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International Competition and U.S. R&D Subsidies:
a Quantitative Welfare Analysis

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**EUROPEAN UNIVERSITY INSTITUTE
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Abstract

The geographical distribution of R&D investment changes dramatically in the 1970s and 1980s. In the early 1970s 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. In this period of increasing competition we also observe a substantial increase in the U.S. R&D subsidy. In a version of the multi-country quality ladder growth model I study the effects of foreign R&D competition on domestic welfare and on the optimal R&D subsidy. I build a new empirical index of international R&D rivalry that can be used to perform quantitative analysis in this type of frameworks. In a calibrated version of the model I focus on the period 1979-1991 and perform the following quantitative exercises: first, I evaluate the quantitative effects of the observed increase in foreign R&D competition on U.S. welfare. I find that the positive growth effect and the negative business-stealing effect of foreign competition on U.S. welfare substantially balance each other, and the overall welfare effect of competition is negligible - less than 1 percent of per-capita consumption. Moreover, using estimates of the effective U.S. R&D subsidy rate, I compute the distance from optimality of the observed subsidy at each level of competition. I find that international competition increases the optimal subsidy and that, surprisingly, the U.S. subsidy observed in the data is fairly close to the optimal subsidy.

Keywords

international competition, R&D-driven growth theory, strategic R&D policy, international trade and growth.

JEL Classification: F12, F13, O38, O41.

International competition and U.S. R&D subsidies: a quantitative welfare analysis*

Giammario Impullitti[†]

1 Introduction

In the debate on the economic costs and benefits of globalization, some recent works have battled over the welfare effects on leading economies of technical progress in trailing countries. Most of the attention has been dedicated to the consequences for 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 1980s and early 1990s. 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 Key issues in both debates are, on the one hand, the quantitative assessment of the welfare effect of foreign competition and, on the other hand, the identification of the optimal policy response to it. In this paper I focus on the second debate and study the effects of Japanese and European technological catch-up on U.S. welfare and the optimal U.S. R&D subsidy.

There are two main reasons for focusing on R&D subsidies: first, the WTO and other international institutions restrict the use of trade policy and of production subsidies, 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.

Two stylized facts provide the basic motivation for the paper: the evolution of foreign competition experienced by U.S. firms and the dynamics of U.S. R&D subsidies in the 1970s and 1980s. The dimension of international competition on which this paper focuses is R&D rivalry among firms from different countries. A preliminary measure of this feature of competition is represented by countries' share of global R&D investment. Using OECD ANBERD data on R&D investment in 2-digit and 3-digit manufacturing industries for the U.S., Japan, and 10 European countries, I find substantial changes in the geographical distribution of R&D investment in the 1970s and 1980s. More precisely,

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¹See Baumol and Gomory (2000), Samuelson (2004), Bhagwati, Panagariya, and Srinivasan (2004), Blinder (2005).

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

the U.S. share declines from 52 percent in 1973 to 37 percent in 1991, 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 was increasingly challenged by foreign firms in this period. Digging deeper into the dynamics of countries' R&D shares by industry it is possible to show that a significant role was played by shifts in global R&D leadership in medium and high-tech sectors. The second relevant piece of evidence is that 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 effective subsidy produced by the R&D tax credit increases from 6 percent in 1979 to 30 in 1991.

These two stylized facts lead us to the following research questions: first, what is the effect of the observed increase in foreign R&D on U.S. welfare? Second, how does foreign competition affect the optimal R&D subsidy in the U.S. and, consequently, how far is this from subsidy observed in the data? I set up a framework to study the effect of international R&D competition on domestic welfare and on the optimal domestic R&D subsidy. Moreover, I build a measure of international R&D rivalry that can be used in the model to perform quantitative analysis, and use it to calibrate the model and quantify the effects of the observed increase competition on the welfare and on the optimal subsidy in the U.S. between 1979 and 1991.

I set up a two-country quality ladder 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.³ There are two countries, domestic and foreign, sharing the same size, technology and preferences but with different allocations of R&D investment across sectors and different research subsidies. Following the evidence discussed above, I model foreign competition as follows: I assume that the 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.⁴

Increases in competition, that is, increases in the share 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 in R&D at the country level, caused by the presence of fixed costs or by a fixed endowment of a workforce with heterogeneous ability (Eaton and Kortum, 1999), imply that increases in competition lead to a more *efficient* international distribution of research labor, thus spurring innovation and growth. More precisely, a concave research technology implies that in competitive sectors, where R&D firms from both countries are active, ideas

³Population 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).

⁴This working assumption is similar to the one in Krugman (1979), where the leading country is assumed to be able to produce virtually all the 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 a more skilled labor force, external economies, or to a difference in "social atmosphere".

are produced more efficiently than in non-competitive industries.⁵ As a consequence, increases in competition raise global R&D efficiency and growth. This is the *growth effect* of competition (*GRE* henceforth) which, by improving the quality of goods, raises domestic welfare via the consumer surplus channel.

This channel of growth through foreign entry represents a novelty in the literature on trade and growth. This literature has focused on the *selection* and on the *competition* effect. In Melitz (2003), exposure to trade induces the less productive firms to exit the market, thus increasing the average productivity level of the economy. Baldwin and Robert-Nicoud (2007) and Gustafsson and Segerstrom (2007) have extended the Melitz model to explore the effects of firms' selection on the long-run growth rate of productivity. Aghion et al. (2006), Peretto (2003), Klundert and Smulders (1997), Tang and Waelde (2001), and Licandro and Navas (2007) among others have studied the effect of foreign entry on incumbent firms' incentives to innovate. In Aghion et al., incumbents increase their innovation activity to *stay ahead* of competition. In the other papers, firms' incentives to innovate are affected by changes in the market structure produced by foreign competition; changes in the total number of firms and in markups are the sources of a *pure competition* effect on innovation.

The growth channel highlighted in the present paper is different from those in the literature for the following reasons: first, firms are homogeneous and, consequently, foreign entry cannot produce any selection effect that raises productivity. Second, existing papers focus on foreign entry in the product market and study the innovation effect of changes in the market structure produced by entry. This paper, instead, spotlights on entry in the innovation activity, thus no changes in the structure of the product market are considered. Furthermore, since the R&D activity is assumed to be carried out under perfect competition, foreign entry does not affect the R&D market structure either. It follows that there is no pure competition effect, and the innovation effect of foreign entry is produced exclusively by the interaction between changes in the geographical composition of R&D in some industries and the non-linear R&D technology.⁶ Third, in the version of the quality ladder model used in this paper, incumbent firms do not innovate, therefore no 'stay ahead' of competition mechanism is obtainable.

The second 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. Second, when domestic firms are taken over by foreign firms, domestic jobs are temporarily lost and the labor market clears at a lower wage level. In this paper I focus on the profit-shifting effect and, assuming that the presence of multinational corporations

⁵For estimates of returns to R&D in several countries supporting a non-linear R&D technology similar to the one used in this paper see Kortum (1993), Eaton and Kortum (1999), and Jones and Williams (1998).

⁶This dimension 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 changes in the market structure: before Airbus started producing wide-body aircrafts the global market was an *American oligopoly* in that it was led by three American producers, Boeing, Lockheed, and McDonnell-Douglas; shortly after airbus entry Lockheed and McDonnell-Douglas exited and the market became a *American-European oligopoly*. The market structure did not change much but the geographical allocation of production, innovation, and ownership did change. These are the type of situations better described by the new measure of competition.

equalizes wages across countries, I do not consider the negative effect of competition on wages. The overall effect of competition on welfare is the result of both the *GRE* and the *BSE* and depends on their relative strength. While qualitatively these two effects can be derived analytically, to measure their quantitative impact on welfare I need to calibrate the model and solve it numerically. This feature of the paper is methodologically related to the works on fully-calibrated multi-country endogenous growth models, such as Eaton and Kortum (1999), and Klenow and Rodriguez-Claire (2005).

The quantitative analysis begins with the construction of an empirical index of the measure of competition presented in the model. Using OECD STAN data on R&D investment for the set of countries mentioned above, I obtain a measure of the share of sectors where domestic and foreign firms compete effectively in R&D. Since the index is targeted at measuring the increase of competition experienced by U.S. firms with the entry of Japanese and European firms into the global market for innovation, the U.S. will be the domestic country in the model and Japan and Europe the foreign country. 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 considered non-competitive, while those sectors where the U.S. and the rest of the world are more ‘neck-and-neck’ in their innovation efforts are considered competitive; the share of neck-and-neck sectors will be the measure of international competition for innovation. The baseline version of the index shows that U.S. global leadership in R&D was increasingly challenged by foreign countries in 1970s and 1980s. More precisely, I find an increase in the share of competitive sectors - the share of neck-and-neck industries - from 30 percent in 1973 to 68 percent in 1991.

I use this measure of R&D competition and other long-run statistics to calibrate the model. Numerical simulations show that the effect of competition on welfare is negative but small, implying that the GRE does not completely offset the negative BSE but it limits its welfare effect substantially. More precisely, I find that the observed increase in foreign competition leads to a welfare loss for the U.S. of 0.8 percent of quality adjusted per-capita consumption between 1979 and 1991 - when the competitive share of sectors rise from 0.42 to 0.68.⁷

The next step is to analyze the effects of foreign competition on the optimal domestic subsidy. There are two motives for R&D subsidies: first, the market failures related to *knowledge spillovers* typical of closed-economy models, that characterize the public good feature of R&D (e.g. Segerstrom, 1998). In the model, innovation-driven growth, by increasing the quality of goods or reducing their quality-adjusted price, raises consumers’ surplus. Thus, R&D subsidies can be used to maximize consumers’ surplus by correcting socially inefficient levels of investment in R&D due to the presence of knowledge externalities. Secondly, there is a *strategic motive* related to international R&D rivalry (e.g. Spencer and Brander, 1983, Grossman and Eaton, 1986). More precisely, R&D subsidies can be used to protect national income, profits and wages, by helping domestic firms competing in global R&D races for market leadership. The effect of foreign competition on the optimal domestic subsidy works through the impact of foreign entry in R&D on these two motives for subsidies.

The only other paper I am aware of that studies both the consumer surplus and strategic motive

⁷I cannot study the effect of competition for the entire time frame of the index because of the lack of data for calibrating R&D subsidies before 1979.

for subsidies is Haaland and Kind (2007). That paper also explores the effect of increasing competition on innovation and on the optimal strategic R&D subsidy, but focuses on product market competition and, as standard in the strategic industrial policy literature, presents a static model of innovation. The present paper, instead, spotlights on international competition for innovation, and introduces a strategic subsidy game into an endogenous growth framework to account for the long-run effects of innovation on consumer surplus. Brander (1995) and Krugman (1994) suggest that taking into account long-run growth effects could increase the welfare gains associated to the consumer surplus motive of strategic policy.⁸

The main findings can be summarized as follows: first, increasing foreign competition strengthens both the strategic and the knowledge spillovers (consumer surplus) motive for subsidies, thus raising the optimal domestic R&D subsidy. Second, applying the model to evaluate the optimality of the U.S. subsidy response to competition, I obtain that an increase in the R&D competition index from 0.42 in 1979 to 0.68 in 1991 produces an increase in the optimal subsidy that is fairly close to that observed in the U.S. data. Thus, the quantitative analysis suggests that R&D subsidies were set *as if* American policy makers were responding optimally to increasing international competition.

The quantitative analysis of the distance between the observed and the optimal R&D subsidy response to competition is related to the literature on calibrated models of strategic trade and industrial policy. Following the seminal work by Dixit (1988), several papers have performed calibration exercises to evaluate quantitatively the welfare gains implied by the gap between the observed policy and the optimal strategic policy (e.g. the papers in Krugman and Smith, 1994, and the work surveyed in Brander, 1995). The present paper contributes to this literature on the following dimensions: first, most existing papers focus on policies affecting specific industries, while this paper studies subsidies to R&D affecting all industries symmetrically. Secondly, the existing literature has dealt with trade policies or production subsidies and, to my knowledge, this is the first attempt at a quantitative study of strategic R&D subsidies. Finally, while models in the literature are limited to the two-industry framework with static innovation, this paper is more general in that there is a continuum of industries and the dynamic effects of innovation are studied.

2 Features of the data

In this section I introduce and discuss the data that will function both as a motivation for the paper and as empirical support for the quantitative analysis performed later on. First I explore the evolution of countries' shares of R&D investment in the period 1973-91. My interest is in international competition among technological leaders and - hence - I restrict my attention to the U.S., Japan, and 10 European countries: Germany, France, the U.K., Italy, Sweden, Denmark, Finland, Ireland, Spain, and the Netherlands. In the period 1973-1991, R&D expenditures in these countries represent between 95 and 98 percent of the global R&D investment in manufacturing.⁹ Secondly, I report the estimates of R&D

⁸Peretto (2003), Klundert and Smulders (1997) and Tang and Waelde (2001) employ two-country endogenous growth models to study the effects of foreign competition on welfare, but no formal analysis of how competition affects the optimal policy is performed.

⁹See OECD ANBERD Rev.2, 2005.

tax subsidies from Bloom, Griffith, and Van Reenen (2002) for a smaller but representative group of countries in the period 1979-1991.

2.1 Global R&D investment shares

I use OECD ANBERD data on R&D investment for two and three-digit manufacturing industries. Grouping together the 10 European countries, figure 1 reports sectorial average R&D investment shares for the U.S., Japan, and Europe. The figure shows that, while European countries as a whole kept a fairly constant share, the U.S. share declined substantially, from 52 percent in 1973 to 37 percent in 1991, while Japan's share increased from 17 percent in 1973 to 28 percent in 1991.¹⁰ This suggests that the U.S. position as the global leader in R&D investment was increasingly challenged by Japanese firms in the 1970s and 1980s.

[FIGURE 1 ABOUT HERE]

Figure 2 reports countries' shares for each sector. The U.S. share is declining in many sectors of the economy, but this decline is stronger in the most innovative sectors. With the exception of Aircrafts and Drugs and Medicines, where global R&D shares are substantially constant or decline slightly, we can observe that all other industries show a fairly large increase of Japan's and, in some cases, of Europe's share at the expense of the U.S.

[FIGURE 2 ABOUT HERE]

High-tech and medium-high-tech industries, grouped according to the OECD classification, represent 77 percent of total manufacturing R&D. In this group of industries, the larger drop in the U.S. share takes place in Office and Computing Machineries (OCM), which accounts on average for 8 percent of total manufacturing R&D and in Radio, TV, and Communication Equipment (RTCE), which accounts on average for 16 percent of total R&D: the U.S. share dropped from 0.76 to 0.53 in OCM and from 0.54 to 0.4 in RTCE, while Japan's share rose from 0.06 to 0.32 in OCM and from 0.13 to 0.26 in RTCE.

2.2 R&D subsidies

Next, I compute the R&D subsidy produced by tax policies in the U.S., Japan and some European countries using Bloom, Griffith, and Van Reenen (2002)'s 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 active in only a few countries.

¹⁰Similar results are obtained with the weighted average, where sectors' share of total R&D are used as weights. The U.S. weighted 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 setting $A_d = \tau_\pi$, 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 $1 - B \text{ index}$, where $B \text{ index} = \frac{1 - A_d - A_c}{1 - \tau_\pi}$; assuming $A_d = \tau_\pi$, it is easy to see that $s = 1 - B \text{ index}$. Figure 3 shows the subsidy rates s for different countries obtained using 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 a jump in U.S. subsidies takes place with the introduction of the Research and Experimentation Tax Credit on incremental R&D in 1981 and with the revision of the base defining incremental R&D in 1990;¹¹ 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 U.S. R&D subsidy from 13 percent in 1979 to 30 percent in 1990. Recalling the evidence in figures 1 and 2 we can observe that this substantial increase in public support for 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

¹¹Only “incremental” R&D is eligible for the U.S. R&D tax credit: incremental meant above the level of the previous year in 1981, and in the following years the increase was measured over the average R&D in the previous three years. In 1990 the base was defined as the average of the last 3 years of the R&D-sales ratio.

generates no disutility. Dropping country indexes for notational simplicity, households are modelled as dynastic families that maximize intertemporal utility

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

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 $j \in \{0, 1, 2, \dots\}$, 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 moment 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 for each product is:

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

The standard solution of the intertemporal maximization problem is:

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

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.¹² Successful innovators obtain the market leadership and earn monopoly profits; 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.¹³

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' profits are maximized through limit pricing, so the price $p^K(\omega, t)$ of every top quality good is:

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

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:

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

where $c^D(t)$ and $c^F(t)$ are domestic and foreign expenditures at time t . The above equation says that, in equilibrium, the 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 who produces the state-of-the-art quality product in country $K = D, F$ will be equal to

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

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

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

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

¹²An incumbent considering investing in R&D needs to subtract its present monopoly profits from the payoff of successful innovation. More precisely, the value to the incumbent of successful innovation is $v(\omega, t+1) - v(\omega, t)$, which is less the value of innovation for the follower, $v(\omega, t+1)$. For a recent novel interpretation of the Arrow effect in quality ladder models see Cozzi (2007).

¹³As I will discuss later, relaxing this assumption would increase the effects of competition on national income and strengthen the results in the paper.

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:

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

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 efforts 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.¹⁴ 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 a heterogeneous research ability of the workforce.¹⁵

The technological complexity index $X(\omega, t)$ was introduced into endogenous growth theory after Jones' (1995) found that 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 $X(\omega, t)$ were introduced to rule out scale-effects. I will adopt a specification introduced by Dinopoulos and Thompson (1998), according to which $X(\omega, t) = 2\kappa N(t)$, with positive κ , thereby formalizing the idea that it is more difficult to introduce a new product in a more crowded market. 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 permanent effects on the long-run

¹⁴Eaton and Kortum (1999), Kortum (1993), and Jones and Williams (1998) provide empirical evidence on the existence of DRS in R&D at the country level. I will discuss this more in details in the calibration exercise.

¹⁵While fixed costs and institutional difference can motivate the country-specific R&D externality in the benchmark model, the presence of heterogeneous workers require the removal of the assumption of global labor markets. In a similar setup but with global labor markets Eaton and Kortum (1999) use the workers' heterogeneity motivation of 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.

growth.

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.¹⁶ Free entry into R&D races drives the expected profits to zero, generating the following equilibrium condition:

$$v^K(\omega, t) \frac{A \left(\frac{L^K(\omega, t)}{X(\omega, t)} \right)^{-\alpha}}{X(\omega, t)} = (1 - s^K). \quad (9)$$

Substituting for the value of the firm from (7) into (9) we get:

$$\frac{\pi^K(\omega, t)}{r(t) + I(\omega, t) - \frac{\dot{v}(\omega, t)}{v(\omega, t)}} = \frac{(1 - s^K)X(\omega, t)}{A} \left(\frac{L^K(\omega, t)}{X(\omega, t)} \right)^\alpha, \quad (10)$$

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 (10) has an immediate economic interpretation: the right hand side is the cost of producing one unit of innovation $I(\omega, t)$, and the left hand side 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 $\bar{\omega} \in (0, 1)$ 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:

$$\begin{aligned} I(\omega, t) &= I_c^D(\omega, t) + I^F(\omega, t) = I_c^D(t) + I^F(t), & \text{for } \omega \leq \bar{\omega} \\ I(\omega, t) &= I_m^D(\omega, t) = I_m^D(t), & \text{for } \omega > \bar{\omega} \\ X(\omega, t) &= 2\kappa N(t) & \text{for all } \omega, \end{aligned} \quad (11)$$

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 $X(\omega, t) = 2\kappa N(t)$.

¹⁶The discounted profits are

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

3.5 Steady-state equilibrium

Next, 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 (9), (8), $X(\omega, t) = 2\kappa N(t)$, 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:

$$\left(\frac{c^D + c^F}{\lambda}\right) = 2 - 2\kappa \left[\bar{\omega} \left(\frac{I_c^D}{A}\right)^{\frac{1}{1-\alpha}} + (1 - \bar{\omega}) \left(\frac{I_m^D}{A}\right)^{\frac{1}{1-\alpha}} + \bar{\omega} \left(\frac{I^F}{A}\right)^{\frac{1}{1-\alpha}} \right] \quad (12)$$

where I have used $X(\omega, t)/N(t) = 2\kappa$ from the specification of the R&D difficulty index.

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).¹⁷

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

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

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 owned completely domestically and foreign firms are completely foreign-owned.¹⁸

The international division of research labor specified in the previous section leads to the following

¹⁷In 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 subsidies cancel out in the constraint with the reduction in R&D costs due to the subsidies. Considering R&D as current expenditures does not change our qualitative results.

¹⁸This 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.

steady-state expressions for the no-arbitrage and free entry conditions in (10):

$$\begin{aligned}
\frac{2\kappa}{A}(1-s^F)\left(\frac{I^F}{A}\right)^{\frac{\alpha}{1-\alpha}} &= \frac{(c^D+c^F)\left(\frac{\lambda-1}{\lambda}\right)}{\rho+I_c^D+I^F-n}, \quad \omega \leq \bar{\omega} \\
\frac{2\kappa}{A}(1-s^D)\left(\frac{I_c^D}{A}\right)^{\frac{\alpha}{1-\alpha}} &= \frac{(c^D+c^F)\left(\frac{\lambda-1}{\lambda}\right)}{\rho+I_c^D+I^F-n}, \quad \omega \leq \bar{\omega} \\
\frac{2\kappa}{A}(1-s^D)\left(\frac{I_m^D}{A}\right)^{\frac{\alpha}{1-\alpha}} &= \frac{(c^D+c^F)\left(\frac{\lambda-1}{\lambda}\right)}{\rho+I_m^D-n}, \quad \omega > \bar{\omega}
\end{aligned} \tag{15}$$

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 (12), turns out to be the sum of the two resource constraints (13) and (14), so the three equations are not linearly independent; I can omit one of them, and solve for the three equations in (15), and the remaining (13), (14).

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:

$$W^K \equiv (\rho - n)U = \ln \frac{c^K}{\lambda} + \frac{g^K}{\rho - n} \tag{16}$$

where g^K 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 obtainable from (1) as follows:

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

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 (11), and that investment in R&D is constant in steady-state we obtain $\Omega(\omega, t) = \int_0^1 \left[\int_0^t I(\omega, \tau) d\tau \right] d\omega = \bar{\omega}t [I_c^D + I^F] + (1 - \bar{\omega})tI_m^D$. The growth rate is obtained by differentiating $\ln u(c^K(t))$ with respect to t :

$$g = \frac{\dot{u}}{u} = [\bar{\omega}(I_c^D + I^F) + (1 - \bar{\omega})I_m^D] \ln \lambda. \tag{17}$$

In this growth equation, international knowledge spillovers are assumed to be perfect, thus $g^D = g^F = g$ in (17). Eaton and Kortum (1999) and Klenow and Rodriguez-Claire (2005) find evidence that international spillovers of ideas are high but not perfect. For a representative set of OECD countries, Eaton and Kortum show that countries adopt one-half to three-fourths of the ideas generated

abroad. Introducing partial international knowledge spillovers, the growth rates of the two countries will become

$$g^D = 2 \{ \gamma^D [\bar{\omega} I_c^D + (1 - \bar{\omega}) I_m^D] + (1 - \gamma^D) \bar{\omega} I^F \} \ln \lambda \quad (18)$$

for the domestic country, and

$$g^F = 2 \{ \gamma^F \bar{\omega} I^F + (1 - \gamma^F) [\bar{\omega} I_c^D + (1 - \bar{\omega}) I_m^D] \} \ln \lambda \quad (19)$$

for the foreign country, where γ^K represent the impact on national growth of innovation performed in nation K . When $\gamma^D = \gamma^F = 0.5$, international spillovers are perfect and the symmetric growth rate is that in (17), otherwise the growth rates will be (18) and (19). In the following sections I will start from the simple specification of the growth equation in (17) to derive analytically the two main effects of competition. In the quantitative analysis, following the suggestion of the empirical evidence, I will assume imperfect international knowledge spillovers and use (18) and (19).

4 The growth and business-stealing effect of competition on welfare

In this section I characterize the two basic effects of foreign competition on the domestic welfare, the business-stealing and the growth effect, and explain the economic mechanism behind them. In order to focus on the pure effects of competition on welfare and derive them analytically, I assume symmetric subsidies and, for simplicity, I set $s^D = s^F = 0$.¹⁹ I begin analyzing the growth effect. Equations (15) imply that innovation intensity is the same in both countries in competitive sectors, that is $I_c^D = I^F$; as mentioned above, this is a consequence of the basic symmetry of the two countries in those sectors. Let $I_c^D = I^F = I_c$ and substitute into (15), (13), (14) to obtain a system in four equations and four unknowns, I_c, I_m^D, c^D, c^F . Summing up the new versions of (13) and (14), solving for $(c^D + c^F)$ and substituting into the new version of (15) the equilibrium system is summarized by these two equations:

$$\left(\frac{I_m^D}{A} \right)^{\frac{\alpha}{1-\alpha}} (\rho + I_m^D - n) = \left(\frac{I_c}{A} \right)^{\frac{\alpha}{1-\alpha}} (\rho + 2I_c - n) \quad (I)$$

$$\left(\frac{I_m^D}{A} \right)^{\frac{1}{1-\alpha}} = \frac{1}{\lambda(1-\bar{\omega})} - \left[\frac{\rho + 2I_c - n}{A\lambda(1-\bar{\omega})} \left(\frac{I_c}{A} \right)^{\frac{\alpha}{1-\alpha}} + \frac{2\bar{\omega}}{(1-\bar{\omega})} \left(\frac{I_c}{A} \right)^{\frac{1}{1-\alpha}} \right] \quad (II)$$

Equation (I) is upward sloping and equation (II) is downward sloping in the space (I_m^D, I_c) . As shown in figure 4, the two curves intersect only once, thus a steady state equilibrium for I_m^D and I_c is uniquely determined. These equilibrium values can be substituted back into (15) to obtain the balanced growth path of c^D and c^F .

[FIGURE 4 ABOUT HERE]

¹⁹Results do not change if we set the subsidies at a common positive or negative level.

I now turn to analyze the effects of increases in foreign competition on long-run growth. Proposition 2 below summarizes the results:

Proposition 1 *Increases in foreign competition have two counteracting effects on the steady state growth rate:*

i. The increase in the number of competitive sectors raises global R&D efficiency, thus benefiting growth. This is the ‘efficiency’ effect of competition.

ii. Innovation arrival rates per-sector decrease, thereby slowing down growth. This is the ‘obsolescence’ effect.

iii. The ‘efficiency’ effect is dominant and competition has a positive overall effect on growth

Proof. See appendix. ■

The *efficiency* effect is produced by the R&D externality α in (8). As R&D is characterized by a negative country-specific externality, the competitive sectors, where R&D is performed by domestic and foreign firms, can accommodate a larger global investment in R&D. The country-level concavity of the R&D technology implies that in each industry, two researchers from two different countries are more productive than two researchers from the same country. Thus, a higher $\bar{\omega}$ leads to a larger number of sectors with higher arrival rate of innovation and, consequently, to higher long-run growth. Differentiating the growth equation (17) with respect to $\bar{\omega}$ we can see how this effect operates on the growth rate:

$$\frac{\partial g}{\partial \bar{\omega}} = \left\{ \underbrace{(2I_c - I_m^D)}_{\text{efficiency effect}} + \underbrace{\left[2\bar{\omega} \frac{\partial I_c}{\partial \bar{\omega}} + (1 - \bar{\omega}) \frac{\partial I_m^D}{\partial \bar{\omega}} \right]}_{\text{obsolescence effect}} \right\} \quad (20)$$

The source of the *efficiency* effect is the difference between innovation intensity in competitive and non-competitive sectors. This effect can be offset by a negative impact of competition on the sectorial levels of innovation I_c and I_m^D . As we can see in figure 4, an increase in $\bar{\omega}$, on the one hand, raises the intercept of $II(\bar{\omega})$, thus raising both investments levels but, on the other hand, increases the slope of $II(\bar{\omega})$, thus reducing I_c and I_m^D . If the latter force dominates, there will be a negative effect of competition on R&D investment per-sector that could offset the positive efficiency effect. This the case drawn in figure 4 and, in fact, as shown in the appendix it is possible to prove that $\partial I_c / \partial \bar{\omega}$ and $\partial I_m^D / \partial \bar{\omega}$ are always negative. Intuitively, foreign R&D presence in more sectors raises, in equilibrium, the obsolescence of innovation, thus reducing the incentives to innovate - this is the *obsolescence* effect. In the appendix I show that the obsolescence effect cannot completely offset the positive efficiency effect, which implies that the overall *growth* effect (*GRE*) of competition is positive.²⁰ Since growth increases welfare through improvements of goods’ quality, we can conclude that competition has a positive effect on welfare through the growth channel.

Next, I analyze the effect of competition on national income. As foreign R&D firms enter some industries previously dominated by domestic firms, with a probability proportional to their research

²⁰In the numerical solution, we will see that the negative effect of competition on I_c and I_m^D is substantially of second order.

effort they will discover the next top-quality good and obtain global market leadership. This *business-stealing* effect (*BSE*) reduces domestic aggregate profits because foreign firms appropriate a bigger share of the world market. Since, by assumption, the labor market is not affected by shifts in the global ownership distribution of firms, only the profit component of domestic income will decrease. This leads to:

Proposition 2 *An increase in the scale of foreign R&D competition $\bar{\omega}$ shifts domestic profits abroad, thus reducing domestic income.*

Proof. See appendix. ■

Considering the expression for the domestic resource constraint (13), it is easy to see that a reduction in income, right hand side of (13), can lead to a reduction in domestic consumption, and thus to a decline in national welfare (16) if domestic savings - R&D spending - do not absorb the whole reduction in income. Unfortunately, it is not possible to obtain an analytical proof of the effect of foreign business-stealing on domestic welfare.²¹ Moreover, if profit-stealing affects negatively domestic welfare, which is what one would expect, the overall effect of competition on welfare would depend on the relative strength of the two counteracting effects - the *BSE* and the *GRE*. Hence, a quantitative measure of the two effects is needed. For this reason I will now calibrate the model and explore its full properties numerically.

5 Taking the model to the data

The analysis proceeds in three steps: first, I adapt the data discussed in section 2 to the model economy. More precisely, in this section I first build an indicator that embeds the definition of competition used in the model; that is, I construct a measure of $\bar{\omega}$, the share of industries where domestic and foreign countries effectively compete for innovation. Secondly, I adapt the R&D subsidy computed above to the specific form of subsidy adopted in the model. Thirdly, I use these data and other long-run statistics to calibrate the parameters of the model.

5.1 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 (9),

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

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

²¹At the roots of the reduced tractability of the model is the assumption of non-linear R&D technology. Once the non-linearity in (8) is removed, by setting $\alpha = 0$, it is easy to prove that the BSE has a negative impact on domestic welfare. This result is available upon request from the author.

model. 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.²² 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.²³ Figure 5 below reports the R&D subsidy obtained from this calculation.

[FIGURE 5 ABOUT HERE]

Figure 3 and 5 are substantially similar except for the fact that subsidies are lower for all countries when the measure is cleaned of the effects of changes in depreciation allowances and corporate taxes. In particular the U.S. subsidy increases from 6 percent in 1979 to 18 percent in 1991.

5.2 Measuring the set of competitive industries

The measure of R&D competition is built using the OECD ANBERD data on R&D investment mentioned above. The U.S. is assumed to be the domestic (leading) country; Japan and Europe, are the foreign (follower) countries. The index is based on the following criterion: for each year, in the period 1973-91, 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 henceforth). The industries set is composed of 21 two and three-digits manufacturing industries, and the competitive set of industries \bar{w} is the share of sectors with U.S. R&D investment share below CT . The share is computed for different threshold values in the plausible set $CT \in (0.35, 0.55)$, and the final index is chosen taking the average across thresholds.²⁴

[FIGURE 6 ABOUT HERE]

Figure 6 shows the measure for \bar{w} obtained using the bottom threshold $CT = 0.35$ and the top threshold $CT = 0.55$; it also shows the average \bar{w} , which is computed taking the mean of all the \bar{w} s obtained at each threshold levels in the set $CT \in (0.35, 0.55)$. All measures show an increasing trend; the average \bar{w} , which will be used in the calibration exercise, increases from 0.3 - 30 percent of the sectors are competitive - in 1973 to 0.68 in 1991. Using the average index allows me to deal with the problem of sensitivity to small changes that fixing one specific threshold might produce. For instance, suppose that I arbitrarily choose the threshold $CT = 0.5$, and in an industry the U.S. share is 0.51 in one year and 0.49 the next year, this small change will be enough to shift the industry from non-competitive to competitive in the index. Taking the average \bar{w} across thresholds allows me to avoid the problem of small changes making big differences in the index.

²²This is also problematic because in the model there are no corporate taxes.

²³For the U.S. this leads to subsidy levels close to those estimated in Hall (1993), who isolated the effect of the R&D tax credit on the cost of innovation.

²⁴This is the interesting range to study because from figure 1 we see that the average US R&D share is never above 0.55 and below 0.35. This is also confirmed by figure 2 where we can see very few sectors with a US share outside that range.

5.3 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 with 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 0.05, slightly below the average real return on the stock market for the past century of 0.07 estimated in Mehra and Prescott (2003).²⁵ I set λ to 1.2, to match an average markup over the marginal cost of 20 per cent. Since, estimates of average 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%, which is the average business sector labor force growth rate in the period 1948-97 (Bureau of Labor Statistics, 1999). Decreasing returns due to duplicative R&D at the country level have been estimated to be between 0.4 and 0.9 (Kortum 1993, and Jones and Williams, 1998, Eaton and Kortum, 1999).²⁶ I choose a value in this interval and set the R&D externality coefficient α to 0.4. Finally, motivated by the empirical evidence discussed above I focus on a world with imperfect knowledge spillovers. Eaton and Kortum (1999) decompose the geographical sources of R&D-driven growth and find that about 60 percent of U.S. growth comes from domestic research and the rest from research performed abroad. Hence, I set the international knowledge spillovers parameter for the U.S. γ^D at 0.6.

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

²⁵Jones 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.

²⁶Empirical estimates of decreasing returns in R&D are usually obtained using a specification of the R&D technology different from the one in this paper. The general form for the technology used is , $I = AL_R^\beta$, where I is the innovation intensity and L_R are resources invested in research, and $0 < \beta < 1$. Estimates for β suggest values between 0.1 and 0.6 (e.g. Kortum,1993, Jones and Williams,1998, and Eaton and Kortum,1999). Since all sectors in my model are symmetric, technology (8) can be expressed as follows

$$I^K(\omega, t) = A \left(L^K(\omega, t)/X(\omega, t) \right)^{(1-\alpha)}.$$

Thus, estimates of β in the interval (0.1, 0.6) using the general technology above, roughly translate in values for α in the interval (0.4, 0.9) with my specification of the R&D technology. It follows that $\alpha = 0.4$ is the lower bound of the empirical estimates; this is a conservative choice in that it allows the benchmark model to be as close as possible to the textbook case of linear technology. In the robustness analysis i will explore an exhaustive set of values for α .

GDP, are obtained by subtracting investment in tangible capital from the data. After this adjustment the CHS data report an average growth in 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 an average of 13.5% over the period 1975-2003. Finally, in the internal calibration I have set the two subsidies at their 1979 values, that is $s^D = s^F = 0.06$: this is the earliest value available for the measure of R&D subsidy computed in the previous section and shown in figure 5. I have also used the 1979 value for international competition shown in figure 6 above, that is I have set $\bar{\omega} = 0.42$.²⁷

The parameters calibrated internally have been found by minimizing the quadratic distance between the model and two long-run statistics listed above: the resulting values are $A = 0.46$ and $\kappa = 0.92$.

[TABLE I ABOUT HERE]

Table I shows how well the model fits the U.S. data at the initial date, 1979. The calibrated model fits the targeted and some relevant non-targeted statistics closely enough.

6 Quantitative analysis

In this section I use the calibrated parameters to explore the quantitative properties of the model. First, I measure the relative strength of the growth and business-stealing effects of competition on welfare. Second, I numerically compute the optimal domestic subsidy and analyze the effects of foreign competition on its level.

6.1 Foreign competition and welfare

Figure 7 shows the effects of an increase in the share of competitive industries $\bar{\omega}$. The numerical simulation allows us to quantify the analytical results derived above. First, when foreign researchers enter sectors in which previously only domestic firms were active, some of the monopolistic rents of domestic leaders shift abroad, and domestic income and welfare are negatively affected. This is the business-stealing effect (*BSE*) of foreign entry.

[FIGURE 7 ABOUT HERE]

Second, the growth effect (*GRE*) of competition is positive; more precisely, more precisely increasing $\bar{\omega}$ from 0 to 1 raises domestic growth from 1.65 to 1.88 percent. Thirdly, the welfare effect of competition depends on the relative strength of the *BSE* and the *GRE*. As we can see in figure 7, when competition rises from $\bar{\omega} = 0$ to $\bar{\omega} = 1$, domestic income decreases by 14.7 percent and domestic growth rises by 12.8 percent. The GRE counterbalances the negative BSE but not completely, and the overall effect of competition on welfare is negative; more precisely increasing $\bar{\omega}$ from 0 to 1 reduces domestic welfare, measured in terms of quality-adjusted per-capita consumption, by 3.2 percent.

²⁷Although 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.

[FIGURE 8 ABOUT HERE]

Figure 8 also shows the robustness of the BSE, the GRE, and their impact on welfare to changes in the specification of parameters. Precisely it shows how the results are affected by doubling and halving, one at the time, the parameters from their baseline calibration values.²⁸ There are three things to notice: first, the BSE is strongly robust to changes in parameters, and its scale is mainly affected by changes in the profit rate pinned down by the markup $\lambda - 1$.

Second, the growth effect (*GRE*) of competition crucially depends on the value of the externality α , and on the level of international knowledge spillovers for the domestic country γ^D . When α is low, and/or γ^D is high, the *GRE* can also be negative. This happens because in the quantitative analysis I assumed imperfect international knowledge spillovers. When γ^D and γ^F are different from 0.5, the growth rate is not symmetric across countries anymore, and the spillovers of past on future research differ according to the location of past research. Proposition 1 shows that in the symmetric world, where $\gamma^D = \gamma^F = 0.5$, the growth effect of competition is always positive, independently of the specification of parameters. Repeating the proof of proposition 1 for γ^D different from 0.5 it is easy to show that a necessary condition for competition to have a positive effect on growth is $\gamma^D \leq 0.5$. In the quantitative analysis, the domestic country is the U.S. and, following estimates in Eaton and Kortum (1999), 60 percent of U.S. growth comes from domestic sources. Thus, with the benchmark γ^D set at 0.6, foreign competition has a smaller *efficiency* effect on domestic growth because R&D spillovers are mainly domestic. It follows that the growth effect of competition becomes sensitive to changes in α . At low levels of α , the reduction I_c^D and I_m^D produced by competition - the *obsolescence* effect - dominates the *efficiency* effect, and the *GRE* becomes negative. In the figure we can see that for $\alpha = 0.2$ and/or for $\gamma^D = 0.8$ the *GRE* becomes negative. More precisely, repeating the sensitivity analysis for a thinner grid of α and γ^D , I find that the *GRE* is negative for $\alpha \leq 0.22$ and for $\gamma^D \geq 0.68$. Since empirical estimates suggest that the relevant interval for α is (0.4, 0.9), and for γ^D not above 0.6 (see Eaton and Kortum, 1999), we can conclude that in the space of plausible α s and γ^D s the *GRE* is positive.

The third important feature emerging from the robustness analysis is that there is only one case where the overall effect of competition on welfare is positive, that is when the discount factor (interest rate) is below 3 percent - in the figure we report the simulation for $\rho = 0.025$. Intuitively, when consumers are more patient, the welfare effect of quality-improving innovation is higher and it completely offsets the negative *BSE*. Mehra and Prescott (2005) show that the average returns on stocks in the past century never go below 0.07 for the U.S., and below 0.047 other OECD countries in their sample. It follows that in the plausible set of ρ s the welfare effect of competition is negative.

6.2 Foreign competition and optimal R&D subsidies

Next, I use the calibrated model to compute the effect of foreign competition on the optimal domestic subsidy. Since I am interested in studying the effect of foreign competition on the domestic subsidy, I

²⁸For brevity I only report the sensitivity analysis for parameters producing more interesting changes. The robustness for the whole set of parameters is available upon request. Notice that, in those cases where doubling is not possible, because the parameters space is in (0, 1), I have increased them by a substantial amount.

keep the foreign subsidy fixed at its average value in the period of analysis, that is $s^F = 0.68$.²⁹ The timing of the subsidy game is the following: I assume that at stage 1, the domestic 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. For each level of competition and for a given level of the foreign subsidy, the domestic policy maker sets the subsidy according to the following best-response function:

$$s^D(\bar{s}^F; \bar{\omega}) = \{ \arg \max W^D(s^D, \bar{s}^F; \bar{\omega}) \}. \quad (21)$$

Figure 9 below shows that higher foreign competition increases the optimal domestic R&D subsidy.³⁰

[FIGURE 9 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 (16) in the following form:

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

where the G equals the present value of the growth rate, $G^K = g^K / (\rho - n)$; 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 $R^K = w^K \int_0^1 I^K(\omega, t) d\omega$.³¹

In quality ladder models of closed economies, innovation has three external effects affecting the level of the optimal subsidy: a *consumer-surplus or growth* effect (GR), a *business-stealing* effect (BSE), and a *resource constraint* effect (RCE). First, the GR 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. They also benefit from the new good 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 produce underinvestment in innovation.

Secondly, every time a firm innovates it drives another firm out of business; the appropriation of the incumbent firm's monopoly profits reduces aggregate profits and consumption, thus having a negative effect on welfare. This is the BSE 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, thus it leads to overinvestment in R&D.

Finally, because of the externality represented by α in the 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,

²⁹In Impullitti (2006) I consider the strategic policy game with both countries active in R&D subsidies and responding optimally to changes in competition. The qualitative results are not affected.

³⁰The calibration has been pointed to 1979, therefore the starting level of competition is the 1979 level, $\bar{\omega} = 0.42$.

³¹All values for the new expression for consumption are in logs. The expressions in extensive form for wages, profits, and R&D expenditures for both countries can be found in (13) and (14).

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 effects into account, they produce another bias toward overinvestment. Both components affect welfare through the resource constraint: in the metric of the 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.³² Using (22) we can express the different marginal effects of the R&D subsidy on domestic welfare as follows:

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

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.

As shown in Grossman and Helpman (1991) and Segerstrom (1998), in closed economies the policy maker sets the optimal subsidy balancing at the margin these three effects. Whether it is optimal to tax or subsidize R&D generally depends on the specification of parameters. In closed economy models policy intervention is only motivated by the presence of *knowledge spillovers*, which is at the roots of the three external effects discussed above. The novelty introduced by my two-country version of the model is that of adding a *strategic motive* for subsidies: in sectors where foreign followers drive domestic incumbent out of the market, profits shift abroad and domestic income and welfare are reduced. I call this the *international business-stealing effect (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. Intuitively the presence of foreign innovator produces an additional role for subsidies, that of protecting domestic profits.

The main force driving the results in figure 9 is the *strategic motive* for subsidies: as international R&D rivalry rises, the foreign rent-stealing threat becomes more relevant and triggers higher domestic subsidies. It is possible to see in equation (13) that the domestic policy maker has no rents to protect at $\bar{\omega} = 0$, while to role of s^D in protecting domestic rents raises with the share of sectors exposed to international R&D competition. Hence, an higher $\bar{\omega}$ implies an higher *scale* of foreign business-stealing and a higher role of the domestic subsidy as a rent-protecting device.

The country-specific negative R&D externality in (8) implies that competition also affects 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. The country-level concavity of the R&D technology implies that research efficiency increases in newly-competitive sectors. Since this effect is external to the firm, the single domestic investor does not take it into account, thus underinvestment in research emerges. This channel 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

³²In the literature this effect is sometimes called the *intertemporal R&D spillovers effect* because it depends on the impact of current innovation on future R&D productivity (see e.g. Segerstrom, 1998).

of innovation. This reduces the overinvestment in innovation produced by the *RCE*. It follows that increasing competition raises the growth effect of subsidies and reduces the overinvestment due to the *RCE*. We can thus conclude that competition raises the domestic subsidy also via the knowledge spillovers channel.

6.3 Robustness

Figure 9 shows an extensive robustness analysis of the effect of competition on the optimal subsidy. Precisely it shows how the results are affected by doubling and halving, one at the time, the parameters λ , α , ρ , A , κ , n , γ^D from their baseline calibration values. The basic qualitative result is confirmed under all parameters' changes: increases in foreign competition raise the optimal domestic subsidy.³³ Two features deserve special attention. First, the effect of changes in parameters on the *level* of the optimal subsidy is in line with standard results in the literature. As in Segerstrom (1998), the optimal subsidy is higher with higher λ , γ^D , n , and lower with higher ρ . These, changes can be explained using (23). From the welfare equation (22) and recalling that $g^D = \{\gamma^D [\bar{\omega}I_c^D + (1 - \bar{\omega})I_m^D] + (1 - \gamma^D)\bar{\omega}I^F\} \ln \lambda$, it is easy to see that the growth, or consumers surplus, motive for subsidy G^D 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).

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} . Segerstrom (1998) finds similar results for his technology parameters but in his paper the R&D technology is linear. Jones and Williams (2000), using a R&D technology with decreasing returns, show that the degree of decreasing returns is positively associated with higher overinvestment in research with respect to the social optimum. Correspondingly, in my model, when decreasing returns in R&D are strong - high α - the optimal subsidy becomes negative. Finally, notice that the positive relation between competition and subsidy is confirmed also in those cases where the specification of parameters leads to negative optimal R&D subsidies. In these cases increases in competition reduce the optimal R&D tax.

³³This sensitivity analysis is only meant to show that effects of a change in each parameters on the qualitative results; but on the quantitative side, the effects shown here are not reliable. This is due to the fact that, parameters A and κ have been calibrated internally and, as a consequence, changes in each of the externally calibrated parameters would involve a re-calibration of A and κ . Thus, the standard procedure for robustness of changing one parameter at the time, without re-calibrating A and κ , affects the fit of the model obtained in table I and it may yield implausible levels of the optimal subsidy. For brevity and since I am only interested in showing that the positive effect of competition on subsidies is robust, I do not recalibrate the internal parameters. Moreover, this procedure allows me to single out the qualitative effect of each parameter; while recalibrating A and κ any time one of the externally calibrated parameter changes would make the effect of each parameter harder to isolate.

7 Foreign competition, welfare, and R&D subsidies in the U.S.

In this final section I apply the calibrated model to, first, quantify the welfare effect of the increase in foreign R&D competition observed in the data shown in figure 6, keeping constant the R&D subsidies in both countries. Secondly, I quantify the welfare gains obtainable if the domestic country, the U.S., had implemented an optimal R&D subsidy response to the observed increase in foreign competition in the period 1979-91. I compare the domestic welfare under optimal subsidies with that under the actual subsidies observed in the data, for each level of international competition.³⁴

In figure 6 we can see that international R&D competition increases from $\bar{\omega} = 0.42$ in 1979 to $\bar{\omega} = 0.68$ in 1991. In the numerical results shown in figure 8, this change in competition produces an increase in the U.S. growth rate of 3.1 percent and a decrease in U.S. income of 3.6 percent. These two effects combine to an overall reduction in U.S. welfare of 0.8 percent of quality-adjusted per-capita consumption. Thus, as we mentioned above, although the positive growth effect of competition does not completely offset the *BSE*, it limits the negative overall effect of competition on welfare substantially.

Next, I compute the difference between to optimal and the observed subsidy in the period 1979-1991 and its welfare implications. The welfare improvement is obtained considering the following version of the welfare equation (16) for the domestic country:

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

choosing β such that $\widehat{W}^D = W^{*D}$, where $W^{*D}(s^{*D}, \bar{\omega}_{obs})$ is the present value of welfare under the optimal subsidy s^{*D} and observed competition $\bar{\omega}_{obs}$, and $c^D(s_{obs}^D, \bar{\omega}_{obs})$, $I_c^D(s_{obs}^D, \bar{\omega}_{obs})$, and $I^F(s_{obs}^D, \bar{\omega}_{obs})$ 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 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 the optimal policy are very low: an increase in competition from its 1979 level, $\bar{\omega} = 0.42$, to its 1991 level, $\bar{\omega} = 0.68$, leads to a welfare gain from the optimal subsidy of at most 0.04 percent of quality-adjusted per-capita consumption per-year. This result has been obtained with a benchmark calibration showing a sufficiently good fit of the model with the data shown in table I.

³⁴Unfortunately, the lack of subsidy data imposes a restriction of the focus to the period 1979-91, and the period of major increase in competition, 1973-79, cannot be analyzed.

8 Conclusion

In this paper I have shown that increases in international technological competition, measured as the number of industries in which domestic and foreign innovators effectively 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; and a *growth* effect produced by the increase in the efficiency of R&D, brought about by foreign entry, which raises welfare. The overall welfare effect is ambiguous and depends on the relative strength of these two counteracting effects.

Although these two effects have opposite implications for national welfare, they work in the same direction on the core external effects determining the optimal domestic R&D subsidy. More precisely, on the one hand, competition, by increasing the scale of international business-stealing, raises the *strategic* role of 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 R&D competition that matches the dimension of technological competition analyzed in the model. In other words, I have built a measure of the share of sectors where domestic and foreign firms are neck-and-neck in R&D investment. This empirical measure shows that U.S. global leadership was increasingly challenged by foreign competition in 1970s and 1980s. Using this measure in a calibrated version of the model, and focusing on the period 1979-91, I perform a quantitative analysis that leads to two main results: first, the growth and business-stealing effect of foreign competition on U.S. welfare substantially balance each other, thus leading to a negligible welfare loss of less than 1 percent of U.S. per-capita consumption in the 12-year period. Secondly, using R&D subsidies data from Bloom et al. (2002) I have compared the optimal U.S. R&D subsidy with the subsidy observed in the data during this period of rapidly increasing foreign competition. The results show that the observed U.S. subsidy is surprisingly close to the optimal subsidy response to competition produced by the model.

There are two important aspects that have not been considered in this paper: first the effect of foreign competition on domestic wages, and second, the strategic complementarity between the domestic and foreign subsidy. The impact of 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-stealing* effect that would be observed in an economy where labor markets are partially local, would represent an additional channel through which competition, on the one hand, affects domestic welfare negatively and, on the other hand, 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.³⁵ Finally, solving for the full Nash subsidy game, where both domestic and foreign governments respond optimally to changes in competition, would add an additional source of strategic subsidy and increase the effect of foreign competition on the

³⁵This channel, limited to the effect of competition on domestic welfare, has been explored in Impullitti (2007).

optimal domestic subsidy.³⁶

9 Appendix: proofs

9.1 Proposition 1.

The comparative statics stated in proposition 2 can be derived analytically solving the equilibrium system for the following 3 variables I_m^D , I^F , $(c^D + c^F)$. In order to do this we consider the reduced system composed of (15), and the sum of (13) and (14) and obtain:

$$\frac{2\kappa}{A} \left(\frac{I_c}{A} \right)^{\frac{\alpha}{1-\alpha}} = \frac{(c^D + c^F) \left(\frac{\lambda - 1}{\lambda} \right)}{\rho + 2I_c - n} \quad (24)$$

$$\frac{2\kappa}{A} \left(\frac{I_m^D}{A} \right)^{\frac{\alpha}{1-\alpha}} = \frac{(c^D + c^F) \left(\frac{\lambda - 1}{\lambda} \right)}{\rho + I_m^D - n} \quad (25)$$

$$2\kappa\lambda \left[2\bar{\omega} \left(\frac{I_c}{A} \right)^{\frac{1}{1-\alpha}} + (1 - \bar{\omega}) \left(\frac{I_m^D}{A} \right)^{\frac{1}{1-\alpha}} \right] = 2\lambda - (c^D + c^F) \quad (26)$$

Substituting $(c^D + c^F)$ from (26) into the other two equations we obtain (I) and (II) shown in the main text. Totally differentiating equations (I) and (II) yields

$$\begin{aligned} \Phi_1 dI_c + \Phi_2 dI_m^D &= 0 \\ \Phi_3 dI_c + \Phi_4 dI_m^D &= \Phi_5 d\bar{\omega}, \end{aligned}$$

where Φ_1, Φ_2 are the derivatives of (I) w.r.t. I_c and I_m^D respectively, and Φ_3, Φ_4, Φ_5 , are the derivatives of (II) w.r.t. I_c, I_m^D , and $\bar{\omega}$ respectively. Rewriting these equations in matrix form we obtain

$$\begin{bmatrix} \Phi_1 & \Phi_2 \\ \Phi_3 & \Phi_4 \end{bmatrix} \begin{bmatrix} \frac{dI_c}{d\bar{\omega}} \\ \frac{dI_m^D}{d\bar{\omega}} \end{bmatrix} = \begin{bmatrix} 0 \\ \Phi_5 \end{bmatrix}.$$

Since the $\Phi_j > 0$ for $j = 1, 2, 3, 4$, Cramer's rule allows us to conclude that

$$\begin{aligned} \text{Sign} \left(\frac{dI_c}{d\bar{\omega}} \right) &= \text{Sign} (\Phi_2 \Phi_5) = \text{Sign} (\Phi_5) \\ \text{Sign} \left(\frac{dI_m^D}{d\bar{\omega}} \right) &= \text{Sign} (\Phi_2 \Phi_5) = \text{Sign} (\Phi_5), \end{aligned}$$

and

³⁶A qualitative exploration of this channel is studied in Impullitti (2006).

$$\begin{aligned}
\Phi_5 &= \frac{1}{\lambda(1-\bar{\omega})} - \frac{1}{\lambda A(1-\bar{\omega})^2} \left(\frac{I_c}{A}\right)^{\frac{\alpha}{1-\alpha}} (\rho + I_c - n) - \frac{2}{(1-\bar{\omega})^2} \left(\frac{I_c}{A}\right)^{\frac{1}{1-\alpha}} \\
&= \frac{1}{(1-\bar{\omega})} \left[\left(\frac{I_m^D}{A}\right)^{\frac{1}{1-\alpha}} - 2 \left(\frac{I_c}{A}\right)^{\frac{1}{1-\alpha}} \right].
\end{aligned}$$

where I have used (II) to obtain the second equality. The effect of competition on I_c and I_m^D is zero only if $\Phi_5 = 0$, which happens iff $I_m^D = 2^{1-\alpha} I_c$; but then for (I)

$$\begin{aligned}
\left(\frac{I_c}{A}\right)^{\frac{\alpha}{1-\alpha}} (\rho + 2I_c - n) &= \left(\frac{2^{1-\alpha} I_c}{A}\right)^{\frac{\alpha}{1-\alpha}} (\rho + 2^{1-\alpha} I_c - n) \\
(\rho - n) &= 2^\alpha (\rho - n),
\end{aligned}$$

and since $\rho > n$ we find $\Phi_5 = 0$ only for $\alpha = 0$, while $\Phi_5 < 0$ otherwise and, consequently, $dI_c/d\bar{\omega}$, $dI_m^D/d\bar{\omega} < 0$ for $\alpha > 0$. This proves the second part of proposition 1. Moreover, it confirms the result analytically obtained in proposition 1 that when $\alpha = 0$, $dI_c/d\bar{\omega}$, $dI_m^D/d\bar{\omega} = 0$ and $I_m^D = 2I_c$, thus both effects of competition on growth are absent.

Since we have established that $I_m^D < 2^{1-\alpha} I_c$, this implies that $I_m^D < 2I_c$ and from (20) we can conclude that competition increases the number of sectors with higher investment in innovation, thus spurring long-run growth. This proves the positive *efficiency effect* in proposition 2. The next step is to show that this effect dominates the negative effect of competition on I_m^D and I_c . Since $dI_c/d\bar{\omega}$, $dI_m^D/d\bar{\omega} < 0$, differentiating (24) and (25) w.r.t. $\bar{\omega}$ we can see that $d(c^D + c^F)/d\bar{\omega} < 0$. Then, taking the derivative of (26) w.r.t. $\bar{\omega}$ we obtain

$$\begin{aligned}
2 \left(\frac{I_c}{A}\right)^{\frac{1}{1-\alpha}} + \frac{2\bar{\omega}}{A(1-\alpha)} \left(\frac{I_c}{A}\right)^{\frac{\alpha}{1-\alpha}} \left(\frac{dI_c}{d\bar{\omega}}\right) - \left(\frac{I_m^D}{A}\right)^{\frac{1}{1-\alpha}} + \frac{(1-\bar{\omega})}{A(1-\alpha)} \left(\frac{I_m^D}{A}\right)^{\frac{\alpha}{1-\alpha}} \left(\frac{dI_m^D}{d\bar{\omega}}\right) &= \\
&= -\frac{1}{2\kappa\lambda} \left[\frac{\partial(c^D + c^F)}{\partial\bar{\omega}} \right] > 0.
\end{aligned}$$

Rearranging the left hand side and simplifying yields

$$2I_c + \left(\frac{1}{1-\alpha}\right) \left(2\bar{\omega} \frac{dI_c}{d\bar{\omega}}\right) + \left(\frac{I_m^D}{I_c}\right)^{\frac{1}{1-\alpha}} \left[\frac{(1-\bar{\omega})}{(1-\alpha)} \left(\frac{dI_m^D}{d\bar{\omega}}\right) - I_m^D \right] > 0. \quad (27)$$

Since $\frac{1}{1-\alpha} > 1$ and $\frac{I_m^D}{I_c} > 1$ it is easy to see that (27) is a sufficient condition for

$$\frac{\partial g}{\partial\bar{\omega}} = \left\{ (2I_c - I_m^D) + \left[2\bar{\omega} \frac{\partial I_c}{\partial\bar{\omega}} + (1-\bar{\omega}) \frac{\partial I_m^D}{\partial\bar{\omega}} \right] \right\} \ln \lambda > 0,$$

thus proving that the overall effect of competition on growth is positive.

9.2 Proposition 2

Substituting $I_c^D = I^F$ into the right hand side of (13) we obtain the following expression for domestic income:

$$Y^D = 1 + (c^D + c^F) \left(\frac{\lambda - 1}{\lambda} \right) \left[1 - \frac{\bar{w}}{2} \right].$$

Since $d(c^D + c^F)/d\bar{w} < 0$, as i showed above, it is easy to see that $\partial Y^D/\partial \bar{w} < 0$.

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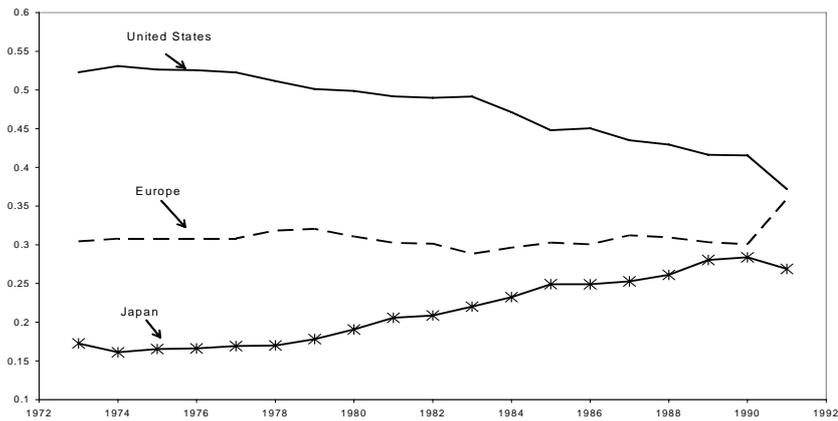
TABLE I
MODEL FIT

Moments	Data	Benchmark model
TARGETED		
growth	0.019	0.018
R&D/GDP	0.135	0.145
NON TARGETED		
Labor share	0.67	0.75
cons/GDP	0.86	0.85

TABLE II
WELFARE GAINS WITH OPTIMAL SUBSIDY

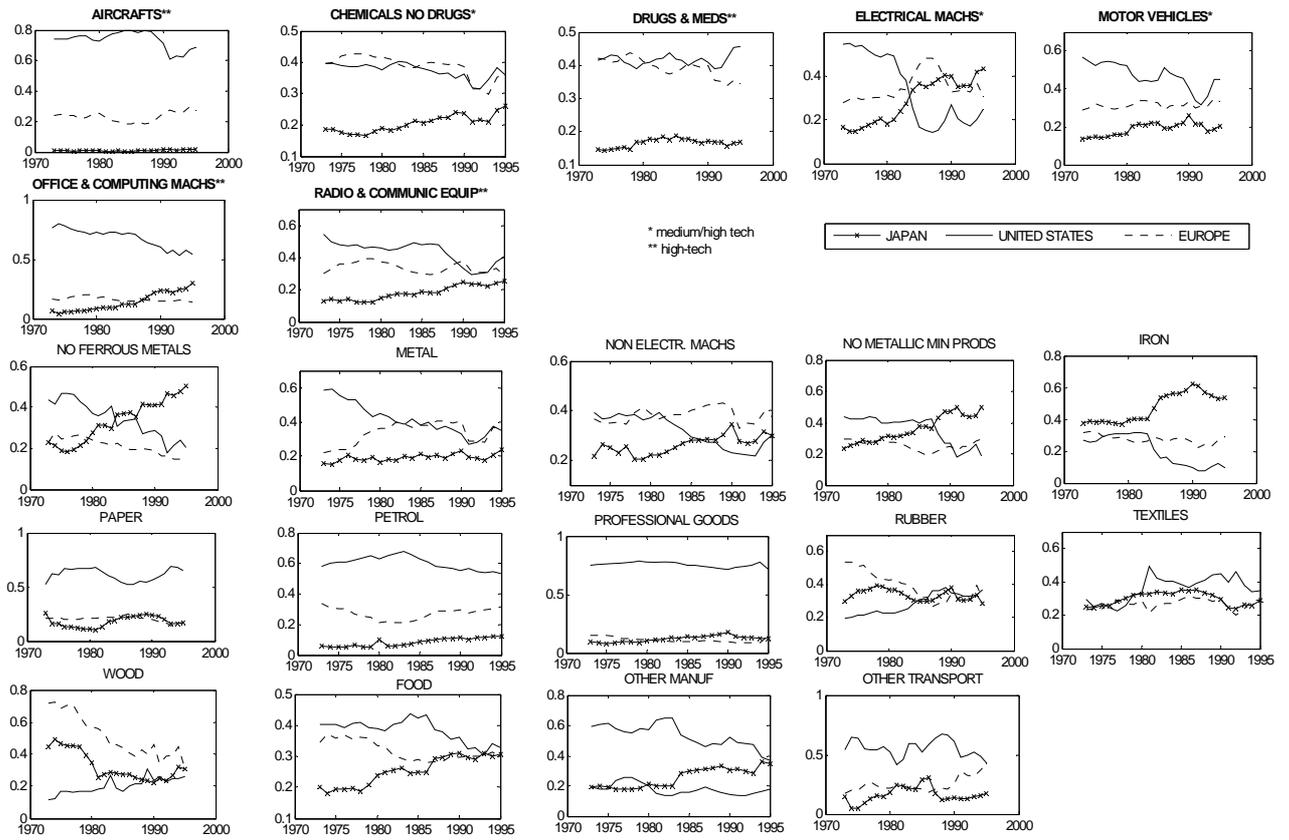
		1979	1981	1983	1985	1987	1989	1991
competition	$\bar{\omega}$.42	.47	.49	.54	.57	.62	.68
observed subsidy	s^D	.066	.115	.115	.115	.12	.114	.188
optimal subsidy	s^{D*}	.04	.065	.075	.1	.11	.13	.155
welfare gain	β	.00009	.0004	.00024	.00004	.00001	.00005	.0003

Figure 1. Global R&D investment shares: sectorial average



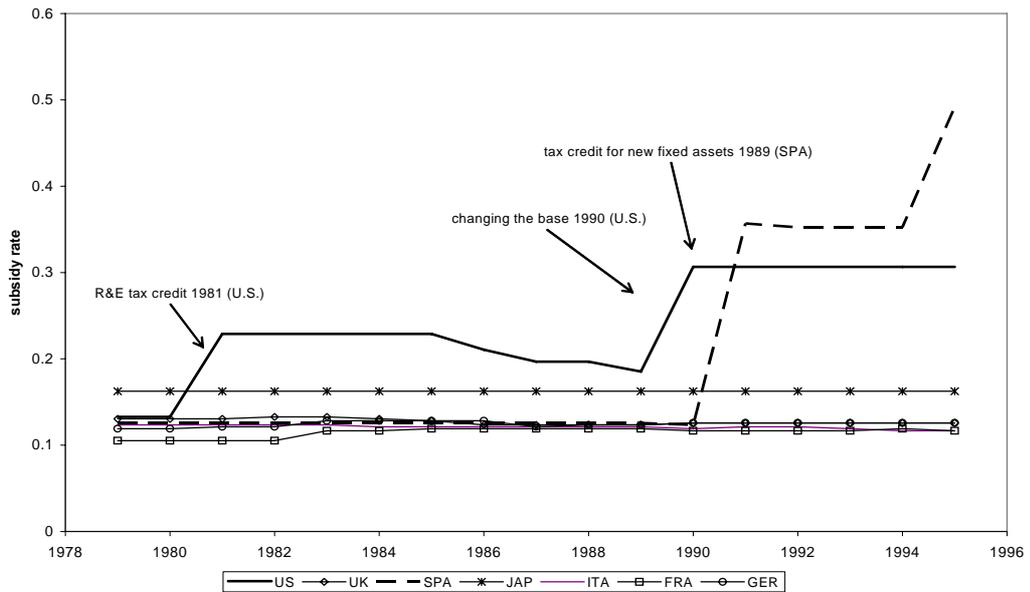
Source: OECD ANBERD (ISIC Rev.2)

Figure 2. Global R&D investment shares by sector



Source: OECD ANBERD (ISIC Rev. 2)

Figure 3. R&D TAX subsidies



Source: author's calculations in Bloom, Griffith, and Van Reenen (2002)

Figure 4. Steady state equilibrium and the growth effect

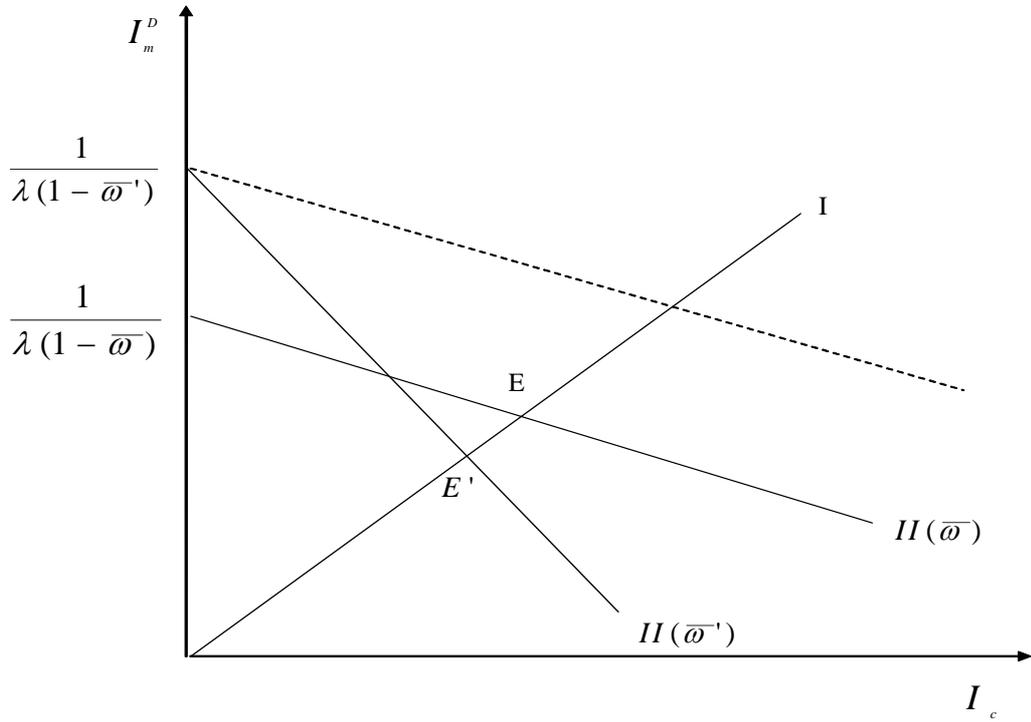
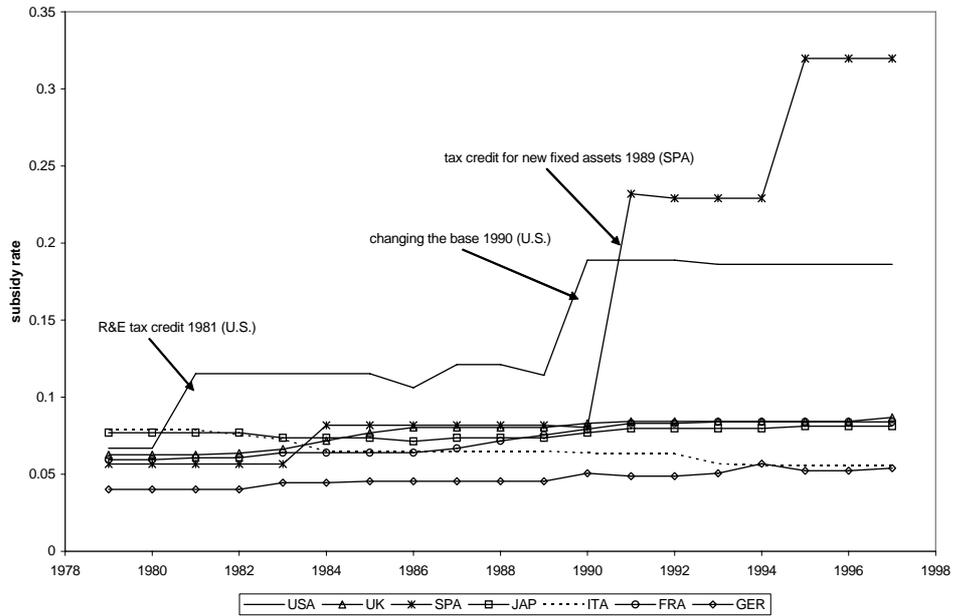
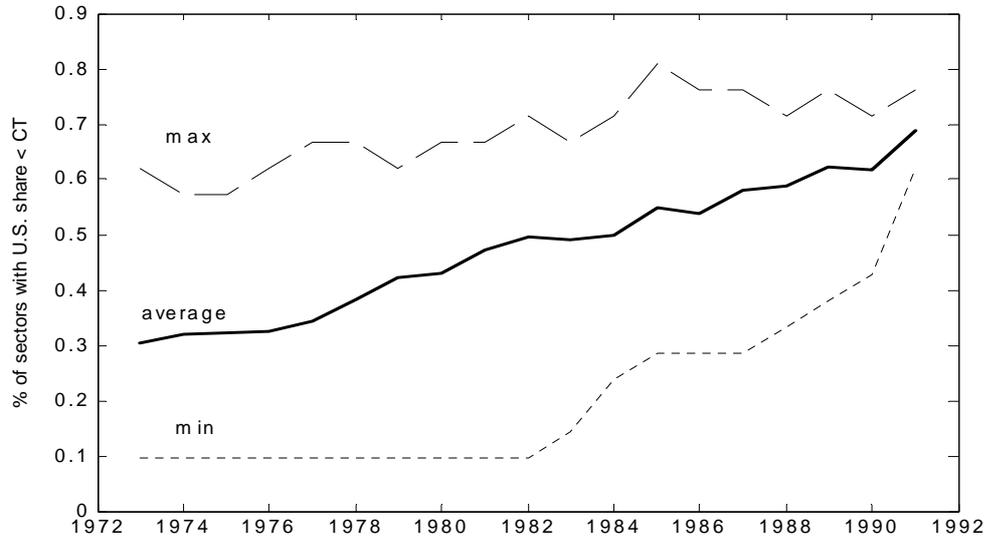


Figure 5. R&D TAX subsidies used for calibration



Source: author's calculations in Bloom, Griffith, and Van Reenen (2002)

Figure 6. International R&D competition



Data source: OECD ANBERD (ISIC Rev. 2)

Figure 7. Effects of foreign competition on domestic welfare

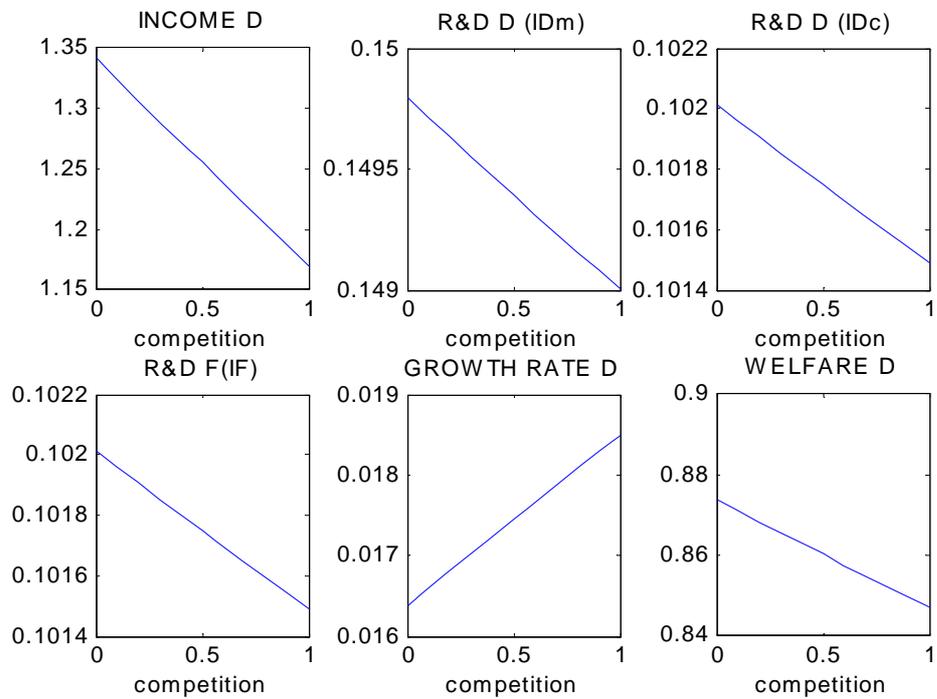


Figure 8. Competition and welfare: robustness

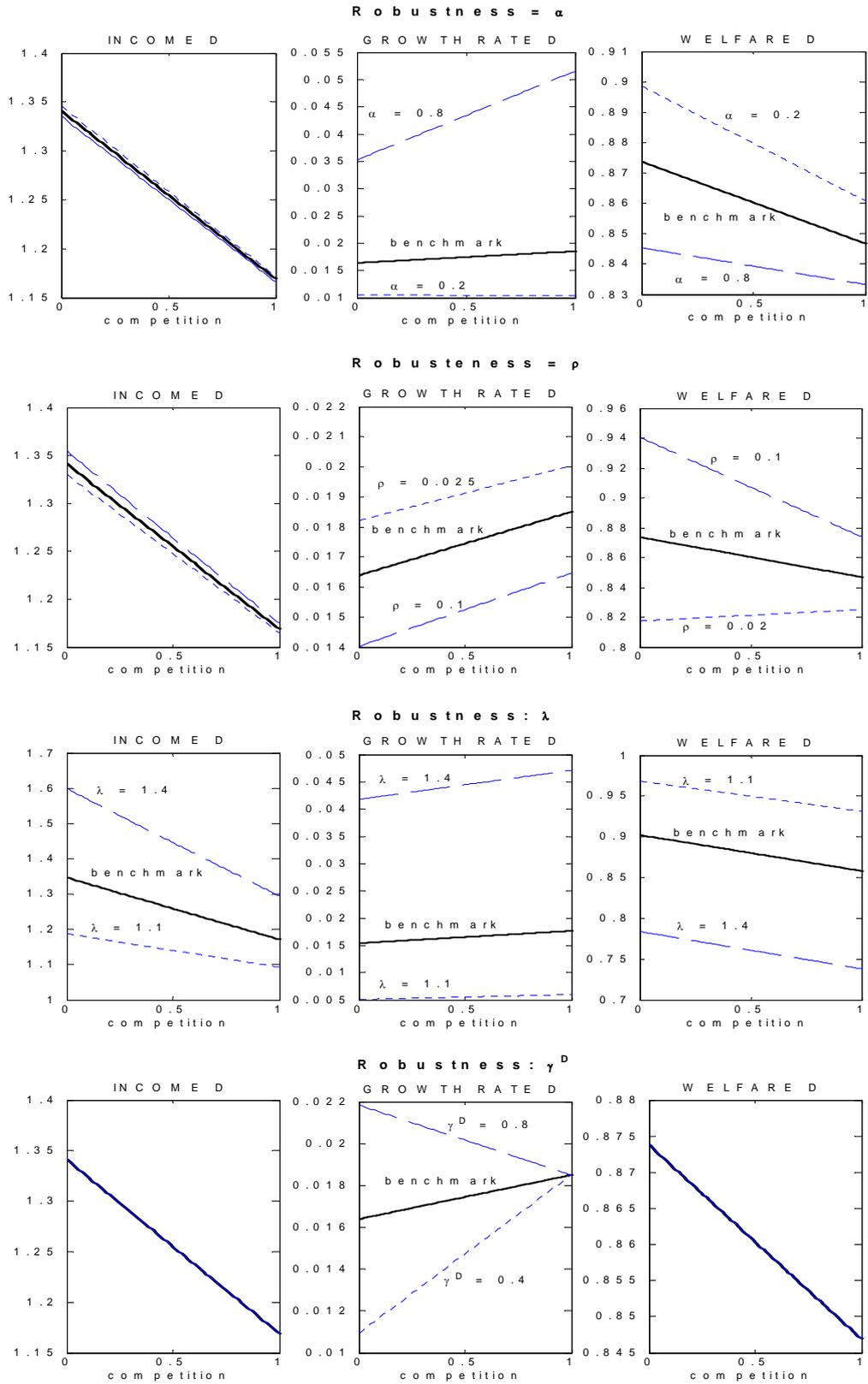


Figure 9. Foreign competition and optimal domestic subsidy

