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Would global patent protection be too weak without international coordination?[☆]

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ABSTRACT

In the standard model with free trade and social-welfare-maximizing governments à la Grossman and Lai (2004), cross-border positive policy externalities result in countries choosing a combination of patent strengths that is weaker than optimal from a global perspective. This paper introduces three new features to the analysis: trade and FDI barriers, firm heterogeneity and political economy considerations in setting patent policies. Based on calibration, we find that there would be global under-protection of patent rights when there is no international policy coordination. The empirical fact that firm revenues follow a fat-tailed distribution implies that the barriers to exploit inventions internationally are quite low, despite the fact that only a small fraction of firms sell overseas and an even smaller fraction of firms carry out FDI as a result of trade barriers. Furthermore, requiring all countries to harmonize their patent standards with the equilibrium standard of the most innovative country (the US) does not lead to global over-protection of patent rights.

1. Introduction

The global intellectual property rights (IPR) protection system was given a boost by the implementation of the TRIPS agreement (Agreement on Trade-Related Aspects of Intellectual Property Rights), which started a gradual process of IPR harmonization in 1995. This agreement effectively requires the strengthening of patent protection of many countries, and pushes the world IPR protection policies toward harmonization (albeit a partial one). TRIPS is unprecedented in its ability to coordinate international IPR protection, not least because of the large number of countries involved (it is under the auspices of the WTO) and its ability to enforce rulings due to the credible threat of punishment through trade sanctions. Given the tremendous repercussions of such a coordinated increase in the strengths of IPR protection, it is fair to ask whether TRIPS is really a solution to a global coordination problem. It is clear that TRIPS creates distributive effects among countries.[2] However, the more important question is whether global IPR protection was too weak before TRIPS. If it was, then TRIPS can potentially be globally welfare-improving and therefore it can potentially make all countries better off. For example, if less developed countries (LDCs) lose from the strengthening of their IPR and developed countries (DCs) gain from it, but the DCs' gains outweigh the LDCs' losses, then it can be mutually beneficial for the LDCs to accept (partial) harmonization of IPR standards with the DCs in exchange for the DCs' opening their markets to goods from the LDCs. However, if global patent protection was already too strong before TRIPS, then no such synergy exists between negotiations on trade-related IPR and other issues of global trade.

The objective of this paper is twofold. First, we address the question of whether global patent protection would be too weak if individual governments were left to decide their own level of protection in the absence of international coordination. Second, we want to know whether the patent policy harmonization mandated by the TRIPS offers too much global patent protection. Both questions are important for us to evaluate the welfare consequences of TRIPS. To answer these questions, we derive sufficient conditions for global under-protection or over-protection of IPR and calibrate the model to check whether the conditions are satisfied.

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[2] McCalman (2001) has shown that the US was by far the largest beneficiary, followed by Germany and France as distant second and third beneficiaries. On the other hand, the greatest loser was Canada, followed by Brazil and UK.

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The theoretical framework of this paper builds on Grossman and Lai (2004) (henceforth G–L) who develop a non-cooperative game model with free trade and social-welfare-maximizing governments.[3] It explains how a global system of patent protection affects incentives to innovate and how it creates distortions (deadweight losses). In particular, their model provides a basic theory that explains (a) how the national levels of patent protection is determined in a non-cooperative equilibrium, and (b) what the optimal global system of patent protection would look like.

In the basic G–L model, in the absence of international coordination, countries play a Nash game in setting the strengths of patent protection. The best response function of a country's government is obtained by setting the strength of patent protection that equates the marginal costs (deadweight loss due to longer duration of monopoly pricing) and marginal benefits (increased incentives of innovation) of extending protection, given the strengths of protection of other countries. Each country confers positive externalities on foreign countries as it extends patent protection, because it increases profits of foreign firms in the home market, and increases consumer surplus of foreign consumers due to induced innovations. As a result, there is global under-protection of patent rights in Nash equilibrium relative to the global optimum. In fact, the degree of under-protection in Nash equilibrium increases with the number of independent decision-makers in the patent-setting game.

However, two factors prevent us from directly applying G–L's basic model to answer whether global patent protection would be too weak without international coordination. First, as discussed in the political economy literature, governments may put extra weight on profits as opposed to consumer surplus in their objective functions due to firm lobbying. We call this profit-biased preferences of governments. When governments put more weight on profits, the marginal cost of patent protection decreases since deadweight loss is smaller. Therefore, the strength of patent protection in Nash equilibrium is stronger. Second is the existence of trade barriers and firm heterogeneity. As the recent empirical trade literature documents, only a small fraction of (more productive) firms sell to foreign markets. Moreover, the firms that do sell overseas have to bear trade costs, which include market entry costs, transportation costs and import tariffs. When only a fraction of domestic firms would enter a foreign market, and when there are trade costs, the positive international externalities of patent protection are diminished. Both profit-bias and trade barriers tend to diminish the degree of global under-protection in Nash equilibrium relative to the global optimum. If these forces are strong enough, there may even be over-protection of patent rights in Nash equilibrium. Therefore, whether or not there is global under-protection of patent rights in the non-cooperative equilibrium is an empirical question. To answer this question, we extend the G–L model by introducing three new elements: trade barriers, firm heterogeneity in productivity and political economy considerations. We also allow for FDI/licensing to be alternative means of serving a foreign market besides exporting.[4]

The contributions of this paper are twofold, one theoretical and one empirical. On the theory front, we develop a model to analyze the interaction among innovation, firm heterogeneity, trade and FDI and patent protection in a unified framework. An innovator invests in R&D and develops a new product. The labor productivity of the resulting production firm follows a Pareto distribution. Because of the existence of fixed costs of exporting and of FDI, only the most productive firms export to or carry out FDI in foreign countries. Because it offers greater profit potential, a country with a larger market or stronger patent protection attracts more foreign firms to sell there. Successes in exploitation of inventions internationally increase the profits of firms and induce more innovation. Thus, there is a positive connection between patent protection and market size in one country and innovation in another. However, this connection may be weakened by exporting or FDI barriers. Given the strengths of patent protection of other governments, each government chooses its patent strength to maximize its objective function, which is biased in favor of firm profits because of firm lobbying. Thus, the strength of patent protection and the probability that foreign inventions are exploited in each country are endogenously determined in the model.

On the empirical front, this paper uses data and parametric values estimated in the literature to calibrate the theoretical model so as to answer two empirical questions. First, we find that global patent protection is too weak without international coordination. There are two reasons: (a) despite the existence of trade barriers, the free-rider problem becomes serious when there is a large number of independent country-players in the patent-setting game. (b) The empirical fact that firm revenues follow a fat-tailed distribution implies that the barriers to exploit inventions internationally are quite low, despite the fact that only a small fraction of firms sell overseas and an even smaller fraction of firms carry out FDI as a result of trade barriers. This implies that the positive cross-border externalities of patent protection remain quite high. The fat-tailed distribution of firm sizes and the fact that only the most productive firms carry out FDI overseas implies that FDI is a very important channel of international exploitation of inventions. Therefore, it must be taken into account in any modeling of international exploitation of technology. Second, we find that requiring all countries to harmonize their strengths of patent protection with the equilibrium strength of the most protective country does not lead to global over-protection of IPR. This is because the distribution of innovative capability among countries is not too skewed as to overcome the free-rider effect. We therefore conclude that there is no evidence that TRIPS leads to global over-protection of patent rights.

The present paper is similar in spirit to that of Eaton and Kortum (1999), though the model they use is different. Like them, we try to link together innovation, patenting and international exploitation of inventions. Unlike them, however, we focus on product innovation instead of productivity-enhancing inventions, and so productivity growth is not the focus of our analysis. Another difference is that, in our model, the benefits of inventions are spread mainly through exporting and FDI, whereas in their model the main mechanism of international exploitation of inventions is diffusion of knowledge. We focus on analyzing the market of patent-sensitive goods whereas they focus on the entire macroeconomy.

The structure of the rest of the paper is as follows. Section 2 augments the G–L model by introducing trade and FDI barriers, firm heterogeneity and firm lobbying. It derives the key equations for the non-cooperative equilibrium and those for the globally efficient patent regime for both the two-country and multi-country cases. In Section 3, we calibrate the multi-country model and investigate (i) whether there is global under-protection of IPR in the absence of international coordination and (ii) whether the harmonization mandated by TRIPS over-protects IPR globally. Section 4 concludes.

2. A theory of innovation and international patenting

The theory described in this section is modified from Grossman and Lai (2004) by introducing trade and FDI barriers, firm heterogeneity and profit-bias of governments.

In this section, we study the national incentives for protection of intellectual property in a world economy with innovation, international patenting, trade and imitation. We derive the Nash equilibrium of a game in which countries set their patent policies simultaneously and noncooperatively. Then we derive the globally optimal patent regime. This is followed by a comparison between the Nash equilibrium

[3] We start with the working assumption that the world was in a non-cooperative equilibrium before TRIPS. There is no doubt that some countries attempted to coordinate their IPR policies somewhat even before TRIPS, but empirical studies have shown that even as late as 1990, market sizes and innovative capabilities significantly affected variation in the strengths of patent protection across countries, as would be expected of a world where each country sets its own optimal IPR standard.

[4] Some preliminary ideas of these extensions first appeared in Lai (2008).

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and the global optimum, and a discussion of the policy implications. For ease of exposition, we first start with a two-country case, and then generalize it to a multi-country one.

2.1. The setup

2.1.1. Two-country case

The two countries are distinguished by their wage rates, their market sizes, and their stocks of human capital, which proxies for their different capacities for R&D. For the sake of convenience, we shall term the countries "North" and "South".

Consumers in the two countries share identical preferences. In each country, the representative consumer maximizes the intertemporal utility function. The instantaneous utility of a consumer in country j is given by

$$u_j(z) = y_j(z) + \int_0^{n_S(z)+n_N(z)} h\left[x_j(i,z)\right] di, \tag{1}$$

where $y_j(z)$ is consumption of the homogeneous good by a typical resident of country j at time z, $x_j(i,z)$ is consumption of the *ith* differentiated product by a resident of country j at time z, and $n_j(z)$ is the number of differentiated varieties previously invented in country j that remain economically viable at time z. We make the standard assumption that $h'[.]>0$ and $h''[.]<0$.[5] There are M_j consumers in country j.[6] It does not matter for our analysis whether consumers can borrow and lend internationally.

In country j, it takes a_j units of labor to produce one unit of the homogeneous (numeraire) good. To capture firm heterogeneity, we assume that it takes a_jc units of labor to produce one unit of a variety of differentiated good, where c is a stochastic variable. It follows that c is the unit cost of a differentiated product when the cost of the homogeneous good is normalized to one. Each differentiated variety is produced by one firm (before its patent expires), and therefore the firm's productivity is equal to $1/c$. We further assume that $1/c$ follows the distribution $Pr(\frac{1}{c}<x) = 1-(\frac{b}{x})^{\lambda}$ where $x\in[b,\infty]$, i.e. a Pareto distribution with a lower bound b and shape parameter λ. This implies that $Pr(c<z)=(bz)^{\lambda}$ where $z\in[0,1/b]$. The flow of new goods invented in each region is given by $\phi_j = \mathcal{F}(H_j, L_{Rj}/a_j) = B(L_{Rj}/a_j)^{\beta}H_j^{1-\beta}$, where B is a constant, H_j is a fixed input whose quantity determines the innovative capability of country j, and L_{Rj} is the labor devoted to R&D there. We assume that the numeraire good is tradeable with negligible trade costs, and that it is produced in positive quantities in both countries, so that wage in country j in equilibrium is given by $w_j=1/a_j$, and hence $w_N/w_S=a_S/a_N$. Define $\bar{T} = (1-e^{-\rho\bar{\tau}})/\rho$, where $\bar{\tau}$ is the product life of a differentiated good, and ρ is the time rate of discount.

2.1.2. Multi-country case

We now describe the IPR regime, trade barriers and profit-bias. Let us generalize the above description to a multi-country setting, and let there be J countries in the set $\mathcal{N}$ of country-players. In each country, there is *national treatment* in the granting of patent rights. Assume for simplicity that all unexpired patents are fully enforced. Under national treatment, the government of country j affords the same protection Ω_j to all inventors of differentiated products regardless of their national origins, where $\Omega_j=(1-e^{-\rho\tau_j})/\rho$, and τ_j is the length of the patents granted by country j. In our model, a patent is an exclusive right to make, sell, use, or import a product for a fixed period of time (see Maskus, 2000, p. 36). This means that, when good i is under patent protection in country j, no firm other than the patent holder or one designated by it may legally produce the good in country j for domestic sale or for export, nor may the good be legally imported into country j from an unauthorized producer outside the country. We also rule out parallel imports — unauthorized imports of good i that were produced by the patent holder or its designee, but that were sold to a third party outside country j. When parallel imports are prevented, patent holders can practice price discrimination across national markets.

The recent empirical trade literature documents that only a small fraction of firms export. To capture this phenomenon, we assume that firms are heterogeneous in labor productivities (more will be said about this later). Furthermore, each producer of differentiated goods is faced with trade barriers when selling abroad. They include: a fixed cost in exporting, which is denoted by F_{EX}, a fixed cost in setting up production facilities in a foreign country (which we call "carrying out FDI"), which is denoted by F_{FDI}, and a variable trade cost of the iceberg type (which consists of transport costs and import tariffs), which is equal to a fraction t of the production cost if a good is exported from one country to another. As a result, only a fraction of domestic firms will export to or set up production facilities in another foreign country. In this paper, we do not distinguish between FDI and licensing as they can be regarded as more or less equivalent. We assume that when an innovator licenses his technology to a foreign firm, he extracts all the rents from the latter. Assuming that the licensee has to bear the same fixed and variable costs of production, FDI and licensing are equivalent.[7] Hereinafter, therefore, "FDI" shall mean "FDI or licensing". We assume that the demand of a typical consumer is given by $x=Ap^{-\epsilon}$ (where A is a constant, p denotes the price, and $\epsilon>1$ denotes the price elasticity of demand), and define $y\equiv(1+t)^{-\epsilon+1}$, which is less than one. Therefore, y is an inverse measure of the variable trade cost.[8] As a first cut, we assume that each of the three parameters F_{FDI}, F_{EX} and t are the same across countries. It is assumed that not only is $F_{FDI}>F_{EX}$ but also $y\cdot F_{FDI}>F_{EX}$, which guarantees that firms who choose to carry out FDI in a foreign country always have the option of exporting but choose not to do so. Thus, we have a structure as depicted in Helpman et al. (2004). For any given foreign market, a firm with high unit cost of production will not sell to that market; a firm with a sufficiently lower unit cost will export to there, and a firm with a still lower unit cost will carry out FDI there. For any given firm, a sufficiently large foreign market or sufficiently strong patent protection there will induce the firm to export to that market; further increases in the market size or strength of patent protection there will eventually induce the firm to carry out FDI in that market. See Fig. 1 for a graphical analysis. Define $\tilde{\pi}(c)$ as the flow of monopoly profit per consumer as a function of a firm's unit cost c. The bold curve in Fig. 1 is the upper envelope of the three profit lines corresponding to no exporting to k, exporting to country k besides selling domestically, and doing FDI in country k besides selling domestically, as described below the figure. When the value of $\tilde{\pi}M_k\Omega_k$ lies in the range marked "Domestic Sales Only", the upper envelope corresponds to the profit from pure domestic sales. When $\tilde{\pi}M_k\Omega_k$ lies in the range marked "Domestic Sales plus Exporting to k", the upper envelope corresponds to the profit from both export and domestic sales. When $\tilde{\pi}M_k\Omega_k$ lies in the range marked "Domestic Sales plus FDI in k", the upper envelope corresponds to the profit from carrying out FDI and domestic sales.

Recent political economy models indicate that politicians' desire for campaign contributions tends to bias the objective function of a

[5] We further assume that $h'(0)=\infty$, and $-xh''(x)/h'(x)<1$ for all x. The first assumption ensures a positive demand for every variety at any finite price. The second ensures that any firm producing a differentiated product charges a finite price.

[6] We remind the reader that market size is meant to capture not the population of a country, but rather the scale of its demand for innovative products.

[7] By and large, casual observation suggests that licensing is a relatively minor channel of exploiting an invention overseas, compared with exporting and FDI. Nonetheless, we believe that in analyzing certain markets where licensing is pervasive one should include licensing as a separate mode of entry. This will be left to future research.

[8] The profit flow and consumer surplus per consumer are given by Eqs. (16) and (17) in Appendix A. It can be easily shown from Eqs. (16) and (17) that, for any given unit cost of production, the profit flow per consumer obtained by a firm in a foreign market is multiplied by a factor of y when an iceberg trade cost of t is incurred. So is the consumer surplus flow per consumer enjoyed by foreign consumers.

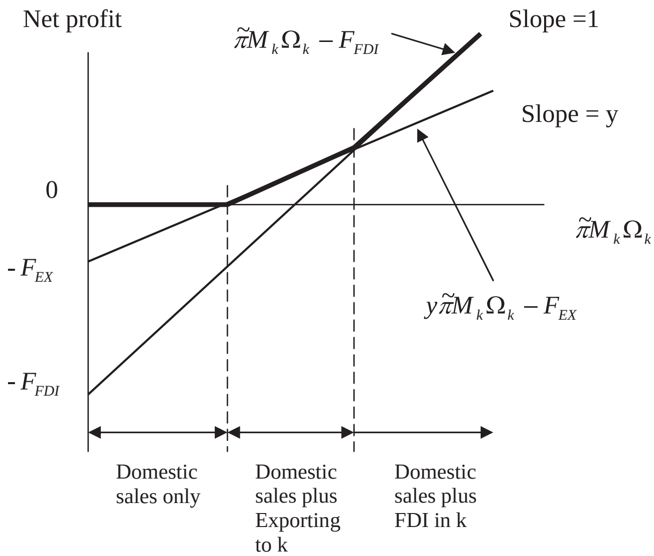

Fig. 1. A foreign firm's decision concerning exporting to and carrying out FDI in country k. 1. The horizontal line with vertical intercept 0 represents the net profit (normalized to zero) when a foreign firm does not sell to country k. 2. The line $y\tilde{\pi}M_k\Omega_k - F_{EX}$ represents the net profit when a foreign firm exports to country k besides selling domestically. 3. The line $\tilde{\pi}M_k\Omega_k - F_{FDI}$ represents the profit when a foreign firm carries out FDI in country k besides selling domestically.

government in favor of the contributors. In our model, owners of research capital are owners of firms, who donate campaign contributions to politicians. Following the literature, we let $1+a$ be the weight each government puts on domestic profits when a weight of one is put on domestic consumer surplus in its objective function. Therefore, the parameter a measures the profit-bias of governments. It can also be interpreted as the weight a politician puts on campaign contribution when a weight of one is put on social welfare, given that his objective function is the weighted sum of the two terms. See, for example, Bagwell and Staiger (2004) and Grossman and Helpman (1994).

Define π as the (unconditional) mean profit flow per consumer for a monopoly selling a typical brand; define C_m as the (unconditional) mean surplus flow that a consumer enjoys from the consumption of a good produced at a unit cost of $w_j a_j c = c$ and sold at the monopoly price $p_m > c$; and define C_c as the (unconditional) mean surplus flow he enjoys from a product sold at the competitive price of $p_c = c$. It can be shown (in Appendix A) that

$$C_c = \left(\frac{1}{\epsilon-1}\right)\left(\frac{\lambda}{1-\epsilon+\lambda}\right)Ab^{\epsilon-1} \tag{2}$$

and

$$\pi = C_m = \Lambda C_c \quad \text{where } \Lambda \equiv \left(\frac{\epsilon-1}{\epsilon}\right)^{\epsilon}. \tag{3}$$

Based on the assumption of $\Pr(c<z) = (bz)^{\lambda}$ above, it can be easily shown (in Appendix B) that the distribution of revenue per consumer $\tilde{R}$ is Pareto with shape parameter $\frac{\lambda}{\epsilon-1}$:

$$Pr\left(\tilde{R} < \mathfrak{s}\right) = 1-\left(A\Lambda b^{\epsilon-1}\right)^{\frac{\lambda}{\epsilon-1}} \cdot \mathfrak{s}^{-\frac{\lambda}{\epsilon-1}}, \quad \text{where } \mathfrak{s} \in \left(A\Lambda b^{\epsilon-1}, \infty\right).$$

Axtell (2001) finds that the size (number of employees) as well as revenue distribution of American firms followed a Pareto distribution $P(s,\alpha)$: $\Pr(x<s) = 1-(s_0/s)^{\alpha}$ where $x \in (s_0, \infty)$. He finds that for size distribution, $\alpha = 1.059$, while for revenue distribution, $\alpha = 0.994$. In other words, the estimated α for both distributions are very close to one. Luttmer (2007) finds that all possible size distributions of firms have a tail similar to Pareto distribution, with analogous tail index (equivalent to Axtell's α and our $\frac{\lambda}{\epsilon-1}$) that must be slightly above one in order to fit the data. Based on the above empirical facts, we shall assume $\frac{\lambda}{\epsilon-1}$ to be larger than but close to one in our calibration below.[9]

Now, define θ^k_{EX} as the probability that a foreign firm can profitably export to or carry out FDI in country k; and define θ^k_{FDI} as the probability that a foreign firm can profitably carry out FDI in country k. According to our assumptions above, if a firm can profitably export to (carry out FDI in) a smaller foreign market it can also profitably export to (carry out FDI in) a larger foreign market. Therefore, the probability that a firm in a country can profitably export to (carry out FDI in) some foreign market(s) is equal to the probability that it can profitably export to (carry out FDI in) the largest foreign market. We further define the (inverse) international barrier to exploiting an invention in country k as

$$\theta^k = y\left(\theta^k_{EX}\right)^{\frac{1-\epsilon+\lambda}{\lambda}} + (1-y)\left(\theta^k_{FDI}\right)^{\frac{1-\epsilon+\lambda}{\lambda}} \quad \text{for } k = 1, 2 \ldots, J. \tag{4}$$

The economic meaning of θ^k can be understood as follows. We have assumed that a foreign producer gets a patent in country k whenever it sells there. It can be shown that in country k each consumer can obtain an expected consumer surplus equal to $\theta^k C_m$ from consuming a foreign-developed product, due to the existence of trade barriers in k.[10] Note that $\theta^k C_m < C_m$, as trade barriers in k not only increase the cost of serving country k market by foreign firms but also prevent some foreign firms from serving the market. Likewise, a foreign firm can only earn an expected profit per consumer equal to $\theta^k \pi$ from country k market due to the existence of trade barriers.[11] Note that, for given θ^k_{EX} and θ^k_{FDI}, lower trade barriers (higher y) lead to higher θ^k, while a fatter tail distribution of firm productivity ($\frac{\lambda}{\epsilon-1}$ closer to one) leads to higher θ^k, as the firms that do export have a higher average productivity. Clearly, $\theta^k = 1$ (the model collapses to the case of free trade) when $\frac{\lambda}{\epsilon-1} = 1$, regardless of the values of t, F_{EX} and F_{FDI}.

It follows that the expected value of a patent of an invention by a firm in country i is given by

$$v_i = \pi\left[\sum_{k\neq i}\left(\theta^k M_k \Omega_k\right) + M_i \Omega_i\right] - \sum_{k\neq i}\left[\left(\theta^k_{EX} - \theta^k_{FDI}\right)F_{EX} + \theta^k_{FDI} F_{FDI}\right] \tag{5}$$

for $i = 1, 2, \ldots, J$.

In general $v_i \neq v_j$ for $i \neq j$. As F_{FDI} and F_{EX} are the same in all countries, it can be easily shown from Eqs. (19) and (20) in Appendix C that, in equilibrium,

$$M_{US}\Omega_{US}\left(\theta^{US}_{EX}\right)^{\frac{1-\epsilon}{\lambda}} = M_k \Omega_k \left(\theta^k_{EX}\right)^{\frac{1-\epsilon}{\lambda}} \quad \text{for all } k \neq US. \tag{6}$$

and

$$M_{US}\Omega_{US}\left(\theta^{US}_{FDI}\right)^{\frac{1-\epsilon}{\lambda}} = M_k \Omega_k \left(\theta^k_{FDI}\right)^{\frac{1-\epsilon}{\lambda}} \quad \text{for all } k \neq US. \tag{7}$$

[9] Note that we preclude the cases with $\alpha < 1$, as this would correspond to infinite mean. We are most interested in the cases when the value of α is greater than one but very close to one.

[10] The expression for θ^k in Eq. (4) is obtained via the following equation:

$$\theta^k \int_{c=0}^{\frac{1}{b}} \tilde{C}_m(c)dF(c) = \int_{c=c^k_{FDI}}^{c^k_{EX}} y\tilde{C}_m(c)dF(c) + \int_{c=0}^{c^k_{FDI}} \tilde{C}_m(c)dF(c)$$

where C^k_{EX} is the threshold unit-cost for exporting to country k; C^k_{FDI} is the threshold unit-cost for carrying out FDI in country k. $F(c) = (bc)^{\lambda}$ where $c \in [0, \frac{1}{b})$ is the c.d.f. of unit-cost c, $\tilde{C}_m(c)$ is the realized flow of surplus per consumer. Thus, $\theta^k_{EX} = (b \cdot c^k_{EX})^{\lambda}\Omega_S$ and $\bar{T}$. Refer to Appendixes A, B and C for further details.

[11] This can be easily shown by replacing $\tilde{C}_m(c)$ by $\tilde{\pi}(c)$ in the equation in the last footnote.

As $1-\epsilon<0$, Eqs. (6) and (7) indicate that a country with stronger patent protection or a larger market tends to attract a higher fraction of foreign firms to sell to the country as well as a higher fraction of foreign firms to set up production facilities there.

Substituting the expressions for θ^k_{FDI} and θ^k_{EX} derived in Appendix C (i.e. Eqs. (19) and (20)) into (5) and invoking Eqs. (3) and (4), we can simplify Eq. (5) to

$$v_i = \pi\left[\sum_{k\neq i}\left(\frac{\epsilon-1}{\lambda}\right)\theta^k M_k\Omega_k + M_i\Omega_i\right] \tag{8}$$

This is an interesting equation as v_i can be expressed in a very simple form though it has taken into account a myriad of factors including fixed costs of exporting and FDI, variable cost of exporting, heterogeneous firms and screening of firms by the market. The simplicity of the equation is attributed to the Pareto distribution of firm productivity.

2.2. The theory: two-country case

Let us describe, for given patent strengths Ω_N and Ω_S, the life cycle of a typical differentiated product developed in South. After the invention of a product, an innovator makes a productivity draw to find out her unit cost of production. Then, she will apply for and obtain a patent in each country. After that, she decides whether or not to sell overseas.[12] There is a probability θ^N_{EX} that she would be able to profitably sell to the Northern market. During an initial phase after the product is invented, the inventor holds an active patent in both countries. Even if a good is not sold in a foreign market, the innovator still has incentives to obtain a patent there, as it is costless to do so. Consequently, consumers cannot purchase a product before its patent expires in the country if the innovator does not sell it there.[13] The patent holder earns an expected flow of profits of $\theta^N M_N\pi$ from sales in the Northern market and an expected flow of profits of $M_S\pi$ from sales in the Southern market. Each Northern consumer realizes a flow of expected surplus of $\theta^N C_m$ from his purchases of the good. A Southern consumer realizes an expected flow of consumer surplus of C_m from his purchases of the good.

After a while, the patent will expire in one country. For concreteness, let's say that this happens first in the South. We assume that local firms do not have to incur the fixed cost of market entry.[14] Therefore, the good will be legally imitated by competitive firms producing there for sales in the local (Southern) market. The imitators will not, however, be able to sell the good legally in the North, because the live patent there affords protection from such infringing imports. When the patent expires in the South, the price of the good falls permanently to $w_s a_s c=c$, and the original inventor ceases to realize profits in that market. The flow of consumer surplus in the South rises to $M_S C_c$.[15]

Eventually, the inventor's patent expires in the North. Then the Northern market can be served completely by competitive firms producing in the North. If the North has been served by the innovator, then, at this time, the price of the good in the North falls to $p_c=c$ and households there begin to enjoy the higher flow of consumer surplus $M_N C_c$. The original inventor loses his remaining source of monopoly income. If the North has not been served by the innovator, then at this time, the market begins to be served by competitive firms in the North. Finally, after a period of length $\bar{\tau}$ has elapsed from the moment of invention, the good becomes obsolete and all flows of consumer surplus cease.

Alternatively, one could assume that an innovator only patents in the countries in which she can profitably sell. This can be justified by the assumption that there is a small cost of patenting in any country. This assumption will align with the fact that most inventions are patented only at home and only a fraction of inventions are patented internationally. To make the model consistent with the fact that trade and FDI are the major channels of international exploitation of inventions, we need to further assume that a domestic firm can technically imitate a foreign-developed product only if the good has previously been sold there. The alternative formulation based on these two assumptions will make the exposition more complicated and the intuition more obscure. Nonetheless, we carried out robustness check based on this alternative formulation and found that the numerical results are about the same, and the conclusions of the paper intact.[16] The results are reported in online Appendix F, the link of which is found at the end of this paper.

2.2.1. Nash equilibrium

Here we solve the Nash game in which the governments set their patent policies once-and-for-all at time 0. These patents apply only to goods invented after time 0; goods invented beforehand continue to receive the protections afforded at their times of invention. Consider the choice of patent policies Ω_N and Ω_S that will take effect at time 0 and apply to goods invented thereafter. The expressions for the government objective function in country i, discounted to time 0, is given by

$$\begin{aligned}
W_i(0) &= \Lambda_{i0} + \frac{w_iL_i}{\rho} + (1+a)\frac{r_iH_i}{\rho} + \frac{M_i\phi_i}{\rho}\left[\Omega_iC_m + (\bar{T}-\Omega_i)C_c\right] \\
&\quad + \frac{M_i\phi_{-i}}{\rho}\left[\theta^i\Omega_iC_m + (\bar{T}-\Omega_i)C_c\right] \\
&= \Lambda_{i0} + \frac{w_i[L_i-(1+a)L_{Ri}]}{\rho} + \frac{M_i\phi_i}{\rho}\left[\Omega_iC_m + (\bar{T}-\Omega_i)C_c\right] \\
&\quad + \frac{M_i\phi_{-i}}{\rho}\left[\theta^i\Omega_iC_m + (\bar{T}-\Omega_i)C_c\right] \\
&\quad + \frac{\phi_i}{\rho}\pi(1+a)\left[M_i\Omega_i + \theta^{-i}M_{-i}\Omega_{-i}\left(\frac{\epsilon-1}{\lambda}\right)\right], \quad \text{for } i=S,N,
\end{aligned} \tag{9}$$

where Λ_{i0} is the fixed amount of discounted surplus that consumers in country i derive from goods that were invented before time 0; X_{-i} or X^{-i} refers to the value of variable X pertaining to country j where $j\neq i$; r_i is the return to the factor H_i. The second equality arises from the fact that there is zero present-discounted profit for each firm, so that $r_iH_i+w_iL_{Ri}=\phi_iv_i$, where $v_i=\pi\left[M_i\Omega_i+\theta^{-i}M_{-i}\Omega_{-i}\left(\frac{\epsilon-1}{\lambda}\right)\right]$ is the value of a new patent developed in country i as shown in Eq. (8).

[12] The assumption that a firm patents in all countries may be unrealistic. However, such a formulation simplifies the analysis without sacrificing the intuition. Moreover, the conclusions of the basic model are robust to an alternative formulation that an innovator only patents in countries in which she can profitably sell, as discussed in the paragraph just before subsection 2.2.1.

[13] We rule out compulsory licensing and working requirement here as they are not of first order importance in the context of our analysis. Important as these issues are, we believe they should be addressed in future research. By and large, researchers such as McFetridge (1998) observe that the number of compulsory licenses granted were generally small in most countries, and mainly concentrated in special types of products such as food and medicines.

[14] Melitz (2003), for example, makes a similar assumption.

[15] Since there is no cost of patenting, a firm always patents its good in all countries once it is developed. Once patented, the technology is disclosed. But the good cannot be legally imitated in that market until the patent expires. So, when a patent has expired consumer surplus is C_c whether a good was developed overseas or locally, as countries can always imitate foreign-developed goods when the patent has expired, and these imitated goods are produced locally, and so there is no trade barrier when imitated goods are sold.

[16] The intuition is that fat-tailed firm productivity distribution in a country implies that even though a small fraction of firms patent and sell to foreign markets, they are firms with exceptionally high productivities, and therefore foreign consumer surplus attributed to this country's inventions is very close to that when all firms patent and sell to all foreign markets. As $\lambda/(\epsilon-1)\to1^+$, the two formulations yield the same results.

We are now ready to derive the best response functions for the two governments. The best response expresses the strength of patent protection that maximizes a national government's objective as a function of the given patent policy of its trading partner. We assume that country *i's* government treats θ^i_{EX}, θ^i_{FDI} and therefore θ^i as parametric as it chooses Ω_i. Consider the choice of Ω_S by the government of the South. This country bears two costs from strengthening its patent protection slightly. First, it expands the fraction of goods previously invented in the South on which the country suffers a static deadweight loss of $M_S\,[C_c-C_m-(1+a)\pi]$. Second, it augments the fraction of goods previously invented in the North on which its consumers realize expected surplus of $\theta^S M_S C_m$ instead of $M_S C_c$. Notice that the profits earned by Northern producers in the South are not an offset to the South's marginal cost, because they accrue to patent holders in the North. The marginal benefit accrued to the South from strengthening its patent protection reflects the increased incentive that Northern and Southern firms have to engage in R&D. If the objective-maximizing Ω_S is positive and less than $\bar{T}$, then the marginal benefit *per consumer* of increasing Ω_S must match the marginal cost, which implies

$$\begin{aligned}&\phi_N\left(C_c-\theta^S C_m\right)+\phi_S[C_c-C_m-(1+a)\pi]\\&=\frac{d\phi_S}{dv_S}\cdot\frac{dv_S}{d\Omega_S}\left[C_c\bar{T}-(C_c-C_m)\Omega_S\right]+\frac{d\phi_N}{dv_N}\cdot\frac{dv_N}{d\Omega_S}\left[C_c\bar{T}-\left(C_c-\theta^S C_m\right)\Omega_S\right]\\&=\gamma\frac{\phi_S}{v_S}M_S\pi\left[C_c\bar{T}-(C_c-C_m)\Omega_S\right]+\gamma\frac{\phi_N}{v_N}\theta^S M_S\pi\left[C_c\bar{T}-\left(C_c-\theta^S C_m\right)\Omega_S\right],\end{aligned}\tag{10}$$

where $\gamma=\frac{\beta}{1-\beta}$ is the elasticity of the flow of new products developed in each region with respect to the value of a patent, i.e. $\frac{d\phi_i}{dv_j}=\gamma\frac{\phi_i}{v_j}$; Eq. (8) implies that $v_S=\pi\left[M_S\Omega_S+\theta^N M_N\Omega_N\left(\frac{\epsilon-1}{\lambda}\right)\right]$ and $v_N=\pi\left[M_N\Omega_N+\theta^S M_S\Omega_S\left(\frac{\epsilon-1}{\lambda}\right)\right]$. On the other hand, Eq. (5) implies that $\frac{dv_S}{d\Omega_S}=M_S\pi$ and $\frac{dv_N}{d\Omega_S}=\theta^S M_S\pi$, as we assume that each government treats θ^i_{EX}, θ^i_{FDI}, θ^i $(i=N,S)$, F_{EX} and F_{FDI} as parametric.

It is straightforward to write down the condition for the best response of the North, analogous to Eq. (10) above, so we do not put it here in the interest of space.

If we define $\mu_i=\phi_i/(\phi_S+\phi_N)$, it can be easily shown that $\mu_i=H_i/(H_S+H_N)$ when $\frac{\lambda}{\epsilon-1}=1$, which means that it is unaffected by patent policies in that case. Given that $\frac{\lambda}{\epsilon-1}$ is close to one, which is true empirically, we can show from Eq. (10) and its Northern counterpart that the best response functions are downward sloping, and that the best response function for the South is everywhere steeper than that for the North, when the two are drawn in (Ω_S,Ω_N) space. This guarantees uniqueness of the Nash equilibrium and ensures stability of the policy setting game.

2.2.2. Global optimum

In this section, we study the welfare impacts of international patent policy coordination. We begin by characterizing the combination of patent policies that are jointly efficient for the two countries, which is called the global optimum. We then compare the Nash equilibrium outcome with the efficient policies, to identify changes in the patent regime that ought to be effected by an international agreement.

Let $Q_S=M_S\Omega_S+\theta^N\left(\frac{\epsilon-1}{\lambda}\right)M_N\Omega_N$. A Southern firm that earns a discounted sum of expected profits of $M_S\Omega_S\pi$ for a period of length τ_S in the South and discounted sum of expected profits of $\theta^N\left(\frac{\epsilon-1}{\lambda}\right)M_N\Omega_N\pi$ for a period of τ_N in the North earns a total discounted sum of expected profits equal to $Q_S\pi$. On the other hand, a Northern innovator earns total discounted sum of expected profits equal to $Q_N\pi$ where $Q_N=\theta^S\left(\frac{\epsilon-1}{\lambda}\right)M_S\Omega_S+M_N\Omega_N$.

Consider the choice of patent policies Ω_N and Ω_S that will take effect at time 0 and apply to goods invented thereafter. Eq. (9) becomes an expression for welfare when $a=0$. Summing the expressions in Eq. (9) for $i=S$ and $i=N$ with a set to zero, we find that

$$\begin{aligned}\rho W^w&=\rho\left[W_S(0)|_{a=0}+W_N(0)|_{a=0}\right]\\&=\rho(\Lambda_{S0}+\Lambda_{N0})+w_S(L_S-L_{RS})+w_N(L_N-L_{RN})\\&\quad+M_S\phi_S\left[\bar{T}C_c-\Omega_S(C_c-C_m-\pi)\right]\\&\quad+M_S\phi_N\left\{\bar{T}C_c-\Omega_S\left[C_c-\theta^S C_m-\theta^S\left(\frac{\epsilon-1}{\lambda}\right)\pi\right]\right\}\\&\quad+M_N\phi_N\left[\bar{T}C_c-\Omega_N(C_c-C_m-\pi)\right]\\&\quad+M_N\phi_S\left\{\bar{T}C_c-\Omega_N\left[C_c-\theta^N C_m-\theta^N\left(\frac{\epsilon-1}{\lambda}\right)\pi\right]\right\}\end{aligned}\tag{11}$$

where W^w denotes world welfare (without any bias in favor of firm profits).

There is clearly a tradeoff as patent strength is increased in either country. For example, as Ω_S increases there is a direct effect of an increase in the deadweight losses $M_S\Omega_S(C_c-C_m-\pi)$ per Southern invention and $M_S\Omega_S\left[C_c-\theta^S C_m-\theta^S\left(\frac{\epsilon-1}{\lambda}\right)\pi\right]$ per Northern invention, which lower global welfare. But there are indirect effects that tend to increase global welfare: an increase in Ω_S leads to an increase in Q_N (Q_S), which induces faster innovation in the North (South), thus increasing ϕ_N (ϕ_S) and L_{RN} (L_{RS}). These effects are globally welfare-improving as L_{RN} and L_{RS} are optimally chosen by firms. In fact, it can be shown that when $\frac{\lambda}{\epsilon-1}$ is sufficiently small, there exists a unique globally optimum combination of Ω_N and Ω_S.

How do the efficient combination of patent policies compare to the policies that emerge in a noncooperative equilibrium? The answer to this question — which informs us about the likely features of a negotiated patent agreement — is illustrated in Fig. 2. The figure depicts the best response functions and the efficient policy combination in the same diagram.

In this figure, the globally optimal policy combination is depicted by point G. The iso-global-welfare lines such as $W^w=\bar{W}$ around G are also shown. The diagram shows that simultaneous increases of Ω_N and Ω_S from point E lead to an increase in global welfare. That is, a movement from E to G is globally welfare-improving. This is true when a is small, i.e. when governments' profit-bias is weak. The reasons are clear. Starting from a point on the South's best response function curve SS, a marginal strengthening of IPR protection in the South increases the world's welfare when profit-bias is weak. This is because such a change in Southern policies has only a second-order effect on the welfare of the South, but it conveys two positive externalities to the North. First, it provides extra monopoly profits to Northern innovators, which contributes to the aggregate income there. Second, it enhances the incentives for R&D, inducing an increase in both ϕ_S and ϕ_N. The extra product diversity that results from this additional R&D creates additional surplus for Northern consumers.

By the same token, a marginal increase in the strength of Northern patent protection from a point along NN increases world welfare. However, both SS and NN shift out as a increases, but the position of G is independent of a. Therefore, if a is not "small", then it is possible that an efficient patent treaty may require all countries to reduce their strengths of patent protection. Whether or not a is small in practice is an empirical question, which we answer in Section 3.

We define global under-protection of patent rights to be a situation when global welfare rises as Ω_N and Ω_S are both raised from their Nash equilibrium levels. If there is global under-protection of patent rights, then starting from any interior Nash equilibrium, an efficient patent treaty must strengthen patent protection in both countries. It also implies that the treaty will strengthen global incentives for R&D and induce faster innovation in both countries.

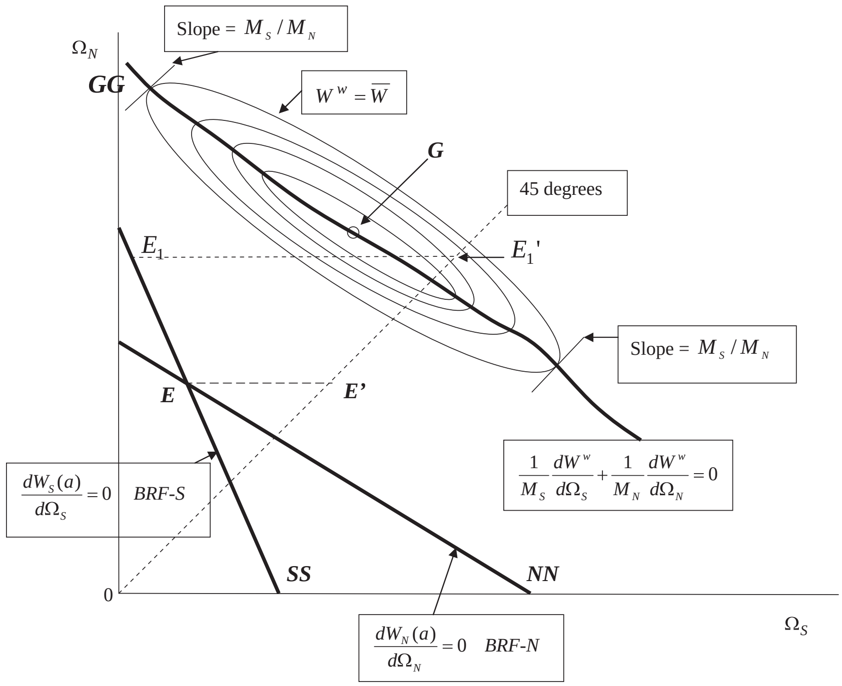

Fig. 2. Relationship between the Nash equilibrium E and global optimum G. The curve $W^W = \bar{W}$ is an example of an iso-global-welfare line. *BRF-S* and *BRF-N* are the best response functions of South and North respectively. Starting from any point on an iso-global-welfare line to the left of ***GG*** (defined by $\frac{1}{M_S}\frac{dW^W}{d\Omega_S}+\frac{1}{M_N}\frac{dW^W}{d\Omega_N}=0$), any small increase in Ω^N and Ω^S would increase the global welfare W^W. Hence, simultaneous increases of Ω^N and Ω^S from point ***E*** lead to an increase in global welfare. The globally optimal policy combination is depicted by point ***G***. A movement from ***E*** to ***G*** is globally welfare-improving.

2.3. The theory: multi-country case

Before bringing the model to the data, it is useful to extend the model to a multi-country setting, as the number of independent decision-making governments plays a crucial role in whether there is global under-protection of IPR in Nash equilibrium. Recall that there are J countries in the set $\mathcal{N}$ of country-players. Define $f_i \equiv C_c\bar{T}-(C_c-C_m)\Omega_i$ as the present discounted value of consumer surplus for a consumer in country i derived from the consumption of a home-developed differentiated good over its product life; and $f'_i \equiv C_c\bar{T}-\left(C_c-\theta^i C_m\right)\Omega_i$ as the corresponding expected consumer surplus derived from the consumption of a product developed by a foreign country.

2.3.1. Nash equilibrium

In a multi-country setting, the best-response function of country i is given by

$$\underbrace{\left(\sum_{j\neq i}\phi_j\right)\left(C_c-\theta^i C_m\right)+\phi_i[(C_c-C_m)-(1+a)\pi]}_{marginal\ \ cost}$$
$$=\left(\sum_{j\neq i}\frac{d\phi_j}{dv_j}\frac{dv_j}{d\Omega_i}f'_i\right)+\frac{d\phi_i}{dv_i}\frac{dv_i}{d\Omega_i}f_i \qquad (12)$$
$$\underbrace{\left(=\sum_{j\neq i}\gamma\frac{\phi_j}{v_j}\right)\theta^i\pi M_i f'_i+\gamma\frac{\phi_i}{v_i}\pi M_i f_i}_{marginal\ \ benefit} \quad \text{for } i=1,2,\ldots,J.$$

Eq. (12) is analogous to Eq. (10). The *left-hand side* (*LHS*) of Eq. (12) is, in fact, the marginal cost per consumer in country i of strengthening IPR there. The first term is the loss in consumer surplus attributed to protection of inventions from firms outside country i; the second term is the loss of consumer surplus attributed to protection of inventions from country i, offset by the gains in profits of firms in country i (augmented by the profit-bias a). The *right-hand side* (*RHS*) or the last line of Eq. (12) is the marginal benefit per consumer in country i. The first term is the increase in expected consumer welfare in country i due to increases in flows of innovations from firms outside country i; the second term is the increase in consumer welfare in country i due to the increase in the flow of innovation from country i. If we define the left-hand side of Eq. (12) as $MC_i(a)$ and the right-hand side of Eq. (12) as MB_i, then $\frac{1}{M_i}\frac{dW_i(a)}{d\Omega_i}=MB_i-MC_i(a)=$ marginal net national benefit to i, where $W_i(a)$ is government i's objective function. Hereinafter, we put an argument 'a' after the name of a function if profit-bias affects the value of the function.

Invoking Eqs. (2), (3) and (8), Eq. (12) can be re-written as

$$\left(\sum_{j\neq i}\phi_j\right)\left(1-\Lambda\theta^i\right)+[1-(2+a)\Lambda]\phi_i$$
$$=\gamma\left\langle\sum_{j\neq i}\left\{\frac{\phi_j\theta^i M_i\left[1-\left(1-\Lambda\theta^i\right)\omega_i\right]}{\sum_{k\neq j}\left(\frac{\epsilon-1}{\lambda}\right)\left(\theta^k M_k\omega_k\right)+M_j\omega_j}\right\}+\frac{\phi_i M_i[1-(1-\Lambda)\omega_i]}{\sum_{k\neq i}\left(\frac{\epsilon-1}{\lambda}\right)\left(\theta^k M_k\omega_k\right)+M_i\omega_i}\right\rangle$$
$$\text{for } i=1,2,\ldots,J \qquad (13)$$

where $\omega_k \equiv \Omega_k/\bar{T}$ and $\Lambda \equiv C_m/C_c = \pi/C_c$. The endogenous variables are ω_i and θ^i for $i=1,2,\ldots,J$. In order to solve for the values of ω_i for $i=1,2,\ldots,J$, we also need Eqs. (4), (6), and (7), as well as the calibrated value of θ^R_{EX} and θ^R_{FDI}, where the superscript R denotes the country with the largest market outside the US. It turns out that R is Japan. We shall adopt $\theta^R_{EX}=0.15$ and $\theta^R_{FDI}=0.03$ based on the estimates of the fractions of French and American firms that export and of those that carry out FDI in foreign countries, as provided in Eaton et al. (2004) (French) and Bernard et al. (2003) (American). More discussion will be provided about this in the next section.

2.3.2. Global optimum

Next, we turn to the comparison between the Nash equilibrium and the global optimum. It can be easily shown that the first-order condition for global welfare maximization with respect to the choice of Ω_i is given by

$$\begin{aligned} & M_i\left[MC_i(a)+\pi a\phi_i-\theta^i\left(\frac{\epsilon-1}{\lambda}\right)\pi\left(\sum_{j\neq i}\phi_j\right)\right] \\ & = M_i\times MB_i+\sum_{k\neq i}\left(\sum_{j\neq k}\frac{d\phi_j}{dv_j}\frac{dv_j}{d\Omega_i}M_k f'_k\right)+\sum_{k\neq i}\frac{d\phi_k}{dv_k}\frac{dv_k}{d\Omega_i}M_k f_k \\ & = M_i\times MB_i+\sum_{k\neq i}\left[M_k\left(\gamma\frac{\phi_i}{v_i}M_i\pi f'_k\right)+M_k\left(\sum_{j\neq k,i}\gamma\frac{\phi_j}{v_j}\right)\theta^i M_i\pi f'_k\right] \\ & +\sum_{k\neq i}M_k\left(\gamma\frac{\phi_k}{v_k}\theta^i M_i\pi f_k\right) \end{aligned} \tag{14}$$

The *LHS* of Eq. (14) (call it LHS_{14}) is the marginal global cost of strengthening IPR protection in country *i*. The second term inside the squared brackets ($\pi a\phi_i$) is the welfare that will not be taken into account when IPR protection in country *i* is chosen to maximize the global welfare instead of government *i*'s profit-biased objective function (therefore it is an addition to marginal cost); the third term inside the squared brackets ($\theta^i\left(\frac{\epsilon-1}{\lambda}\right)\pi\left(\sum_{j\neq i}\phi_j\right)$) reduces the global marginal cost as it takes into account the increases in profits of firms outside country *i*. The *RHS* (or the last line) of Eq. (14) (call it RHS_{14}) represents the marginal global benefit of strengthening IPR in country *i*. The second term and the third term are both increases in welfare of consumers outside country *i*. The second term is due to faster foreign rate of innovation, while the third term is due to faster domestic rate of innovation ("foreign" and "domestic" here are relative to each country other than country *i*). The cross-border externalities of IPR protection are captured by the third term inside the squared brackets on the *LHS* plus the second and third terms on the *RHS*. Let us define LHS_{14}/M_i as MC_i^W (marginal cost to the world) and RHS_{14}/M_i as MB_i^W (marginal benefit to the world). It follows that $\frac{1}{M_i}\frac{dW^w}{d\Omega_i}=MB_i^W-MC_i^W=$ marginal net global benefit from *i*.

Suppose we start with a world of Grossman and Lai (2004) where $a=0$ and $y=1$ (i.e. free trade). G–L have shown that there is global under-protection of IPR in Nash equilibrium, as the marginal net global benefit from *i* is larger than the marginal net national benefit to *i*. It is apparent that since an increase in the variable trade cost (i.e. a decrease in *y*, which in turn lowers θ^i for all *i*) leads to less international spillover, it narrows the net-benefits gap, thus lowering the likelihood of under-protection of IPR in equilibrium. Likewise, an increase in profit-bias (an increase in *a*) reduces the net-benefit gap, making under-protection of IPR less likely. Therefore, we expect that the lower is *a* and the higher is each θ^i, the more likely there is global under-protection of patent rights. This is exactly what Eq. (15) indicates below.

3. Calibration of the model

3.1. Is there global under-protection of IPR?

We define under-protection as a situation when, starting from Nash equilibrium, global welfare increases when there are positive changes in some or all of the elements in the set $\{\Omega_i|i\in\mathcal{N}\}$. The point of the analysis is to come up with a sufficient condition under which, starting from Nash equilibrium $\left\{\Omega_i^E|i\in\mathcal{N}\right\}$, the simultaneous increases in IPR protection of some countries is globally welfare-improving. Note that increases in the strengths of protection in some countries raise the values of all patents. This increases global deadweight losses but encourages innovation. If there is global under-protection of patent rights, then the rate of innovation in the world is too low from a global welfare point of view.

In Appendix D, it is proven that a sufficient condition for global under-protection of IPR in Nash equilibrium is

$$a-\sum_{i\neq max}\theta^i<0 \tag{15}$$

where θ^{max} is the largest θ^i among all countries. This is intuitive, as it means that the positive force that arises from profit-bias (measured by *a*) is weaker than the negative force that arises from cross-border externalities (measured by $\sum_{i\neq max}\theta^i$), thus making the Nash equilibrium more likely to yield under-protection.

In what follow, we shall explain a calibration exercise that tries to find out whether the above sufficient condition (15) is satisfied. We shall solve Eqs. (4), (6), (7) and (13) for $i=1,2,\ldots J$ with parametric values calibrated using estimates in the literature.

As explained earlier, the parameter *a* can also be interpreted as the weight politicians put on campaign contributions. In the political–economic literature (Grossman and Helpman, 1994; Goldberg and Maggi, 1999; Gawande and Bandyopadhyay, 2000; Mitra et al., 2002, 2006; Eicher and Osang, 2002; McCalman, 2004), researchers have estimated the weight the US government puts on campaign contributions given a weight of unity on social welfare. The estimates range from 0.000315 to 1.3333. For robustness check in the calibration exercise, we tried the values of $a=0.000315$ (low profit-bias), 1 (strong profit-bias) and 1.3333 (very strong profit-bias).[17]

The parameter *J* denotes the number of independent government decision-makers in the patent-setting game. Thus, it is the number of countries in the world that consumes and trade patent-sensitive goods, and that adopt neither zero nor full patent protection. In Table 1, we list the patent counts and market sizes of the twenty largest markets for patent-sensitive goods among the forty most innovative countries.[18] As Eq. (15) suggests, the more countries that are included in the game, the more likely the condition is satisfied. Therefore, it suffices to prove under-protection if we find that Eq. (15) holds for the twenty countries with the largest markets for patent-sensitive goods. These countries are thus included in our empirical analysis. Hence, $J=20$.

We proxy the market size (M_i) by the natural logarithm of the dollar value of the consumption of patent-sensitive goods in each country and proxy the innovative capability (ϕ_i) by the number of patents granted to residents of each country by the US patent office divided by the population of the country (we adjust for home bias of American patentees).[19] Data on M_i for 1996–1999 are obtained from Lai et al. (2007), and data on ϕ_i for 1996–1999 are from the website of World Intellectual Property Organization (WIPO).

θ_{EX}^i and θ_{FDI}^i are respectively the probabilities that foreign firms can sell to and carry out FDI in country *i*. Eaton et al. (2004) report that in 1986 only 17.4% of French manufacturing firms exported, and of those who exported, only 19.7% exported to ten or more countries. Moreover, in 1987, only 14.6% of US manufacturing firms exported. Bernard et al. (2003) report that 79% of US manufacturing plants did not export at all in 1992. A summary of the existing studies in the literature indicates that 15–20% of manufacturing firms sell to

[17] Since *a* is a preference parameter, it should be the same in the context of patent protection. Suppose there is a patent lobby, and suppose there is no consumer lobby or lobbying from other sectors of the economy, it is easy to show that the value the government puts on campaign contributions is exactly the same as *a* in our model. A proof is available from the author upon request.

[18] Innovative capability is measured by the average number of patents granted to domestic residents of the country by the US patent office per year over the years 1996–1999 divided by population. Russia is not included due to the lack of reliable data. See Appendix E.

[19] We also tried using the patent counts without dividing by population to proxy for innovative capability, and the sufficient condition for under-protection Eq. (15) is still satisfied. But the rank order of ω_i^E matches more closely the actual rank order of the Ginarte–Park patent rights indexes (see Park, 2008) when we use patent counts divided by population.

Table 1
Data on the market size of patent-sensitive goods and patent counts.

	Innovative capacity (ϕ)	Market size (M)
US	187.83	9.25
Japan	214.25	9.07
Germany	98.32	8.75
France	56.76	8.57
UK	52.08	8.45
China	0.06	8.45
Italy	24.24	8.43
Brazil	0.43	8.31
Spain	5.07	8.19
Canada	89.80	8.17
India	0.07	8.15
South Korea	55.34	8.13
Netherlands	65.15	8.02
Australia	31.91	7.99
Mexico	0.57	7.97
Argentina	1.06	7.88
Switzerland	167.53	7.85
Belgium	57.50	7.83
Sweden	122.82	7.77
Austria	50.25	7.76

Note:
1. M is the logarithm of the average annual consumption (or absorption) of patent-sensitive goods in the country over the years 1996–1999.
2. ϕ is the average number of patents granted to residents of the country per year by the US Patent Office over the years 1996–1999 divided by the population of the country. The patent count of the US is adjusted for the home-bias effect discussed in Appendix E.

foreign markets, of which about 1/5 produce in the foreign market in which they sell. (See, for example, Bernard et al., 2009). Patent-sensitive goods are likely to be more tradeable than the average manufactured goods. Therefore, to be conservative, we assume that 15% of American firms in the patent-sensitive industries sell to foreign markets, while 3% produce in the foreign countries in which they sell their goods. In other words, we set $\theta_{EX}^{Japan}=0.15$ and $\theta_{FDI}^{Japan}=0.03$ as Japan is the largest foreign market for the US firms. The θ_{EX}^{i} and θ_{FDI}^{i} for other countries are determined endogenously by Eqs. (6) and (7) respectively.

We estimate γ, the elasticity of innovation rate with respect to patent value, based on the work of Boldrin and Levine (2009), who suggest a point estimate of around 4.[20] As we find that our results are robust to alternative values of γ, we just report the case of $\gamma=4$ in this paper.

Lai et al. (2007) estimate the parametric values of the elasticity of demand for patent-sensitive goods (ϵ) across thirty countries. These values average to 5.63. Given this, we assume $\epsilon=5$. This coincides with the value implied by putting together the findings of literature that the shape parameter of the Pareto distribution of firm revenues ($\frac{\lambda}{\epsilon-1}$ in our model) is close to 1 and the finding of Simonovska (2011) that λ is approximately 4. For robustness, we also try a low elasticity scenario with $\epsilon=1.5$ and a high elasticity scenario with $\epsilon=9.28$. The upper value of 9.28 is obtained based on $\frac{\lambda}{\epsilon-1}\approx 1$ and the finding of Eaton and Kortum (2002) that λ is approximately 8.28.

Based on the empirical finding that $\lambda/(\epsilon-1)$ is very close to one but above one, we report the cases of $\lambda/(\epsilon-1)=1$ and 1.049, as these two values lie roughly at the two ends of the spectrum of estimates obtained in the literature. Adopting this range also ensures that there are interior solutions to all endogenous variables of interest.

For the variable trade cost, we try a wide range of values from $t=0$ (no iceberg trade cost) to 0.5 (very high iceberg trade cost). For the case $\lambda/(\epsilon-1)=1$, the results are invariant to the value of t.

Based on the above parametric values and data, we solve for the Nash equilibrium values of $\left\{\omega_i^E, \theta^i, \theta_{EX}^i, \theta_{FDI}^i | i\in\mathcal{N}\right\}$ from Eqs. (4), (6), (7) and (13) for $i=1,2,\ldots J$. A summary of the calibration results is presented in Table 2. A wide range of values of profit-bias have been tried ($a=0.000315$, $a=1$ and $a=1.3333$) but it has relatively minor effects on θ^i. So we only report the results for the most conservative case of $a=1.3333$ in the interest of space. More tables of results are available from the authors upon request.

As expected, a higher value of a is associated with a higher level of equilibrium strengths of IPR protection in each country $\{\omega_i^E\}$ as governments put more weight on the profits of patent-holders. Furthermore, from Table 2, we find that a higher t leads to lower probabilities of exploiting an invention in each country ($\{\theta^i\}$).

The calibration exercise yields two important results.

1. We find that the values of θ^i are above 0.7 for all countries under all scenarios. It follows that the sufficient condition for under-protection of IPR in the Nash equilibrium specified in Eq. (15) is satisfied under all parametric values considered. As a result, we conclude that there is global under-protection of patent rights when there is no international coordination. The main reason is the existence of a free-rider problem in the protection of patent rights, which becomes very serious when there is a large number of government-players in the patent-setting game. The value of θ_{EX}^i varies across countries, but never exceeds 0.2 under various sensitivity tests, while the values of θ_{FDI}^i for different countries are all below 0.04.[21]
2. If we ignored FDI/licensing, we would have severely overestimated the barriers to exploit an invention internationally. For example, in the case of the US firms selling to Japan, if the iceberg trade cost is $t=0.5$, $a=1.333$, $\frac{\lambda}{\epsilon-1}=1.049$, $\epsilon=9.28$, and if we accept the estimate that 15% of US firms sell to Japan and assume that they do not do FDI/licensing, then the estimated θ^{Japan} is 0.032 [i.e. $(1+0.5)^{-9.28+1}\cdot(0.15)^{1-\frac{1}{1.049}}$].[22] If we take into account the fact that 1/5 of those firms that sell to Japan (i.e. 3% of all US firms) in fact carry out FDI/licensing, then the estimated θ^{Japan} is 0.851 [i.e. $(1+0.5)^{-9.28+1}\cdot(0.15)^{1-\frac{1}{1.049}}+\left[1-(1+0.5)^{-9.28+1}\right](0.03)^{1-\frac{1}{1.049}}$]. That is a huge difference. The errors in the estimation of θ^i of other countries would be equally large. In fact, had we omitted FDI/licensing, we would have concluded that the sufficient condition for under-protection would not be satisfied, as the magnitudes of the calibrated cross-border externalities would be really small. As the error becomes more serious as $\frac{\lambda}{\epsilon-1}$ gets closer to one, the empirical fact that firm revenues follow a fat-tailed distribution implies that it is really important to include FDI as an alternative channel of exploiting an invention internationally (besides exporting) in any empirical work.

3.2. Harmonization with the most protective country

Our analysis in the previous section indicates that there would be under-protection of IPR without international coordination. A natural question to ask is whether the current form of international coordination mandated by TRIPS is over-protective from a global welfare perspective. Adopting the views of Reichman (1995) and Lai and Qiu (2003), we assume that TRIPS requires all countries in the world to harmonize their IPR standards with the pre-TRIPS standards of the

[20] Details of the derivation can be obtained from the authors upon request.

[21] The relatively high value of θ^i we obtain is consistent with the finding of Eaton and Kortum (1999), who find that the extent of international diffusion of technology is about two-third of the way between total absence of diffusion and perfect diffusion. In our model, total absence of diffusion before a patent expires in country i corresponds to $\theta^i=0$, while perfect diffusion before a patent expires corresponds to $\theta^i=1$. Two-third of the way from the state of zero diffusion corresponds to $\theta^i=0.67$ in our model.

[22] This is the case when F_{FDI} is so large that $\theta_{FDI}^k\rightarrow 0\,\forall k$.

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Table 2
Nash equilibrium and harmonized global optimum (a = 1.333).

	Trade cost (t) = 0												Trade cost (t) = 0.5											
	ε = 1.5				ε = 5				ε = 9.28				ε = 1.5				ε = 5				ε = 9.28			
	$\frac{\lambda}{\varepsilon-1}=1$		$\frac{\lambda}{\varepsilon-1}=1.049$		$\frac{\lambda}{\varepsilon-1}=1$		$\frac{\lambda}{\varepsilon-1}=1.049$		$\frac{\lambda}{\varepsilon-1}=1$		$\frac{\lambda}{\varepsilon-1}=1.049$		$\frac{\lambda}{\varepsilon-1}=1$		$\frac{\lambda}{\varepsilon-1}=1.049$		$\frac{\lambda}{\varepsilon-1}=1$		$\frac{\lambda}{\varepsilon-1}=1.049$		$\frac{\lambda}{\varepsilon-1}=1$		$\frac{\lambda}{\varepsilon-1}=1.049$	
	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i	ω_i^E	θ^i
US	0.373	1	0.423	0.917	0.529	1	0.588	0.915	0.561	1	0.621	0.915	0.373	1	0.424	0.904	0.520	1	0.579	0.862	0.550	1	0.607	0.851
Japan	0.367	1	0.418	0.915	0.520	1	0.597	0.915	0.550	1	0.633	0.915	0.367	1	0.419	0.903	0.529	1	0.589	0.862	0.561	1	0.620	0.851
Germany	0.285	1	0.318	0.901	0.368	1	0.418	0.898	0.384	1	0.439	0.897	0.285	1	0.318	0.889	0.368	1	0.409	0.845	0.384	1	0.425	0.834
France	0.246	1	0.267	0.893	0.298	1	0.331	0.887	0.307	1	0.344	0.886	0.246	1	0.266	0.881	0.298	1	0.321	0.834	0.307	1	0.331	0.823
UK	0.231	1	0.247	0.889	0.276	1	0.303	0.882	0.285	1	0.315	0.881	0.231	1	0.246	0.877	0.276	1	0.293	0.830	0.285	1	0.302	0.819
China	0.207	1	0.208	0.881	0.217	1	0.210	0.867	0.218	1	0.211	0.864	0.207	1	0.206	0.869	0.217	1	0.197	0.814	0.218	1	0.194	0.801
Italy	0.215	1	0.222	0.884	0.241	1	0.251	0.874	0.245	1	0.258	0.873	0.215	1	0.221	0.872	0.241	1	0.240	0.822	0.245	1	0.243	0.810
Brazil	0.189	1	0.181	0.875	0.196	1	0.168	0.856	0.196	1	0.035	0.790	0.189	1	0.180	0.863	0.196	1	0.154	0.804	0.196	1	0.034	0.735
Spain	0.176	1	0.161	0.869	0.182	1	0.040	0.798	0.182	1	0.044	0.799	0.176	1	0.159	0.857	0.182	1	0.040	0.752	0.182	1	0.043	0.743
Canada	0.214	1	0.228	0.884	0.279	1	0.308	0.881	0.291	1	0.325	0.881	0.214	1	0.228	0.872	0.279	1	0.302	0.830	0.291	1	0.316	0.819
India	0.170	1	0.148	0.865	0.171	1	0.052	0.808	0.170	1	0.056	0.808	0.170	1	0.147	0.853	0.171	1	0.052	0.761	0.170	1	0.056	0.752
S. Korea	0.192	1	0.193	0.877	0.232	1	0.239	0.870	0.239	1	0.250	0.870	0.192	1	0.193	0.865	0.232	1	0.232	0.819	0.239	1	0.240	0.808
Netherlands	0.182	1	0.180	0.873	0.226	1	0.231	0.868	0.234	1	0.244	0.868	0.182	1	0.180	0.861	0.226	1	0.226	0.817	0.234	1	0.235	0.807
Australia	0.163	1	0.142	0.863	0.182	1	0.037	0.794	0.185	1	0.038	0.793	0.163	1	0.141	0.851	0.182	1	0.035	0.746	0.185	1	0.036	0.735
Mexico	0.145	1	0.088	0.842	0.141	1	0.078	0.823	0.139	1	0.081	0.822	0.145	1	0.084	0.829	0.141	1	0.075	0.774	0.139	1	0.076	0.763
Argentina	0.133	1	0.064	0.829	0.127	1	0.082	0.825	0.125	1	0.084	0.823	0.133	1	0.064	0.818	0.127	1	0.078	0.775	0.125	1	0.079	0.764
Switzerland	0.208	1	0.231	0.883	0.323	1	0.367	0.887	0.346	1	0.395	0.888	0.208	1	0.232	0.871	0.323	1	0.365	0.836	0.346	1	0.390	0.826
Belgium	0.153	1	0.130	0.858	0.187	1	0.158	0.851	0.193	1	0.167	0.851	0.153	1	0.130	0.847	0.187	1	0.155	0.802	0.193	1	0.161	0.791
Sweden	0.177	1	0.181	0.872	0.257	1	0.280	0.875	0.273	1	0.302	0.876	0.177	1	0.182	0.860	0.257	1	0.278	0.825	0.273	1	0.297	0.815
Austria	0.140	1	0.094	0.844	0.166	1	0.049	0.804	0.170	1	0.048	0.801	0.140	1	0.094	0.833	0.166	1	0.045	0.754	0.170	1	0.043	0.742
Harmonized global optimum	$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$		$\omega^*=1$	

Note:

1. ω_i^E denotes the patent protection of country i in Nash equilibrium. θ^i is defined as $y\left(\theta^i_{Ex}\right)^{\frac{1-\varepsilon+\lambda}{\lambda}}+(1-y)\left(\theta^i_{FDI}\right)^{\frac{1-\varepsilon+\lambda}{\lambda}}$, where θ^i_{EX} and θ^i_{FDI} represent the probabilities of a foreign firm selling to and carrying out FDI in country i respectively. ω^* denotes the globally optimal level of harmonized patent protection.

2. ε refers to the price elasticity of demand of a typical consumer. The value of ε = 5 is obtained from Lai et al. (2007) and by putting together the findings of Axtell (2001) and Luttmer (2007) that the shape parameter of the Pareto distribution ($\frac{\lambda}{\varepsilon-1}$) is close to but larger than 1 and the finding of Simonovska (2011) that λ is approximately 4. The alternative value of ε = 9.28 is obtained based on $\frac{\lambda}{\varepsilon-1}\approx 1$ and the finding of Eaton and Kortum (2002) that λ is approximately 8.28.

3. $\frac{\lambda}{\varepsilon-1}$ refers to the shape parameter of the distribution of firm revenues. Based on the data on US's firm size distributions in 1988–1997, Axtell (2001) obtain that $\frac{\lambda}{\varepsilon-1}$ is close to and larger than 1. A recent study by Luttmer (2007) finds that the shape parameter is also close to but larger than 1. We perform robustness check on $\frac{\lambda}{\varepsilon-1}$ by setting its upper end to 1.049.

4. "1 + a" is the weight a government puts on domestic profits when a weight of one is put on domestic consumer surplus in its objective function. The parameter "a" measures the profit-bias of governments. It ranges from 0.000315 to 1.3333 in the literature (Goldberg and Maggi, 1999; Gawande and Bandyopadhyay, 2000; Mitra et al., 2002; Eicher and Osang, 2002; McCalman, 2004; Mitra et al., 2006). Since a = 1.3333 gives the most conservative case that makes us hardest to reach the under-protection conclusion, we only present this case here. Lower values of "a" yield an even larger degree of under-protection in Nash equilibrium.

most protective country. We try to answer the above question based on this characterization of TRIPS.[23]

Suppose we sum up all the J first order conditions (14) and impose the restriction $\Omega_j=\Omega^*\ \forall j\in\mathcal{N}$ on this equation. The solution of Ω^* will then yield the harmonized patent strength that is globally efficient. Suppose country k is the most protective country in equilibrium, i.e. $\Omega_k^E=\max\left\{\Omega_j^E|j\in\mathcal{N}\right\}$. Then, $\Omega_k^E<\Omega^*$ is the necessary and sufficient condition that there is no over-protection of patent rights even if all countries harmonize their IPR standards with the most protective country in the world. We have already solved for Ω_k^E, which is Ω_{US}^E, in the earlier section. Adopting the same set of parametric values and the same set of countries as in the previous section, we compute the value of Ω^*. The values of Ω^* under different parameter values are provided in the last rows of Table 2. As the values of Ω^* are all close to 1, which exceeds the equilibrium protection strengths of all countries including the US in all cases, we conclude that $\Omega_{US}^E<\Omega^*$. This means that there is no global over-protection of IPR resulting from TRIPS.

The intuition of the above result is that the distribution of innovative capability among countries is not too skewed so that requiring all countries to harmonize their patent standards with that of the most protective (and most innovative) country in Nash equilibrium (i.e. the US) does not lead to over-protection of patent rights from the global welfare point of view. The situation in a two-country case is shown in Fig. 2. It shows that global harmonization with the North's pre-TRIPS standard is a movement from point E to point E'. As E' is still inside the frontier GG, global welfare increases from E to E'. The North gains more than the South loses in this global IPR harmonization scheme, and global welfare increases. Taken together, the two results in this section indicate that TRIPS is globally welfare-improving.[24]

4. Conclusion

On the theoretical front, we extend the Grossman and Lai (2004) model to analyze the interaction among innovation, firm heterogeneity, exporting, FDI and patent protection in a unified framework. On the empirical front, we find that there is global under-protection of patent rights in the non-cooperative equilibrium given the estimates of the profit-bias parameter in the political economy literature and the estimates of the barriers to international exploitation of inventions. Our conclusion to this question is robust to alternative parametric values obtained in the literature. This result arises from the fact that, despite the existence of trade barriers, the free-rider problem becomes very serious when there is a large number of country-players in the patent-setting game. The empirical fact that firm revenues follow a fat-tailed distribution mitigates trade and FDI barriers a great deal, leading to low barriers to international exploitation of inventions. Thus, the cross-border externalities in strengthening national patent rights are high, despite the fact that only a small fraction of firms sell overseas (no more than say 15%) and an even smaller fraction of firms carry out FDI (no more than say 3%). Calibrating the model, we find that requiring all countries to harmonize their patent strengths with the equilibrium strength of the most protective country does not lead to global over-protection of IPR. This is because the distribution of innovative capability among countries is not too skewed as to overcome the free-rider effect. If such an IPR harmonization scheme captures what the TRIPS has done, then there is no evidence that TRIPS leads to global over-protection of patent rights. In other words, TRIPS is globally welfare-improving.

Last but not least, in our calibration exercise, we find that omitting FDI/licensing as an alternative channel of exploiting an invention internationally (besides exporting) can severely over-estimate the barriers to international exploitation of inventions. Therefore, it is important to include both exporting and FDI in any model that attempts to explain international exploitation of technology.

The theoretical framework can possibly be exploited further to analyze empirically the relationship between innovation, trade barriers, market size, patent protection, and trade flows of patent-sensitive goods among countries. This is left to future research.

Appendix A. Mean values of profit and consumer surplus

Define the unconditional means of the monopoly profit, the competitive consumer surplus and consumer surplus under monopoly, per consumer, as

$$\pi=\int_{c=0}^{\frac{1}{b}}\tilde{\pi}(c)dF(c);\quad C_c=\int_{c=0}^{\frac{1}{b}}\tilde{C}_c(c)dF(c);\quad \text{and}$$
$$C_m=\int_{c=0}^{\frac{1}{b}}\tilde{C}_m(c)dF(c)$$

where c is the unit cost of production. $\tilde{\pi}(c)$, $\tilde{C}_c(c)$ and $\tilde{C}_m(c)$ are monopoly profit, the competitive consumer surplus and consumer surplus under monopoly, respectively, expressed as functions of c. From Subsection 2.1.1, the c.d.f. of c is given by $F(c)=(bc)^{\lambda}$, where $c\in\left[0,\frac{1}{b}\right]$.

Recall that the demand of a typical consumer is $x=Ap^{-\epsilon}$ (where $\epsilon>1$). It can be easily shown that

$$\tilde{C}_c=\frac{Ac^{-\epsilon+1}}{\epsilon-1.} \tag{16}$$

Therefore,

$$C_c=\frac{A\lambda b^{\epsilon-1}}{(\epsilon-1)(1-\epsilon+\lambda).}$$

Similarly,

$$\tilde{\pi}=\tilde{C}_m=\Lambda\tilde{C}_c\quad \text{where}\quad \Lambda\equiv\left(\frac{\epsilon-1}{\epsilon}\right)^{\epsilon} \tag{17}$$

and so $\pi=C_m=\Lambda C_c$.

Appendix B. The distributions of firm profits and revenues

From Subsection 2.1.1, we have $\Pr(c<z)=(bz)^{\lambda}$, where $z\in\left[0,\frac{1}{b}\right]$. From Appendix A, we have $\tilde{\pi}=A\left(\frac{1}{\epsilon-1}\right)\Lambda c^{-\epsilon+1}$. Therefore,

$$Pr(\tilde{\pi}<s)=1-\left(\frac{A\Lambda b^{\epsilon-1}}{\epsilon-1}\right)^{\frac{\lambda}{\epsilon-1}}\cdot s^{-\frac{\lambda}{\epsilon-1}},\ \text{where}\ s\in\left(\frac{A\Lambda b^{\epsilon-1}}{\epsilon-1},\infty\right) \tag{18}$$

and revenue per consumer $\tilde{R}=(\epsilon-1)\tilde{\pi}$ follows a distribution

$$Pr\left(\tilde{R}<\mathfrak{s}\right)=1-\left(A\Lambda b^{\epsilon-1}\right)^{\frac{\lambda}{\epsilon-1}}\cdot\mathfrak{s}^{-\frac{\lambda}{\epsilon-1}},\ \text{where}\ \mathfrak{s}\in\left(A\Lambda b^{\epsilon-1},\infty\right).$$

[23] If one examines the Ginarte–Park patent rights index for the periods 1960–1990, 1995, 2000 and 2005 (refer to Park, 2008), one sees that the most protective country before TRIPS (i.e. 1960–1990) was the US, whose index was 4.14. By 2005, all developed or newly industrialized economies would have already adopted the patent standard required by TRIPS. The patent rights indexes for countries that adopt the minimum requirement mandated by TRIPS turned out to be about 4.1 (e.g. Israel 4.13, Australia 4.17, New Zealand 4.01, Norway 4.17). So harmonization with the pre-TRIPS standard of the US is more or less what the TRIPS mandated.

[24] If the distribution of innovative capability is too skewed, then the equilibrium may be at E_1 shown in Fig. 2. In that case, a movement from E_1 to E'_1 leads to over-protection.

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Appendix C. Fixed cost of exporting and probability of exporting

Define c^k_{FDI} as the critical c for FDI to country k and c^k_{EX} as the critical c for exporting to country k. From Fig. 1, we get

$$y\tilde{\pi}\left(c^k_{EX}\right)M_k\Omega_k = F_{EX}.$$

From Appendix A, we obtain

$$\tilde{\pi}\left(c^k_{EX}\right) = \left(\frac{A\Lambda}{\epsilon - 1}\right)\left(c^k_{EX}\right)^{-\epsilon+1}.$$

From Appendix B, we obtain

$$\theta^k_{EX} = Pr\left(c < c^k_{EX}\right) = \left(b \cdot c^k_{EX}\right)^{\lambda}.$$

From the above three equations we can obtain C^k_{EX} and θ^k_{EX} in terms of the exogenous variables and Ω_k:

$$\theta^k_{EX} = b^{\lambda}\left[\frac{y\Lambda A M_k\Omega_k}{F_{EX}(\epsilon-1)}\right]^{\frac{\lambda}{\epsilon-1}} \quad \text{and} \quad c^k_{EX} = \left[\frac{y\Lambda A M_k\Omega_k}{F_{EX}(\epsilon-1)}\right]^{\frac{1}{\epsilon-1}}. \tag{19}$$

By the same token, we can obtain the following three equations

$$y\tilde{\pi}\left(c^k_{EX}\right)M_k\Omega_k - F_{EX} = \tilde{\pi}\left(c^k_{FDI}\right)M_k\Omega_k - F_{FDI},$$

$$\tilde{\pi}\left(c^k_{FDI}\right) = \left(\frac{A\Lambda}{\epsilon - 1}\right)\left(c^k_{FDI}\right)^{-\epsilon+1},$$

$$\theta^k_{FDI} = Pr\left(c < c^k_{FDI}\right) = \left(b \cdot c^k_{FDI}\right)^{\lambda},$$

which allow us to obtain C^k_{FDI} and θ^k_{FDI} in terms of the exogenous variables and Ω_k:

$$\theta^k_{FDI} = b^{\lambda}\left[\frac{(1-y)\Lambda A M_k\Omega_k}{(F_{FDI}-F_{EX})(\epsilon-1)}\right]^{\frac{\lambda}{\epsilon-1}} \quad \text{and} \quad c^k_{FDI} = \left[\frac{(1-y)\Lambda A M_k\Omega_k}{(F_{FDI}-F_{EX})(\epsilon-1)}\right]^{\frac{1}{\epsilon-1}}. \tag{20}$$

Appendix D. Proof of condition (15)

Recall that the Nash equilibrium condition (12) is equivalent to $\frac{1}{M_i}\frac{dW_i(a)}{d\Omega_i} = 0$ while the global optimum condition (14) is equivalent to $\frac{1}{M_i}\frac{dW^w}{d\Omega_i} = 0$. A sufficient condition for under-protection in Nash equilibrium is $\sum_i \frac{1}{M_i}\frac{dW^w}{d\Omega_i} > 0$ for all combinations of $\{\Omega_i | i \in \mathcal{N}\}$ that satisfy $\sum_i \frac{1}{M_i}\frac{dW_i(a)}{d\Omega_i} = 0$. This is because $\sum_i \frac{1}{M_i}\frac{dW^w}{d\Omega_i} > 0 \Leftrightarrow \left(\sum_i \frac{1}{M_i}\frac{dW^w}{d\Omega_i}\right)\delta > 0$ where $\delta = M_i d\Omega_i \ \forall i$, which means that increasing each Ω_i slightly by an amount proportional to $1/M_i$ is globally welfare-improving. Furthermore, the set of equilibrium IPR $\left\{\Omega^E_i | i \in \mathcal{N}\right\}$ is obviously a subset of $\left\{\Omega_i \middle| \sum_i \frac{1}{M_i}\frac{dW_i(a)}{d\Omega_i} = 0\right\}$. From Eq. (14), we know that the above sufficient condition is equivalent to

$$\sum_i \left[\pi a\phi_i - \theta^i\pi\left(\sum_{j\neq i}\phi_j\right)\right] < \sum_i \left[\sum_{k\neq i}\left(\gamma\frac{\phi_i}{v_i}\pi M_k f'_k + \sum_{j\neq k,i}\gamma\frac{\phi_j}{v_j}\theta^i\pi M_k f'_k\right) + \sum_{k\neq i}\gamma\frac{\phi_k}{v_k}\theta^i\pi M_k f_k\right] \tag{21}$$

for all combinations of $\{\Omega_i\}_{i\in\mathcal{N}}$ that satisfy $\sum_i \frac{1}{M_i}\frac{dW_i(a)}{d\Omega_i} = 0$.

The RHS of Eq. (21) is greater than zero, as there are positive cross-border externalities as a country strengthens its patent protection. Therefore, a sufficient condition for Eq. (21) to hold is $\sum_i \left[a\phi_i - \theta^i\left(\sum_{j\neq i}\phi_j\right)\right] < 0$, a sufficient condition of which is $a - \Sigma_{i\neq \max}\theta^i < 0$. ■

Appendix E. Data for market size (M) and innovative capability (ϕ)

The market size variable (M_i) is proxied by the natural logarithm of the average dollar value of consumption (or use) of patent-sensitive goods per year by country i over the years 1996–1999 (estimated by Lai et al., 2007). Our choice of the set of patent-sensitive goods is mainly based on Maskus (2000), with some modifications. The set includes Chemicals, Electromedical machines, Special industry machines, Electric microcircuits, Metalworking machines, Measuring and control instruments, and Data processing equipment. The innovative capability variable (ϕ_i) is proxied by the average number of patents granted to the resident of country i by the US patent office per year over the years 1996–1999 (obtained from the WIPO website) divided by population. However, to adjust for home-bias of the US data, we calculate the US innovative capability as the mean of an upper bound and a lower bound. The upper bound is given by the yearly average of the actual number of patents granted to US residents by the US patent office, P^{US}_{US}, where P^j_i denotes the number of patents granted to residents of country i by country j. This is an upper bound because it probably over-states the innovative capability of the US because even relatively trivial inventions might be patented in the US by US residents as the cost of patenting and subsequent working of the patents by domestic residents is relatively low. This is the home bias effect. The lower bound estimate is obtained by the formula

$$\widetilde{P^{US}_{US}} = \frac{P^{EPO}_{US}}{P^{EPO}_{Japan}} \times P^{US}_{Japan}.$$

The idea is that the American capability to obtain patents relative to that of Japan in Europe is approximately equal to the American capability to obtain patents relative to that of Japan in the US. Comparison with Japan is chosen because its innovative capability is comparable to that of the US while other countries are much further behind. The reason for choosing patents awarded in Europe is because European countries have a longer tradition of patent protection and have patent systems similar to that of the US. Japan, on the other hand, has a more liberal patent system with narrower protection than in the US and Europe. Therefore, calibration with the Japanese patent counts is not done. The estimate $\tilde{P}^{US}_{US}$ is considered a lower bound of US innovative capability as some useful American innovations are not patented overseas perhaps because they are relatively less significant (though may be still useful). This is just the opposite of the home bias effect.

The estimated innovative capability of the US is therefore calculated as

$$\widehat{\phi_{US}} = \frac{\widetilde{P^{US}_{US}} + P^{US}_{US}}{2}.$$

After taking the above into account, we obtain Table 1, which shows the patent counts and market sizes of the twenty most innovative countries.

Appendix F. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jinteco.2012.07.004.

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