Foreign competition and R&D subsidies in the U.S.: a quantitative welfare analysis*

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Abstract

The geographical distribution of R&D investment changes dramatically in the 1970s and 1980s. In the early 1970s the distribution is very skewed: U.S. firms are the uncontested world leaders in R&D investment in most manufacturing sectors. Later, led by Japan and Europe, foreign firms start challenging American R&D leadership in many sectors of the economy. What is the effect on U.S. national welfare of foreign innovators entering sectors previously dominated by American firms? What are the implications for the optimal U.S. R&D subsidy? In this paper I build an empirical measure of international R&D rivalry tracking down these changes in international distribution of research efforts. In a version of the quality-ladders growth model I evaluate the quantitative effects of the increase in foreign R&D rivalry observed in the data on U.S. welfare. Using estimates of the effective R&D subsidy rate in the U.S., and the international R&D rivalry index, I compute the distance from optimality of the observed U.S. subsidy at each level of competition in the period 1979-91, and quantify the welfare gains associated with the optimal subsidy.

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1 Introduction

In the debate on the economic costs and benefits of globalization some recent works battled over the welfare effects on leading economies of technical progress in trailing countries. Most of the attention has been dedicated to the consequences on advanced industrial countries of cost-driven and technology-induced offshoring to developing countries, and especially to Asia's giants, India and China.[1] Another similarly heated debate took place in the 1970s and 1980s, at the time economists and political analysts warned the American public about the consequences of losing the "race" of the 21st century, the race for world technological leadership, to catching-up Japan and Europe.[2]

In both situations there seems to be a sufficient consensus among economists that, even in those cases where international competition could hurt leading countries, restrictions to free trade are a cure 'worse than the disease'. Innovation policy is instead seen as a more 'respectable' candidate for helping national economies perform in the global market.[3] There are two main reason to focus R&D subsidies instead of trade policy: first, the WTO and other international institutions restrict the use of trade policies, while individual countries are free to set their R&D subsidies autonomously. Secondly, R&D subsidies allow policy makers to protect the domestic economy without giving up gains from trade. A key issue is then understanding how international competition affects public incentives to support innovation. This paper analyzes the quantitative effects of the European and Japanese technological competition in the 1970s and 1980s on U.S. welfare and evaluates the gains associated with the optimal R&D subsidies response to competition.

International competition in this paper is represented by rivalry in the global innovation activity among firms from different countries. In order to obtain a rough measure of this dimension of competition I analyze the global distribution of investments in R&D. Since the focus

[1] See Baumol and Gomory (2000), Samuelson (2004), Bhagwati, Panagariya, and Srinivasn (2004), Blinder (2005). Another related work with a different role for technical change is discussed in Grossman and Rossi-Hansberg (2006a).

[2] See Tyson (1992) and Thurow (1992), Krugman (1996).

[3] The standard argument is that since causes for intervention are market imperfections the remedies should directly deal with these market failures. In Krugman's words. "What is wrong with markets is usually a *domestic* distortion, best fixed by a surgical policy directly aimed at the source of the market failure." (Krugman 1993, p.364). More sophisticated arguments in favor of innovation policy can be found in Gomory and Baumol (1992) and (2000).

is on R&D I use OECD STAN data on R&D investment in 2-digit manufacturing industries for 12 OECD countries - the U.S., the U.K., Japan, Italy, France, Germany, Spain, Sweden, Denmark, Finland, Ireland, and the Netherlands- in the period 1973-95.[4] The average sectorial Gini coefficient, and the Herfindhal and the Theil index, computed using this data, show that the geographical concentration of R&D investment declines substantially in this period; more firms from different countries participate into the global R&D race in each sector of the economy. This evidence is suggestive of a process of entry of firms from different countries in the global competition for innovation that was previously taking place among firms from a smaller set of countries. Moreover, the data on countries' share of global R&D investment provide additional information on the sources of this higher geographical diversification of R&D. U.S. share decline from 52 percent in 1973 to 37 percent in1991, while Japan's share increases from 17 percent in 1973 to 28 in 1991. This suggests that U.S. global leadership in R&D activity has been increasingly challenged by foreign firms in the period considered.

Estimates of R&D subsidies from Bloom, Griffith and Van Reenen (2002) show an increase in the subsidy given to U.S. firms starting with the introduction of the Research and Experimentation Tax Credit in 1981. The tax subsidy due to the R&D tax credit increases from 6 percent in 1979 to 18 in 1991. This facts lead us to the question of whether the sort of *defensive* R&D subsidy response to foreign competition suggested by the data can be socially optimal. The main goal of this paper is to build a framework to study how increases in international R&D competition affect the optimal domestic R&D subsidy. A calibrated version of the model is used to study the effects of the observed increase in foreign R&D rivalry, coming from Japan and Europe, on the optimal R&D subsidy in the U.S.. The optimal subsidy response is compared to the actual U.S. subsidy shown in the data and welfare implications are drawn.

I set up a two-country quality ladders growth model where monopolistic competitive firms compete for market leadership through investment in quality-improving R&D (Grossman and Helpman 1991, Aghion and Howitt 1992). Scale effects are removed assuming that increasing labor force 'dilutes' the research effort per variety of goods.[5] There are two countries, domestic and foreign, sharing the same size, technology and preferences but with different allocation of R&D investment across sectors and different research subsidies. Following the evidence

[4] R&D expenditures in this set of countries represents 95 to 98 percent of global R&D spending in the period considered.

[5] Population growth mimics the expansion in the variety of goods and eliminates the impact of population levels on the steady state growth rate (e.g., Dinopoulos and Thompson,1998, Howitt 1999, and Peretto, 1998).

discussed above I model foreign competition as follows: I assume that domestic country is the world leader in that its firms invest in R&D in all sectors of the economy; while the foreign country is the follower, in that its R&D firms are concentrated only in few sectors. The share of sectors where R&D firms from both countries compete for innovation is used as a measure of international technological competition.[6]

Increases in competition, that is, increases in the number of sectors where domestic leaders are challenged by foreign innovators, produce two potentially opposite effects on domestic welfare. First, competition has a positive effect on long-run growth. Decreasing returns to R&D at the country level, motivated by the presence of fixed costs or by the fixed endowment of workforce with heterogeneous ability (Eaton and Kortum, 1999), imply that increases in competition lead to a more *efficient* international distribution of research labor and spurs innovation and long-run growth in goods' quality. More precisely, the concave research technology implies that in competitive sector, where R&D firms from both countries are active, ideas are produced more efficiently than in non competitive industries. As a consequence, increases in competition, represented by increases in the number of sectors with domestic and foreign innovators, raises global R&D efficiency and growth. This is the *growth effect* of competition (*GRE* henceforth).

This efficiency effect will not lead to higher growth only in those situations where the domestic country is technologically isolated from the rest of the world; that is, when international knowledge spillovers are very low and the growth rate depends almost exclusively on domestic innovation. Eaton and Kortum (1999) and Klenow and Rodriguez-Claire (2005) provide evidence that knowledge spillovers are substantially high and that world is well away from technological autarky. Thus, if we exclude the case of technological autarky, as the evidence suggests, the present model shows a positive effect of foreign competition on growth, which improves welfare though increases in consumer surplus.

This effect of competition on growth is similar in the spirit to the *selection effect* formalized in the recent literature on trade, firms heterogeneity, and productivity. In Melitz (2003) exposure to trade induces the less productive firms to exit the market, thus increasing the average productivity level of the economy. Gustafsson and Segerstrom (2007) show that when a this

[6] This working assumption is similar to the one in Krugman (1979) where the leading country is assumed to be able to virtually produce all goods in the economy, while the follower country can produce only the "old" goods. As in the present paper both countries have the same preferences, technology and environment, and the difference in production possibilities is exogenous. As Krugman suggests, the source of the productive advantage of the leading economy might be related to more skilled labor force, external economies, or to a difference in "social atmosphere".

mechanism is nested into a model of growth through expanding variety (Romer, 1992) foreign entry can affect the long-run growth rate of the economy. In the present paper, the growth effect of international competition is, though, different from those in the existing literature for the following reasons: first, the effect is produced by foreign entry in R&D and not by trade liberalization; second, the growth mechanism does not operate through the productivity gap between entrant and exiting firms - firms are homogenous in production - but through improvements in the efficiency of the innovation activity in the newly competitive sectors.

The paper is also related to the literature on competition, innovation and growth (see e.g. Peretto 2003, and the papers surveyed in Aghion and Griffith 2005). The existing literature focuses on changes in product market competition -due to domestic or foreign entry - and restricts the focus on the effects of competition on growth without considering the overall impact on national welfare. Some papers extend the analysis to welfare effects of competition but no optimal policy implications are formally derived (see e.g., Klundert and Smulders 1997, Tang and Waelde 2001). The present paper contributes to this literature by exploring a new dimension of competition that is determined by the international distribution of R&D efforts and that does not involve any changes in entry or market structure - neither in product markets nor in R&D sectors.[7]

The second basic effect of competition on domestic welfare is the standard *business-stealing effect* (*BSE* henceforth): when foreign innovators enter a market previously dominated by domestic firms some monopolistic rents shift abroad. Foreign business-stealing can affect national income through two potential channels: first, it reduces aggregate profits by destroying the rents of those domestic leaders that have been pushed out of the market by foreign innovators. Second, when domestic firms are taken over by foreign firms, domestic jobs are temporarily lost and the labor market clears at lower level. In this paper I focus on the profit-shifting effect and, assuming that the presence of multinational corporations equalizes wages across countries, I do not consider the negative effect of competition on wages.[8] The overall effect of competition on welfare is the results of the *GRE* and the *BSE* and depends on their relative strength.

[7] This new measure of competition complements the existing ones in the process of understanding the nature and mechanisms of global competition in the market place. In many cases foreign entry do not involve dramatic change in the market structure: before Airbus entered the market for aircraft there was an American oligopoly in that industry, and after Airbus entry there has been a European and American oligopoly. The market structure is similar but the geographical allocation of production, innovation, and ownership has changed. These are the type of situations better described by the new measure of competition.

[8] This additional channel as been explored in the companion paper Impullitti (2007).

Finally, there are two motives for R&D subsidies, or taxes: the market failures related to *knowledge spillovers* typical of closed economy models (see e.g. Segerstrom, 1998, Jones and Williams, 2000) that characterize the public good features of R&D, and the *strategic motive* related to international trade (see e.g. Spencer and Brander, 1983, Grossman and Eaton, 1986). It follows that subsidies can be used both to correct non-optimal levels of R&D due to the presence of knowledge spillovers and to protect national firms from foreign competition. The effect of foreign competition on optimal domestic subsidies depends on the impact of foreign entry in R&D in new sectors on these two motives for subsidies. Haaland and Kind (2007) is the only paper I am aware of that studies the effect of increasing competition on innovation and on the optimal strategic R&D subsidy. While this paper focuses on product market competition and, as standard in the strategic industrial policy literature, presents a static model of innovation, I zero in on international competition for innovation, and introduce a strategic subsidy game into an endogenous growth framework to account for the long-run effects of innovation on welfare.

Using OECD STAN data on R&D investment for the set of countries mentioned above, I build an empirical index of the measure of competition presented in the model. The basic idea in the construction of the index is the following: the sectors where U.S. investment in research dominates global spending in innovation are going to be considered non-competitive, while those sectors where U.S. and the rest of the world are more 'neck-to-neck' in their innovation effort will be considered competitive; the share of neck-to-neck sectors will be the measure of international competition for innovation. The baseline version of the index shows first, that the U.S. is the leading R&D investor in the world and second, that this leadership has been increasingly challenged by foreign countries in the period considered. More precisely, I find an increase in share of competitive sectors from 38 percent in 1973 to 76 percent from 1991 onward. It follows that this model-specific measure of R&D rivalry evolves in the same direction of the standard indexes of geographical R&D concentration, that is, it shows that foreign R&D has challenged American leadership in the 1970s and 1980s.

In a calibrated version of the model I compute the optimal U.S. subsidy response to the observed increase in foreign R&D competition and measure the distance from the observed subsidy in this period.[9] This quantitative exercise is related to the empirical literature on

[9] This feature of the paper is methodologically related to the works on fully-calibrated multi-country models of trade and growth, such as Eaton and Kortum (1999), Klenow and Rodriguez-Claire (2005). Although, the

strategic trade and industrial policy. Most existing works have focused on case studies of specific sectorial policies (i.e. tariffs, quotas, export and production subsidies) and have compared the welfare gains or losses of trade versus industrial policies.[10] In a seminal work Dixit (1988) evaluates the welfare effects of a U.S. trade policy in a specific sector, the automobile industry, in a general equilibrium model. Dixit's paper also contains a quantitative evaluation of the welfare losses implied by the gap between the observed and the optimal policy. I follow a similar strategy but focusing on a different policy instrument, R&D subsidies, that affects all industries in the economy. Thus, the quantitative analysis is appropriately carried out in a general equilibrium framework.

The rest of the paper is organized as follows. Section 2 sets up the model and derives the steady state equilibrium conditions. Section 3 presents the data on R&D subsidies and constructs the index of international R&D competition. In section 4 the model is calibrated to match the relevant long-run statistics. Sections 5 and 6 explore the basic theoretical mechanism, the business-stealing and growth effects of competition and their role in determining the optimal subsidy. Section 7 performs the quantitative welfare analysis: the competition index and the model are used to compute gap between the optimal and the observed U.S. subsidy response to competition and its welfare implications. Section 8 concludes.

2 Features of the data

In this section I introduce and discuss the data that will function both as a motivation and as working material in the quantitative analysis performed later on. First I use R&D investment data to construct standard indexes of geographical R&D concentration and track down their evolution in the period 1973-92. My interest is in international competition among technological leaders, hence, I restrict the attention to the U.S., Japan, and 10 European countries: Germany, France, U.K., Italy, Sweden, Denmark, Finland, Ireland, Spain, and the Netherlands. In the period 1973-1992, R&D expenditures in these countries represent between 95 and 98 percent of the global R&D investment in manufacturing.[11] Secondly, I report the estimates of R&D tax subsidies from Bloom, Griffith, and Van Reenen (2002) for a representative set countries.

basic questions I tackle are substantially different from the ones in those papers.

[10] See Feenstra (1995) for a survey. Most of the existing literature is based on calibrated general equilibrium models. See Berry, Levinshon, and Pakes (1999) for a pioneering econometric analysis of a strategic trade policy.

[11] See OECD ANBERD Rev.2, 2005.

2.1 Geographical distribution of R&D investment

The measures of geographical R&D concentration is built using OECD ANBERD data on R&D investment for two and three-digit manufacturing industries. In Figure shows a negative trend of the average sectorial Gini coefficient and Herfindahl index in the period considered.[12] This suggests that there has been a reduction in the concentration of R&D investment among the set of countries considered.

[FIGURE 1 ABOUT HERE]

Digging deeper into the performance of single countries one informative descriptive statistics is the evolution of global R&D investment shares. In Figure 2 I report sectorial average R&D investment share for the US., Japan, and the aggregate of European countries listed above.

[FIGURE 2 ABOUT HERE]

The figure shows that while European countries as a whole have kept a fairly constant share, U.S share has declined substantially, from 52 percent in 1973 to 37 percent in1991, while Japan's share have increased from 17 percent in 1973 to 28 percent in 1991.[13] This suggests that U.S. position as the global leader in R&D investment has been increasingly challenged by Japanese firms in the 1970s and 1980s.

2.2 R&D subsidies

Next, I show compute the R&D subsidy produced by the tax treatment in the U.S., Japan and some European countries using Bloom, Griffith, and Van Reenen (2002) corporate tax data. The data take into account the different tax and tax credit systems used in each country, and measure the reduction in the cost of 1$ of R&D investment produced by the tax system. The tax subsidy is the sum of depreciation allowances for R&D investment and of tax credits specifically aimed at reducing the cost of R&D. In all countries in the data there are depreciation allowances for R&D, and in most of the countries R&D costs are fully expensed, that is, depreciation allowances imply a complete write off of R&D costs for tax purposes. Specific R&D tax credits, instead, are only active in few countries.

[12] Other measures of concentration, such as the coefficient of variation and Theil index, have also been computed and yield similar results.

[13] Similar results are obtained with the weighted average, where sectors' share of total R&D are used as weights. The U.S. share, for instance, decreases from 57 percent in 1973 to 44 percent in 1991.

The subsidy rate is computed as follows: let V be the before-tax present value of the marginal investment in R&D, τ_π be the corporate tax rate, A_d be depreciation allowances, and A_c be the specific tax credit rate. Equalizing the marginal benefits and costs of one additional unit of R&D investment we obtain

$$V(1-\tau_\pi) = (1 - A_d - A_c)\,.$$

Assuming full expensing, that is $A_d = \tau_\pi$, and rearranging we obtain

$$V = 1 - \frac{A_c}{1-\tau_\pi},$$

The subsidy to R&D will be $s = \frac{A_c}{1-\tau_\pi}$, and will represent the reduction in the unit cost of research produced by the tax system. This computation of the R&D subsidy follows the standard procedure used in OECD (2005) to compare the generosity of tax treatment for R&D in different countries. More precisely, the standard tax subsidy is computed as $1 - B\ index$, where $B\ index = \frac{1-A_d-A_c}{1-\tau_\pi}$; assuming $A_d = \tau_\pi$, it is easy to see that $s = 1 - B\ index$. Figure 3 shows the subsidies rates s for different countries obtained with this procedure.

[FIGURE 3 ABOUT HERE]

The differences among countries are mainly due to the presence and effectiveness of a specific tax credit for R&D. In fact, we can see that the jump in US subsidies takes place with the introduction of the Research and Experimentation Tax Credit on incremental R&D in 1981, and in Spain with the introduction of a tax credit for all new fixed assets in 1989. In Japan there is a fixed tax credit of limited effectiveness for the entire period considered. In the rest of the countries there are no special tax provisions or credits given on R&D expenditures, and the positive and fairly constant subsidy rates are produced by tax credits common to all assets.

A key feature emerging from figure 3 is the increase in the R&D subsidy level in the U.S. from 13 percent in 1979 to 30 percent in 1990. Recalling the evidence in figure 1 and 2 we can observe that this substantial increase in public support to private innovation takes place in years when R&D investment from foreign countries, especially from Japan, is challenging U.S. global leadership in research.

3 The model

In this section I set up the model and derive the steady state equilibrium system of equations.

3.1 Households

Consider a two-country economy in which population, preferences, technologies, and institutions are identical in both countries. Each household is endowed with a unit of labor time whose supply generates no disutility. Dropping country indexes for notational simplicity, households are modeled as dynastic families that maximize intertemporal utility

$$\max U = \int_0^\infty N_0 e^{-(\rho-n)t} \log u(t)dt, \tag{1}$$

with static utility given by

$$\log u(c(t)) \equiv \int_0^1 \log \left[\sum_{j=0}^{j^{\max}(\omega,t)} \lambda^{j(\omega,t)} q(j,\omega,t) \right] d\omega,$$

subject to

$$c(t) \equiv \int_0^1 \left[\sum_{j=0}^{j^{\max}(\omega,t)} p(j,\omega,t) q(j,\omega,t) \right] d\omega,$$

$$W(0) + Z(0) - \int_0^\infty N_0 e^{-\int_0^t (r(\tau)-n)d\tau} T dt = \int_0^\infty N_0 e^{-\int_0^t (r(\tau)-n)d\tau} c(t)dt.$$

Initial population is N_0, and I normalize it to 1, while n is its constant growth rate; ρ is the rate of time preference - with $\rho > n$. $q(j,\omega,t)$ is the per-member flow of good ω, of quality $j \in \{0,1,2,...\}$, purchased by a household at time $t \geq 0$. $p(j,\omega,t)$ is the price of good ω of quality j at time t. A new vintage of a good ω yields a quality equal to λ times the quality of the previous vintage, with $\lambda > 1$. Different versions of the same good ω are regarded by consumers as perfect substitutes after adjusting for their quality ratios, and $j^{\max}(\omega,t)$ denotes the maximum quality in which the good ω is available at time t. As is common in quality ladders models I will assume price competition at all dates, which implies that in equilibrium only the top quality product is produced and consumed in positive amounts. $W(0)$ and $Z(0)$ are the present discounted values of labor and non-labor income, and T is a per-capita lump-sum tax.

Households solve the maximization problem in two stages. First, they choose the optimal allocation of expenditures across the different lines of product at a given period t. Second, they choose the optimal expenditure (consumption) path over time. The instantaneous utility function has unitary elasticity of substitution between every pair of product lines. Thus, households maximize static utility by spreading their expenditures $c(t)$ evenly across the product line and by purchasing in each line only the product with the lowest price per unit of quality, that is the product of quality $j = j^{\max}(\omega, t)$. Hence, the household's demand of each product is:

$$q(j, \omega, t) = \frac{c(t)}{p(j, \omega, t)} \quad \text{for } j = j^{\max}(\omega, t) \text{ and is zero otherwise} \tag{2}$$

The standard solution of the intertemporal maximization problem is:

$$\frac{\dot{c}}{c} = r(t) - \rho \tag{3}$$

3.2 Product market

In each country, firms can hire workers to produce any consumption good $\omega \in [0, 1]$ under a constant return to scale technology with one worker producing one unit of product. The wage rate is w^K, where $K = D, F$ is the country indicator, domestic (D) and foreign (F). However in each industry the top quality product can be manufactured only by the firm that has discovered it, whose rights are protected by a perfectly enforceable world-wide patent law. Due to the Arrow effect in each industry only followers do R&D to discover the new top quality of a good (see Aghion and Howitt, 1992). Successful innovators obtain the market leadership and earn monopoly profits. As standard in the literature, patents expire when further innovation occurs in the industry.

I assume that technology is mobile, firms own the technology but can use it everywhere; it follows that multinational companies are free to establish subsidiaries in low wage countries to carry out the manufacturing of their products, so in equilibrium labor prices will equalize. I choose the wage as the numeraire, that is: $w^D = w^F = 1$. With this assumption the income effects of international competition are limited to profits.[14]

The unit elastic demand structure encourages the monopolist to set the highest possible price to maximize profits, while the existence of a competitive fringe sets a ceiling equal to the world's lowest unit cost of the previous quality product. This allows us to conclude that firms

[14] As I will discuss later relaxing this assumption would increase the effects of competition on national income and strengthen the results in the paper.

profit are maximized through limit pricing, so the price $p^K(\omega, t)$ of every top quality good is:

$$p^K(\omega, t) = \lambda w^K, \text{ for all } \omega \in [0,1],\ K = D, F, \text{ and } t \geq 0, \tag{4}$$

where $w^K = 1$ for $K = D, F$. From the static consumer demand (2), we can immediately conclude that the demand for each product ω is:

$$\frac{(c^D(t) + c^F(t))N(t)}{\lambda} = q(\omega, t), \tag{5}$$

where $c^D(t)$ and $c^F(t)$ are domestic and foreign expenditures at time t. The above equation says that, in equilibrium, supply and demand of every consumption good coincides. Since wages and prices are equal in both countries the stream of monopoly profits accruing to the monopolist which produces a state-of-the-art quality product in country $K = D, F$ will be equal to

$$\pi^K(\omega, t) = \pi(\omega, t) = q(\omega, t)\left[p(\omega, t) - 1\right] = (c^D(t) + c^F(t))N(t)\left(1 - 1/\lambda\right) \text{ for all industries } \omega. \tag{6}$$

Hence a firm that produces good ω in country $K = D, F$ has market value

$$v^K(\omega, t) = \frac{\pi^K(\omega, t)}{r(t) + I(\omega, t) - \frac{\dot{v}(\omega,t)}{v(\omega,t)}}, \tag{7}$$

where $I(\omega, t)$ denotes the worldwide Poisson arrival rate of an innovation that will destroy the monopolist's profits in industry ω. This is a no-arbitrage condition which states that the expected rate of return of a stock issued by an R&D firm is equal to the riskless rate of return $r(t)$. This follows from the assumption that there are efficient financial markets channelling savings into R&D firms.

3.3 R&D races

In each industry, leaders are challenged by the R&D firms that employ workers and produce a probability intensity of inventing the next version of their products. The arrival rate of innovation in industry ω at time t is $I(\omega, t)$, which is the aggregate summation of the Poisson arrival rate of innovation produced by all R&D firms targeting product ω.

Every R&D firm can produce a Poisson arrival rate of innovation according to the following technology:

$$I_i^K(\omega, t) = \frac{A l_i^K(\omega, t)\left(\frac{L^K(\omega,t)}{X(\omega,t)}\right)^{-\alpha}}{X(\omega, t)}, \tag{8}$$

where $X(\omega, t) > 0$ measures the degree of complexity in the invention of the next quality product in industry ω, $\alpha > 0$ represents a negative externality, $L^K(\omega, t) = \sum_i l_i^K(\omega, t)$ is the total labor used by R&D firms and $I^K(\omega, t) = \sum_i I_i^K(\omega, t)$ is the total investment in R&D (total arrival rate) in country K. This technology implies that each firm's instantaneous probability of success is a decreasing function of the total domestic R&D investment in the industry. A possible interpretation of this property is that when firms increase R&D in a sector, the probability of duplicative research effort also increases, thereby reducing the probability that any single firm will discover the next vintage of goods and appropriate the profit rent associated with it. Therefore, the sector-specific negative externality in research technology produces decreasing returns to scale (DRS) in R&D at the industry level. Moreover, I assume that this negative externality is country-specific.[15] The country-specific nature of DRS in R&D could be motivated by the presence of some fixed costs such as lab equipment, by institutional and/or cultural differences, and finally by heterogeneous ability in research of the workforce.[16]

The technological complexity index $X(\omega, t)$ was introduced into endogenous growth theory after Jones' (1995) found the prediction of the first generation R&D-driven growth models that countries of different size should show different steady-state growth rates was not consistent with the empirical evidence. This led to a second generation of models where different specifications of $X(\omega, t)$ where introduced to rule out scale effects. I will adopt one specification introduced by Dinopoulos and Thompson (1998), according to which

$$X(\omega, t) = 2\kappa N(t), \tag{9}$$

with positive κ, thereby formalizing the idea that it is more difficult to introduce a new product in a more crowded market. The acronym PEG refers to the fact that this specification of R&D technology allows you to remove the scale effects and, at the same time, preserve a fundamental prediction of the first generation models: policy measures have a "permanent effects on growth".[17]

[15] Hall et. al. (1988), Pakes and Griliches (1984), and Kortum (1993) provide empirical evidence on the existence of DRS in R&D due to duplicative research and fixed costs.

[16] While fixed costs and institutional difference can motivate the country-specific R&D externality in the benchmark model, the presence of heterogeneous workers require to remove the assumption of global labor markets. In a similar setup but with global labor markets Eaton and Kortum (1999) provide a microfundation DRS in R&D at the country level. As investment in research increases in a country, workers of lower ability will be used and R&D productivity will decline.

[17] A different specification of the difficulty index, proposed by Segerstrom (1998), is $\frac{\dot{X}(\omega,s)}{X(\omega,s)} = \mu I(\omega, s)$, which formalizes the idea that early discovery fish-out the easier inventions first, leaving the most difficult ones for the

Governments subsidize R&D expenditures at the rate s^K financed with a lump-sum tax T. Each R&D firm chooses l_i^K in order to maximize its expected discounted profits.[18] Free entry into R&D races drives the expected profits to zero, generating the following equilibrium condition:

$$v^K(\omega,t)\frac{A\left(\frac{L^K(\omega,t)}{X(\omega,t)}\right)^{-\alpha}}{X(\omega,t)} = (1-s^K). \tag{10}$$

Substituting for the value of the firm from (7) into (10) we get:

$$\frac{\pi^K(\omega,t)}{r(t)+I(\omega,t)-\frac{\dot{v}(\omega,t)}{v(\omega,t)}} = \frac{(1-s^K)X(\omega,t)}{A}\left(\frac{L^K(\omega,t)}{X(\omega,t)}\right)^{\alpha}, \tag{11}$$

where I have substituted the profit equation (6) into the equation for the value of the firm. This condition, together with the Euler equation summarizes the utility maximizing household choice of consumption and savings, and the profit maximizing choice of manufacturing and R&D firms. Equation (11) has a immediate economic interpretation: the RHS is the cost of producing one unit of innovation $I(\omega,t)$, and the LHS is the benefit of one unit of innovation, that is, the discounted value of the monopolistic firm. Next, I introduce the concept of international competition for innovation and specify the geographical structure of $I(\omega,t)$.

3.4 International R&D competition

The scale of foreign competition in this model is determined by the measure of the set of sectors where firms from both countries compete in R&D. Let $\overline{\omega}\in(0,1)$ be the set of industries where domestic and foreign researchers compete to discover the next vintage of products. Therefore the composition of worldwide investment in innovation will be the following:

future. This specification is called (TEG), and it refers to the fact that policy has only "temporary effects on growth". That is the reason why models that use this specification are also known as semi-endogenous growth models (see also, among others, Kortum 1997 and Jones 1995).

[18] The discounted profits are

$$v(\omega,t)Al_i^K\left(\frac{L^K(\omega,t)}{X(\omega,t)}\right)^{-\alpha}\frac{1}{X(\omega,t)} - l_i^K(1-s^K).$$

$$
\begin{aligned}
I(\omega,t) &= I_c^D(\omega,t)+I^F(\omega,t)=I_c^D(t)+I^F(t), && \text{for } \omega\le\overline{\omega} \\
I(\omega,t) &= I_m^D(\omega,t)=I_m^D(t), && \text{for } \omega>\overline{\omega} \qquad (12)\\
X(\omega,t) &= 2\kappa N(t) && \text{for all } \omega,
\end{aligned}
$$

where $\kappa>0$, $I_c^D(\omega,t)$ and $I_m^D(\omega,t)$ are country D's investment in R&D in the competitive and in the non-competitive sectors respectively, and $I^F(\omega,t)$ is the research investment of country F. The symmetric structure of the model leads us to study only symmetric allocations of R&D investment, $I_c^D(\omega,t)=I_c^D(t)$, $I_m^D(\omega,t)=I_m^D(t)$, $I^D(\omega,t)=I^D(t)$ for all $\omega\in(0,1)$. Finally, the R&D difficulty index is proportional to the size of the global market, that is $X(\omega,t)=2\kappa N(t)$.

3.5 Steady state equilibrium

In this section I derive the steady state properties of the model, where per-capita endogenous variables are stationary. To close the model I need to introduce the labor market clearing condition and the national resource constraints. Using From the (10) , (8), (9), it is easy to show that $\dot{v}^K(t)/v^K(t)=\dot{X}(t)/X(t)=n$, for $K=D$, F, and using the Euler equation we find that in steady state the interest rate is equal to the intertemporal preference parameter, $r(t)=\rho$.

The unit cost of production for every good implies that the total production of goods in a country is equal to the total labor used for manufacturing in that country. The total manufacturing labor is given by the total labor supply minus the labor used in R&D. The presence of multinationals implies that both the labor and goods markets clear globally. Thus, the following condition clears both markets:

$$
\left(\frac{c^D+c^F}{\lambda}\right)=2-2\kappa\left[\overline{\omega}\left(\frac{I_c^D}{A}\right)^{\frac{1}{1-\alpha}}+(1-\overline{\omega})\left(\frac{I_m^D}{A}\right)^{\frac{1}{1-\alpha}}+\overline{\omega}\left(\frac{I^F}{A}\right)^{\frac{1}{1-\alpha}}\right] \qquad (13)
$$

where I have used $X(\omega,t)/N(t)=2\kappa$ from (9).

The left hand side represents the total demand for goods (labor), while the right hand side is the total supply, given by total labor resources minus labor used in research. Finally, I consider the resource constraint of the two countries: in each country total expenditures plus savings (investment in R&D) must equal the national income, wages plus profits (or interest income on assets).[19]

$$2\kappa\left[\varpi\left(\frac{I_c^D}{A}\right)^{\frac{1}{1-\alpha}}+(1-\varpi)\left(\frac{I_m^D}{A}\right)^{\frac{1}{1-\alpha}}\right]+c^D=1+(c^D+c^F)\left(\frac{\lambda-1}{\lambda}\right)\left[1-\varpi+\varpi\frac{I_c^D}{I_c^D+I^F}\right] \quad (14)$$

$$2\kappa\left[\varpi\left(\frac{I^F}{A}\right)^{\frac{1}{1-\alpha}}\right]+c^F=1+(c^D+c^F)\left(\frac{\lambda-1}{\lambda}\right)\left[\varpi\frac{I^F}{I_c^D+I^F}\right]. \quad (15)$$

Notice that R&D investment is simply the wage bill of R&D workers and that each country appropriates the monopoly rent in the subset of industries where that country is the world leader. It is also worth noticing that I am assuming complete "home-bias" in asset ownership, in the sense that domestic firms are completely owned domestically and foreign firms are completely foreign-owned.[20]

The international division of research labor specified in the previous section leads to the following steady state expressions for the no-arbitrage and free entry conditions in (11):

$$\begin{aligned}
\frac{2\kappa}{A}(1-s^F)\left(\frac{I^F}{A}\right)^{\dfrac{\alpha}{1-\alpha}} &= \frac{(c^D+c^F)\left(\dfrac{\lambda-1}{\lambda}\right)}{\rho+I_c^D+I^F-n}, \quad \omega\in\xi_c \\
\frac{2\kappa}{A}(1-s^D)\left(\frac{I_c^D}{A}\right)^{\dfrac{\alpha}{1-\alpha}} &= \frac{(c^D+c^F)\left(\dfrac{\lambda-1}{\lambda}\right)}{\rho+I_c^D+I^F-n}, \quad \omega\in\xi_c \qquad (16)\\
\frac{2\kappa}{A}(1-s^D)\left(\frac{I_m^D}{A}\right)^{\dfrac{\alpha}{1-\alpha}} &= \frac{(c^D+c^F)\left(\dfrac{\lambda-1}{\lambda}\right)}{\rho+I_m^D-n}, \quad \omega\in 1-\xi_c,
\end{aligned}$$

where, using the R&D technology (8) we have expressed research labor as a function of the innovation arrival rate. We have 6 equations and 5 unknowns $\{c^D, c^F, I_m^D, I_c^D, I^F\}$. The labor market clearing condition (13), turns out to be the sum of the two resource constraints (14) and (15), so the three equations are not linearly independent; I can omit one of them, and solve for the three equations. in (16), and the remaining (14), (15).

[19] In a similar two-country quality-ladders model Segerstrom and Lundborg (2002) do not treat R&D expenditures as investment. They acknowledge that R&D should be treated as investment in national accounts but in reality, they claim, this is not done. We instead include R&D investment in the national budget constraint: one implication of this is that taxes levied to fund R&D subsidy cancel out in the constraint with the reduction in R&D costs due to subsidies. Considering R&D as current expenditures does not change our qualitative results.

[20] This assumption is supported by empirical evidence on home-bias in asset ownership. French and Poterba (1991) and Tesar and Werner (1995) estimated the percentage of aggregate stock market wealth invested in domestic equities at the beginning of the 1990s to be well above 90% in the U.S. and Japan and around 80% in the UK and Germany. I have also performed the quantitative exercises in the next sections with partial home biases calibrated at 90 and 95% and, while the quantitative results are not dramatically altered, the model becomes computationally less tractable.

Before solving the equilibrium systems and deriving the main conclusions I will complete the description of the model by showing the expressions for welfare. Substituting the steady state instantaneous utility of the household problem (1) into the discounted utility, I obtain discounted welfare indicators for both countries,

$$W^K \equiv (\rho - n)U = \ln \frac{c^K}{\lambda} + \frac{g^K}{\rho - n} \tag{17}$$

where is the growth rate in country K. In the present framework with quality improving goods, growth is interpreted as the increase over time of the representative consumer utility level, hence the symmetric growth rate is from (1) as follows:

$$\ln u(c^K(t)) = \ln(\frac{c^K}{\lambda}) + \ln \int_0^1 \lambda^{j(\omega,t)} d\omega = \ln(\frac{c^K}{\lambda}) + \ln \lambda \int_0^1 \Omega(\omega, t) d\omega$$

where $\Omega(\omega, t) = \int_0^t I(\omega, \tau) d\tau$ is the expected number of innovations in industry ω before time t. In a world with perfect international knowledge spillovers R&D performed in one country would have the same impact on the growth rate of both countries, and the growth rate will be the same in the two economies. Considering the symmetric structure of the model, the distribution of R&D effort specified in (12), and that investment in R&D is constant in steady state we obtain $\Omega(\omega, t) = \int_0^1 \left[\int_0^t I(\omega, \tau) d\tau\right] d\omega = \overline{\omega} t \left[I_c^D + I^F\right] + (1 - \overline{\omega})\, t I_m^D$. The growth rate is obtained differentiating $\ln u(c^K(t))$ with respect to t:

$$g = \frac{\dot{u}}{u} = \left[\bar{\omega}(I_c^D + I^F) + \left(1 - \bar{\omega}\right) I_m^D\right] \ln \lambda$$

Eaton and Kortum (1999) and Klenow and Rodriguez-Claire (2005) find evidence that international spillovers of ideas are high but not perfect. Eaton and Kortum, for instance, show that countries adopt one-half to three-fourths of the ideas generated abroad. Introducing partial international knowledge spillovers the growth rates will be

$$g^D = \left\{\gamma^D \left[\overline{\omega} I_c^D + (1 - \overline{\omega})\, I_m^D\right] + (1 - \gamma^D) \overline{\omega} I^F\right\} \ln \lambda$$

for the domestic country, and

$$g^F = \left\{\gamma^F \overline{\omega} I^F + (1 - \gamma^F) \left[\overline{\omega} I_c^D + (1 - \overline{\omega})\, I_m^D\right]\right\} \ln \lambda$$

for the foreign country, where γ^D and γ^F represent the impact on national growth of innovation performed within the nation. Motivated by this empirical evidence we are going to focus on a world with imperfect knowledge spillovers.

4 Taking the model to the data

In this section I first, build an indicator that embeds the definition of competition used in the model, that is, a measure of $\overline{\omega}$, the share of industries where domestic and foreign countries effectively compete for innovation. Secondly, I adapt the computation of the R&D subsidy discussed in section 2 to the specific form of subsidy adopted in the model. Finally, I calibrate the parameters of the model.

4.1 A model-specific measure international R&D competition

The measure of competition is built using OECD ANBERD data on R&D investment for two and three-digit manufacturing industries previously described. The construction of the measure of international R&D competition proposed below has two main targets: first, it is a measure that can be directly used for quantitative analysis in the two-country quality ladders model used in this paper. Second, it aims at exploring the role of single countries, or groups of countries, in the decline of geographical R&D concentration shown in figure 1. The U.S. is taken as the domestic (leading) country, Japan and Europe, as the foreign (follower) countries. The index is based on the following criterion: for each year, in the period 1973-92, I consider a sector *competitive* if the U.S. share of total R&D investment in that sector is smaller than a competitive threshold CT^*. The industries set is composed of 21 two and three-digits manufacturing industries, and the competitive subset is the share of sectors with U.S. R&D investment share below CT^*. The threshold has been chosen by comparing the index obtained at each threshold level in the space and other more traditional measures of concentration: the Gini, Theil, and Herfindhal indexes, and the coefficient of variation. The reason for not using standard indexes of concentration directly in the model is that we need a measure that fits the definition of competition in the model and that can be used to perform quantitative analysis within that framework.[21]

[21] Wackziarg and Imbs (2003) uses a similar approach in measuring sectorial concentration of economic activity. Among several empirical measure of concentration they choose to focus on the Gini coefficient. They explain this choice showing that in their data there is a robust correlation between the Gini and the other measures

CT^* is the threshold level at which the correlation between my measure of geographical R&D concentration and standard measures of concentration is maximized, that is :

$$CT^* = \arg\max\left\{cr(\overline{\omega}, Gin) + cr(\overline{\omega}, Hr) + cr(\overline{\omega}, Cv) + cr(\overline{\omega}, Thei)\right\} \tag{18}$$

Figure 4 shows that the new measure of international competition in manufacturing has a clear increasing trend in the period considered. Competitive sectors are 38 percent of the total in 1973, rising to 76 percent in 1990. Thus confirming the tendency toward a more equal distribution of R&D investment across countries shown in figure 1. When I restrict the focus to medium and high-tech sectors the share of competitive industries reaches its highest value of 72 percent by 1980. This suggests that in technology-intensive sectors foreign challenge to U.S. leadership has grown faster than in the rest of the economy.[22]

[FIGURE 4 ABOUT HERE]

It is important to note that this index is not affected by size-biases because in our sample the two countries in which the world is partitioned, the U.S. and the rest of the world, can be considered of similar size. Moreover, the index is the more accurate the better this group of countries represents the global economy. The fewer action showed in figure 4 after the mid-80s might be related to the fact that R&D investment from other countries not included in our set were becoming more relevant.

4.2 R&D subsidies

The mapping between the subsidy rates shown in figure 3 and the R&D subsidy in the model is as follows: consider the following version of the free entry condition (10),

$$V(1-\tau_\pi) = (1 - A_d - A_c)\,,$$

where $V = v^K(\omega,t)\,(A/X(\omega,t))\left(L^K(\omega,t)/X(\omega,t)\right)^{-\alpha}$, is before-tax present value of the marginal investment and, as before, τ_π is the corporate tax rate, A_d is depreciation allowances, A_c

of competition. The present paper deals with a similar issue; the difference is that they need to pick one representative index, I need to find a rationale for choosing the threshold level CT^*. I do this showing that the model-specific measure of concentration, resulting from the right choice of CT^*, leads to evidence that is similar to that obtained using more standard measures.

[22]The weighted index is computed using sectorial R&D shares to account for the relative size of industries. Since medium and high-tech sectors account on average for 75 to 79 percent of total R&D, the weighted index turns out to be very similar to the index for medium and high-tech and it reflects the faster catch-up of Japan and Europe in these industries.

is the specific tax credit rate. Assuming full expensing, that is $A_d = \tau_\pi$, and rearranging we obtain again $V = 1 - A_c/(1-\tau_\pi)$, and setting $s = A_c/(1-\tau_\pi)$ we obtain exactly the free entry condition in the model (10). This synthetic measure of tax subsidies has the drawback of not allowing for the distinction between depreciation allowances and tax credit. A more relevant problem with the measure is that it includes both the effects of changes in corporate tax rates and in the R&D tax credit.[23] In order to deal with both issues I use $s = A_c$ as the subsidy rate, thus accounting only for the presence and effectiveness of R&D tax credits.[24] Figure 5 below reports the R&D subsidy obtained with this calculation.

[FIGURE 5 ABOUT HERE]

As we can see figure 3 and 5 are substantially similar except for the fact that subsidies are lower for all countries when we the measure is cleaned from the effect of changes in depreciation allowances and corporate taxes. In particular the U.S. subsidy increases from 6 percent in1979 to 18 percent in 1991, and it is fairly constant from 1981 to the late 1980s.

5 Calibration

In this section I calibrate the parameters of the model to match some basic long-run empirical regularities for the U.S. economy. I then compute the numerical solution using the calibrated parameters and show the model's fit of the data. I need to calibrate 7 parameters. Five of them, ρ, λ, n, γ^D and α will be calibrated using benchmarks that are standard in the growth literature, while the others, A and k, will be calibrated internally so that the model's steady state matches salient facts of the U.S. economy.

Parameters calibrated "externally"- Some parameters of the model have close counterparts in real economies so that their calibration is straightforward. I set ρ, which in the steady state is equal to the interest rate r, to 0.07 to match the average real return on the stock market for the past century of 0.07, estimated in Mehra and Prescott (1985).[25] I set λ to 1.2, to match an average markup over the marginal cost of 20 per cent. Since, estimates of average

[23] This si problematic also because in the model there are no corporate taxes.

[24] For the U.S. this leads to subsidies levels close to those estimated in Hall (1993), where she isolated the effect of the R&D tax credit on the cost of innovation.

[25] Jones and Williams (2000) suggest that the interest rate in R&D-driven growth models is also the equilibrium rate of return to R&D, and so it cannot be simply calibrated to the risk-free rate on treasury bills - which is around 1%. They in fact calibrate their R&D-driven growth model with interest rates ranging from 0.04 to 0.14.

sectorial mark-up are in the interval $(0.1, 0.4)$ (Basu 1996), I take an intermediate value in this range. I calibrate n to match the population growth rate of 1.14%, as in Jones and Williams (2000). Decreasing returns due to duplicative R&D at the country-level have been estimated to be between 0.1 and 0.6 (Kortum 1993); as a benchmark I take an intermediate value and set the R&D externality coefficient α at 0.4. Eaton and Kortum (1999) decompose the sources of growth from national research and find that about 60 percent of U.S. growth comes from domestic research and the rest from foreign. Hence, I set international knowledge spillovers parameter for the U.S. γ^D to 0.6.[26]

Parameters calibrated "internally"- I simultaneously choose A and κ so that the numerical steady state solution of the model matches a set of long run stylized facts. Since the paper's focus is on R&D investment it seems natural to use data from Corrado, Hulten and Sichel (2006, CHS henceforth), where U.S. national account data have been revised to introduce investment in intangible capital, including R&D. Moreover, since there is no tangible capital in the model all statistics used in the calibration need to be adapted to the model economy. More precisely, the two statistics targeted in the calibration of A and κ, which will be the growth rate of labor productivity and the R&D ratio to GDP, are obtained subtracting investment in tangible capital from the data. After this adjustment the CHS data report an average growth of labor productivity of 1.9% a year in the period 1975-2003. Since in the model all investment is in R&D, the targeted statistics for the R&D ratio to GDP would be the investment in intangible capital share of total income; after subtracting tangible capital this leads to 13.5% over the period 1975-2003. In the internal calibration I have set the two subsidies at their 1979 values, that is $s^D = 0.062$ and $s^F = 0.061$: this the earliest value available for the measure of R&D subsidy computed in the previous section and shown in figure 3. I have also used the 1979 value for international competition shown in figure 2 above, that is I have set $\overline{\omega} = 0.57$.[27] The parameters calibrated internally have been found by minimizing the quadratic distance between the model and the stylized facts listed above: the resulting values are $A = 0.395$ and $\kappa = 0.46$.

[26] The spillovers parameter for the foreign country is not relevant for the calibration because in the internal calibration procedure below I target only the U.S. growth rate.

[27] Although data for all relevant variables are available from 1973, multi-country data on R&D subsidies start at 1979. Hence I point my calibration at that period. Moreover, I chose to calibrate using data until 1979 because this will be the starting period of the comparative static exercise which yields the main results of the paper.

[TABLE I ABOUT HERE]

Table I shows of well the model fits the U.S. data at the initial date, 1979. The calibration parameters fit the targeted and non targeted statistics closely enough.

6 Competition, growth, and welfare: the basic trade-off

In this section I study the basic effects of foreign entry in the innovation activity on domestic welfare: the *growth effect* (*GRE*) and the *business-stealing effect* (*BSE*). This will help us understanding the mechanism driving the main result of the paper, the effect of competition on the optimal domestic subsidy, that will be explored in the next section. Following the baseline calibration, subsidies will be kept constant at 1979 level $s^D = s^F = 0.06$, to isolate the pure effects of competition.

When foreign R&D targets sectors previously dominated by domestic firms, with probability proportional to foreign innovation efforts domestic profits shift abroad and domestic income and welfare is reduced, this is the *BSE*.[28] Using the domestic resource constraint (14) we can see that increases in the measure of competition ϖ reduce domestic profits, thereby reducing the resources available for consumption, and negatively affecting home welfare given by equation (17). Figure 6 below reports the effects on the key variables of changes in competition, while holding both subsidies constant. The figure shows the *BSE*, affecting negatively national income.

[FIGURE 6 ABOUT HERE]

The innovation or *GRE* of competition is produced by the presence of local decreasing returns in R&D specified in (8). Intuitively, with a concave national R&D technology, research labor is more productive when spread more equally across countries. A detailed explanation of the mechanism involves the analysis of the two margins determining the decision to innovate: the allocation of labor between production of goods and R&D, and the allocation of R&D between competitive and non-competitive sectors. The first margin is not affected by competition because, as we can see in equation(10) the cost of research is fixed by the constant wage rate.

[28] Since, by construction, in the baseline setup the labor market is not affected by competition, the BSE related to changes in the geographic distribution of market leadership across industries produces only a shift in profits with no effects on wages. This assumption will be removed later.

This is easily seen by rearranging the free entry and no-arbitrage conditions (16) in order to represent the costs and benefits of one unit of research labor. The example below is for the case of domestic investment in competitive sectors:

$$(1-s^D)=\frac{(c^D+c^F)\left(\dfrac{\lambda-1}{\lambda}\right)}{\rho+I_c^D+I^F-n}\left[\left(\frac{I_c^D}{A}\right)^{\dfrac{-\alpha}{1-\alpha}}\frac{A}{2\kappa}\right] \tag{19}$$

Consider now the marginal benefits of one unit of research labor: following the rearrangement in (19) these benefits are given by the marginal productivity of R&D times the present value of the monopolistic firm. In equilibrium there is no arbitrage possibility in R&D investment in competitive and non competitive sectors, so the marginal benefits of the two types of investment must be equal:

$$\underbrace{\frac{(c^D+c^F)\left(\frac{\lambda-1}{\lambda}\right)}{\rho+I_m^D-n}}_{v_m^D(\omega,t)}\left(\frac{I_m^D}{A}\right)^{\dfrac{-\alpha}{1-\alpha}}=\underbrace{\frac{(c^D+c^F)\left(\frac{\lambda-1}{\lambda}\right)}{\rho+I_c^D+I^F-n}}_{v_c^D(\omega,t)}\left(\frac{I_c^D}{A}\right)^{\dfrac{-\alpha}{1-\alpha}}. \tag{20}$$

The country-specific decreasing returns in R&D imply that research is more productive in competitive industries and, as a consequence, the value of the firm $v^K(\omega,t)$ in equilibrium will be lower with respect to non competitive sectors. As the value of the firm is given by profits - which are the same in both industries - discounted by the interest rate and the arrival rate of innovation, it follows that innovation in competitive sectors must be higher than in non-competitive sectors. Hence, from (20) we conclude that in equilibrium we must have $I_c^D+I^F>I_m^D$. As shown in figure 4 innovation per sector does not change with competition,[29] that is $\partial I_c^D/\partial\overline{\omega}=\partial I^F/\partial\overline{\omega}=\partial I_m^D/\partial\overline{\omega}\cong 0$. Competition increases the share of industries with a higher arrival rate of innovation ($I_c^D+I^F>I_m^D$), this *reallocation* or *efficiency* effect increases the aggregate growth rate of the economy.

In the simple case of perfect international knowledge spillovers where growth is symmetric in both countries it is easy to see the reallocation effect produced by competition: $\partial g^K/\partial\overline{\omega}=\left[\left(I_c^D+I^F\right)-I_m^D\right]\log\lambda>0$ for all $\alpha>0$, and for $K=D,F$. In the more general case of imperfect spillovers the mechanism is richer; the basic intuition can be obtained under the

[29]The small changes observed in the figure are second order and are due to computation residuals. For instance I_m^D changes from 0.263 to 0.2623 when $\overline{\omega}$ rises from 0 to 1. Similar minor changes happen with Ic^D and I^F

simplifying assumption of symmetric subsidies used in this section. In this case $I_c^D = I^F$ because in competitive industries the two countries are symmetric by construction, thus $\partial g^K/\partial\overline{\omega} = \left[I^F - \gamma^D I_m^D\right]\log\lambda$, which is positive if $I^F > \gamma^D I_m^D$. Intuitively, since $I^F < I_m^D$, competition has a negative effect on growth when international spillovers of ideas are limited, $\gamma^D > I^F/I_m^D$, and the growth rate depends mainly on domestic sources.

Since the domestic economy in the quantitative analysis is assumed to be the U.S. whose growth, as shown in Eaton and Kortum (1999), is highly dependent on domestic innovation, the benchmark calibration yields a positive but limited growth effect of competition, that for $\gamma^D \geq 0.7$ becomes negative. Although the negative growth effect is a theoretical possibility, it should not be considered a quantitatively relevant case. In fact, even with substantially high levels of domestic innovation 'autarky', the $\gamma^D = 0.6$ benchmark value, international competition benefits domestic growth.[30] Another key parameter influencing the growth effect is α that determines the strength of local decreasing returns to R&D. Lower α's reduce the *GRE* and when α is zero the effect disappears completely.

In conclusion, the overall effect of competition on welfare is given by the sum of the *BSE* and the *GRE*. Since in the benchmark calibration the *GRE* is positive but limited the *BSE* turns out to be quantitatively stronger, and competition reduces domestic welfare. Different parameters specifications, in particular higher levels of α, would increase the size of the growth effect and could potentially lead to a positive overall effect of competition on welfare.[31]

7 Foreign competition and optimal R&D subsidies

Next, I use the calibrated model to compute numerically the effect of foreign competition on the optimal strategic subsidy for the domestic country. We assume that only domestic subsidy respond optimally to competition: at stage 1, the government sets the subsidy; at stage 2 R&D and manufacturing firms choose their profit-maximizing level of activity, and households choose their utility-maximizing consumption bundles and assets holdings.[32] For each level of

[30] The evidence reported in Eaton and Kortum (1999) shows that the U.S. relies substantially more on domestic innovation compared to the other countries in the sample. According to their data our γ^F would be 0.16 for Germany, 0.11 for France, 0.13 for Japan, 0.35 for Japan.

[31] The main goal of the paper is to understand the effect of competition on subsidies, and the welfare effects of competition explained here serve only to explore the two basic forces that will drive the effects of competition on the optimal domestic subsidy. For this reason I do not include a sensitivity analysis of the effect of competition on welfare. Although it is available upon request from the author.

[32] In Impullitti (2006) I consider the strategic policy game with both countries active in R&D subsidies and responding optimally to changes in competition. Qualitative results are not affected. Moreover, as I will explain

competition and for a given level of the foreign subsidy, the domestic policy maker sets the subsidy according to the following best-response function

$$s^D(\overline{s}^F;\overline{\omega}) = \left\{\arg\max W^D(s^D, \overline{s}^F;\overline{\omega})\right\}, \tag{21}$$

Figure 7 below shows that higher foreign competition increases the optimal domestic R&D subsidy.

[FIGURE 7 ABOUT HERE]

To grasp the economic mechanism behind this result we need to understand how changes in competition affect the marginal effects of subsidies on national welfare. For this purpose it is convenient to rewrite the present value of national welfare (17) in the following form

$$W^K \equiv (\rho - n)U = \ln\frac{c^K}{\lambda} + \frac{g^K}{\rho - n} = G + Y^K - R^K, \text{ for } K = D, F, \tag{22}$$

where the G equals the present value of the growth rate, $G = g^K/(\rho - n)$; using the national budget (resource) constraints, consumption is rewritten as national income Y^K (wages w^K plus total profits $\Pi^K = \int_0^1 \pi^K(\omega, t)d\omega$) minus savings (investment in R&D $R^K = w^K \int_0^1 I^K(\omega, t)d\omega$).[33]

I now focus on the domestic country and I will first explain the intuition for the result in figure 6. Innovation in this framework has four external effects affecting the level of optimal domestic subsidies: a *consumer-surplus or growth effect* (GRE), a *domestic business-stealing effect* ($DBSE$), an *iinternational business-stealing effect* ($IBSE$), and a *resource constraint effect* (RCE). First, the GRE has two different components: the direct consumer surplus effect and the intertemporal spillover effect. Consumers benefit from a higher-quality product when it is introduced by the current innovator, this is the direct effect, and also after it has been replaced by the next innovators who build on the previous quality ladder, this is the intertemporal effect. Since R&D firms do not take these effects on consumer surplus into account, they lead to underinvestment in innovation.

Secondly, in industries with domestic leaders every time a home firm innovates it drives another home firm out of business. The appropriation of the incumbent firm's monopoly profits

later, for the quantitative analysis performed in the next sections it is better to assume that only domestic country is active.

[33] All values for the new expression for consumption are obviously in logs. The expressions in extensive form for wages, profits, and R&D expenditures for both countries and both specifications of the model can be found in (14) and (15).

reduces aggregate profits and consumption, thus having a negative effect on welfare.[34] This is the $DBSE$ and in (22) it affects Π^D, the per-capita aggregate real profits of the innovating country. This effect is external to the decision of the innovating firm and so it leads to overinvestment in R&D. Thirdly, in sectors with foreign incumbents successful domestic innovation drives foreign firms out of business and shifts monopolistic profits toward the home country, thereby increasing domestic income and welfare. This is the $IBSE$, which in our utility metric (22) works on Π^D. Since home R&D firms do not take this effect into account when innovating, a bias toward underinvestment is produced.

Finally, because of the externality represented by α in technology (8), R&D investment by a national firm increases the sectorial level of research and reduces the productivity of future firms investing in that industry in that country. This is the RCE and has the following components: first, more resources must be allocated to R&D in order to maintain the steady state level of innovation, this makes fewer resources available for consumption. Second, as consumption is reduced, incumbent firms profits in all sectors will also be reduced, resulting in even lower consumption. Since R&D firms do not take this effect into account, this produces another bias toward overinvestment. Both components affect welfare through the resource constraint: in the metric of our utility function in (22) they affect $R^D = \ln(L^D/\lambda)$, total labor resources allocated to R&D, and the total profit Π^D respectively.[35] Using (22) we can express the different marginal effects of the R&D subsidy on domestic welfare as follows:

$$\frac{\partial W^D}{\partial s^D} = \underbrace{\frac{\partial (R^D, \Pi^D)}{\partial s^D}}_{\substack{RCE \\ (-)}} + \underbrace{\frac{\partial G}{\partial s^D}}_{\substack{GRE \\ (+)}} + \underbrace{\frac{\partial \Pi^D}{\partial s^D}}_{\substack{IBSE \\ (+)}} + \underbrace{\frac{\partial \Pi^D}{\partial s^D}}_{\substack{DBSE \\ (-)}} , \tag{23}$$

where the plus and minus signs signal that the external effect leads respectively to underinvestment, thereby motivating R&D subsidies, and overinvestment, thereby motivating R&D taxes.

The first channel behind the result shown in figure 6 works through the effect of competition on the *strategic motive* for subsidy, which in (23) is represented by the $IBSE$. As international

[34] Notice that, we are ignoring the profit of the new quality leader. This comes form the standard procedure to isolate the external effects if innovation in quality ladders model. See Grossman and Helpman (1991) ch.4 and Segerstrom (1998).

[35] This effect is sometimes called in the literature *intertemporal R&D spillovers effect* because it depends on the impact of current innovation on future R&D productivity.

R&D rivalry rises, the foreign rent-stealing threat becomes more relevant and triggers higher domestic subsidies. It is possible to see in equation (14) that the rent-protecting effect of s^D is zero at $\overline{\omega} = 0$, and increases with competition. Higher foreign competition implies a higher *scale* of foreign business-stealing because the number of industries where domestic firms are challenged by foreigners is larger. It follows that the role of domestic subsidies as a rent-protecting device rises. Moreover, the same force makes the domestic best response steeper, which implies that the sensitivity of the optimal s^D to changes in s^F rises. Intuitively, as the scale of foreign competition grows each dollar of foreign subsidies represents a more serious threat to the domestic leadership.

The second channel through which competition affects the optimal R&D subsidies is the growth channel, working through the *knowledge spillovers* motive for subsidies. By increasing the productivity of domestic R&D, competition improves both the RCE and the GRE of home subsidies. Indeed, the presence of the country-specific R&D externality in (8) implies that research efficiency increases in newly competitive sectors. Since this effect is external to firm, the single domestic investor would not take it into account while choosing its investment in R&D, and this produces a bias toward undersinvestment and leads to higher subsidies. This channels works directly through the growth effect of subsidies (GRE). Similarly, an increase in the number of competitive sectors raises the aggregate productivity of domestic research labor, and reduces the labor resources required to maintain the steady state level of innovation. This reduces the overinvestment in innovation produced by the RCE.

A final remark on the sign of the optimal R&D subsidy is necessary. In quality-ladder growth models whether the optimal R&D subsidy is positive or negative depends on the relative strength of the several external effects on innovation present the model. Similarly to Grossman and Helpman (1991) and Segerstrom (1998), in this model the sign of the optimal subsidies depends on parameters specification. In the section on robustness I will show that the main result of the paper is confirmed also when parameters' specification is such that the optimal R&D subsidy is negative.

8 Competition and R&D subsidies in the U.S.

The scope of this quantitative exercise is to quantify the welfare gains obtainable if the domestic country, the U.S., would have implemented an optimal R&D subsidy response to the observed increase in foreign competition documented in figure 2. I compare the domestic welfare under optimal subsidies with that under the actual subsidies observed in the data presented in figure 3, for each level of international competition in the period 1979-91.[36]

The welfare improvement is obtained considering the following version of the welfare equation (17) for the domestic country

$$\begin{aligned}\widehat{W}^D &\equiv \int_0^\infty e^{-(\rho-n)t}\left[\int_0^1 \ln\left(\frac{c^D(s^D_{obs},\overline{\omega}_{obs})}{\lambda}\lambda^{j(\omega,t)}(1+\beta)\right)d\omega\right]dt = \ln\frac{c^D(s^D_{obs},\overline{\omega}_{obs})}{\lambda}+ \\ &+\left\{\bar{\omega}\left[\gamma^D I^D_c(s^D_{obs},\overline{\omega}_{obs})+(1-\gamma^D)I^F(s^D_{obs},\overline{\omega}_{obs})\right]+\left(1-\bar{\omega}\right)\gamma^D I^D_m(s^D_{obs})\right\}\frac{\ln\lambda}{\rho-n}+\ln(1+\beta),\end{aligned}$$

and choosing β such that $\widehat{W}^D = W^{*D}$; where $W^{*D}(s^{*D},\overline{\omega}_{obs})$ is the present value of welfare under the optimal subsidy response, s^{*D}, to observed competition, $\overline{\omega}_{obs}$, and $c^D(s^D_{obs},\overline{\omega}_{obs})$, $I^D_c(s^D_{obs},\overline{\omega}_{obs})$, $I^F(s^D_{obs},\overline{\omega}_{obs})$ is the equilibrium allocation under the observed levels of competition and subsidies. Thus, β is the welfare gain associated with the optimal subsidy, measured in terms of "equivalent compensating variation" of quality-adjusted per-capita lifetime consumption. Table II below reports the welfare gains β.

[TABLE II ABOUT HERE]

Surprisingly, in the benchmark economy the optimal subsidy turns out to be close to the subsidy in the data and, consequently, the welfare gains brought about by optimal policy are very low, precisely they are in the range of 0.021 and 0.16 percent of quality-adjusted per-capita consumption.[37] This result has been obtained with a benchmark calibration showing a sufficiently good fit of the data. In the robustness analysis performed below we lose the good empirical fit but we are able to explore relevant properties of the results both qualitatively and quantitatively.

Table III shows the robustness of the results reported in table II. Precisely it shows how the results are affected by doubling, one at the time, the parameters λ, α, ρ, A, κ, n, γ^D from their baseline calibration values.[38] In those cases where doubling is not possible, because of the parameters space is in $(0,1)$, I have increased them by a substantial amount.

[36]Unfortunately, the lack of subsidy data impose to restrict the focus to the period 1979-91, and the period of major increase in competition, 1973-79, cannot be analyzed.

[37]In table II I report only those year where competition has changed.

[38]I have also performed the exercise halving the parameters from their baseline values and the results are symmetric to those shown below. For simplicity here I only report changes in one direction.

[TABLE III ABOUT HERE]

As we can see in the table the basic qualitative result is confirmed under all parameters' changes: competition increases the optimal domestic R&D subsidy. Two findings deserve special attention. First, changes in the level of subsidies with respect to the benchmark can be explained using (23). From the welfare equation (22) and recalling that $g^D = \left\{\gamma^D \left[\overline{\omega} I_c^D + (1-\overline{\omega})\, I_m^D\right] + (1-\gamma^D)\overline{\omega} I^F\right\} \ln\lambda$ it is easy to see that the growth, or consumers surplus effect of innovation, GRE, increases when quality jumps are larger (high λ), consumers are less impatient (small ρ), there are more future consumers benefiting from the current innovation (large n), and when there are lower international knowledge spillovers (high γ^D). Consequently, as shown in table III, s^{*D} rises with higher λ, γ^D, n, and decreases with higher ρ. Technology parameters A, κ, and α, affect the resource constraint effect, RCE, in (23). Larger A implies higher productivity of R&D labor and lower resources must be devoted to research to maintain the steady state growth rate; this reduces the RCE of the marginal innovation and raises s^{*D}. Parameters κ and α affect the RCE similarly but in the opposite direction: larger values imply smaller s^{*D}.

Second, the positive relation between competition and subsidy is confirmed also in those cases where parameters' specification leads to negative optimal R&D subsidies. As discussed before, in this framework, as in Grossman and Helpman (1991) and Segerstrom (1998), the sign of the optimal subsidy depends on parameters' specification. A negative optimal subsidy, like that obtained doubling α, the discount rate ρ, and the R&D difficulty coefficient κ, does not qualitatively affect the basic mechanism behind the relation between competition and subsidies: increases in competition raise the scale of the business-stealing effect, the $IBSE$ explained above, thus strengthening the *strategic* role of subsidies, or tax-cuts in this case. On the other hand, competition will affect the *growth* motive for subsidies similarly to what explained in the previous section: in the case of negative subsidies the increase in the efficiency of R&D brought about by competition would reduce overinvestment in R&D and lower the optimal taxes on research.

9 Conclusion

In this paper I have shown that increases in international technological competition, measured as the number of industries where domestic and foreign innovators compete for global leadership, have two counteracting effects on domestic welfare: a *business-stealing* effect that reduces domestic profits and income, thus affecting welfare negatively: a *growth* effect produced by the increase in the efficiency of R&D, brought about by foreign entry, that increases welfare. Although these two effects have opposite implications for national welfare, they work in the same direction on the core external effects determining the optimal R&D subsidy. Precisely, on the one hand, competition, by increasing the scale of international business-stealing, raises the *strategic* role of research subsidies. On the other hand, the increase in R&D efficiency produced by foreign entry raises the growth or *knowledge spillovers* motive for subsidies. As a consequence, increases in foreign competition lead to higher optimal domestic R&D subsidies.

Using R&D investment data at the sectorial level for a relevant set of countries I have constructed an index of international competition that matches the dimension of technological competition analyzed in the model. Precisely, I have built a measure of the set of sectors where domestic and foreign firms are neck-to-neck in R&D investment. This empirical measure shows that the U.S. global leadership has been increasingly challenged by foreign competition in the period 1973-95. In calibrated version of the model the optimal U.S. R&D subsidy associated with the observed increase in competition has been computed and compared to the actual U.S. subsidy observed in the data in those years. The quantitative analysis has shown that the observed U.S. subsidy is fairly close to the optimal subsidy response to competition produced by the model.

In this first exploration of the effects of technological competition on optimal subsidies the impact of the international business-stealing on domestic income has been limited to the shift of profits abroad. Removing the simplifying assumption of perfectly global labor markets will increase the income losses associated with competition. The wage-shifting effect that would be observed in an economy where labor markets are partially local, would represent an additional channel through which competition strengthens the strategic motive for subsidies. Consequently, we could expect a larger effect of competition on the optimal subsidy and, in the quantitative analysis, a more substantial distance between this and the observed U.S. subsidy. This is promising material for future research.

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TABLE I

Model Fit

Moments	Data	Benchmark model
TARGETED		
growth	0.019	0.021
R&D/GDP	0.14	0.16
NON TARGETED		
cons/GDP	0.86	0.83
R&D in $\overline{\omega}$	0.56	0.58

TABLE II

Welfare Gains with optimal Subsidy

		1979	1981	1985	1991
competition	$\overline{\omega}$	.57	.66	.71	.76
observed subsidy	s^D	.066	.115	.115	.18
		Benchmark economy			
optimal subsidy	s^{D*}	.005	.055	.08	.10
welfare gain	β	.00048	.00055	.00021	.0016

TABLE III

Welfare Gains with optimal subsidy (Robustness)

		1979	1981	1985	1991	1979	1981	1985	1991
competition	$\overline{\omega}$	0.57	0.66	0.71	0.76	0.57	0.66	0.71	0.76
observed subsidy	s^D	0.066	0.115	.115	0.118	0.066	0.115	.115	0.118
		$\boldsymbol{\lambda = 1.4}$				$\boldsymbol{\alpha = 0.8}$			
optimal subsidy	s^{D*}	0.17	0.195	0.21	0.22	−0.97	−0.83	−0.76	−0.7
welfare gain	β	.0039	.0029	.004	.0006	.04	.039	.035	.042
		$\boldsymbol{\rho = 0.14}$				$\mathbf{A = 0.79}$			
optimal subsidy	s^{D*}	−0.44	−0.29	−0.23	−0.18	0.42	0.425	0.43	0.435
welfare gain	β	0.015	0.013	0.011	0.016	0.046	0.0414	0.0437	0.0312
		$\boldsymbol{\kappa = 0.92}$				$\mathbf{n = 0.028}$			
optimal subsidy	s^{D*}	−0.26	−0.16	−0.12	−0.08	0.19	0.22	0.23	0.24
welfare gain	β	0.0088	0.0082	0.006	0.017	0.0031	0.0025	0.0033	0.0009
		$\boldsymbol{\gamma^D = 0.9}$							
optimal subsidy	s^{D*}	0.4	0.42	0.43	0.44				
welfare gain	β	0.037	0.038	0.043	0.033				

Figure 1. Geographical concentration of R&D investment

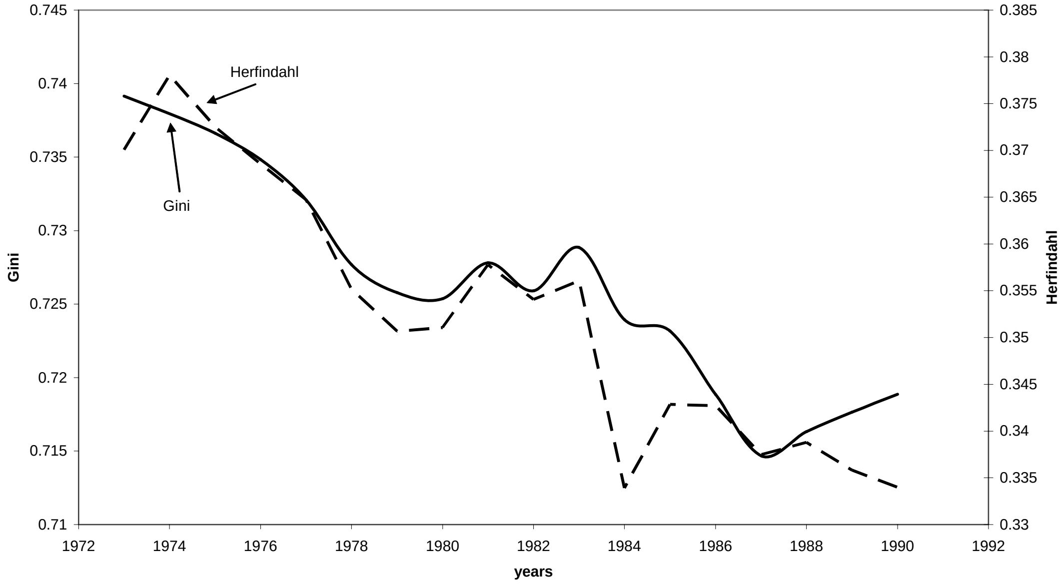

Figure 2. Average sectorial R&D investment shares

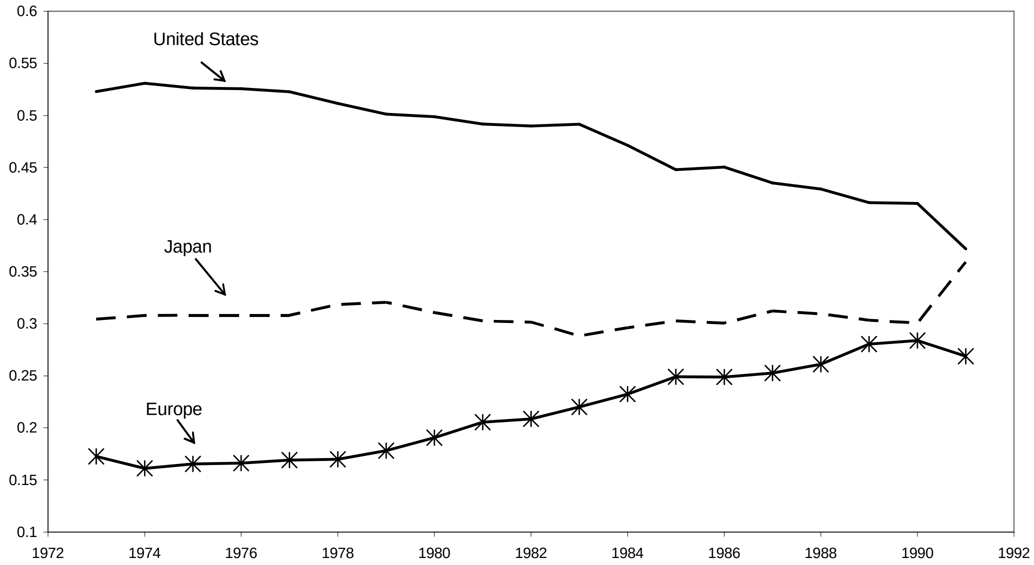

Figure 3. R&D tax subsidies

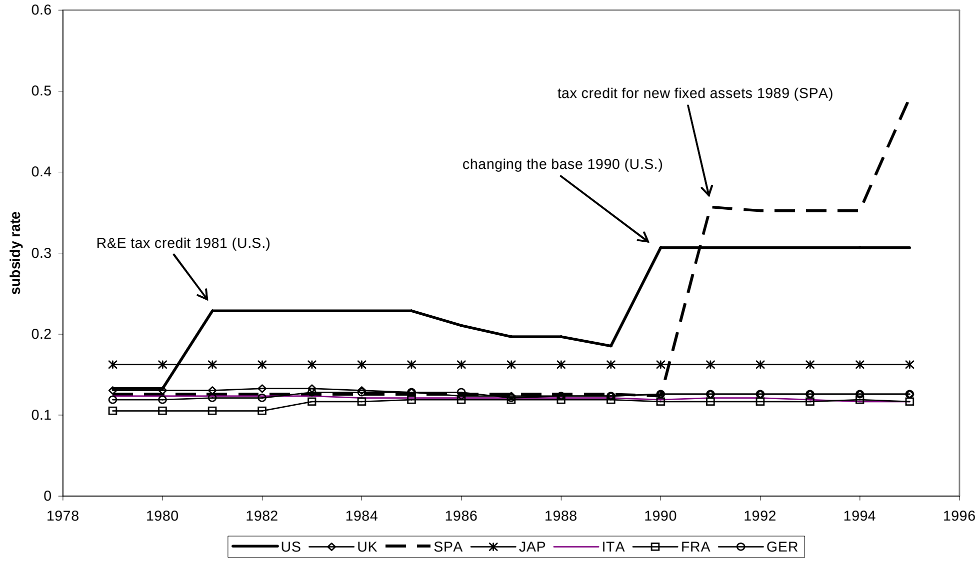

Figure 4. International R&D competition

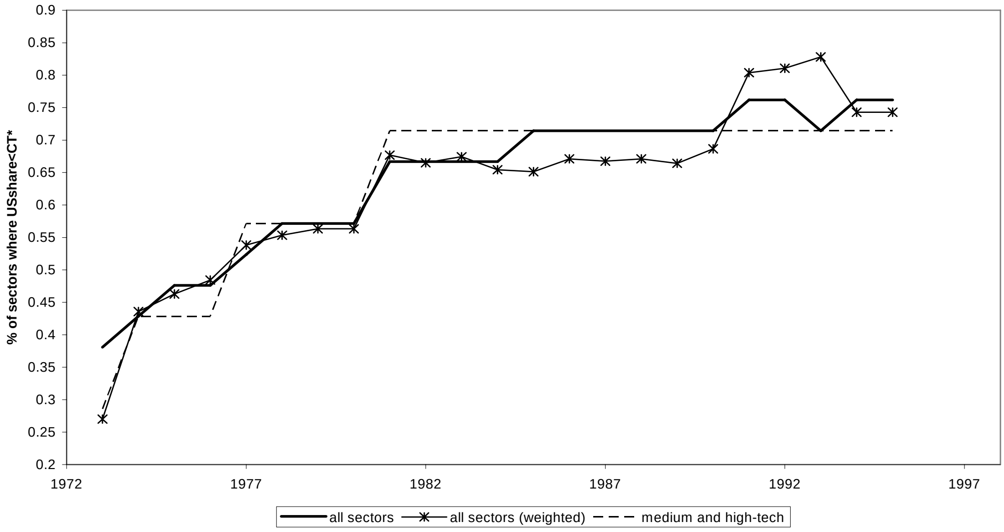

Figure 5. R&D tax subsidies

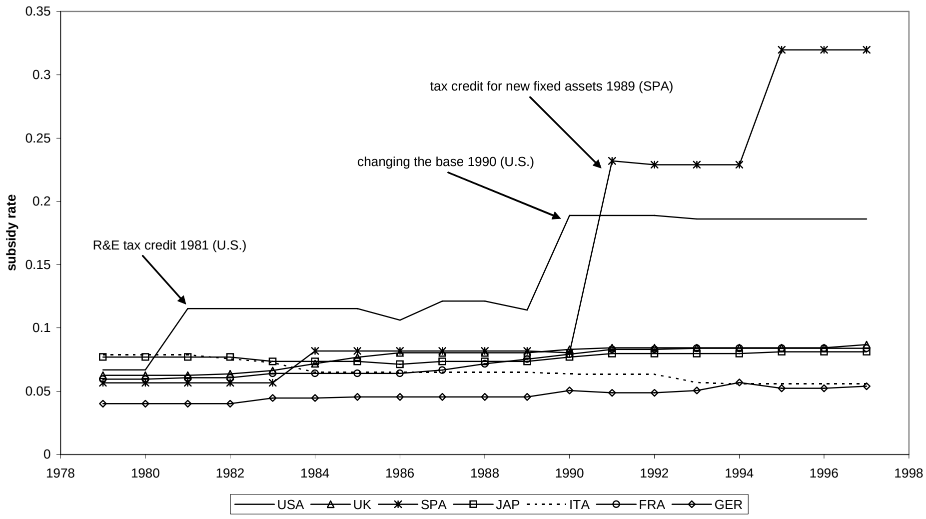

FIGURE 6. Effects of competition on the domestic economy

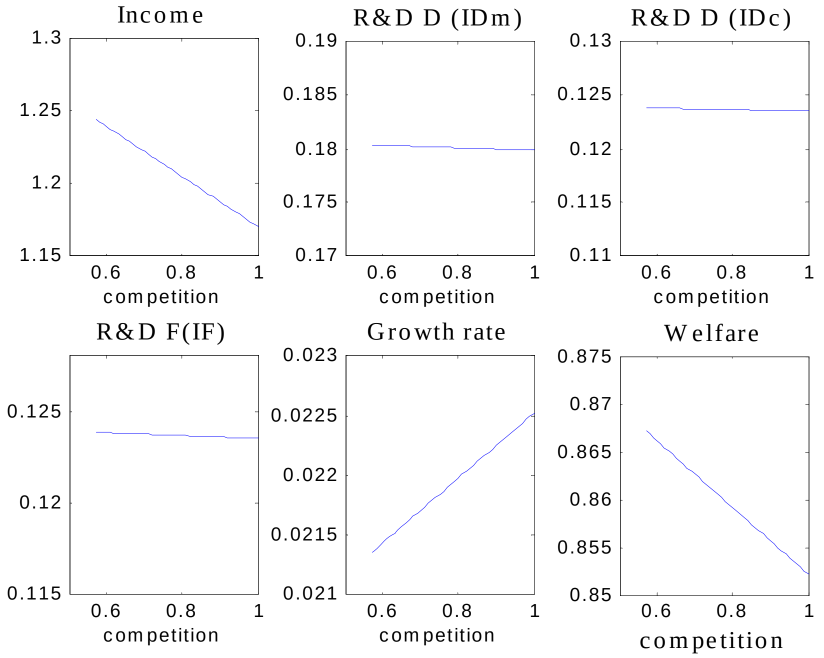

FIGURE 7. International competition and optimal R&D subsidies