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ABSTRACT

We examine the growth promoting roles of R&D, international R&D spillovers, and trade in a world econometric model. A country can raise its total factor productivity by investing in R&D. But countries can also boost their productivity by trading with other countries that have large "stocks of knowledge" from their cumulative R&D activities. We use a special version of MULTIMOD that incorporates R&D spillovers among industrial countries and from industrial countries to developing countries. Our simulations suggest that R&D, R&D spillovers, and trade play important roles in boosting growth in industrial and developing countries.

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I. Introduction

National economies are embedded in a global system that generates mutual interdependence across countries. In this system each country depends on the supply of consumer goods, intermediate products, and capital goods from its trade partners, and it relies on the trade partners to supply markets for its own products. But--as is becoming more and more apparent--countries also rely on each other for technology transfer, and they learn from each other manufacturing methods, modes of organization, marketing, and product design. These features affect their well being and link their growth rates.

Much research has been done in recent years to clarify such links. Some of it has been theoretical, some has been empirical. In this paper we contribute to the empirical literature by providing a quantitative evaluation of the importance of R&D and trade in influencing total factor productivity and output growth. For this purpose we incorporate estimates of international R&D spillovers--among industrial countries and from industrial to developing countries--into a multicountry macroeconomic model in order to simulate the influence of changes in R&D and trade on the evolution of the world economy.

Estimates of international R&D spillovers, which underline trade relations as the major transmission mechanism, are taken from Coe and

Helpman (1995) and Coe, Helpman, and Hoffmaister (1996). They have been embedded in the IMF's MULTIMOD econometric model for this study. The augmented model was then used to simulate changes in R&D in the industrial countries and in the exposure to trade of the developing countries in order to obtain estimates of induced changes in total factor productivity, capital, output, and consumption in each of twelve "countries." The countries consist of the G-7 countries plus five industrial and developing country regions.

Our simulations suggest that the interplay between R&D and capital investment is important. While R&D has a direct effect on productivity and thereby on output, about one fourth of the total increase in output results from investment in capital that is induced by the higher levels of productivity. And we find that international R&D spillovers, leveraged by investment, are very important. Were the United States to increase its R&D investment by $\frac{1}{2}$ of 1 percent of GDP and maintain the new R&D/GDP ratio thereafter, it would raise its output by about 9 percent after 80 years, the output of the other industrial countries by more than 3 percent, and the output of the developing countries by over 4 percent. If all industrial countries were to raise their R&D investment by $\frac{1}{2}$ of 1 percent of GDP, their output would rise after 80 years by almost 20 percent and the output of developing countries would rise by almost 15 percent. Clearly, not only industrial countries benefit from R&D investment; developing countries are also major beneficiaries of R&D investment in the industrial countries. We also find that further expansion of trade by the developing countries by 5 percentage points of their GDP would raise their output by about 9 percent

after 80 years. This indicates that trade expansion can contribute importantly to growth in developing countries.

We outline in the next section the theoretical framework of MULTIMOD and the theoretical considerations that have guided the specification of the R&D spillover equations incorporated into the model. In Section III we describe key features of the empirical model that are important to understand the simulations reported in Section IV. Conclusions are drawn in the closing section.

II. Theoretical Framework

The theoretical structure that drives MULTIMOD's long-run supply behavior are neoclassical. Each country has a Cobb-Douglas production function of the form¹

$$Y = FK^\alpha L^{1-\alpha}, \quad 0 < \alpha < 1, \quad (1)$$

where Y is output, K is capital, L is labor, and F stands for total factor productivity. Although the coefficients and variables differ across countries, and the variables differ across time, we omit country and time subscripts for expositional convenience.

The world capital stock is ultimately determined by the level of world saving, which is derived from an aggregate consumption function. The

¹For more details about MULTIMOD see Masson, Symansky, and Meredith (1990). When we refer to a feature of a country, we mean a feature of a country or a country block. Our exposition focuses on the structure of industrial countries and the newly industrialized countries. Developing countries are treated somewhat differently, as explained in the next section.

allocation of consumption over time is derived from the maximization of an intertemporal utility function subject to a budget constraint. An individual's flow of utility at time τ is given by

$$u_{\tau} = \frac{c_{\tau}^{1-\sigma}}{1-\sigma}, \quad (2)$$

where c_{τ} is the individual's aggregate consumption at time τ . The parameter σ determines the intertemporal elasticity of substitution in consumption. For an individual who is alive at time t and who will live until $T > t$, the discounted flow of utility at time t equals

$$U_t = \int_t^T e^{-\delta(\tau-t)} u_{\tau} d\tau, \quad (3)$$

where δ represents his subjective discount rate and u_{τ} is given in (2).

Following Blanchard (1985), it is assumed that every individual faces a time and age invariant probability of death, λ , and has access to perfect annuity markets. As a result, an individual who is alive at time t maximizes the expected value of U_t (given in (3)). The consumer faces an intertemporal budget constraint that has the following features: at each point in time, the expected present value of aggregate consumption equals the expected present value of labor income plus the value of capital owned at time t . The solution to this problem yields a consumption function, where consumption is proportional to wealth (human and financial). The factor of proportionality depends on the subjective rate of time preference, on the probability of death, and on the intertemporal elasticity of substitution in consumption. Aggregating across individuals yields an aggregate consumption function for the country, with consumption proportional to the country's aggregate human and non-human wealth. For the

country as a whole, the factor of proportionality depends on the same parameters as the individual's factor of proportionality and also on the rate of population growth. This consumption function is used to derive aggregate savings.

Saving and investment are jointly determined, and for the world at large, aggregate investment equals aggregate savings. Investment is allocated across countries to equalize risk-premia-adjusted rates of return.¹ The output of each country is treated as a distinct product. Given aggregate consumption and investment, the allocation of spending across countries depends on relative prices. These patterns of spending determine bilateral imports and exports.

In the standard version of MULTIMOD, total factor productivity and the labor force are exogenous. Although in each country investment need not equal savings (because the gap can be financed by international capital flows), the intertemporal budget constraints imply that the long-run growth of the capital stock is determined by the growth of labor and the growth of total factor productivity. In the long run, the growth of output is also determined by the same factors, and the capital output ratio is constant. An implication of these relationships is that the long-run growth rate of per capita output is entirely determined by the growth rate of total factor productivity. These features are familiar from the neoclassical growth models of Solow (1956) and Cass (1963).

¹In the short run, investment deviates from this rule, as discussed in the next section.

We augment the standard version of MULTIMOD with equations that relate total factor productivity to R&D investment and trade. In doing so, total factor productivity becomes endogenous, as suggested by the "new" growth theory (see Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992)). But we do not follow the new growth theory all the way, since we do not endogenize R&D investment as a function of economic factors. Rather, we hold constant the ratio of R&D investment to GDP. In tracing out the effects of an increase in R&D investment we take account of the fact that, by temporarily raising the marginal product of capital, improvements in total factor productivity induce capital accumulation, which continues until the marginal product of capital falls to the level of the real long-run rate of interest. R&D investment thus affects output directly through total factor productivity and indirectly through induced capital accumulation. The model enables us to evaluate each of these components.

It is important to note that our model incorporates diminishing returns to the reproducible factors of production (physical and R&D capital) in aggregate.¹ This implies that a permanent increase in R&D investment will have a level effect on output, but will not permanently raise the rate of growth. As is apparent from our simulation results, however, it takes more than 80 years to approach the new steady state, and hence the impacts on growth are very long lived.

The theoretical basis for our modelling of total factor productivity, which uses a constant returns to scale aggregate Cobb-Douglas production

¹That is to say, it is not an "AK" model; see, for example, Romer (1990).

function such as (1), is provided by Grossman and Helpman (1991, chapter 5). For example, let the production function of final output be

$$Y = AK^\alpha L_Y^\gamma D^{1-\alpha-\gamma}, \quad 0 < \alpha, \gamma, \alpha + \gamma < 1, \quad (4)$$

where L_Y is the amount of labor used directly in the manufacturing of final output and D is a symmetric CES index of intermediate inputs. The parameter A is constant. We know that in this case $D = n^{1/(\epsilon-1)} L_D$ in equilibrium, where n represents the number of available intermediates, L_D the labor force employed in the manufacturing of intermediates (we assume for simplicity that intermediates are manufactured only with labor), and $\epsilon > 1$ is the elasticity of substitution between intermediate inputs. Using the demand functions for inputs that are implied by (4) and the pricing of intermediates (i.e., a constant markup over marginal costs, with the price/marginal-cost ratio equal to $1/(1-1/\epsilon)$), it follows that the aggregate production function for final output can be represented by (1). In this reduced form, L equals direct plus indirect labor ($L=L_Y+L_D$) while F can be represented by

$$F = Bn^{(1-\alpha-\gamma)/(\epsilon-1)}. \quad (5)$$

In (5) the constant B depends on the parameters of the production function (4).

It is clear from (5) that in this model total factor productivity depends on the available assortment of intermediate inputs (n): the more intermediates are used in production, the higher is total factor productivity. On the other hand, intermediate inputs have to be developed. As a result, the number of available intermediates is a function of past R&D investment levels. We therefore have a link between current productivity

and cumulative R&D investment. This type of link is central to our specification presented in the next section.

But we do not wish to restrict our empirical specification to a narrowly defined structural link between R&D and total factor productivity as described above. Rather, we use this theory to guide our empirical specification. As pointed out by Grossman and Helpman (1991), there are a number of channels through which total factor productivity of a country is affected by the R&D investment of its trade partners in addition to its own R&D investment level. Foreign trade plays an important role in these transmission mechanisms. For example, foreign trade enables a country to employ a larger variety of intermediate inputs, including capital goods, and it stimulates learning from trade partners. For these reasons we specify a functional relationship between total factor productivity and cumulative R&D levels that is broader than (5), and which builds on previous empirical work. The precise specification of these links is described in the next section.

III. Empirical Model

In the version of MULTIMOD used here, total factor productivity is endogenously determined by the stock of R&D capital, international R&D spillovers, and trade. Total factor productivity together with capital and labor inputs then determine potential output. This supply side is augmented by short-run dynamics largely emanating from changes in aggregate demand caused by the interaction between sticky prices and forward-looking

expectations. While changes in aggregate demand move actual output temporarily away from its potential level, monetary policy is neutral in the long run. There is, however, a long-run impact from fiscal policy, reflecting the wedge between the discount rate of individuals and of the government caused by the probability of death. MULTIMOD also incorporates rational expectations in goods, financial, and labor markets. The forward looking aspect of the model means that changes in expectations of future increases in productivity or wealth can have immediate effects on, for example, current consumption and investment.

Our version of MULTIMOD consists of 12 linked econometric models: a model for each of the G-7 countries (the United States, Japan, Germany, France, Italy, the United Kingdom, and Canada), an aggregate model for the other industrial countries, and 4 regional models for non-oil-exporting developing countries. The developing countries are disaggregated into regional models for Africa, the Western Hemisphere, the newly industrializing economies of Asia (the NIEs consisting of Hong Kong, Korea, Singapore, and Taiwan Province of China), and other non-oil-exporting developing countries.¹ Most parameters have been estimated with pooled annual data. The most important features of these models are summarized

¹The main differences from the standard version of MULTIMOD are the regional disaggregation of non-oil exporting developing countries and the more sophisticated modeling of aggregate demand within these regions; see Bayoumi, Hewitt, and Symansky (1995). There is also a very simple model for the oil-exporting developing countries, but there is no model for the economies in transition of central and east Europe and the former Soviet Union.

below to help understand the simulation results presented in the next section.¹

Output is determined by aggregate demand in the short run and by the underlying level of aggregate supply--"potential output"--in the long run. A Cobb-Douglas production function such as (1) determines potential output (Y^{POT}). In logarithmic form, and omitting country subscripts and time subscripts from current period variables,

$$\log Y^{POT} = \kappa + \alpha \log K + (1-\alpha) \log L + \log F,$$

where α is capital's share of national income and κ is a country-specific constant. The real stock of capital is endogenous, as discussed below, and labor supply is determined by the natural rate of unemployment and demographic factors, both of which are exogenous.

We endogenize total factor productivity using the estimation results in Coe and Helpman (1995) for the industrial countries and in Coe, Helpman, and Hoffmaister (1996) for the developing countries.² In both of these studies, total factor productivity is determined by the stock of R&D capital (S) and

¹Complete equation specification and parameter values for the industrial countries are presented in Masson, Symansky, and Meredith (1990); and for the developing countries in Bayoumi, Hewitt, and Symansky (1995).

²Except for the finding that the elasticity of total factor productivity with respect to domestic R&D capital is larger in the G-7 countries than in the other industrial countries, the main empirical results in Coe and Helpman have been confirmed by Keller (1995) based on sectoral data and by Chen and Kao (1995) using different estimation techniques. Eaton and Kortum (1995) also find large and significant international technology spillovers based on patent data.

the share of imports of manufactures in GDP (m).¹ For the industrial countries, which do virtually all of the R&D in the world economy, total factor productivity is determined by both domestic R&D capital (S^D) and foreign R&D capital (S^F). Trade is assumed to be the vehicle for R&D spillovers and thus foreign R&D capital, which is defined below, affects total factor productivity through its interaction with the import share. The equation determining total factor productivity (F) for each of the G-7 countries is,

$$\log F = \phi_1 + 0.234 \log S^D + 0.294m \cdot \log S^F,$$

where ϕ_1 is a country-specific constant. For the small industrial countries in aggregate, total factor productivity is determined in the same manner except that domestic R&D capital has a smaller impact,

$$\log F = \phi_2 + 0.078 \log S^D + 0.294m \cdot \log S^F.$$

The developing countries generally do little, if any, R&D. Their domestic R&D capital is assumed to be constant. For these countries, trade has a direct impact on total factor productivity in addition to its role as the vehicle for R&D spillovers. In each of the non-oil-developing country

¹Coe and Helpman (1995) use total imports of goods and services instead of imports of manufactures. Coe, Helpman, and Hoffmaister (1996) report results using imports from industrial countries of goods and services, of manufactures, and of machinery and equipment. Imports of manufactures from all countries are used here since MULTIMOD does not distinguish between imports from specific countries or regions. The relevant coefficients have been adjusted to reflect different mean values for the import shares.

regions and in the newly industrializing economies, total factor productivity is determined as,¹

$$\log F = \phi_3 + 0.608m \cdot \log S^F + 0.248m.$$

The domestic R&D capital stocks of the G-7 industrial countries and the small industrial countries in aggregate consist of their cumulative real investment in R&D (R), allowing for depreciation,

$$S^D = 0.95S_{t-1}^D + R$$

where S^D is beginning of period. As noted above, real R&D expenditures are a constant share of the simulated level of potential GDP. The foreign R&D capital stock is defined in the same manner for all countries and groups of countries. For a specific country or country grouping j , the foreign R&D capital stock (S_j^F) is,

$$S_j^F = \sum_{i=1}^8 \alpha_{ji} S_i^D, \quad \text{with} \quad \sum_{i=1}^8 \alpha_{ji} = 1 \text{ and } \alpha_{11} = 0,$$

where α_{ji} are the elements of a 12 x 8 matrix of the manufactures imports of country j from industrial country i as a proportion of total manufactures imports of country j from all industrial countries (see appendix table).

Investment in MULTIMOD is modeled as a gradual adjustment of the capital stock towards its optimal level, which is determined by the gap between the market value of the existing stock and its replacement cost, following Tobin (1969). The market value of the capital stock (K^{MAR}),

¹Given an average value of m of about 0.2 for the industrial countries and about 0.3 for the developing countries, the elasticity of total factor productivity with respect to R&D capital (both domestic and foreign) is about 0.3 for the G-7, 0.15 for the small industrial, and 0.2 for the developing countries. In Coe, Helpman, and Hoffmaister (1996) total factor productivity in the developing countries also depends on human capital, proxied by secondary school enrollment ratios.

defined as the discounted value of future after-tax income accruing to owners of capital, is calculated using an iterative process in which today's market value reflects the present value of after-tax income for owners of capital (PROFIT),

$$K^{MAR} = \int_t^{\infty} e^{-i(\tau-t)} PROFIT_{\tau} d\tau,$$

where i is the real interest rate (the model uses, however, a discrete time formulation). Future increases in profitability or total factor productivity are translated into the current market value of the capital stock and hence into increases in current investment. Adjustment of the real capital stock (K) to changes in the market value of capital, however, is gradual. The adjustment equation is,

$$\Delta \log K = 0.08(K^{MAR}/K_{t-1}).$$

Investment is derived from the change in the real capital stock plus depreciation.

Private consumption is also dependent on future income through a forward-looking term in wealth, as discussed in the previous section. Some individuals are assumed to be liquidity constrained in the short run, so that real consumption (C) depends partly on changes in current real disposable income (Y^D) and on real long-term interest rates (i^L) in addition to wealth (W),

$$\Delta \log C = 0.095 \log(W_{t-1}/C_{t-1}) - 0.588 i^L + 0.348 \Delta \log Y^D.$$

In the long-run, consumption moves proportionately with wealth. The structure of the regional developing country models is similar except that investment and consumption depend on imports as well as the factors

discussed above. These countries are also assumed to face external finance constraints and greater domestic liquidity constraints.¹

Long-term interest rates are a moving average of current and expected future short-term rates. Financial assets of the industrial countries are assumed to be perfect substitutes, and nominal exchange rates for the industrial and newly industrializing economies are determined by open interest parity. Each regional developing "country" has a freely floating exchange rate, with the market rate determined by the external financing constraint rather than by international asset arbitrage. Devaluations always improve the current account, and appreciations always worsen it, so the system is stable, i.e., the Marshall-Lerner conditions are satisfied.

Exports and imports are mainly determined by relative prices and activity in all of the models. Export prices are assumed to move with the domestic output price in the long run, but respond to price movements in export markets in the short run. Import prices are a weighted average of the export prices of trade partners. The industrial countries and the NIEs produce manufactured goods, which are imperfect substitutes. Each country's or region's imports of manufactured goods are allocated as exports across the other manufactures-producing countries and regions through a trade matrix, with the initial pattern based on historical trading patterns. Trade shares adjust to changes in relative prices. Non-oil primary commodities are produced by the developing countries, who also produce manufactured goods. The average price of non-oil primary commodities

¹See Bayoumi, Hewitt, and Symansky (1995).

adjusts in the short run to clear the market, with production and supply eventually responding to changes in relative prices.

IV. Simulation Results

We focus on three types of simulations to illustrate the empirical significance of international R&D spillovers: an increase in R&D expenditures in individual G-7 countries, a simultaneous increase in R&D expenditures in all industrial countries, and increased openness in the developing countries. In each case, we mainly focus on the long-run effects. The simulation results are largely independent of the baseline, which is taken from the October 1995 *World Economic Outlook* projections to the year 2000 extended such that each country slowly moves to a steady state by the year 2075.¹ In each simulation, tax rates adjust endogenously to achieve a pre-specified path for real government debt, and real government spending is assumed to remain constant relative to potential GDP. In addition, the money supply is kept proportional to potential GDP, which leaves the price level broadly unchanged.

Before discussing the R&D simulations, we need to address the accounting issue of where R&D expenditures fit into the model. In the early 1990s, about 50 percent of business sector R&D expenditures were labor

¹The simulated shocks are assumed to be expected, and variables representing expectations are consistent with the model's predictions. Compared with the standard version of MULTIMOD, this version with endogenous productivity is considerably more difficult to solve numerically using the Fair-Taylor algorithm. The model was solved instead with the NEW STACK option in portable TROLL; see Juillard and Laxton (1996) for a discussion of this algorithm.

costs, 40 percent were other current expenditures, and 10 percent were capital expenditures.¹ In the simulations discussed below, the increases in R&D expenditures are assumed to raise business consumption, a new element of aggregate demand introduced into the model for these simulations. The allocation of the increase in GDP between profits and wages is determined by the Cobb-Douglas factor shares in the production function. The simulated increases in R&D expenditures, which are sustained throughout the simulation period, are assumed to be financed out of future business profits. The reduction in the discounted value of future profits lowers the market value of the physical capital stock and hence physical investment. In effect enterprises must forego fixed investment in order to increase R&D expenditures.

The impact of an increase in U.S. R&D expenditures is shown in Figure 1 and Table 1. The exogenous sustained increase in R&D expenditures is equivalent to $\frac{1}{4}$ of 1 percent of GDP, which represents an increase in the level of real U.S. R&D expenditures of about 25 percent relative to baseline. While an increase of this size is large, it is not unprecedented over a span of a few years.² Higher R&D expenditures boost the future U.S.

¹These estimates are from OECD (1995a) and refer to the average of the G-7 countries other than the United States (for which a breakdown is not available). Only R&D capital expenditures would be included directly as an element of aggregate demand, although these represented less than 1 percent of business fixed investment in the early 1990s in the G-7 countries other than the United States (OECD (1995a)). Other R&D expenditures would affect aggregate demand indirectly through their effects on incomes and production.

²For example, real business sector R&D expenditures increased 27 percent in the three years to 1984 in the United States, and single-year increases of 10 percent or higher are not uncommon in other industrial countries (OECD (1991, 1995b)). The model is broadly linear, so the simulated effects of a different sized shock would be roughly proportional.

R&D capital stock above its baseline level. The bulk of the rise in the R&D capital stock takes place early in the simulation period as a progressively larger proportion of the higher R&D expenditures are needed to replace a growing amount of obsolete R&D capital. After 15 years, the R&D capital stock has increased by about half its long-run value and by 2075 it has risen by almost the full amount of its steady-state increase of about 40 percent.

The higher R&D capital stock implies an increase in the future level of total factor productivity, potential output, and profits. This increase in future profits, however, has to be weighed against the extra costs to firms to finance the higher level of R&D spending. In the first few years, the increased cost of R&D expenditures dominates, and both the market value of the capital stock and business fixed investment fall.¹ The boost to aggregate demand from higher R&D spending and consumption also increases real interest rates, which further reduces investment in the short run. From 2003 onward, however, the discounted benefits from future profits cause both the market value of the capital stock and investment to start to rise sharply. Physical investment increases relatively fast for the next 15-20 years and then begins to taper off as the actual capital stock slowly adjusts to the higher level of its market value. In contrast to investment, real consumption rises steadily throughout the simulation as consumers react to the expected increase in future wealth.

¹This fall in investment reflects partly the assumption that the rise in R&D occurs in a single year, rather than more gradually.

Compared with the baseline, the level of potential output in the United States is about 4½ percent higher in 2010 and 9 percent higher in 2075, with the time pattern reflecting the simulated paths of the increases in the R&D and physical capital stocks. During the first 15 years, almost all of the increase in potential output is due to higher total factor productivity, but by 2075 the rise in the physical capital stock accounts for about one quarter of the total increase in output. The annual growth of real output is more than 0.3 percentage point higher during the first 10 years of the simulation compared with the baseline. Growth remains stronger than in the baseline, although by progressively smaller amounts, throughout the 80 years of the simulation. In the last 25 years, potential output growth is only 0.025 percentage points higher than in the baseline. In the long run, the rate of growth returns to the same level as in the baseline.¹

The rise in output in the United States relative to the rest of the world requires a real devaluation of the U.S. dollar to create the needed demand for higher U.S. exports. This is a standard result from multicountry models,² and represents one channel through which other countries are affected by the higher output in the United States. In our model, R&D spillovers represent an additional channel of influence through which other countries benefit from the increase in U.S. R&D expenditures. The foreign R&D capital stocks of U.S. industrial and developing country trade partners

¹In simulations assuming a 15 percent depreciation rate for R&D capital, growth stabilizes at the baseline level by about 2050.

²See, for example, Bryant *et al.* (1988). This result, which stems from the absence of a distinction between traded and nontraded goods in the model, takes no account of the Belassa-Samuelson effect in which differences in productivity growth between traded and non-traded goods cause the exchange rate to appreciate as countries become relatively more wealthy.

increase 24 and 20 percent, respectively, by 2075 compared with the baseline. The increases in the foreign R&D capital stock in specific countries and regions depend on the relative weight of U.S. imports compared with imports from other industrial countries.

Manufactures imports are the vehicle for the R&D spillovers. The higher imports of U.S. industrial country trade partners stemming from the depreciation of the dollar magnify the impact on growth from the rise in their foreign R&D capital stocks. In the United States, on the other hand, manufactures imports as a share of GDP decline somewhat with the depreciation of the dollar, which reduces the spillover from foreign R&D capital arising from R&D investment by U.S. trade partners. The assumption that developing countries other than the NIEs are finance constrained implies that their manufactures imports relative to GDP remain broadly unchanged from baseline levels. A simulation illustrating how increased openness boosts R&D spillovers to the developing countries is discussed below.

The rise in foreign R&D capital interacted with the import share boosts total factor productivity, investment, and potential output in U.S. trade partners in much the same way that the rise in domestic R&D did in the United States. Potential output increases gradually, again slowing after 15-20 years. By 2075, potential output in other industrial countries is 3½ percent above its baseline level while potential output in the developing countries is 4½ percent higher. On average, the developing countries benefit more than the industrial countries, reflecting the greater scope for catch up through R&D spillovers implied by the larger elasticities discussed

in the previous section. The long-run impacts of higher R&D expenditures in the United States on potential output in individual countries and groups of countries are shown in the first column of the top panel of Table 2. Canada, the newly industrializing economies of Asia, and the developing countries of the Western Hemisphere benefit most from higher R&D expenditures in the United States, reflecting strong trade linkages.

Changes in output are important summary measures of the overall economic impact of R&D expenditures. Economic welfare, however, largely depends on real private consumption. In the United States, private consumption is 7 percent above baseline by 2075, a somewhat smaller rise than the 9 percent increase in output. The opposite occurs for the other countries and regions, as shown in the first column of the lower panel of Table 2. By 2075, the average percentage increase of consumption in other industrial countries is one and a quarter times that of output. The increases for developing country regions tend to be slightly smaller, reflecting the impact of the finance constraint (the particular case of the NIEs is discussed below). This compression of the variability of consumption responses compared with those for output reflects the reduction in the U.S. terms of trade caused by the need to find markets for new goods, and constitutes an important channel through which the benefits of R&D in one country are disseminated to its trading partners.

The impact of higher R&D expenditures in the United States on consumption in Canada and the developing countries of the Western Hemisphere, both of which are close trading partners with the United States, is particularly large. Indeed, Canadian consumption increases by almost as

much as in the United States. The newly industrializing economies is the only region in which the long-run increase in consumption is smaller than the increase in output. This reflects, at least in part, their trilateral trading arrangements as net importers from Japan and net exporters to the United States. Consumption is lowered by the negative terms of trade shock in the NIEs caused by the depreciation of the dollar against the yen.

Higher R&D expenditures in any of the other major industrial countries have broadly similar effects as higher expenditures in the United States. Table 2 shows the long-run effects on potential output and consumption in simulations in which R&D expenditures are exogenously increased by an amount equivalent to $\frac{1}{2}$ of 1 percent of GDP in each G-7 country. Compared with the U.S. simulation, the main differences are that the domestic effects are often larger while the international spillovers are smaller. The larger domestic effects reflect the smaller R&D capital stocks in these countries, and hence the larger percentage increase from raising R&D by a uniform $\frac{1}{2}$ of 1 percent of baseline GDP--the long-run increase in R&D capital in Canada, for example, is about 100 percent compared with 40 percent in the United States. The spillover effects from R&D in countries other than the United States are smaller since the size of the simulated increase in R&D expenditures are smaller (reflecting the lower level of GDP) and since the United States typically accounts for the largest share of other countries' foreign R&D capital stocks. The regional distribution of the spillovers also differs, reflecting different bilateral trade patterns. Higher R&D expenditures in Japan, for example, have a relatively larger impact on other

countries in Asia, while increased R&D expenditures in France have a relatively larger impact in other European countries and in Africa.

Similar spillover patterns are apparent for consumption, as shown in the lower panel of Table 2. Unlike the output responses, the domestic gains to consumption from a rise in R&D are smaller for the more open European countries than for the United States and Japan, reflecting the greater potency of the terms of trade effect. The importance of trade linkages in determining the long-run rise in consumption can also be seen in the large positive consumption spillovers that increases in R&D in European industrial countries have on other countries in the region. These spillovers also depend on the magnitude of the trade elasticities for individual countries, which partly determine the size of the required change in the terms of trade. This helps explain, for example, the larger consumption spillovers for Italy than for Germany.

The impact of a simultaneous, exogenous increase in R&D expenditures in all industrial countries equivalent to $\frac{1}{2}$ of 1 percent of GDP is shown in Figure 2 and Table 3. Domestic and foreign R&D capital stocks increase about 50 percent in all countries and groups of countries by 2075. Potential output is 18½ percent above baseline by 2075 in the industrial countries as a group and 14 percent higher in developing countries. In both cases, higher total factor productivity accounts for roughly three quarters of the increase in output. Private consumption rises by an average of 17½ percent above baseline in the industrial countries, with the increase in European countries being somewhat higher and in North America somewhat lower. Consumption in the developing country regions increase by 15½

percent on average, with Africa gaining the most and the Western Hemisphere the least. This regional pattern, which is also reflected in output gains, reflects the lower level of R&D capital in Europe compared with the United States and Japan.

Trade has played a relatively minor role in the simulations discussed thus far. This is mainly because the developing countries are generally assumed to be financed constrained, implying that their current accounts can not change very much from the baseline levels. In the simulation reported in Figure 3 and Table 4, the African, Western Hemisphere, and other developing countries region are assumed to adopt more outward oriented development strategies that have proved so successful for the NIEs. This is implemented by exogenously increasing imports of manufactures by 5 percentage points of baseline GDP. To avoid violating the financing constraint, exports of manufactures are also exogenously increased by the same amount, so that the trade balance is largely unchanged from the baseline level.

Higher imports of manufactures raises productivity in developing countries both directly and through the interaction between trade and the stock of foreign R&D capital. The direct effect falls slightly over time: as output rises, the external finance constraint results in a real exchange rate depreciation which causes the ratio of real imports to GDP to fall over time. The beneficial effects of foreign R&D capital, however, outweighs this, and total factor productivity for the region as a whole, which jumps by 2½ percent at the start of the simulation, increases steadily to 5 percent above baseline by 2075. As in the earlier simulations, higher

investment further boosts potential output, which is 9 percent higher by 2075. Consumption, however, only rises by 6 percent because of the adverse impact of the deterioration in the terms of trade.

V. Conclusions

This paper has explored the quantitative implications of R&D spending, technological advance, and trade in a world with endogenous growth. This was done through simulations on a special version of MULTIMOD in which total factor productivity is endogenously determined by R&D spending, R&D spillovers, and trade. To the best of our knowledge, this paper is the first to incorporate aspects of endogenous growth models into a multicountry econometric model (Helliwell (1995)).

The simulation results illustrate several features about the gains from R&D. Increases in R&D spending can significantly raise the level of domestic output in an economy. An increase in U.S. R&D investment equivalent to $\frac{1}{2}$ of 1 percent of GDP raises U.S. real output by about 9 percent in the long run, with about three quarters of this gain coming through increases in productivity and the remainder from higher investment. Half of these output gains occur during the first fifteen years. Over a period of a decade or two, therefore, sustained increases in R&D generate a significant boost to the rate of growth of the economy.

Domestic R&D spending can also generate significant spillovers to output in other countries. When all industrial countries raise R&D spending by an amount equivalent to $\frac{1}{2}$ of 1 percent of GDP, the long-run U.S. output

gain is 70 percent higher than in the case when only U.S. R&D spending rises. As the size of output spillovers between industrial countries depends largely on trade linkages between countries, they tend to be particularly large between European countries and between the United States and Canada. Output spillovers to developing countries tend to be larger than to industrial countries, reflecting their greater technology gap.

Real consumption rises by less than output in the country carrying out the R&D, while it rises by more than output in other countries. This is because the country with higher R&D experiences a deterioration in its terms of trade, which represents an important mechanism through which the benefits of higher domestic R&D spending are disseminated abroad. As a result, the long-run gain to U.S. consumption from an increase in R&D equivalent to $\frac{1}{4}$ of 1 percent of GDP in all industrial countries is more than double that when only U.S. R&D is increased (16 percent versus 7 percent). The size of these consumption spillovers increases with the openness of the economy, and particularly benefits close trading partners. (The spillovers also decline as trade volumes become more responsive to changes in the real exchange rate.)

Finally, open trading policies of the type followed by the NIEs can benefit developing nations through facilitating technology transfer from industrial countries. Expanding imports of manufactures in developing countries other than the NIEs by 5 percentage points of GDP--roughly equivalent to the increase that has occurred in these regions between 1992 and 1995--raises output by about 9 percent in the long run, and consumption by 6 percent. These results indicate that part of the success of the NIEs

over the last 20 years can be attributed to productivity improvements stemming from foreign R&D spillovers through trade. Other factors that have boosted growth in these countries include rapid increases in labor and capital input (Young (1995)).

As with any set of simulations, these results reflect the specific parameters chosen for the model and should be taken as illustrative rather than definitive. What they do demonstrate, however, is that, using reasonable parameter estimates, R&D linkages can have important effects on the evolution of the world economy over time.

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Table 1. Increased R&D Expenditures in the United States
(deviations from baseline, in percent)

	1996	2000	2010	2030	2050	2075
<u>United States</u>						
Potential output	--	1.6	4.2	7.1	8.4	9.0
Total factor productivity	--	1.7	4.1	5.9	6.5	6.7
from domestic R&D	--	1.7	4.2	6.3	7.1	7.5
from foreign R&D	--	--	-0.2	-0.4	-0.6	-0.7
Capital	--	-0.4	0.3	3.4	5.6	6.8
Investment	-0.4	-1.0	1.8	5.0	6.4	7.2
Consumption	0.1	1.3	3.3	5.2	6.3	6.9
R&D spending/GDP ¹	0.5	0.5	0.5	0.5	0.5	0.5
Domestic R&D stock	--	7.4	19.7	31.0	35.2	37.2
Foreign R&D stock	--	--	0.3	1.1	2.0	2.9
Manufactures imports/GDP ¹	--	-0.1	-0.5	-0.9	-1.0	-1.0
<u>Other</u>						
<u>Industrial countries</u>						
Potential output	--	0.2	0.8	1.7	2.6	3.3
Total factor productivity	--	0.3	0.9	1.7	2.1	2.4
from domestic R&D	--	--	0.1	0.3	0.4	0.6
from foreign R&D	--	0.3	0.9	1.4	1.6	1.8
Capital	--	-0.1	--	1.1	2.3	3.4
Investment	--	-0.4	0.4	2.0	3.1	4.0
Consumption	--	0.5	1.3	2.4	3.3	3.8
R&D spending/GDP ¹	--	--	--	--	--	--
Domestic R&D stock	--	--	0.3	1.1	1.9	2.8
Foreign R&D stock	--	4.7	12.5	19.6	22.5	24.0
Manufactures imports/GDP ¹	--	0.1	0.3	0.5	0.4	0.4
<u>Developing countries</u>						
Potential output	0.1	0.5	1.6	3.0	3.7	4.3
Total factor productivity	0.1	0.6	1.7	2.6	3.0	3.4
from foreign R&D	0.1	0.6	1.7	2.6	3.0	3.3
from trade	--	--	--	--	--	0.1
Capital	--	-0.1	0.5	2.8	4.0	5.0
Investment	0.1	-0.4	1.7	3.8	4.5	5.4
Consumption	0.1	0.4	1.4	3.0	3.8	4.4
Foreign R&D stock	--	4.0	10.4	16.2	18.7	20.1
Manufactures imports/GDP ¹	0.2	-0.1	0.1	0.2	0.2	0.2

¹In percentage points.

Table 2. Long-Run International Spillovers
from Increased R&D in Industrial Countries
(deviations from baseline in 2075, in percent)

	United States	Japan	Germany	France	Italy	United Kingdom	Canada
<u>Potential output</u>							
United States	9.0	2.7	0.5	0.4	0.7	0.4	1.1
Japan	3.2	10.5	0.3	0.2	0.5	0.2	0.2
Germany	3.2	2.1	6.5	1.3	1.7	0.7	0.2
France	2.7	1.4	1.4	9.7	1.7	0.6	0.2
Italy	2.8	1.3	1.6	1.4	13.5	0.5	0.2
United Kingdom	3.5	1.8	1.3	1.0	1.4	9.5	0.3
Canada	6.8	1.7	0.3	0.3	0.8	0.3	16.9
Smaller industrial countries	3.0	1.7	1.5	0.9	1.0	0.6	0.2
All developing countries	4.3	3.7	1.0	0.9	1.2	0.7	0.4
Africa	3.3	2.3	1.5	2.4	1.8	1.2	0.3
NIEs	6.1	8.0	0.8	0.8	1.3	0.7	0.4
Western Hemisphere	4.7	1.5	0.6	0.5	0.8	0.4	0.4
Other developing countries	3.9	3.9	1.0	0.8	1.2	0.7	0.3
<u>Consumption</u>							
United States	6.9	3.3	0.9	0.9	1.2	0.8	1.6
Japan	3.9	7.4	0.4	0.4	0.8	0.3	0.4
Germany	3.4	2.5	2.7	1.4	2.3	0.8	0.4
France	3.3	2.0	1.6	3.9	2.6	0.9	0.4
Italy	3.9	2.2	1.7	1.9	2.5	0.9	0.4
United Kingdom	3.8	2.4	1.4	1.3	2.0	2.8	0.4
Canada	6.8	2.3	0.3	0.5	1.2	0.5	7.0
Smaller industrial countries	3.4	2.2	1.7	1.2	1.6	0.9	0.3
All developing countries	4.4	3.3	1.1	1.1	1.5	0.9	0.5
Africa	3.6	2.3	1.7	2.6	2.2	1.4	0.5
NIEs	4.1	5.8	0.9	0.9	1.6	0.9	0.5
Western Hemisphere	5.3	1.7	0.8	0.7	1.1	0.5	0.5
Other developing countries	4.1	3.8	1.2	1.0	1.5	0.9	0.5

This table reports the results of seven independent simulations where R&D expenditures are exogenously increased by an amount equivalent to $\frac{1}{2}$ of 1 percent of GDP in each G-7 country, with the R&D/GDP ratios maintained constant thereafter.

Table 3. Increased R&D in all Industrial Countries
(deviations from baseline, in percent)

	1996	2000	2010	2030	2050	2075
<u>Industrial countries</u>						
Potential output	--	2.6	7.1	12.9	16.4	18.7
Total factor productivity	--	2.7	7.0	10.9	12.7	13.8
from domestic R&D	--	2.2	5.5	8.6	10.0	10.9
from foreign R&D	--	0.6	1.5	2.3	2.7	2.9
Capital	--	-0.4	0.7	6.9	12.2	16.0
Investment	-0.2	-1.5	3.7	11.1	15.0	17.2
Consumption	0.2	2.8	6.9	11.9	15.1	17.3
R&D spending/GDP ¹	0.5	0.5	0.5	0.5	0.5	0.5
Domestic R&D stock	--	9.3	24.2	38.1	44.6	48.8
Foreign R&D stock	--	9.3	24.3	38.2	44.6	48.6
Manufactures imports/GDP ¹	0.2	0.3	0.4	0.4	0.4	0.3
<u>Developing countries</u>						
Potential output	0.2	1.6	4.6	9.1	11.9	14.1
Total factor productivity	0.2	1.6	4.4	7.3	8.9	10.3
from foreign R&D	0.1	1.5	4.1	6.9	8.4	9.8
from trade	0.1	0.1	0.3	0.4	0.4	0.5
Capital	0.1	0.1	1.9	8.5	13.0	16.2
Investment	0.7	-0.1	5.0	11.7	14.9	17.2
Consumption	0.5	1.9	5.1	10.1	13.2	15.5
Foreign R&D stock	--	8.5	21.8	34.4	40.4	44.4
Manufactures imports/GDP ¹	0.4	0.4	1.1	1.6	1.7	1.8

R&D expenditures are exogenously and simultaneously increased by an amount equivalent to $\frac{1}{2}$ of 1 percent of the baseline level of GDP in each industrial country; R&D expenditures endogenously increase further to remain stable as a proportion of the simulated level of GDP.

¹In percentage points.

Table 4. Increased Trade in Developing Countries
(deviations from baseline, in percent)

	1996	2000	2010	2030	2050	2075
<u>Developing countries except NIEs</u>						
Potential output	2.8	3.5	4.7	6.4	7.6	9.0
Total factor productivity	2.6	2.9	3.4	4.2	5.0	5.8
from foreign R&D	1.4	1.7	2.3	3.3	4.1	5.0
from trade	1.2	1.2	1.1	1.0	0.9	0.8
Capital	0.4	1.8	4.3	7.0	8.4	9.8
Investment	5.2	5.0	6.6	8.0	9.0	10.5
Consumption	2.9	2.7	3.0	4.3	5.2	6.0
Manufactures imports/GDP ¹	4.9	4.7	4.3	3.8	3.6	3.3
<u>Africa</u>						
Potential output	2.3	3.2	4.7	6.7	8.0	9.3
Total factor productivity	2.2	2.8	3.6	4.3	5.1	6.0
Capital	0.4	1.1	3.9	7.9	9.4	10.8
Investment	5.2	3.2	7.3	9.1	10.0	11.5
Consumption	4.0	2.7	2.6	4.5	5.3	6.1
Manufactures imports/GDP ¹	4.2	4.6	4.5	4.0	3.7	3.4
<u>Western Hemisphere</u>						
Potential output	3.4	4.1	5.3	7.1	8.5	10.2
Total factor productivity	3.2	3.2	3.6	4.6	5.6	6.6
Capital	0.6	3.0	5.9	8.1	9.5	11.4
Investment	8.2	8.8	7.9	8.9	10.3	12.3
Consumption	3.6	3.9	4.7	6.0	7.0	8.1
Manufactures imports/GDP ¹	6.2	5.4	4.7	4.4	4.1	3.9
<u>Other developing countries</u>						
Potential output	2.6	3.2	4.4	6.0	7.1	8.2
Total factor productivity	2.5	2.8	3.4	4.1	4.8	5.5
Capital	0.4	1.4	3.5	6.3	7.5	8.7
Investment	3.8	3.6	5.7	7.2	8.0	9.2
Consumption	2.3	2.0	2.1	3.3	4.1	4.8
Manufactures imports/GDP ¹	4.3	4.3	4.0	3.5	3.3	3.0

Imports and exports of manufactures are exogenously increased by an amount equivalent to 5 percent of the baseline level of GDP in each developing country region except for the NIEs.

¹In percentage points.

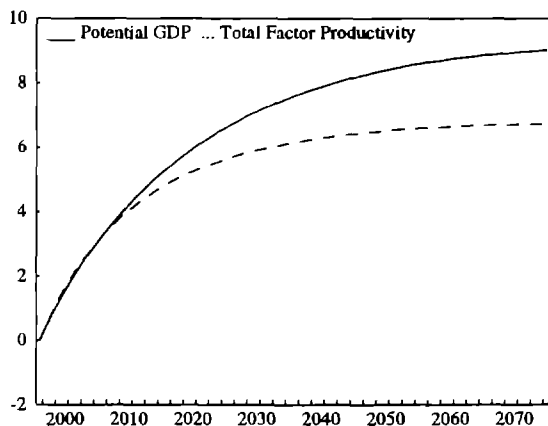
Appendix Table. Bilateral Import Shares for Manufactures
(average, 1970-90)

	Imports from:							
	US	JA	GR	FR	IT	UK	CA	SI
Imports of:								
United States	--	.32	.09	.05	.04	.06	.30	.14
Japan	.46	--	.08	.05	.04	.04	.08	.25
Germany	.09	.08	--	.15	.11	.09	.01	.47
France	.10	.05	.24	--	.14	.09	.01	.37
Italy	.07	.03	.28	.20	--	.06	.01	.35
United Kingdom	.13	.07	.19	.11	.07	--	.02	.41
Canada	.76	.08	.03	.02	.02	.04	--	.05
Smaller Industrial Countries	.12	.09	.23	.10	.08	.09	.01	.28
Africa	.09	.11	.15	.29	.09	.14	.01	.14
NIEs	.28	.51	.07	.03	.02	.04	.01	.06
Western Hemisphere	.48	.13	.12	.06	.05	.04	.02	.10
Other Developing Countries	.18	.35	.16	.07	.05	.09	.01	.10

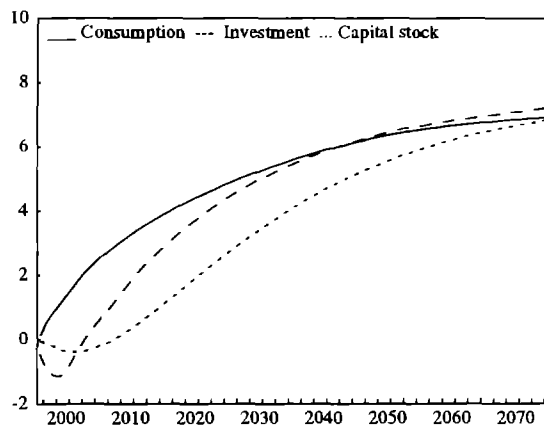
Imports of manufactures of each row country from each of the seven column countries and the small industrial countries as a group as a share of total imports of manufactures from these countries. Each row sums to 1.0.

Figure 1. Increased R&D in the United States
(Deviations from baseline, in percent)

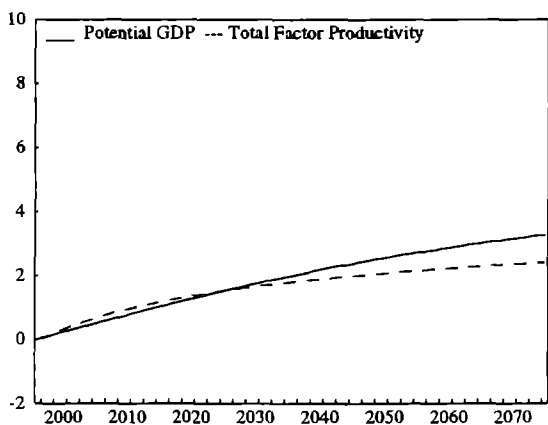
United States
 Output and Total Factor Productivity



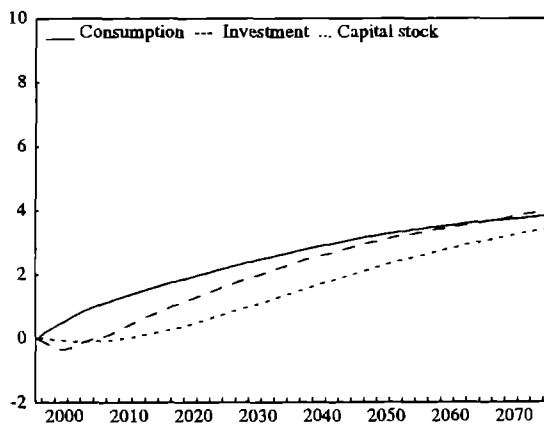
United States
 Consumption, Investment, and Capital Stock



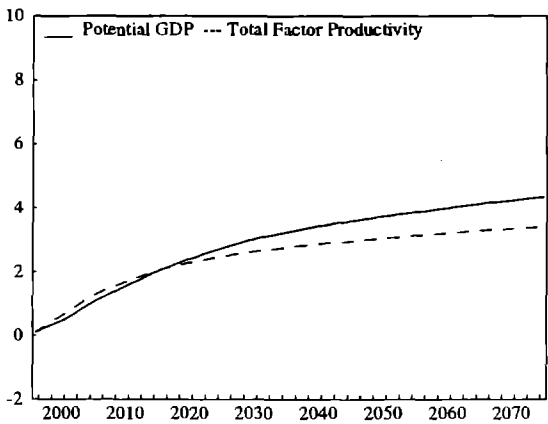
Other Industrial Countries
 Output and Total Factor Productivity



Other Industrial Countries
 Consumption, Investment, and Capital Stock



Developing Countries
 Output and Total Factor Productivity



Developing Countries
 Consumption, Investment, and Capital Stock

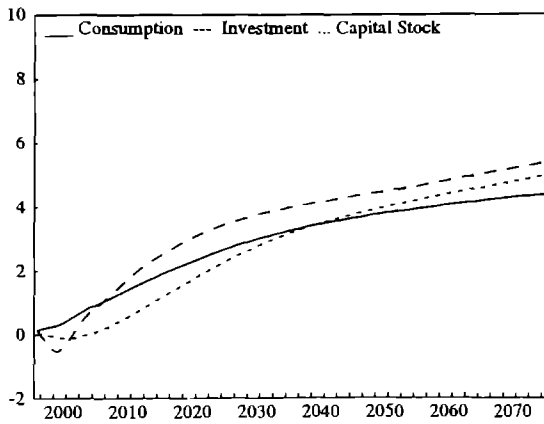
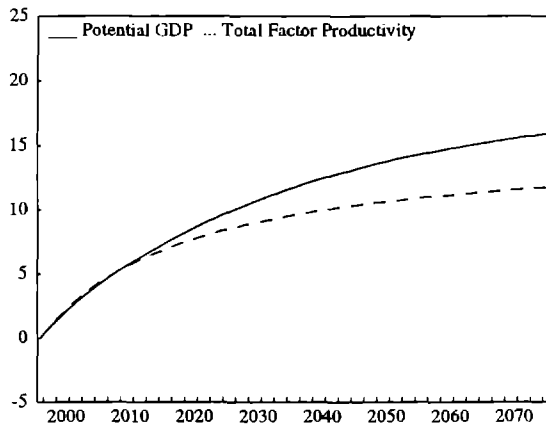
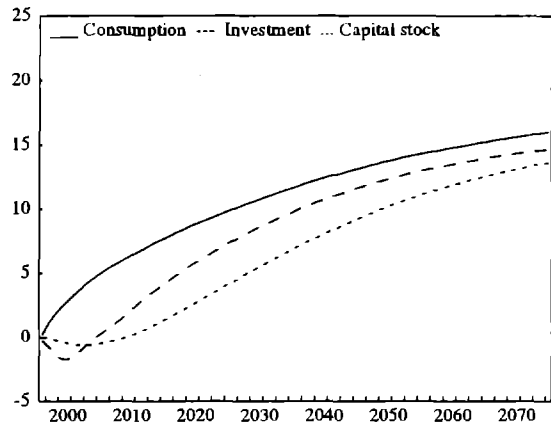


Figure 2. Increased R&D in all Industrial Countries
(Deviations from baseline, in percent)

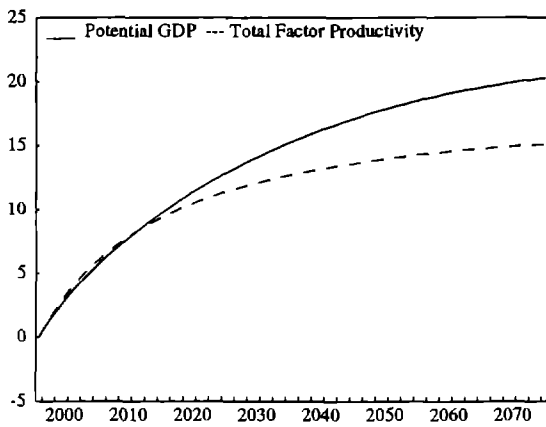
United States
 Output and Total Factor Productivity



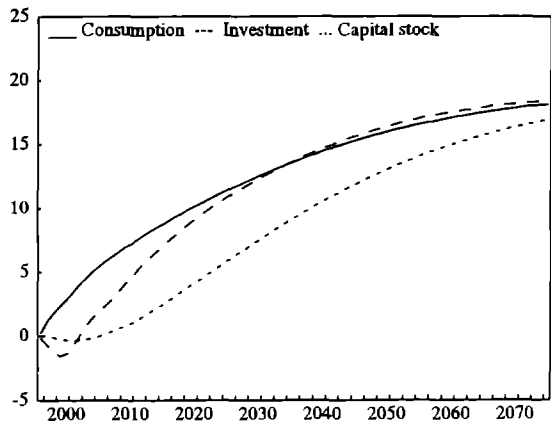
United States
 Consumption, Investment, and Capital Stock



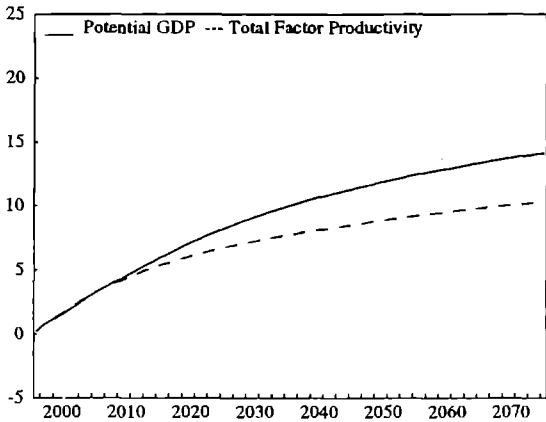
Other Industrial Countries
 Output and Total Factor Productivity



Other Industrial Countries
 Consumption, Investment, and Capital Stock



Developing Countries
 Output and Total Factor Productivity



Developing Countries
 Consumption, Investment, and Capital Stock

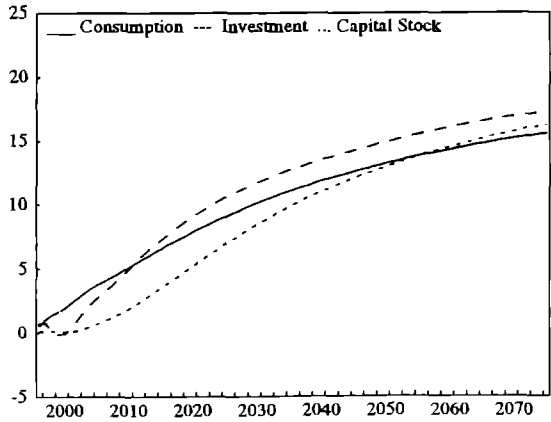
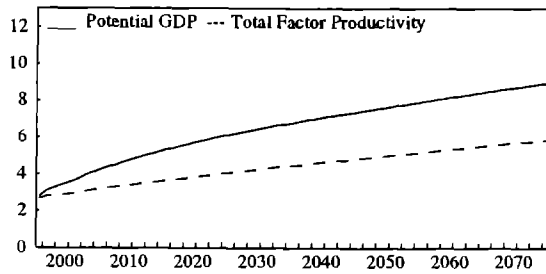
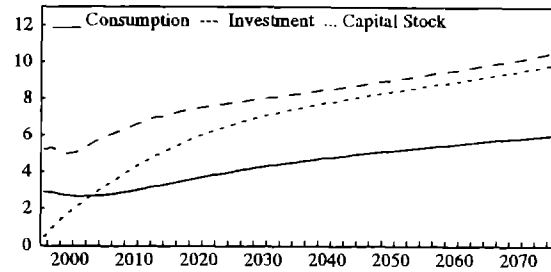


Figure 3. Increased Trade in Developing Countries
(Deviations from baseline, in percent)

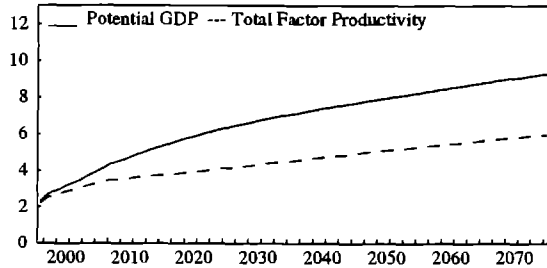
Developing Countries
 Output and Total Factor Productivity



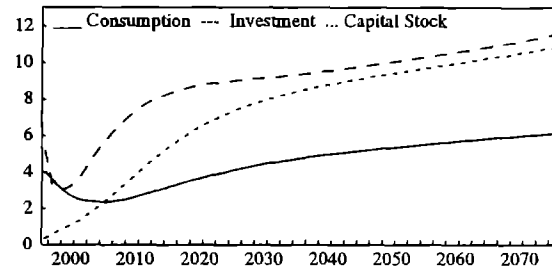
Developing Countries
 Consumption, Investment, and Capital Stock



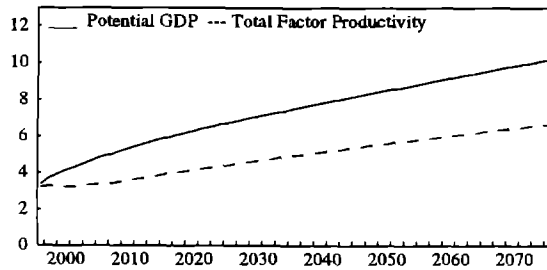
Africa
 Output and Total Factor Productivity



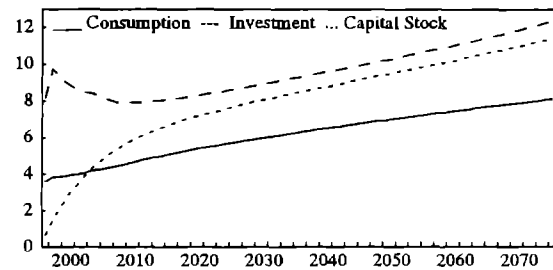
Africa
 Consumption, Investment, and Capital Stock



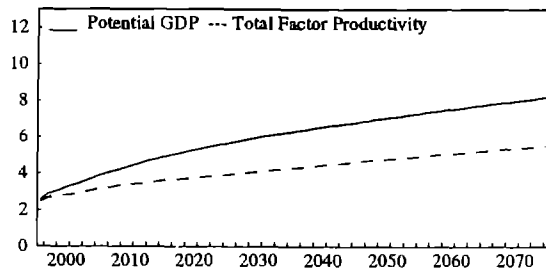
Western Hemisphere
 Output and Total Factor Productivity



Western Hemisphere
 Consumption, Investment, and Capital Stock



Other Developing Countries
 Output and Total Factor Productivity



Other Developing Countries
 Consumption, Investment, and Capital Stock

