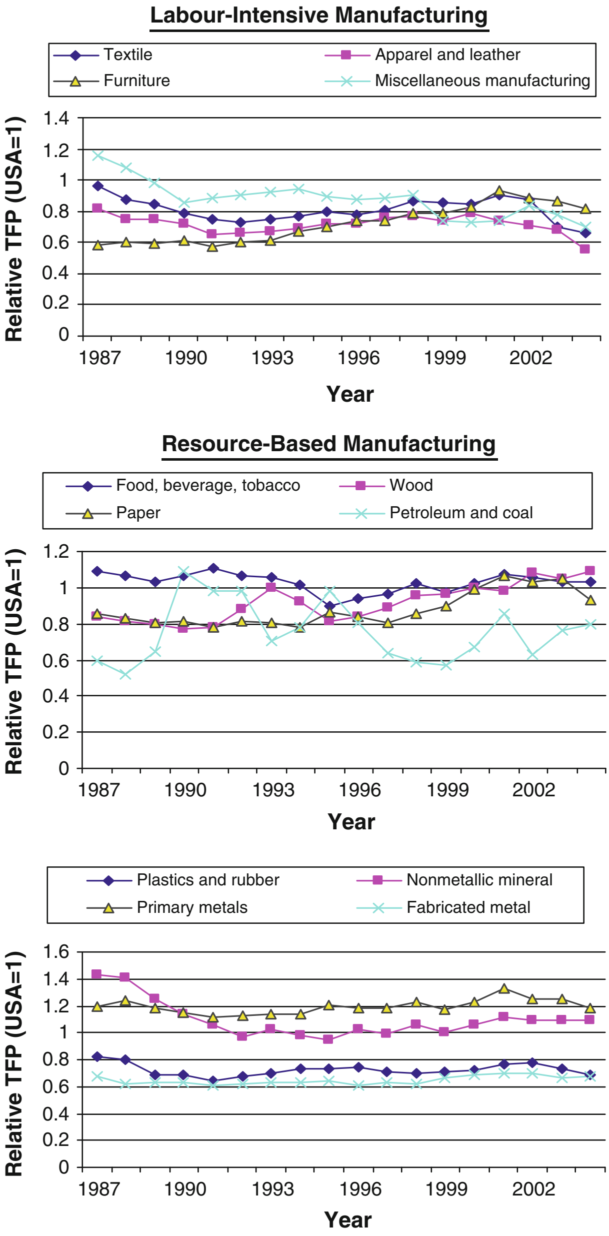
[6] Note that these data (as shown in Fig. 1) on the two-country relative TFP levels have also been used in Rao et al. (2008).

[7] This functional form for the technology diffusion process was first specified by Nelson and Edmund (1996).

[8] The endogenous growth theory provides a similar formulation. In a closed-economy endogenous growth model, productivity *growth* is a function of resources devoted to technology innovation, $GTFP = g(R)$, where *GTFP* denotes TFP growth rate and R denotes R&D intensity. Extended to an open economy, productivity growth can come from both domestic innovation and absorption of foreign technology.



Labour-Intensive Manufacturing

Resource-Based Manufacturing

Fig. 1 Canada–U.S. relative TFP levels

the exponential diffusion process imposes convergence ex-ante—it implies that catch-up holds.

Besides, it is noteworthy that productivity growth in the frontier economy is driven solely by domestic innovation such that

$$\Delta \ln A_{Fjt} = \gamma_{Fj} \tag{3}$$

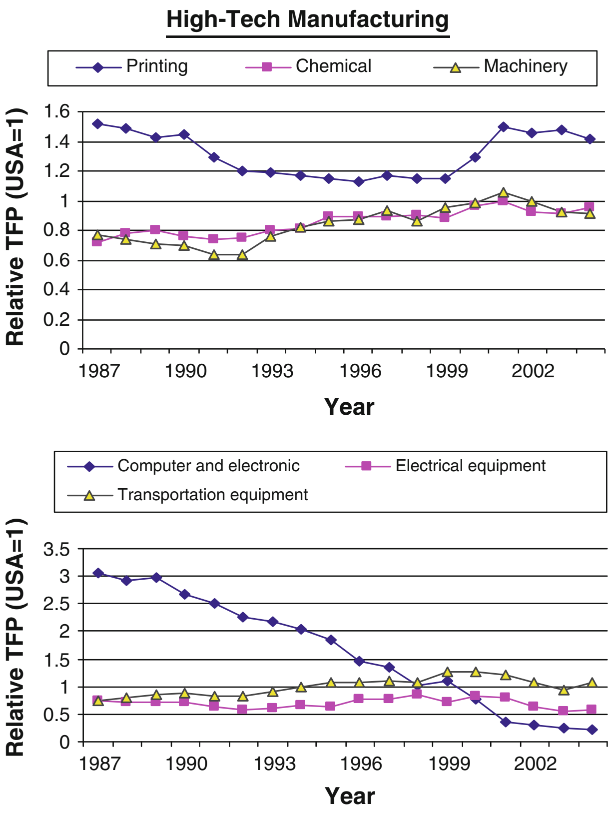


Fig. 1 continued

Applying the approximation formula $\{(w/z) - 1 \approx \ln w - \ln z = \ln(w/z)\}$ to Eq. (2) and then combining Eqs. (2) and (3) yield the following first-order difference equation for the evolution of relative TFP:

$$\Delta \ln\left(\frac{A_{ijt}}{A_{Fjt}}\right) = \left(\gamma_{ij} - \gamma_{Fj}\right) - \lambda_{ij} \ln\left(\frac{A_{ijt-1}}{A_{Fjt-1}}\right) \tag{4}$$

Equation (4) can be thought of as an equilibrium correction model, with adjustment towards a long-run or steady-state level of relative TFP. Assuming that in the long run, $\Delta \ln\left(\frac{A_{ijt}}{A_{Fjt}}\right) = 0$, the steady-state equilibrium is given by[9]

$$\ln\left(\frac{A^*_{ij}}{A^*_{Fj}}\right) = \frac{\gamma_{ij} - \gamma_{Fj}}{\lambda_{ij}} \tag{5}$$

Thus, in steady-state, country i will remain behind country F at an equilibrium distance where TFP growth from both innovation *and* technology transfer in the non-frontier

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[9] To see how quickly we converge to this steady-state equilibrium relative TFP $-$ $RTFP^* = \ln\left(A^*_{ij}/A^*_{Fj}\right)$, one can use the following general solution to the first-order difference equation for the relative TFP in Eq. (4): $(RTFP_t - RTFP^*) \approx e^{-\lambda t}(RTFP_0 - RTFP^*)$, where the subscripts t and 0 denote time and the initial value—for further details on this general solution (see Romer 2006).

country (i) exactly equals TFP growth from innovation alone in the frontier country (F)—i.e., a world balanced growth path. Note that there will be a productivity level gap between the two countries as long as the rate of innovation in the frontier is greater than the rate of innovation in the non-frontier country $(\gamma_{Fj} > \gamma_{ij})$.

Alternatively, there exits another technology diffusion process often neglected in the empirical literature, namely the logistic model of technology diffusion:

$$\begin{aligned} \Delta \ln A_{ijt} &= \gamma_{ij} + \lambda_{ij}\left(1 - \frac{A_{ijt-1}}{A_{Fjt-1}}\right) \\ &= \gamma_{ij} + \lambda_{ij}\left(\frac{A_{ijt-1}}{A_{Fjt-1}}\right)\left(\frac{A_{Fjt-1}}{A_{ijt-1}} - 1\right) \end{aligned} \tag{6}$$

Comparing Eqs. (2) and (6), the difference of the dynamics under the logistic model of technology diffusion and the confined exponential one is due to the presence of the extra term (A_{ijt-1}/A_{Fjt-1}). This term acts to dampen the rate of technology diffusion as the distance to the frontier increases, reflecting perhaps the difficulty of adopting more advanced technologies. Thus, although the logistic model also suggests that the further a country is behind the frontier, the greater the potential for technology spillovers, *but* it also implies the lesser is the country's absorptive capacity (or speed of the catch up), which is defined as its degree of success in adopting foreign technology. In other words, in contrast to exponential diffusion process, the logistic model allows for a dampening of the diffusion process so that the TFP gap between the frontier and a non-frontier country can keep growing. This means that the logistic diffusion process does not necessarily imply a catch-up or convergence. This discrepancy across the two diffusion models is illustrated in Fig. 2. As can be seen, the productivity growth in a lagging country is an increasing (linear) function of the productivity gap to the frontier under the exponential diffusion process; *but* it is a concave function of the gap under the logistic one where greater technological gap may impede growth. Consequently, the implications of these two specifications can be quite different for the growth pattern in a technologically lagging country. Shortly, we will further discuss and illustrate these differential impacts (across the two models) when analyzing the findings of some existing studies that have only used the exponential model.

The exposition so far has treated the terms γ_{ij}, λ_{ij}, and γ_{Fj} as parameters. However, a variety of mechanisms are proposed through which international trade and FDI may affect productivity growth, including knowledge spillovers and promoting innovation through increased competition, reverse engineering, and the elimination of redundancy in research. Besides, there is an extensive theoretical and empirical literature which argues that R&D is an important determinant of innovation. Another strand of research suggests that R&D may also play a role in promoting technology transfer by raising *absorptive capacity* (see, e.g., Cohen and Levinthal 1989; Griffith et al. 2004).[10] As a result, we assume both innovation (γ_{ij}) and technology transfer (λ_{ij}) to be a function of international trade, FDI, and R&D:

$$\gamma_{ij} = \eta_{ij} + \delta Z_{ijt-1}, \quad \lambda_{ij} = \theta + \mu Z_{ijt-1} \tag{7}$$

where Z is a vector including international trade (here imports), inward FDI, and R&D.[11] Thus, Eqs. (2) and (6) can be respectively rewritten as

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[10] The concept of absorptive capacity refers to the ability of countries to understand and adopt foreign technology for use in the domestic market. It is believed that the receiving country's learning or absorptive capacity depends on its R&D investments—hence the notion of R&D-based absorptive capacity.

[11] The literature on the diffusion of technology across countries involves two broad schools of thought; the first one emphasizes the importance of *absorptive capacity* and the second one stresses the role of *bilateral*

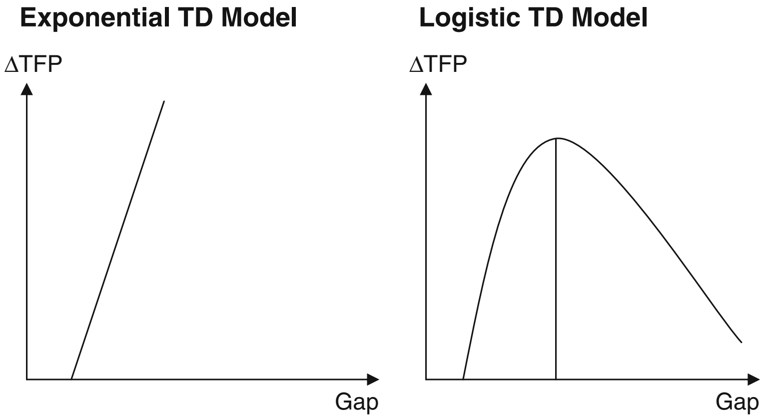

Fig. 2 Exponential and logistic technology diffusion models: implications for domestic TFP growth. Applying the approximation formula $\{(w/z) - 1 \approx \ln w - \ln z = \ln(w/z)\}$ to Eqs. (2) and (6) and denoting $X = (A_{Fjt-1}/A_{ijt-1}) \equiv Gap$, we have $\Delta TFP(X) = \ln(X), X \in [1, \infty)$ (exponential TD model); $\Delta TFP(X) = \frac{\ln(X)}{X}, X \in [1, \infty)$ (logistic TD model)

$$\Delta \ln A_{ijt} = \eta_{ij} + \delta_1 Z_{ijt-1} + \theta_1 \ln\left(\frac{A_{Fjt-1}}{A_{ijt-1}}\right) + \mu_1 Z_{ijt-1} \ln\left(\frac{A_{Fjt-1}}{A_{ijt-1}}\right) + \varepsilon_{ijt} \tag{8}$$

$$\Delta \ln A_{ijt} = \eta_{ij} + \delta_2 Z_{ijt-1} + \theta_2 \frac{A_{ijt-1}}{A_{Fjt-1}} \ln\left(\frac{A_{Fjt-1}}{A_{ijt-1}}\right) + \mu_2 Z_{ijt-1} \frac{A_{ijt-1}}{A_{Fjt-1}} \ln\left(\frac{A_{Fjt-1}}{A_{ijt-1}}\right) + \varepsilon_{ijt} \tag{9}$$

The parameter δ captures the (direct) effect of trade, FDI, and R&D variables on the rate of innovation and thereby TFP growth. On the other hand, μ is the coefficient on the interaction term and denotes the effect of these variables on the speed at which the technology gap between Canada and the U.S. in sector j is closed—i.e., the speed of convergence to the frontier economy. θ captures the evidence of international technology diffusion in disembodied forms whose importance has been underlined in many theoretical models of technology diffusion (see, e.g., Barro and Sala-i-Martin 1997). Finally, η_{ij} represents a country-industry fixed effect, which accounts for unobserved sector-specific and time-invariant heterogeneities.[12]

Now let's briefly discuss certain implications of the use of these technology diffusion models in some existing studies. As mentioned earlier, the exponential specification [Eq. (8)] has been widely used in the empirical literature, but some associated resulting

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Footnote 11 continued
ties. Thus, by specifying the speed of technology transfer (λ_{ij}) as a function of international trade, FDI, and R&D, we cover both aforementioned views.

[12] Assuming a very simple linear specification where $\gamma_{ij} = \delta Z_{ijt}$ and $\lambda_{ij} = \mu Z_{ijt}$ with Z being a single variable, one can specify a diffusion process that nests the logistic and exponential diffusion processes: $\Delta \ln A_{ijt} = \left(\delta + \frac{\mu}{s}\right) Z_{ijt} - \frac{\mu}{s} Z_{ijt} \left(\frac{A_{ijt}}{A_{Fjt}}\right)^S$ with $s \in [-1, 1]$. Note that this nested specification collapses to the logistic model when $s = 1$, and if $s = -1$, it collapses to the exponential model. Using a general Bernoulli equation, Benhabib and Spiegel (2003) show that the "the catch-up or convergence condition" for the growth rate of a non-frontier country to converge to the growth rate of the frontier becomes (under logistic model): $1 + \frac{\mu}{\delta} > \frac{Z_{Ft}}{Z_{it}}$. Thus, countries for which this inequality does not hold, will not converge to the frontier's growth rate unless they invest in their economic variable, Z_{it}, to meet this inequality.

findings are open to discussion. For example, using this specification, many OECD studies (including Scarpetta and Tressel 2002; Nicoletti and Scarpetta 2003; Conway et al. 2006) investigate the impact on productivity growth of product market regulations. They all find that regulatory reforms, which aimed at strengthening competition, have higher positive impact on productivity the further a country (or an industry) lags behind the technological frontier. However, this finding is exactly the opposite of what is predicted by recent endogenous growth theories (see, e.g., Aghion et al. 2004a, b, 2005). Similarly, using the exponential diffusion process, Griffith et al. (2004) find the overall social rate of return to R&D (i.e., returns from both R&D-based innovation and absorptive capacity) to be higher in the technologically lagging countries (such as Canada) than in the frontier (the U.S.). This finding has raised the important question of why many non-technological frontier countries (such as Canada) do not invest more in R&D—relative to the U.S.—since its overall return is higher?

To understand the above potential conflicting results, consider the marginal product of Z (MPZ)[13] in the exponential diffusion model [i.e., Eq. (8)]: $MPZ_{\exp} = \delta_1 + \mu_1 \ln\left(A_{Fjt-1}/A_{ijt-1}\right)$. Thus, it emerges that the contribution of Z (to productivity growth) through technology transfer (i.e., the second term) is an *increasing* function of the productivity gap to the frontier, and this feature translates into the results reported by the OECD and Griffith et al. (2004) studies[14]—recall that for the frontier country, the second term in MPZ expression is null.

On the other hand, the use of logistic diffusion model may help reconcile the aforementioned conflicting findings, as the marginal product of Z [from Eq. (9)], $MPZ_{\log} = \delta_2 + \mu_2 \frac{A_{ijt-1}}{A_{Fjt-1}} \ln\left(A_{Fjt-1}/A_{ijt-1}\right)$, is a *concave* function of the productivity gap. In other words, when the productivity gap is higher (i.e., above a certain threshold level), lagging behind the frontier becomes penalizing due to the extra term $\left(A_{ijt-1}/A_{Fjt-1}\right)$, which acts to dampen the rate of technology diffusion.[15] Thus, unlike the exponential diffusion process, the logistic model involves the possibility of a decreasing productivity impact of the variable (Z) when a country (or an industry) *further* lags behind the frontier. This illustration of the potential differential impacts (across the two models) is a contribution to the existing literature, which has mostly overlooked the logistic model.

4 Relative levels of TFP and other variables

TFP growth in country i and industry j at time t is estimated using a superlative index number—this index, also known as the Tornqvist index, allows a flexible specification of production technology (i.e., consistent with the homogenous translog production function)—(see Caves et al. 1982a, b).

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[13] In OECD studies, Z measures the degree of competition, while in Griffith et al. (2004) it denotes R&D intensity.

[14] It is noteworthy that in the three OECD studies, the source of productivity growth that is always conclusive is the effect of competition via the speed of technology transfer (i.e., the interaction term coefficient, μ_1); the effect of competition through innovation (i.e., δ_1) is often either insignificant or counterintuitive. As for Griffith et al. (2004), they find R&D to be statistically and economically important through both technology transfer and innovation.

[15] Therefore, the catch-up or convergence may be slower when the frontier is either too distant or too close, and is fastest at intermediate distance.

Table 1 Industry coverage

NAICS code	Industry name
311, 312	Food, beverage, tobacco
313, 314	Textile
315, 316	Apparel and leather
321	Wood
322	Paper
323	Printing
324	Petroleum and coal
325	Chemical
326	Plastics and rubber
327	Non-metallic mineral
331	Primary metals
332	Fabricated metal
333	Machinery
334	Computer and electronic
335	Electrical equipment
336	Transportation equipment
337	Furniture
339	Miscellaneous manufacturing

$$\ln\left(\frac{A_{ijt}}{A_{ijt-1}}\right) = \ln\left(\frac{Y_{ijt}}{Y_{ijt-1}}\right) - \alpha^*_{ijt}\ln\left(\frac{L_{ijt}}{L_{ijt-1}}\right) - (1-\alpha^*_{ijt})\ln\left(\frac{K_{ijt}}{K_{ijt-1}}\right) \tag{10}$$

where Y denotes real value added in common currency units, L is a measure of labor input, K denotes real physical capital in common currency units, and $\alpha^*_{ijt} = (\alpha_{ijt} + \alpha_{ijt-1})/2$ is the average share of labor in value added in sector j of country i in the periods t and $t-1$.

The relative level of TFP in sector j across countries is similarly estimated using the Tornqvist index approach as follows

$$\ln\left(\frac{A_{ijt}}{A_{Fjt}}\right) = \ln\left(\frac{Y_{ijt}}{Y_{Fjt}}\right) - \alpha^*_{jt}\ln\left(\frac{L_{ijt}}{L_{Fjt}}\right) - (1-\alpha^*_{jt})\ln\left(\frac{K_{ijt}}{K_{Fjt}}\right) \tag{11}$$

where $\alpha^*_{jt} = (\alpha_{ijt} + \alpha_{Fjt})/2$ is the average share of labor in value added in sector j in the two countries.

These superlative index number measures of TFP are more general than those commonly derived from the Cobb–Douglas production function. Our analysis covers 18 manufacturing industries for the period of 1987–2004—see Table 1 for a full list of industry names and classification codes. Moreover, for details concerning the data and data sources that are used, see the "Appendix".

Figure 1 reports the Canada–U.S. TFP level gap across manufacturing industries.[16] As is clear from that figure, there is substantial variation in levels of relative productivity

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[16] The relative levels of TFP are estimated using the number of employees rather than total hours worked. Although the preferred labour input measure is hours worked, the comparable U.S. hours data at the industry level are not readily available. It is noteworthy that since Canadians work on average about 10 % less hours per person employed in a year than their U.S. counterparts, the Canada–U.S. TFP gaps measured by using the number of employees (as shown in Fig. 1) is about 10 % points higher than the gaps measured using the hours worked.

Table 2 Descriptive statistics of the key variables

Variable	Mean	SD
TFP growth in Canada	0.0152	0.0616
Canada–U.S. Relative TFP Level	0.9273	0.3508
R&D intensity	0.0378	0.0774
Intensity of imports from the whole world	1.7828	1.3810
Intensity of imports from the G7 countries	1.2946	0.9735
Intensity of imports from the U.S.	1.0569	0.7620
Intensity of FDI from the whole world	0.7780	1.2147
Intensity of FDI from the U.S.	0.4756	0.6002

Intensity of a given variable refers to the ratio of that variable over GDP

across industries, and productivity levels in most Canadian industries have tended to be relatively lower than those in the U.S. over the period under study. The only two industries to have maintained a TFP advantage in Canada are primary metals and printing. Canada also enjoys a significant productivity lead in computer and electronic industry between 1987 and 1999, but the U.S. overtakes thereafter—the loss in TFP advantage in this industry is substantive, with the Canada–U.S. TFP ratio declining from 3.05 in 1987 to 1.10 in 1999 and to 0.23 in 2004. In food, beverage and tobacco, non-metallic minerals, and transportation equipment industries, Canada's productivity levels are (on average) similar to those in the U.S. In all other industries, the U.S. productivity dominance is visible and quite acute in some industries. Overall, across these 18 manufacturing industries, the Canada–U.S. TFP level ratio is on average about 92 % with a standard deviation of 35 %.

As for other variables, the ratios of imports, inward FDI (position), and R&D expenditures to GDP account respectively for international trade, FDI, and R&D variables—see the "Appendix" for further details concerning the construction of these variables and the data sources. Table 2 presents the summary statistics for the key variables.

5 Econometric estimation and results

For the econometric estimation, we take into account that TFP growth is likely to be related to the business cycle as input factors will be used more efficiently in a booming economy. Specifically, TFP growth is likely to be procyclical. Using a sample of 18 Canadian manufacturing industries (3-digit NAICS) over the period 1987–2004, we estimate variations of the following two equations. The method of estimation is the generalized least squares (GLS) with panel-corrected standard errors (PCSE) that is robust to both period heteroskedasticity and general correlation of observations within a given cross-section.

$$\Delta \ln A_{ijt} = \eta_{ij} + \delta_1 Z_{ijt-1} + \theta_1 ETFPgap_{ijt-1} + \mu_1 Z_{ijt-1} ETFPgap_{ijt-1} + \pi_1 BC_{ijt} + \varepsilon_{ijt} \quad (8')$$

$$\Delta \ln A_{ijt} = \eta_{ij} + \delta_2 Z_{ijt-1} + \theta_2 LTFPgap_{ijt-1} + \mu_2 Z_{ijt-1} LTFPgap_{ijt-1} + \pi_2 BC_{ijt} + \varepsilon_{ijt} \quad (9')$$

where BC denotes business cycle as measured by output fluctuations, $ETFPgap_{ijt-1} = ((A_{Fjt-1}/A_{ijt-1}) - 1)$, $LTFPgap_{ijt-1} = (1 - (A_{ijt-1}/A_{Fjt-1}))$, and Z is a vector including international trade, inward FDI, and R&D variables.[17]

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[17] The inclusion of the business cycle as a control variable is equivalent to including time dummies in the regression analysis. Moreover, all explanatory variables are lagged one period in order to reduce simultaneity problems and direction of causality issues.

Table 3 Correlation matrix for variables

Variable	(RD/Y)	$(M^{U.S.}/Y)$	(M^{G7}/Y)	(M^{World}/Y)	$(FDI^{U.S.}/Y)$	(FDI^{World}/Y)
(RD/Y)	1.00					
$(M^{U.S.}/Y)$	0.59	1.00				
(M^{G7}/Y)	0.66	0.99	1.00			
(M^{World}/Y)	0.60	0.87	0.90	1.00		
$(FDI^{U.S.}/Y)$	0.16	0.19	0.15	0.11	1.00	
(FDI^{World}/Y)	0.13	0.05	0.03	0.02	0.94	1.00

We assess the two functional technology diffusion processes (Eqs. $8'$ and $9'$) according to the best statistical fit. We find that the exponential diffusion model always outperforms the corresponding logistic one. Therefore, all results reported in Table 4 pertain to exponential specifications. However, we contrast the findings between the two models in Table 5.

To examine whether the region or country sources of Canadian imports and inward FDI matter, we consider the imports from the U.S., G7 and the whole world as well as FDI from the U.S. and the whole world. However, given the strong collinearity between some of these variables (see Table 3), we examine each of them separately up to finding a *parsimonious* specification.[18] In Table 4, we report our estimation results starting with the 'exponential' productivity gap to the frontier $\{ETFPgap_{ijt-1} = ((A_{Fjt-1}/A_{ijt-1}) - 1)\}$ as the only explanatory variable in column (1).[19] The result shows that domestic productivity growth is increasing in the technology gap to the frontier, indicating evidence of autonomous (or disembodied) technology transfer. According to the estimated coefficient, a 1 percentage point increase in the (exponential) technology gap raises productivity growth in the lagging country by 0.08 percentage points. Thus, consistent with the theoretical predictions, the further an industry lies behind the technological frontier, the higher is its rate of TFP growth. The business cycle variable enters with the expected positive and statistically significant coefficient.

Next, column (2) of Table 4 introduces a role for R&D in determining both rates of innovation and technology transfer. The positive and statistically significant coefficient on the R&D level term (upper panel of Table 4) implies that R&D has a direct effect on innovation and thereby on productivity growth—this coefficient may be interpreted as a social rate of return to R&D-based innovation. However, the counterintuitive sign and lack of significance of the coefficient on the R&D interaction term (bottom panel of Table 4) implies that there is no *absorptive capacity* effect of R&D. Thus, although other studies have found some empirical evidence that R&D may play a role in the imitation of others' discoveries, our results suggest that, for the Canadian manufacturing, the effect of R&D is on the rate of innovation.

Columns (3) through (5) in Table 4 examine the impact of international trade as measured by the intensities of imports from the U.S., G7, and the whole world,

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[18] Table 3 shows that R&D and trade variables are highly correlated. Note that Bassanini and Ernst (2002) find that R&D activity tends to increase with trade openness. They explain this as firstly evidence of positive knowledge spillovers and secondly, the possibility that by increasing product variety, trade openness may induce greater R&D spending when domestic producers try to imitate the new products.

[19] Note that we include the business cycle variable and cross-section fixed effects (which are not reported) in all regressions throughout the paper.

Table 4 Results with exponential technology diffusion

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable: annual TFP growth								
$ETFPgap_{t-1}$	0.080*** (3.305)	0.115*** (2.719)	0.094*** (4.070)	0.083*** (3.617)	0.078*** (3.153)	0.115*** (3.409)	0.108*** (3.719)	0.099*** (4.206)
$(RD/Y)_{t-1}$		0.028*** (3.081)						0.004 (0.496)
$(M^{U.S.}/Y)_{t-1}$			0.046*** (5.619)					0.022** (2.226)
$(M^{G7}/Y)_{t-1}$				0.054*** (5.744)				
$(M^{World}/Y)_{t-1}$					0.052*** (5.540)			
$(FDI^{U.S.}/Y)_{t-1}$						0.073*** (7.268)		0.048*** (3.908)
$(FDI^{World}/Y)_{t-1}$							0.059*** (6.203)	
Business cycle	0.090** (2.367)	0.103*** (2.720)	0.110*** (3.113)	0.116*** (3.249)	0.116*** (3.248)	0.124*** (3.461)	0.125*** (3.410)	0.129*** (3.699)
Interaction terms								
$(RD/Y) \times ETFPgap$		−0.011 (−1.097)						
$(M^{U.S.}/Y) \times ETFPgap$			0.053** (2.262)					0.060** (2.549)
$(M^{G7}/Y) \times ETFPgap$				0.050** (2.061)				
$(M^{World}/Y) \times ETFPgap$					0.042* (1.806)			
$(FDI^{U.S.}/Y) \times ETFPgap$						0.029 (1.467)		–

Table 4 continued

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$(FDI^{World}/Y) \times ETFPgap$							0.023 (1.235)	
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of observations	324	324	324	324	324	324	324	324
R^2	0.097	0.123	0.205	0.203	0.195	0.231	0.199	0.252

Numbers in parentheses are *t* statistics. ***, **, and * represent statistical significance at the 1, 5, and 10 % levels, respectively

respectively. We include both a level term (to capture an effect on innovation) and an interaction term between imports and productivity gap to the frontier (to capture an effect on technology transfer). As is reported in the table, regardless of the origin (or the trading partner), imports have a positive and statistically significant effect on TFP growth through both innovation and faster technology transfer.[20] The finding that the imports interaction term is positively signed and statistically significant, provides evidence that trade is a channel for international technology diffusion. Columns (6) and (7) present results for inward FDI (from both the U.S. and the whole world, respectively). The estimated coefficients on the FDI level are positive and statistically significant, while the FDI interaction term is statistically insignificant although enters with a positive sign. It is noteworthy that the estimated coefficient on the FDI level (innovation) term is higher for the U.S—than world-originated FDI. Moreover, the specification's goodness of fit is better with the former variable. Overall, these findings suggest that increases in FDI inflows have had a positive effect on Canada's productivity growth through the rate of innovation but have not enhanced the speed of technology transfer. In other words, no evidence is found for (inward) FDI-based technology transfer. Besides, despite the inclusion of international trade or inward FDI as a channel for (embodied) technology transfer, international technology diffusion still takes place autonomously (i.e., in disembodied form).

Finally, in the search for a parsimonious specification, column (8) in Table 4 includes simultaneously all variables previously found (on their own) to be a statistically significant determinant of TFP growth. For imports and inward FDI, we retain the intensity for U.S-originated imports and FDI, which gave the best statistical fit relative to other source countries or regions. It turns out that all previous findings (but the R&D-based innovation) remain unchanged in terms of sign and statistical significance of coefficients. Although the R&D level (innovation) term is positively signed, it is no longer statistically significant likely due to the strong correlation with the trade variable (see Table 3).[21]

In summary, the estimation results indicate a robust role for the autonomous (or disembodied) technology transfer, international trade- and FDI-based innovation, as well as trade-embodied technology transfer in explaining Canadian manufacturing productivity growth. Further, some evidence on R&D effect on the rate of innovation and thereby on productivity growth is also detected.

As noted earlier, the results so far pertain to the exponential technology diffusion process, which outperforms the logistic model for this Canada–U.S. study, based on the statistical fitness criterion. Nevertheless, it is useful to compare the results across the two models as shown in Table 5. First, consistent with the theoretical predictions, the estimated coefficient on the autonomous technology transfer (i.e., *TFPgap*) is higher (across all specifications) in the exponential than logistic diffusion model—Recall that this productivity gap, which measures the potential for technology transfer, is defined respectively in the two models as follows: $ETFPgap_{ijt-1} = \left(\left(A_{Fjt-1}/A_{ijt-1}\right) - 1\right)$ and $LTFPgap_{ijt-1} = \left(1 - \left(A_{ijt-1}/A_{Fjt-1}\right)\right)$; hence $LTFPgap_{ijt-1} = \left(A_{ijt-1}/A_{Fjt-1}\right)_{*} ETFPgap_{ijt-1}$. As a result, the reported findings are consistent with the lower potential for technology spillovers in the logistic diffusion model. Also, as is shown in Table 5, the coefficient on the trade interaction (technology transfer) term

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[20] Regressions in columns (3)–(5) indicate that imports from the U.S. provide a slightly better statistical fit (see R^2), while the magnitude of coefficients on all three import intensities (both the level and interaction terms) are almost equal.

[21] In regressions not reported here, we also included the FDI interaction (technology transfer) term, but it remains statistically *in*significant (although positively signed) at conventional critical values, and its inclusion resulted in lower R^2 value.

Table 5 Results with exponential & logistic technology diffusion

	(1)		(2)		(3)		(4)	
	ETD	LTD	ETD	LTD	ETD	LTD	ETD	LTD
Dependent variable: annual TFP growth								
$TFPgap_{t-1}$	0.080*** (3.305)	0.051** (2.387)	0.115*** (2.719)	0.100** (2.379)	0.094*** (4.070)	0.041** (2.037)	0.099*** (4.206)	0.037* (1.761)
$(RD/Y)_{t-1}$			0.028*** (3.081)	0.025** (2.566)			0.004 (0.496)	0.007 (0.755)
$(M^{U.S.}/Y)_{t-1}$					0.046*** (5.619)	0.047*** (5.607)	0.022** (2.226)	0.023** (2.186)
$(FDI^{U.S.}/Y)_{t-1}$							0.048*** (3.908)	0.048*** (3.733)
Business cycle	0.090** (2.367)	0.072* (1.906)	0.103*** (2.720)	0.088** (2.239)	0.110*** (3.113)	0.089** (2.443)	0.129*** (3.699)	0.100*** (2.811)
Interaction terms								
$(RD/Y) \times TFPgap$			−0.011 (−1.097)	−0.016 (−1.632)				
$(M^{U.S.}/Y) \times TFPgap$					0.053** (2.262)	*0.014* (*0.641*)	0.060** (2.549)	*0.021* (*0.955*)
$(FDI^{U.S.}/Y) \times TFPgap$							–	–
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of observations	324	324	324	324	324	324	324	324
R^2	**0.097**	0.081	**0.123**	0.106	**0.205**	0.164	**0.252**	0.203

ETD and LTD denote exponential and logistic technology diffusion model, respectively. Numbers in parentheses are *t* statistics. ***, **, and * represent statistical significance at the 1, 5, and 10 % levels, respectively reduces significantly in magnitude (and becomes statistically *in*significant) in the logistic model. Brief, all these differential empirical findings (across the two models) are consistent with the theoretical discussion above.

In the two models, the coefficients on both the autonomous technology transfer and trade interaction (technology transfer) term can be related to the speed of convergence towards the implied steady-state equilibrium level of relative TFP [see Eq. (5)]. Recall that the general solution to the first-order difference equation for relative TFP ($RTFP = \ln(A_{ijt}/A_{Fjt})$) in Eq. (4) is: $(RTFP_t - RTFP^*) \approx e^{-\lambda t}(RTFP_0 - RTFP^*)$.
Thus, for example, the estimated coefficient of about 0.1 on the exponential productivity gap in column (4) of Table 5 implies that autonomous technology transfer closes half of the gap between actual and steady-state equilibrium relative TFP every 7 years. The corresponding coefficient of about 0.04 on the logistic productivity gap implies that autonomous technology transfer closes half of the gap between actual and steady-state relative TFP about every 19 years. This suggests relatively rapid 'conditional' TFP convergence in exponential diffusion model. Thus, from the convergence perspective as well, it emerges that the two models of technology diffusion may have different implications for the growth dynamics in a technologically lagging country.

Thus, this paper contributes to the literature by applying and comparing the two models of technology diffusion (exponential and logistic) within a single study—which has not often been done in previous work. However, since this paper finds that the exponential diffusion model outperforms (in this Canada–U.S. study), one might raise the question of whether the use of the exponential model in nearly all previous research is simply an artifact of this outcome. The answer is no. First, as noted most previous studies have overlooked the logistic model, and without applying and comparing the two models, there is no reason—a priori—to favor one model over the other. Second, among the very few existing studies that have applied and compared the two models, Benhabib and Spiegel (2003) found that the logistic model outperformed the exponential one in their cross-section study of developed and developing countries. Interestingly, as shown in Fig. 2, when a lagging country's productivity gap to the frontier is low or modest, both models predict that technological gap exerts a positive impact on the productivity growth in the lagging country—nonetheless, due to the concave functional form (as opposed to the linear one) the marginal effect is lower in the logistic specification. This is consistent with both the Canada–U.S. relative TFP level being on average about 92 % and the results reported in Table 5. However, when the productivity gap to the frontier is higher as is often the case in cross-section studies (involving several countries), the two models predict conflicting results (see Fig. 2). Finally, when we analyzed above the findings of some existing studies that have only used the exponential model, we illustrated that certain of their counterintuitive results could have been overturned with the use of the logistic diffusion model.

6 Summary and conclusions

Canada's weak productivity performance, particularly in the manufacturing sector, relative to the U.S. (and other OECD countries) has been noted by many observers. In this context, it has been argued that the transfer of new technologies from the leading country is an important source of productivity growth—at least as important as domestic inventiveness itself—in a small open (technologically lagging) country such as Canada. Against this background, this paper investigates the productivity growth effects of international technology diffusion using panel data on Canadian manufacturing industries over the period 1987–2004. We examine international trade and FDI as two channels for (embodied) technology transfer across national borders, while also allowing for autonomous technology diffusion (i.e., in disembodied form). The empirical framework used considers domestic innovation and technology transfer as two sources of productivity growth for a technologically lagging country. Within this framework, we examine the roles played by international trade, FDI, as well as other factors in stimulating each source of productivity growth, using the confined exponential and logistic models of technology diffusion. In these models, the (industrial) difference in levels of TFP between Canada and a technology frontier country (the U.S.) is used as a direct measure of the potential for technology transfer.

Our main results are as follows. First, we find evidence of a robust role for the autonomous and international trade embodied technology transfer in explaining TFP growth in the Canadian manufacturing sector. Second, international trade, FDI, and R&D all contribute to productivity growth through the rate of innovation. Finally, we find that the exponential and logistic models of technology diffusion may have different implications for the growth dynamics of a technologically lagging country.

From a public policy perspective, these findings highlight the potential for openness to international trade and FDI to improve a country's productivity performance. These results are consistent with the views of Canada's recent competition policy review panel, which suggested that the country would benefit from reducing its barriers to inward FDI across the board and in specific protected sectors.

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Appendix: Variable definitions and data sources

GDP and labour (or capital) share of income

The Canada–U.S. GDP ratio is calculated using GDP at factor cost, re-referenced to the year of 1999. GDP at factor cost in 1999 for Canada is obtained from Statistics Canada (STC) CANSIM table 381-0013 and converted into U.S. dollars using the Canada–U.S. bilateral GDP PPP values by industry from Rao et al. (2004). The imputed value for owner-occupied dwellings is not included. The time series of GDP at factor cost in 1999 dollars are estimated using the growth rates of GDP at basic price in 1997 chained-Fisher dollars. The GDP at basic price in 1997 chained-Fisher dollars from 1997 onward come from STC CANSIM table 379-0017, which are extended back to 1987 using the growth rates of GDP at factor cost in 1992 constant dollars from STC CANSIM table 379-0001. The labour (or capital) share of income is calculated using the data from STC CANSIM table 381-0013.

GDP at factor cost in 1999 for the U.S. is calculated using the data from BEA NAICS-based GDP-by-industry tables. The imputed value for owner-occupied dwellings is excluded using BEA NIPA table 7–12. The time series of GDP at factor cost in 1999 dollars are estimated using the chained-Fisher quantity index for GDP at market price from BEA NAICS-based GDP-by-industry tables. The labour (or capital) share of income is calculated using the same source tables.

Capital stock and employment

The capital stock is the private fixed non-residential geometric end-year net stock.[22] To calculate Canada–U.S. capital stock ratio, capital stock in Canadian dollars for Canada is converted into U.S. dollars using the Canada–U.S. bilateral total investment PPP values by industry. All the PPP values are obtained from Rao et al. (2008). The capital stock is in chained-Fisher dollars and re-referenced to the year of 1999.

The Canadian data for capital stock by industry are obtained from Statistics Canada (STC) CANSIM table 031-0002. The capital stock data for the U.S. come from the U.S. Bureau of Economic Analysis (BEA) fixed assets tables.

The data used for Canadian employment from 1997 onward is the total number of jobs from STC CANSIM table 383-0010. These data are extended back to 1987 using the growth rates of the total number of jobs from STC CANSIM table 383-0003. The employment data for the U.S. is the number of persons engaged in production. The source for the data from 1998 onward is the BEA NAICS-based GDP-by-industry tables, which are extended back to 1987 using the growth rates of the number of persons engaged in production from the BEA1987 SIC-based GDP-by-industry tables.

Import intensity

Import intensity is defined as imports to GDP ratio. Data on bilateral trade comes from OECD, STAN *Bilateral Trade Database* (BTD), 2006. The date covers the values of imports from different countries and regions in thousands of U.S. dollars at current prices over the period of 1980–2004. We used exchange rates for imports (U.S. dollars per national currency) to convert the values in Canadian dollars.

FDI intensity

FDI intensity is defined as inward FDI stock to GDP ratio. The data by NAICS-based industry from 1999 onward is obtained from Statistics Canada (STC) CANSIM table 376-0052. These data are extended back to 1987 using the growth rates from the SIC-based data provided by DFAIT.

R&D intensity

R&D intensity is defined as R&D expenditure to GDP ratio. The R&D expenditure data used is the intramural R&D expenditures that are obtained from the Science, Innovation and Electronic Information Division of Statistics Canada. The data from 1994 onward is NAICS-based. It is extended back to 1987 using the growth rates from the SIC-based data.

Business cycle (a proxy for capacity utilization)

The output fluctuation (i.e., the business cycle) is used as the indicator of capacity utilization because firms will adjust factor inputs accordingly in response to output change. The data used for output is real GDP by industry. The Hodrick–Prescott (H–P) filter is used to decompose GDP into two parts: the long-term trend and the short-term fluctuation. For normalization, the fluctuation is divided by the trend.

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[22] Capital includes structure and M&E capital. Land and inventory are not included.

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