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Openness, Growth and R&D Spillovers: Uncovering the Missing Link?*

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1 Introduction

Are countries with lower barriers to trade experiencing more economic progress? Trade economists typically answer this question affirmative despite the fact that neo-classical trade theory predicts that lower barriers to trade will lead to higher levels of welfare only (as long as a country is small). The Solow growth theory predicts no link between trade barriers and growth whatsoever. Only in the transition phase openness might have an effect on growth. Models of endogenous growth provide the 'missing link' between openness and growth.[1] Openness has growth effects via knowledge spillovers related to openness that affect the productivity of research or production, or reduce duplicationary research effort. Openness can also allow countries to benefit from specialisation (or scale) opportunities in research or generate a market-size effect.[2]

Coe and Helpman (1995) have quantified directly the relation between technological change, openness and research expenditures within the OECD. They have shown that R&D is not only beneficial for the performing countries but also for their trade partners.[3]

This paper integrates the empirical results and the theory in an Applied General Equilibrium (further AGE) model. We examine the importance of R&D and R&D spillovers in quantifying the effects of trade liberalisation.[4] We do so in two steps. First, we estimate the relation between total factor productivity and R&D and R&D spillovers, based on Coe and Helpman (1995). The results are subsequently implemented in WorldScan, an AGE model for the world economy with considerable sectoral detail Second, we simulate the consequences of trade liberalisation.

Closely related is the work by Bayoumi, Coe and Helpman (1999, further BCH) who implement the estimated equation of Coe and Helpman (1995) in the dynamic

[1] That such a link exists is partly based on casual observations about the effect of an isolationalist policy on technological sophistication and partly on empirical work, by, for example, Sachs and Warner (1995). The empirical relation is, however, controversial. See Rodriguez and Rodrik (1999).

[2] Grossman and Helpman (1991) discuss the effects on research productivity and the reduction of duplicationary research. See Romer and Rivera-Batiz (1991) for the scale effect in research. The market-size effect is discussed in Acemoglu (1998).

[3] How important trade partners are is still open to debate. Lichtenberg and Pottelsberghe de la Potterie (1998) argue that FDI flows matter.

[4] Numerical estimates in AGE modelling have shown consistently low welfare increases by trade liberalisation in case the models where of the static CRS type.

multicountry model of the IMF (MULTIMOD). They show that a trade expansion by developing countries of 5% of their GDP raises their output by 6.5%-points in 2075.[5]

The analysis in this paper adds to BCH's paper in several respects. First, given that we have sectoral detail in the model we can distinguish intra-regional spillovers alongside inter-regional spillovers. Second, we collect and incorporate R&D data for non-OECD regions whereas BCH's assumptions imply that these regions do not perform any R&D till 2075. Third, to highlight the role for trade as a vehicle for R&D spillovers we perform a different exercise as BCH. We argue that a relevant policy shock is to reduce existing trade barriers over time, whereas BCH increase exogenously imports and exports of manufactures by 5%-points. Finally, we distinguish high- and low-skilled workers. This allows us to examine the hypothesis, propagated by Wood (1994), that trade liberalisation causes 'defensive' innovations in skilled-intensive industries that are harmful for low-skilled workers in the OECD. These differences in the approaches immediately allow us to pin down the points this paper makes.

First, we show that trade-related R&D spillovers not *necessarily* magnify the effects of trade liberalisation. The reason is that trade liberalisation affects relative prices of the regional varieties because trade barriers differ between countries. This may redirect trade flows and thereby affect the 'imported' knowledge flows. This results (for some regions) in very low benefits from international spillovers as they import less knowledge-intensive products. BCH veiled this because they increased the import intensity in a neutral way.

The second point this paper makes is that it is crucial to distinguish intra-national spillovers alongside international spillovers as it brings to the fore the trade-off between the two. This point is easily understood once the trivial observation, that goods that are imported are not produced domestically, is recognized. Note that a large market induces more R&D. Hence, increased 'imported' international spillovers come at a cost of domestically generated knowledge (which might be important for intra-national

[5] There exist, to our knowledge, few other studies that perform similar exercises. Exceptions are Van Meijl and Van Tongeren (1999), who propose an absorption-capacity based spillover measure and test the numerical consequences of that by bringing the spillover measure to the GTAP data and model. Rutherford and Tarr (1998) develop an R&D based CGE model for the small-open economy. Their model, however, remains highly stylized and is not empirically calibrated. We add to these contributions by estimating the relations present in the data and implementing them in a calibrated model that is able to generate transition dynamics.

spillovers).[6] Hence, trade liberalisation might cause regions to specialize in sectors that have low growth potential.

The third point of the paper is that there is no evidence for a technology-related magnification effect on the relative wages of high- and low-skilled workers. The intuition for a magnification effect on relative wages in the OECD goes as follows. Trade liberalisation implies a lower relative price of unskilled-intensive goods. This induces a sectoral reallocation towards skilled-intensive industries, which leads to higher R&D expenditures in these industries. Finally a sector bias in TFP results. We do not find such an effect. There are three reasons for this. First, the sensitivity of TFP for 'own'-sector R&D is low. Second, some OECD regions do not specialise in high-skill / R&D-intensive sectors. Third, the high-skill / R&D-intensive sectors generate considerable spillovers within the domestic economy towards low-skilled intensive sectors.

The remainder of this paper is organized as follows. In Section 2 we discuss our empirical model. The estimation results for this model are presented in Section 3. This section also contains a discussion of the data. Section 4 presents WorldScan, the AGE model. Section 5 presents our main results. Section 6 concludes.

2 The empirical model

There is a substantial literature, both theoretical and empirical, that relates R&D expenditures to productivity growth. The view that technological progress benefits not only from R&D performed within the sector but also from R&D performed 'elsewhere' is also well established (see Nadiri, 1993, for an overview of the literature). More recently the link between productivity and R&D performed in other countries has been emphasised in empirical work.[7] This section sets out a model to re-examine these intra- and international spillovers.

We prefer to incorporate in the AGE model the following specification that is closely related to R&D-based endogenous growth models[8]

$$F_{ik} = A_{ik}\left(R_{ik}^{DD}\right)^{\gamma_{ik}^{DD}}\left(R_{ik}^{ID}\right)^{\gamma_{ik}^{ID}}\left(R_{ik}^{F}\right)^{\gamma_{ik}^{F}}\ , \tag{1}$$

[6] For this point it is crucial that knowledge spillovers are tied to imports. As such, nothing precludes spillovers related to exports (learning by competition on the international market); here we choose, however, to follow the lines set out in the theory and empirical work discussed above.

[7] See Grossman and Helpman (1991) for a thorough theoretical analysis of these issues.

[8] See Keller (1997) for an explicit derivation. C&H (1995) use a similar specification.

F_{ik} is the TFP level for sector *i* in country *k* and the *R*s denote weighted knowledge stocks (that are a function of R&D expenditures). The superscripts to the *R*s have the following meaning: *DD* is Direct (same sector) Domestic and *ID* Indirect (other sectors) Domestic. The superscript *F* should be read as Foreign.

We estimate the time derivative of equation (1):

$$\hat{F}_{ikt} = c + \gamma_{ik}^{DD}\hat{R}_{ikt}^{DD} + \gamma_{ik}^{ID}\hat{R}_{ikt}^{ID} + \gamma_{ik}^{F}\hat{R}_{ikt}^{F} + \varepsilon_{ikt} \,, \tag{2}$$

where a constant *c* captures the unexplained exogenous growth trend. An error term is added.

We assume that the production function exhibits constant returns to scale in labour and capital[9]. Moreover we assume competitive input and output markets.[10] We apply a growth-accounting procedure to capital and labour and estimate for the R&D impact,[11] instead of estimating the complete production function or assessing the impact of R&D also by means of growth accounting. We do so for the following reasons. First, one might argue that by accounting for TFP growth the R^{DD} variable should be included on the left-hand side. However, these expenditures are included in capital and labour already (see also note 10). Second, growth accounting for capital and labour overcomes the problem that - common in the empirical literature - strongly decreasing returns are found (see, for example, Verspagen, 1997b), which are due to measurement errors in the capital stock. Barro (1999, p. 122-123) is more extensive on this issue. Finally, the exogeneity of the growth rates of capital and labour with respect to technological change is doubtful.[12]

[9] Note, for later reference, that the assumption of a production function that is homogeneous of degree one implies that TFP is homogenous of degree zero, hence independent of the scale of the economy.

[10] At first sight this might seem inconsistent; paying for the R^{DD} factor would lead to losses in a competitive market where labour and capital enter in constant returns. However, the expenditures for R^{DD} are included in these inputs already. In the estimation below the elasticity on R^{DD} is to be interpreted as an excess elasticity; hence the effect of R^{DD} should properly be interpreted as an intra-sectoral externality in order to maintain the constant returns assumption.

[11] In Section 3.1 it will become clear that we derive TFP data in a slightly different way, using a translog function.

[12] This point can be made for R&D stocks too, however the data and conceptual problems to account appropriately for the growth in the R&D stock in a growth-accounting sense are huge. Moreover, appropriate instruments for R&D are hard to imagine. See also Barro (1999).

We follow Grossman and Helpman (1991) in the logic that research productivity and thus productivity growth depends on the knowledge stock available for R&D.[13] Therefore, knowledge stocks are weighted *sums* of other sectors' and countries' R&D-capital stocks.

$$R_{ik}^{ID} = \sum_{j \neq i}^{I} \omega_{jik} R_{jk} \qquad R_{ik}^{F} = \sum_{l \neq k}^{K} \sum_{j}^{I} n_{jilk} R_{jl} \ , \tag{3}$$

where ω denote the IO-coefficient from sector *j* to *i* and *n* the sectoral bilateral trade flow from country *l* to *k*. Thus, both changes in the weights and changes in the different R&D-capital stocks affect the knowledge-stock construct. According to equation (3) the spillover stocks from different sectors or countries are complements. This is based on the notion that more ideas leads to higher productivity.

We introduce an additional assumption in the construction of the R&D spillovers. So far we assumed that (trade-weighted) R&D stocks are complements. We, however, argue that the sources of the (sectoral and regional) R&D stocks are imperfect substitutes. To be more specific we assume that the relative likeliness that the R&D stock from sector *j* in country *l* is valuable for sector *i* in country *k* is inversely related to the size (of value added) of sector *j*. This assumption is motivated by the notion that if you import from a large sector with consequently a relatively large R&D stock, a relatively small *share* of that sector's R&D stock will be embodied in these imports.[14] The R&D stocks can than be written as:

$$R_{ik}^{ID} = \sum_{j \neq i}^{I} \omega_{jik} \eta_{jik} R_{jk} \quad \eta_{jik} \equiv \frac{R_{ik}^{ID}}{Y_{jk}} \qquad R_{ik}^{F} = \sum_{l \neq k}^{K} \sum_{j}^{I} n_{jilk} \mu_{jilk} R_{jl} \quad \mu_{jikl} \equiv \frac{R_{ik}^{F}}{Y_{jl}}, \tag{4}$$

where η and μ are the size correction factors. Assuming that only the R&D stocks are time dependent, time differentiation of equation (4) leads to

$$\hat{R}_{ik}^{ID} = \sum_{j \neq i}^{I} \frac{\omega_{jik} \eta_{jik} R_{jk}}{R_{ik}^{ID}} \hat{R}_{jk} \qquad \hat{R}_{ik}^{F} = \sum_{l \neq k}^{K} \sum_{j}^{I} \frac{n_{jilk} \mu_{jilk} R_{jl}}{R_{ik}^{F}} \hat{R}_{jl} \ , \tag{5}$$

13 The assumption is that importing from a knowledge-rich country positively affects the knowledge stock for R&D.

14 A micro foundation for this assumption is provided in Peretto and Smulders (1998).

Moreover we assume that R&D stocks do not depreciate. Here we follow the Terlecky approach (1974). That is, the growth of the R&D knowledge stock can be approximated by the R&D expenditures if is assumed that the depreciation of the stock is zero. As a result equation (5) becomes (substitute also for the η's and μ's)

$$\hat{R}_{ik}^{ID} = \sum_{j \neq i}^{I} \omega_{jik} \frac{RD_{jk}}{Y_{jk}} \qquad \hat{R}_{ik}^{F} = \sum_{l \neq k}^{K} \sum_{j}^{I} n_{jikl} \frac{RD_{jl}}{Y_{jl}} \ . \tag{6}$$

The constructs in equation (6) exhibit several desirable characteristics. First, it does not suffer from an aggregation bias, as equation (3) does. The latter construct is very sensitive to statistical aggregation of countries (see Lichtenberg and Pottelsberghe de la Potterie, 1998, and Jacobs *et al.*, 1999).[15] We have solved this problem by the assumption, that spillovers are related to the size of the country. This approach is largely insensitive to aggregation as it avoids weighting the growth rates of large countries or large delivering sectors heavily. The adjustment of the weights can thus be interpreted as that we allow the η's and μ's to be specific for every sector and region.

Second, a change in the knowledge stocks over time, now approximated by the R&D intensities that vary over time is captured in (6). Third, a change in the weight matrix affects the spillover construct. Now this is only the case if R&D investments are positive whereas in a specification with R&D stocks, integration-induced changes in the weights would affect the R&D construct directly.[16] Related is that by using R&D intensities (equation (6)) instead of an equation based on uncorrected weighted levels (equation (5) without country-sector specific η's and μ's) integrating a country with an average R&D intensity in the global economy has no effect on the R&D construct.

[15] Assume a world with three countries, white domestic R&D capital stocks (R) for countries 2 and 3: $R_2 = 10$, $R_3 = 20$. Then, if country 1 imports 10 from country 2 and 10 from country 3, its foreign R&D capital stock (R^F) should be calculated as follows, assume the weights sum to unity: $R^F = \frac{10}{20}\,10 + \frac{10}{20}\,20 = 15$ If we assume that countries 2 and 3 merge into one single country, the foreign R&D capital stock of country 1 becomes (with the same trade flows as before): $R^F = \frac{20}{20} 30 = 30$ which is twice as large as the foreign R&D capital stock estimated from two distinct countries. That is, the foreign capital stock suffers from an aggregation bias. This example is taken directly from Lichtenberg and Pottelsberghe de la Potterie (1996). The insensitivity to statistical integration is important as the division of countries over the regions in our AGE model is not motivated by considerations of knowledge spillovers.

[16] In the estimations we do not have time-series variation in the weights.

Fourth, we introduce another effect of global integration that is easily clarified by discussing the weighting coefficients, ω and *n*. We use the following definitions:

$$\omega_{ijkt} = \frac{U^{D}_{ijkt}}{Y^{G}_{ikt}} \qquad n_{ijklt} = \frac{U^{M}_{ijkt}}{Y^{G}_{ikt}} \frac{M_{jklt}}{\sum_{l} M_{jklt}} \quad , \tag{7}$$

where *U* indicates intermediate-input use (superscripts *D* and *M* stand for domestic and imported) and Y^G denotes gross production. Hence, integrating a formerly isolated country, with an average R&D intensity, in the global economy will affect the knowledge spillover *if* the import quote, approximated by the imported use over gross production, goes up. This interpretation closely follows a returns to variety production function (see De Groot and Nahuis, 1998). Hence, if the intermediate inputs of an economy are useful, spillovers increase.

We write our estimating equation (equation (2)) as:

$$\hat{F}_{ikt} = c + \beta^{DD} \frac{RD_{ikt}}{Y_{ikt}} + \beta^{ID} \sum_{j \neq i}^{I} \omega_{jikt} \frac{RD_{jkt}}{Y_{jkt}} + \beta^{F} \sum_{l \neq k}^{K} \sum_{j}^{I} n_{jilkt} \frac{RD_{jkt}}{Y_{jkt}} + v_{ikt} \ . \tag{8}$$

The results we report on in the next section are based on this expression. Note that the explanatory variables in (8) are not literally growth rates as we substitute (6) in (2). We replace the γ's by β's to stress the relation between the parameters we estimate and those that will be implemented in the AGE model. The γ's we implement are thus bilaterally country and sector specific (as is required by our assumption motivated above; see Appendix C for further details).

3 Data and estimation

In this section we present the data that are used in the estimation procedure and the model. First, the dependent variable, TFP, is constructed. Second, we describe R&D intensities for OECD and non-OECD regions. Finally, we present estimation results for the specification discussed above.

3.1 TFP growth rates

Explaining differences in technological efficiency is our main interest. Our preferred indicator of technological efficiency is Total Factor Productivity (further TFP) as it measures the efficiency of the combined capital and labour inputs.[17] This section shows how we measure TFP growth.

We calculate the growth rate of TFP ($\hat{F}$) for industry i in country k at time t by a superlative index that is consistent with a translog function (see Diewert, 1976):

$$\hat{F}_{ikt} = \ln\left(\frac{Y_{ikt}}{Y_{ikt-1}}\right) - 0.5(\alpha_{ikt} + \alpha_{ikt-1})\ln\left(\frac{L_{ikt}}{L_{ikt-1}}\right) - (1 - 0.5(\alpha_{ikt} + \alpha_{ikt-1}))\left(\frac{Q_{ikt}}{Q_{ikt-1}}\right) \quad . \qquad (9)$$

Value added, Y, is in PPP-converted constant US dollars. Employment, L, is the number of workers employed, Q is the capital stock estimated by the OECD and α is the wage-income share (see OECD, 1999a).

Table 3.1 presents the mean annual TFP growth rates for the different regions, from 1973 to the early 90s. The numbers presented in the table are generated with OECD (1999a) data, using equation (9) as a starting point. We have adjusted employment for hours worked.[18]

[17] Labour productivity reveals a combination of the efficiency of the technology as well as the amount of capital per unit of labour.

[18] The data on wage-income shares, value added, capital and employment are directly available from the ISDB database, for details see OECD (1999b). The data series for hours worked are not sector specific. The data serie for hours worked for Italy is extended by assuming no change after 1985 whereas for Denmark we use Maddison (1991, Table C9) data (with linear intrapolation).

Table 3.1 Mean annual growth rates of TFP (adjusted for hours worked)

	Agriculture	Raw Materials	Energy-intensive Goods	Consumer Goods	Capital Goods	Total services
US (73-93)	1.91	-0.94	0.39	0.96	1.50	0.13
Japan (73-95)	-3.79	-0.65	-0.82	-0.40	4.19	-0.19
R-OECD (73-93)	1.66	-2.38	1.13	0.79	2.24	0.35
W-Europe (73-91)	1.01	1.09	2.75	1.46	2.80	1.12

Source: OECD (1999b), Maddison (1991) and own calculations.

Across countries as well as across sectors there is considerable variation in the growth rates. Some results are worth emphasising. Europe's current strong position in Energy-intensive Goods (including, for example, the chemical sector) is the result of a high growth rate throughout the period. Remarkable is the low productivity growth in Consumer Goods in Japan. The R&D-intensive Capital Goods sector is the most dynamic sector where the productivity leader – the US – has the lowest average growth rate. The Services sector has experienced hardly any productivity growth, except for Western Europe. The relative backwardness of the Japanese Agriculture sector arose due to low productivity growth in the last three decades whereas productivity growth in US Agriculture is relatively high. The results for Raw Materials have to be taken with a grain of salt, given the fact that this sector has been affected considerably by the oil crisis.

In general Europe's growth rate exceeds the US' as a consequence of catching up. The low Japanese TFP growth rates, despite substantial economic growth, reflect the considerable capital deepening and increases in participation that took place in the last decades throughout Asia (see, for example, Young, 1995, and Kim and Lau, 1994).

3.2 R&D intensities

The size and importance of R&D spillovers between countries and industries depends to a large extent on the knowledge stocks in the different sectors and countries. First, this section describes the observed R&D intensities. These are based on data from OECD (1999a) and UNESCO (1998, 1999). The former provides business-enterprise data for the OECD at a sectoral level, the latter provides business-enterprise data for the non-OECD economies at a macroeconomic level. Second, we discuss the construction of the sectoral and regional business-enterprise R&D intensities in WorldScan.

OECD regions

The ANBERD data base of the OECD (1999a) provides the value of R&D expenditures for business enterprises of 15 OECD countries from 1973 to 1997 at a sectoral level according to the ISIC2 classification. The data are highly disaggregated for the manufacturing sectors but not at all for services. Moreover, for most countries no data for Agriculture and Mining (Raw Materials) are included. The ANBERD data base contains a residual (total, minus R&D in manufacturing and services) which has to be split up between Agriculture and Mining.[19]

We combined the ANBERD data with the ISDB data (OECD, 1999b) to derive R&D intensities per sector for the various countries. The latter database provides value added data at a sectoral level. This enables us to derive R&D intensities per sector and country. Table 3.2 reports these for the four OECD regions in WorldScan. In order to derive the sectoral business enterprise R&D intensities for the OECD regions in WorldScan, we simply aggregate the country data to WorldScan sectors and regions. We assume that the underlying country data (see Table A.2) are representative for the relevant WorldScan regions.[20]

Table 3.2 Sectoral R&D intensities in WorldScan for the OECD as ratio of sectoral value added (1990)

sectoral R&D intensities	Agriculture	Raw Materials	Consumer Goods	Energy - int. Goods	Capital Goods	Services	average
Western Europe	0.62	0.96	0.59	4.49	9.39	0.23	1.81
United States	0.53	0.53	1.11	5.23	15.22	0.53	2.21
Japan	0.10	2.65	1.16	8.10	10.64	0.12	-2.25
Pacific OECD	0.18	0.46	0.61	2.42	7.07	0.41	1.00
Average OECD	0.45	0.68	0.92	5.34	11.84	0.36	2.05

Source: OECD (1999a, 1999b) and own calculations.

[19] For the US, Agriculture and Mining is included in Services. We assume that the R&D intensity is equal in these three sectors in the US. More details are provided in Appendix A.

[20] With respect to the sectoral aggregation we assume that the sectors Services and Trade and Transport have the same R&D intensity which is approximated by the R&D intensity of services in the OECD data. For the manufacturing sectors we aggregate the sectors S3100, S3200, S3300 and S3900 to the sector Consumer Goods. The sector Capital Goods is simply S3800, while the sector Energy-intensive Goods consists of the other desaggregated manufacturing sectors, S3400 to S3700.

In general, the R&D intensities in the sectors Raw Materials and Agriculture are higher than in Services, but lower than in Manufacturing. The variation within Manufacturing is interesting. The R&D intensities in Energy-intensive Goods and Capital Goods are very high, while they are relatively low in Consumer Goods. The latter consists of sub sectors like Wood, Food and Tobacco, Textiles and Paper which are R&D extensive sectors. The sector Energy-intensive Goods is R&D intensive because of the sub sector Chemicals, Rubbers and Plastics is included. The R&D intensity of other sub sectors like Stone and Clay and Basic Metals is lower. The sector Capital Goods consists only of Fabricated Metal products, which is very R&D intensive.

If we compare the regions, we see that the United States and Japan carry out most of the R&D while Pacific OECD is lagging behind. The United States carries out relatively much R&D in Capital Goods, Consumer Goods and Services, while Japan is active in Energy-intensive Goods and Raw Materials. Western Europe carries out a lot of R&D in Agriculture.

Non-OECD regions

UNESCO (1999) provides, for about 100 countries, the expenditures on R&D as ratio of Gross National Product for several years in the 80s and 90s. For the industrial countries these have sometimes a time-series dimension; for most other countries data are limited to a few years. The coverage, however is wide. The R&D intensities vary widely among the countries. In general these intensities are much lower for developing countries than for the industrial countries. Table 3.3 presents the results for the non-OECD WorldScan regions. R&D in the most developed region, South-East Asia, is the highest.[21]

[21] For our purposes we face two problems. First, the data include all expenditures on R&D, not only business enterprise. Second, the data do not include a sectoral division. The first problem is solved by using Table 5.6 from UNESCO (1998). This statistical yearbook provides information on the R&D expenditures by sector of performance. We interpret the productive sector in this table as business enterprises. The second problem is solved by using the average OECD relative R&D intensities also for the non-OECD regions. These relative intensities are multiplied by the business enterprise R&D ratio in Table 3.3. The results are shown in Table A.3.

Table 3.3 R&D intensities for the non-OECD regions in 1995

R&D intensity	total R&D[2]	share BE[1]	BE R&D[2]
Eastern Europe	0.90	47.1	0.42
Former Soviet Union	0.73	67.1	0.49
Latin America	0.55	29.5	0.16
Middle East	0.76	41.6	0.32
Sub-Saharan Africa	0.61	52.7	0.32
China	0.61	31.9	0.19
South-East Asia	1.33	70.0	0.93
South Asia & Rest	0.69	26.5	0.18

Source: UNESCO (1998, 1999).
[1]BE = business-enterprise R&D (as a share of total R&D)
[2] as ratio of GNP

For some regions the coverage is limited to a few countries, such as Sub-Saharan Africa (only South Africa) and Middle East (only Turkey and Israel). The coverage for Former Soviet Union and Eastern Europe, China, South Asia & Rest and South-East Asia is fairly good. The business-enterprise R&D intensities vary more widely than those of total R&D. The numbers on the share of business-enterprise R&D reinforce the differences; see for example the effects on China and South-East Asia.

3.3 Empirical findings

This section presents the main empirical findings. The model in equation (8) is estimated for all sectors WorldScan distinguishes. Appendix B presents robustness analysis and results for the manufacturing sectors only. The results presented in this section will be made operational in the AGE model in the next section.

Our regression analysis has two aims. First, we want to establish that the relations, found in the literature,[22] can also be traced at the aggregation level of WorldScan. Second, the estimates should provide parameters for the AGE model we employ in the next section.

[22] It is difficult to compare our results with the literature because we reduce the variation in the data considerably by aggregating the data to our desired sectoral and regional level.

The aggregate model

Table 3.4 presents the regression results based on equation (8).

Table 3.4 OLS estimation results for equation (7). Dependent variable is ($T\hat{F}P$).†

Variable	*(I) Direct effect*	*(II) Direct + indirect effect*	*(III) Domestic and Total*
DD	.216***	.205***	.167**
	[.069]	[.069]	[.074]
ID		2.112**	2.636**
		[.966]	[1.041]
TF			0.618
			[.457]
R^2 (adjusted)	0.02	0.03	0.03
N	432	432	432

† Sample period is 1973-1991, 6 sectors and 4 regions. All regressions include a constant. The explanatory variables are lagged by one year. Standard errors are given in parentheses under the estimates. *, **, and *** denote statistical significance at the 10% level, the 5% level, and the 1% level, respectively.

First, we include the own R&D stocks. We find a significant rate of return for the own within-sector R&D stock. Inclusion of the indirect domestic R&D stock in column (II) supports the hypotheses that within-region R&D spillovers exist. The estimated coefficient for the indirect effect is relatively high compared to the direct effect, because we use weighting matrices of which the columns do not add up to unity. Inclusion of the foreign spillover variable in column (III) yields an estimate for our foreign R&D construct of 0.6. The estimate is not very precise, however. The inclusion does not substantially affect the coefficients for the domestic variables. This regression is our major input for the modelling exercise in the next section.

How do these findings match with the literature? The initiating contribution on international spillovers is the paper by Coe and Helpman (1995), further CH. They find substantial technological spillovers among OECD countries. The elasticity of the level of TFP with respect to foreign R&D embodied in traded goods is about 6%. Park (1995) examines also country-level data without an industry dimension. Labour-productivity growth is explained by domestic R&D and foreign R&D weighted by technological distance. The elasticity of weighted foreign R&D is 17-18% compared to 11% for domestic R&D.

Keller (1997) carries out a similar exercise to ours, be it on a more disaggregated level. R&D in the 'same' sector abroad turns out to have an equally strong effect on TFP as R&D carried out by the sector itself. Verspagen (1997b) estimates production functions and constructs R&D spillover stocks by using weights differently from ours. He uses R&D stocks in a similar vein as CH. In the most comparable estimate to ours, he finds an own-R&D elasticity of 9 to 10%. The indirect domestic elasticity varies from 3 to 6%, and the foreign from 5 to 7.5%. Our estimates of the *ID* coefficient is not comparable to those which use a weighting scheme with columns summing up to unity Therefore one should divide the estimated coefficient roughly by a factor 5.[23] This implies for regression (III) in Table 3.4 an elasticity of 30%, which is considerably higher than for example Verspagen's. Sakurai *et al*. (1997) use comparable data and estimate rates of return, they find an own-R&D elasticity of 13 to 17%. Our coefficient for foreign R&D seems rather low (note that we pre-multiplied the R&D intensities twice with a weighting coefficient with a sum less than unity).

4 WorldScan: a global applied general-equilibrium model

WorldScan has been developed to construct scenarios. WorldScan relies on the neoclassical *theories of growth and international trade*.[24] The standard neoclassical *theory of growth* distinguishes three factors to explain changes in production: physical capital, labour, and technology. WorldScan augments the simple growth model in three ways. First, WorldScan allows overall technology to differ across countries. Second, the model distinguishes two types of labour: high-skilled and low-skilled labour. Sectors differ according to the intensity with which they use high-skilled and low-skilled labour. Countries can thus raise per capita growth by schooling and training the labour force. Third, in developing countries part of the labour force works in a low-productivity, informal sector. In this sector workers do not have access to capital. Reallocation of labour from the low-productivity sector to the high-productivity sectors enables countries to raise per capita growth as well. In principle – consistent with the neo-classical growth theory – all these three factors affect the performance of a region only

[23] This is a very crude approximation, based on the fact that the sum of the input coefficients is 0.1 to 0.4 (recall that we exclude intra-sectoral use). As, in many estimations present in the literature, the coefficients are adjusted such that they sum to one, we blow up our coefficient by a factor 10 to 2.5. On average the adjustment factor is approximately 5.

[24] An Armington trade specification amends the neo-classical trade theory. This is to explain two-way trade and to allow for market power to determine trade patterns in the medium run, while allowing for Heckscher-Ohlin mechanisms in the long run.

temporarily. Catching-up of technology, training of low-skilled workers and reallocating labour to the high-productivity sector do not raise the growth rate indefinitely.

The simulations in Section 5 are variations on the so-called Globalisation scenario.[25] The idea behind the scenario is that when developing countries grow fast or start to grow fast, the linkages between the OECD and the non-OECD countries intensify. Rapid development outside the OECD area and liberalisation of capital, goods and service markets produce closer economic integration of rich and poor countries. More generally, the scenario extrapolates and probably exaggerates the current globalisation tendencies.

The Globalisation scenario is optimistic about future economic progress in both developed and developing regions. In this scenario many poor countries catch up, though not completely, with rich countries. Non-OECD countries grow at a per-capita rate of about 4%. Only few countries have been able to maintain such a growth rate for two decades or more.

Table 4.1 Applied trade taxes in the OECD and non OECD in 1995

sector	Agriculture	Raw Materials	Energy-int. Goods	Consumer Goods	Capital Goods	Trade and Transport	Services
average import tariff (%)							
OECD	32.0	0.4	2.9	11.0	2.6	1.1	0.3
non OECD	18.6	5.1	11.8	19.7	12.1	0.2	0.5
average export tariff (%)							
OECD	-2.9	1.1	0.6	-3.9	0.3	3.7	2.4
non OECD	3.8	2.3	-0.6	2.6	0.1	1.1	1.2

Source: McDougall *et al.* (1998) and own calculations. A minus sign implies a subsidy.

In the scenario, trade liberalisation is not confined to trade blocs, but applies globally. The OECD countries open up their markets further. Whereas barriers to trade in manufacturing goods are already low, agriculture is still heavily protected in the globalisation scenario. Table 4.1 provides an overview of the average import and export taxes in the OECD and non OECD in 1995. Within manufacturing, the import tariffs are the highest for Consumer Goods. For Energy-intensive Goods and Capital Goods, which

[25] CPB (1999) provides more details of the Globalisation scenario. This scenario is akin to the High Growth scenario which CPB and OECD have constructed for their collaborative study on globalisation and the consequences for the OECD countries (OECD, 1997).

are often used as intermediate goods, the import tariffs are lower. The non-OECD regions often levy higher tariffs than the OECD regions. The tariffs in the service sectors are very low (though the non-tariff barriers are high). The OECD countries subsidize their agricultural and food products (food is a substantial part of Consumer Goods). For this reason the export taxes are negative.

Even though the Globalisation scenario is perhaps not the most plausible one, we take it as point of departure. The reason is that it stresses that linkages between developed and developing regions can become stronger and spillovers between these regions can become larger.

Incorporation of R&D in the model

WorldScan has been calibrated on the GTAP data base, Version 4 (McDougall *et al.*, 1998). From this data set we not only derive the demand, production and trade patterns, but also the labour and capital intensity of the different sectors. The incorporation of R&D affects the model and the data. To start with the latter, our base-year data derived from the GTAP database do not include expenditures on R&D. We assume that these are implicitly incorporated in the intermediate deliveries on services. Therefore, we subtract the expenditures on R&D from the GTAP data on intermediate deliveries on services. As described before, the R&D data are derived from the OECD (1999) and UNESCO (1998) data for the base year 1995. We also subtract the R&D expenditures from the value of production. Based on the modified GTAP data we calibrate the production function. Then we construct a new producer price as the unit cost price plus a mark up which covers the R&D expenditures. As a result, the volume of production times the new producer price is equal to the production value in the original GTAP data. Total demand for services now consists of intermediate demand, investment demand, final consumption demand and R&D demand. The total value of the demand for services is still the same as in GTAP.

We incorporate the relation between TFP and R&D stocks and R&D-spillover stocks, equation (1), in WorldScan. In the base year we calibrate A by inverting equation (1) where we substitute the values of the R&D stocks. The value of F follows from calibrating the production function.

The sectoral R&D stocks in period t equal those in period $t\text{-}1$ – corrected for deprecation – plus the R&D expenditures. The deprecation rate, δ, is set at 5% for the

R&D stock in all sectors and regions.[26] The R&D expenditures are by assumption a constant fraction, $\overline{RI}$, of sectoral value added in period *t-1*, thus

$$R_t = \overline{RI}\, Y_{t-1} + (1-\delta) R_{t-1} \ . \tag{10}$$

We also use this equation to construct the R&D stock for the base year, assuming that the ratio of the R&D stock to value added is constant.

In the scenario period TFP grows due to an exogenous increase in *A* and an endogenous increase in the R&D stocks. In the baseline without R&D we have imposed an exogenous increase in sectoral and regional TFP in the model such that the model produces the characteristics of the Globalisation scenario. In the baseline simulations including R&D we have assumed that the total increase in TFP was similar as in the baseline without R&D. As a result the exogenous increase in *A* is much lower in the simulations with R&D than without R&D. We follow this method to make the baselines comparable to each other. The effects of trade liberalisation are then also comparable.[27]

5. Simulation results

This section presents the effects of trade liberalisation in case R&D is introduced in WorldScan. We distinguish the effects of trade liberalisation in the presence of own R&D efforts, of sectoral spillovers, and of international R&D spillovers. These effects are measured by comparing the results for two simulations: a baseline simulation without trade policy and a policy variant consisting of trade liberalisation. First, we present the results of introducing R&D on GDP growth for the various regions in the baseline simulation. Second, we turn to the macroeconomic effects of trade liberalisation and the role of R&D (spillovers). Third, we discuss the sectoral effects for some regions.

Based on the results we present, we carry out some sensitivity analysis. First, we analyse the effects from an increase of R&D efforts in the non-OECD countries, which is to be expected if these regions become more wealthy. Second, we consider the case that only the OECD regions carry out R&D. Third, we modify the elasticity of TFP to

[26] In the estimations, we assumed that R&D stocks did not depreciate. Some sensitivity analysis of our simulations with respect to the assumed depreciation rate is presented in Appendix D. There we set δ equal to zero. The qualitative results are not altered.

[27] In the policy simulations we use the calculated increases in *A* as exogenous.

R&D spillovers to examine the sensitivity of the importance of the sectoral and international spillovers in case these estimated elasticities are modified

5.1 Growth accounting

The incorporation of R&D and spillovers in our baseline simulation has a significant effect on GDP growth in the model. While thus far a substantial part of GDP growth was explained by TFP growth (CPB, 1999), the contribution of exogenous technological change is declined in favour of growth in R&D and R&D spillovers. Table 5.1 shows the factors that contribute to GDP growth in the various regions.

CPB (1999) explains that a substantial part of GDP growth in the non-OECD regions can be attributed to the growth in employment. This is caused by population growth, schooling and labour reallocation from the low-productivity sectors to the high-productivity sectors. On average capital accumulation contributes for about 40% to GDP growth. The rest can be attributed to R&D and exogenous technological change. This is our main interest here.

According to Table 5.1, R&D explains a part of GDP growth which was attributed to TFP before. Own R&D is only relevant in the OECD and South-East Asia, the regions which perform nearly all R&D in the world. The relevance of the sectoral and international spillovers varies per region. Below we will discuss this issue at greater length. Table 5.1 shows that for most regions the spillovers contribute more to GDP growth than own sectoral R&D efforts. This is not surprising. In particular, the sectoral spillovers are mainly driven by those goods which are relatively important as intermediate goods such as Capital Goods and Energy-intensive Goods. These sectors are also relatively R&D intensive. This implies that the contribution of sectoral spillovers to GDP growth is larger than the contribution of own R&D.

Table 5.1 Growth accounting annual contributions of the productive factors

country	Western Europe	United States	Japan	Pacific OECD	Eastern Europe	Former Soviet Union
employment	-0.1	0.4	-0.2	0.4	0.0	0.2
capital accumulation	0.8	1.0	1.1	1.0	1.3	2.1
own R&D (R^{DD})	0.1	0.2	0.1	0.1	0.0	0.0
sectoral R&D spillovers (R^{ID})	0.1	0.2	0.1	-0.1	0.1	0.1
international R&D spillovers (R^{F})	0.1	0.1	0.0	0.2	0.2	0.1
total factor productivity (A)	1.4	0.8	1.2	0.6	2.9	2.9
gross domestic product	2.4	2.7	2.4	2.1	4.5	5.5
country	Middle East & N. Africa	Sub-Saharan Africa	Latin America	China	South-East Asia	South Asia & Rest
employment	1.6	2.7	1.3	0.7	1.4	1.8
capital accumulation	3.1	2.0	2.5	4.2	3.1	2.6
own R&D (R^{DD})	0.0	0.0	0.0	0.0	0.1	0.0
sectoral R&D spillovers (R^{ID})	0.1	0.1	0.1	0.2	0.5	0.1
international R&D spillovers (R^{F})	0.1	0.1	0.1	0.2	0.2	0.1
total factor productivity (A)	0.8	0.2	1.0	1.9	1.2	1.3
gross domestic product	5.7	5.1	4.9	7.2	6.4	5.9

Source: WorldScan simulations.

5.2 Trade liberalisation and GDP effects

The growth-accounting analysis learns that a part of TFP growth can be explained by R&D. R&D growth thus raises GDP growth. This result is also confirmed in our analysis of trade liberalisation. Without R&D in the model, the effects of trade liberalisation on GDP are in general modest. We want to examine whether this is also the case if R&D is included in WorldScan. We carry out a trade-liberalisation exercise in four different cases. These cases are discriminated by the fact that:

- TFP is not affected by R&D
- TFP is only affected by own R&D expenditures
- TFP is affected by own R&D and sectoral spillovers
- TFP is affected by own R&D and sectoral and international spillovers.

The first simulation assumes no link between R&D and TFP. We assume that all regions agree to abolish their sectoral tariffs and export subsidies between 2000 and 2020. In the sectors Agriculture and Raw Materials the import tariffs and export subsidies are reduced by only 50%, because of the high initial rates of tariff protection. The results are similar to those in Lejour and Tang (2000). The effects on GDP in the OECD are modest, but the Asian regions gain substantially in 2020, the end of the simulation period. Also the GDP gains in Latin America are high.[28] The first column in Table 5.2 presents these results.

[28] The substantial GDP effects can partly be explained by the fact that we assume that the consumer preferences for a certain variety (in the Armington demand functions) depend positively on the share in global production of the region in which the variety is produced.

Table 5.2 Cumulative GDP effects of trade liberalisation in 2020

region	no R&D (1)	own R&D (2)	sectoral R&D spillovers (3)	international R&D spillovers (4)	relative GDP increase due to R&D (5)
United States	1.5	0.0	0.3	0.4	53.2
Western Europe	1.7	0.5	2.3	0.1	169.3
Japan	2.3	1.0	7.4	0.2	372.1
Pacific OECD	3.8	0.2	0.5	0.2	24.1
Eastern Europe	5.0	0.2	1.0	0.8	40.2
Former Soviet Union	1.6	0.1	0.2	0.2	36.2
Latin America	9.5	0.3	0.7	0.4	14.6
Middle East & N. Africa	4.8	0.3	0.4	2.1	58.8
Sub-Saharan Africa	5.0	0.1	-0.3	0.7	10.2
China	15.0	0.1	-0.5	0.9	3.4
South-East Asia	14.9	1.4	6.0	1.5	59.6
South Asia & Rest	15.9	0.2	0.4	0.6	7.0

Source: WorldScan simulations. Columns (2) to (4) present additional effects to the previous column. Some simulation results without depreciation are presented in Appendix D.

The second simulation assumes that increases in the sectoral R&D stock raise the TFP level in that sector. This simulation does not take account of sectoral and international spillovers on TFP. Column (2) shows the extra GDP effects of trade liberalisation on GDP due to own R&D expenditures. These extra effects are modest, except for Western Europe, Japan and South-East Asia. These regions specialise in Capital Goods and Energy-intensive Goods. Trade liberalisation stimulates growth in these sectors and thereby in the R&D efforts.

Column (3) shows the extra GDP effects of trade liberalisation due to the sectoral spillovers. These effects vary widely. In South-East Asia the sectoral R&D spillovers increase the GDP effects of trade liberalisation with 6% points. In Sub-Saharan Africa and China however, the sectoral spillovers have a small negative effect on GDP. The results vary by region because of the regional differences in the development of the R&D-intensive sectors. From Table 3.2 we know that the sectors Capital Goods and Energy-intensive Goods are R&D intensive. In regions which do not specialize in these sectors, the R&D-intensive sectors become relatively less important during the process of trade liberalisation. Then, the average R&D content of the intermediate goods produced in the own region decreases. Examples are Sub-Saharan Africa and China. In other regions, the R&D-intensive sectors expand relatively quickly. As a consequence, the average R&D content of the intermediate goods increases. This explains the sectoral spillovers in Western Europe, Japan, and South-East Asia. Thus, the importance of sectoral spillovers depends on the specialisation pattern. Regions can specialise in R&D-intensive or R&D-extensive sectors. We will discuss this issue in greater detail below.

The international R&D spillovers further raise the GDP effects of trade liberalisation, as can be seen in column (4) of Table 5.2. Its importance differs per region. In general, international R&D spillovers are more important for the non-OECD regions than for the OECD regions. Non-OECD regions import relatively much from the OECD, whose products are relatively R&D intensive, see also Table 3.2. An extreme example is the Middle East. This region imports much more Capital Goods and Energy-intensive Goods from the OECD due to trade liberalisation. As a result the international spillovers are high.

Column (5) shows the increase in the GDP effects of trade liberalisation with R&D in the model relative to the GDP effects of trade liberalisation without R&D. On average the GDP effects are raised significantly (due to R&D-based technology). China, Sub-Saharan Africa, and South Asia and Rest are exceptions, however.[29]

Sectoral and international spillovers

Above we have seen that the large variety in GDP effects of trade liberalisation due to sectoral spillovers depends on the development of the R&D-intensive sectors. The sectors Energy-intensive Goods and Capital Goods are very important in this respect for two reasons. First, these sectors are very R&D intensive. Second, these goods are intensively used as intermediate goods. Table 5.3 presents some indicators of the development of these sectors and their effects on regional R&D stocks in the process of trade liberalisation.

[29] Table 5.2 presents the GDP effects of trade liberalisation. Alternatively, we could present the effects on the volume of consumption. The effects in the initial policy simulation without R&D in the model then look different. The consumption gains for the Asian regions are substantially lower than the percentage gains in GDP in Table 5.2. The effects of introducing R&D in these simulations, is the same as above, however. The same regions have relatively large sectoral or international spillovers. All conclusions thus hold whether the analysis is based on GDP effects or consumption effects.

Table 5.3 Development of R&D-intensive sectors due to trade liberalisation in 2020

region	absolute change in share of R&D-intensive sectors in value added[a]	relative change in R&D stocks of R&D-intensive sectors	relative change in total R&D stocks
United States	-0.7	-1.5	-0.9
Western Europe	2.3	10.4	8.6
Japan	3.9	17.9	16.2
Pacific OECD	-1.0	-0.7	1.1
Eastern Europe	0.7	8.9	8.4
Former Soviet Union	-1.0	-1.6	-0.7
Latin America	-0.6	2.9	4.3
Middle East & N. Africa	-1.3	-5.3	-3.6
Sub-Saharan Africa	-3.3	-13.4	-9.2
China	-7.2	-9.9	-5.6
South-East Asia	3.9	30.6	28.3
South Asia & Rest	-1.4	2.9	6.3

[a] The R&D-intensive sectors are the sectors Energy-intensive Goods and Capital Goods.

Source: WorldScan simulations.

Western Europe, Japan, Eastern Europe and South-East Asia specialise in R&D-intensive sectors. These sectors are also high-skilled labour intensive, which largely explains specialisation in these sectors by the former three regions (which are high-skilled abundant). In these regions, the share of R&D-intensive sectors in value added rises. This enhances the growth of the R&D stocks in these sectors and has the same effect on regional R&D stocks. The last two columns in Table 5.3 show a high positive correlation between the changes in the R&D stocks of the R&D-intensive sectors and the regional R&D stock. If we compare column (3) in Table 5.2 with column (3) in table 5.3, it thus follows that the sectoral spillovers are very high in regions which tend to specialise in the production of R&D-intensive goods. The United States and Pacific

OECD specialise in Agriculture which is R&D extensive. As a consequence, their sectoral spillovers are very modest.[30]

The negative sectoral spillovers in China and Sub-Saharan Africa in Table 5.2 can be explained in a similar way. These regions specialise in Consumer Goods and Agriculture, respectively, at the expense of R&D-intensive goods. So their regional R&D stocks decrease if trade liberalisation takes place. The sectoral spillovers for trade liberalisation are thus negative for these regions.

The size of the international spillovers can analogously be explained by the R&D content of the imports. These spillovers depend on the structure of the imports. Here the origin of imports is important as well as the sectoral composition. Table 5.4 illustrates this.

The importance of international R&D spillovers is determined by the R&D content of the imports. Column (3) in Table 5.4 shows the relative increase in the R&D content of the imports. It is very large for the Middle East, which explains the large international spillovers on GDP (see Table 5.2). The large increases in the R&D content of the imports in the United States and South Asia and Rest also lead to relatively high international R&D spillovers.[31]

The changes in the R&D content of the imports are affected by the changes in the regional and sectoral structure of the imports. The columns (1) and (2) present two indicators for these changes. Table 5.4 shows that regions tend to import less from the OECD, which has the highest R&D stocks. The reason is that trade liberalisation affects the relative consumer prices. Relative prices of products from non-OECD regions tend to become lower on average due to the elimination of import tariffs. Only Japan, Middle East and South-East Asia import relatively more from the OECD after trade liberalisation. This has a positive effect on the R&D content of the imports for these regions.

[30] The numbers in Table 5.3 are summary statistics. The first two columns in Table 5.3 provide an indication for the magnitudes in the third column. The latter presents the change in the R&D stock which also indicates a change in the sectoral spillovers. However, there is no one-to-one relation with column (3) in Table 5.2. For example, the sectoral spillovers for the United States are positive, while the relative change in the total R&D stock is negative. This can be explained by different R&D-stock elasticities between sectors.

[31] As the numbers in Table 5.3, the numbers in Table 5.4 are only indicators of the size of the international spillovers. A one-to-one mapping between the indicators and Table 5.4 is not possible because of different R&D-stock elasticities for sectors and regions.

Table 5.4 R&D content of imports due to trade liberalisation in 2020

region	Absolute change in share of OECD imports in total imports (1)	Relative change in R&D content of import of R&D int. sectors (2)	Relative change in R&D content of total imports (3)
United States	-5.4	24.1	22.2
Western Europe	-4.2	12.6	11.0
Japan	0.9	13.3	13.4
Pacific OECD	-7.7	5.3	4.8
Eastern Europe	-2.8	15.7	13.3
Former Soviet Union	-5.1	12.1	11.0
Latin America	-12.6	5.1	4.2
Middle East & N. Africa	7.8	51.5	46.2
Sub-Saharan Africa	-9.6	10.7	9.9
China	-3.5	8.3	9.5
South-East Asia	0.4	8.0	7.6
South Asia & Rest	-4.3	18.2	16.8

Source: WorldScan simulations.

The changes in sectoral structure of these imports are very important. All regions import relatively more R&D because they import relatively more R&D-intensive goods. Trade liberalisation stimulates particular trade in manufacturing products. The reason is that the fall in trade barriers in these sectors is larger than in Services and Raw Materials. In particular the United States and the Middle East import more of these goods, which leads to a considerable rise in the R&D content of the imports. So, although the sectoral spillovers in the United States are low, because it specialises in Agriculture, the international spillovers are high due to the increased imports of Energy-intensive Goods and Capital Goods. Table 5.4 thus shows that the international spillovers are high if regions import relatively much R&D-intensive goods and if imports originate from the OECD.

Above we have analysed the contribution of R&D and its spillovers to the effects of trade liberalisation. R&D magnifies the positive effects on GDP if the R&D content of the intermediate goods is high. This can be achieved in two ways. The first is that regions carry out a lot of R&D themselves. The second is that they import relatively much R&D-intensive goods. The analysis shows a trade off between specialising in R&D-intensive goods and importing these goods. Western Europe, Japan, Eastern Europe, Latin America and South-East Asia produce relatively much R&D-intensive goods. On the other hand, their R&D-import content is low. These regions thus have high sectoral spillovers compared to the international R&D spillovers (see Table 5.2).

The United States, Middle East, Sub-Saharan Africa, China and South Asia & Rest import relatively much R&D-intensive goods. The contribution of R&D to the GDP effects of trade liberalisation are mainly through international spillovers in these regions whereas they experience low or even negative effects related to the sectoral spillovers.

Wage inequality

In spite of the relatively large GDP effects of trade liberalisation, the relative wages of low-skilled workers are hardly affected in the OECD. Table 5.5 shows the effects of trade liberalisation on the ratio of wages of high-skilled workers to those of low-skilled workers.

Table 5.5 Impact of trade liberalisation on wages of high-skilled workers in 2020 relative to wages of low-skilled workers

region	no R&D (1)	own R&D (2)	sectoral R&D spillovers (3)	international R&D spillovers (4)	total (5)
United States	-0.7	-0.1	0.0	0.0	-0.8
Western Europe	1.2	0.1	0.0	0.0	1.3
Japan	2.2	0.1	0.1	0.0	2.3
Pacific OECD	-1.4	0.0	0.0	0.0	-1.4

Source: WorldScan simulations. Numbers are absolute changes in wage ratios. Columns (2) to (4) present additional effects to the previous column. Column (5) presents the total effect.

The columns in Table 5.5 distinguish the four different cases with and without R&D spillovers. The wage ratio of the four OECD regions is about 1.61 in the base simulation. The numbers in the table refer to absolute changes in this ratio. The effects of trade liberalisation on the labour markets are very modest in the simulation without R&D spillovers. In Western Europe and Japan the skill premium rises with 1 to 2% points. In the other two regions the skill premium decreases a bit, because those regions specialise in Agriculture. Lejour and Tang (2000) derive a similar result. The introduction of R&D and R&D spillovers in TFP exerts a very mild upward pressure on the skill premium in Western Europe and Japan, but this seems hardly significant. From this analysis we conclude that R&D spillovers do not significantly affect the position of low-skilled workers.

5.3 Sensitivity analysis

In this section we analyse the sensitivity of the results from the benchmark simulation to three different assumptions. First, we examine how sensitive the results are for the assumption that the R&D intensities in the non OECD remain at their current level. We analyse increasing intensities in the non OECD by implementing a relation between the R&D intensity and GDP per capita. Second, we analyse what the assumption implies that only the OECD does R&D. And finally, we check the robustness of our results for the size of estimated coefficients.

Increasing R&D intensities in the non OECD

So far we have assumed that the ratio of sectoral R&D expenditures to value added is constant in the simulation period. This seems to be reasonable for the developed regions, in which R&D expenditures do not vary substantially over time, but not for the developing regions. The analysis of the R&D data of the UNESCO (1998) shows that R&D intensities increase as countries become more wealthy (see Appendix A). According to this analysis, the ratio of regional R&D expenditures to value added rises by 0.4% points if per capita income doubles. We analyse the GDP effects of the spillovers once we introduce this relation in our simulations. The R&D intensity rises with 0.2% points in Sub-Saharan Africa to about 0.6% points in South-East Asia and China in the simulation period. In the benchmark simulations presented above some spillovers were negative because the R&D content of the intermediate inputs decreased in the presence of trade liberalisation. As the R&D intensities in the non-OECD regions increase, the R&D content of intermediate goods will increase. Table 5.6 shows the results in deviation from those in Table 5.2.

Column (4) shows that only the non-OECD regions are seriously affected compared to the case of constant R&D intensities in the non OECD. The effects on the OECD regions are negligible. In the non-OECD regions, the sectoral spillovers are much larger. The sectoral spillovers are positive for all regions. For all regions, except China, the total sectoral effect – the sum of the columns(2) in Table 5.2 and 5.6 – is positive. And for China this negative effect is much smaller now. The effects of the international spillovers are ambiguous. However, the changes are fairly small.

Table 5.6 **Deviations in the cumulative GDP effects of trade liberalisation due to increasing R&D intensities in the non OECD**

region	own R&D (1)	sectoral R&D (2)	international R&D (3)	total (4)
United States	0.0	0.0	0.0	0.0
Western Europe	-0.1	0.0	0.0	0.0
Japan	0.0	0.1	0.0	0.0
Pacific OECD	-0.1	0.0	0.2	0.1
Eastern Europe	0.0	0.3	0.1	0.3
Former Soviet Union	0.0	0.1	0.0	0.1
Latin America	0.0	0.5	0.2	0.7
Middle East & N. Africa	0.0	0.4	-0.2	0.2
Sub-Saharan Africa	0.0	0.4	0.2	0.6
China	0.3	0.5	0.2	0.9
South-East Asia	0.0	1.2	-0.1	1.1
South Asia & Rest	0.5	0.6	0.1	1.2

Source: WorldScan simulations. All results are presented in deviation from Table 5.2.

Only R&D in the OECD

It is often claimed that the OECD countries do nearly all the R&D in the world economy. Tables 3.2 and 3.3 underpin this view, with the exception of South-East Asia. As a second sensitivity analysis we consider trade liberalisation from that perspective, that is by assuming that non-OECD regions do no R&D at all. Bayoumi *et al.* (1999) carried out a similar simulation. It gives a clear view of the importance of the international spillovers for the developing economies if trade barriers are eliminated. Table 5.7 shows the results, again in deviation from Table 5.2 (the case in which the non-OECD performs R&D at constant R&D intensities). Column (1) shows the extra GDP effects if own R&D outlays raises TFP. Not surprisingly, the effects for the OECD regions do not change. For the non-OECD regions, there is a small effect on GDP. This is due to the fact that GDP gains in the non-OECD regions do no longer induce R&D investment.

Table 5.7 Cumulative GDP effects of trade liberalisation in 2020 with only R&D in the OECD

region	own R&D (1)	sectoral R&D spillovers (2)	international R&D spillovers (3)	total (4)
United States	0.0	-0.1	-0.1	-0.2
Western Europe	0.0	-0.1	-0.1	-0.2
Japan	0.0	-0.1	-0.1	-0.2
Pacific OECD	-0.1	-0.1	-0.6	-0.7
Eastern Europe	-0.2	-0.8	-0.3	-1.2
Former Soviet Union	0.0	0.0	-0.1	-0.2
Latin America	-0.2	-0.4	-0.6	-1.2
Middle East & N. Africa	-0.1	-0.1	-0.3	-0.5
Sub-Saharan Africa	0.0	0.6	-0.4	0.3
China	0.0	0.8	-0.4	0.3
South-East Asia	-1.4	-5.7	-0.2	-7.3
South Asia & Rest	-0.1	-0.1	-0.3	-0.5

Source: WorldScan simulations. All results are presented in deviation from Table 5.2**.**

The exiting results are presented in columns (2) and (3). First, take the sectoral R&D spillovers. The negative numbers for the OECD regions show that the GDP effects of sectoral spillovers are lower than in the case that the developing economies do also R&D. This is a consequence of the fact that the GDP gains from trade liberalisation are lower for the non-OECD regions. This exerts a downward pressure on the GDP gains for the OECD. Normally GDP gains in one region spill over to another region because of trade and capital flows. Now there are lower GDP spillovers from the non-OECD to the OECD, only the other way around they are substantial. The presence of sectoral R&D spillovers in the OECD and its accompanying GDP gains tend to raise the GDP gains of trade liberalisation in the non OECD but these are dominated anyhow by the absence of domestic sectoral spillovers in the non-OECD (as they perform no R&D in this analysis). Compared to Table 5.2 it appears that GDP increases in column (2) are negative in the non-OECD regions. Only non-OECD regions which specialise in R&D

intensive goods in the previous simulations have modest GDP gains now; examples are China and Sub-Saharan Africa.

The international R&D spillovers are smaller if the non-OECD regions perform no R&D. Trade liberalisation leads to increased trade between the OECD and the non OECD. Most regions import a relative larger share of their products from the non OECD now. These imports do not incorporate a R&D content now. Therefore, the GDP effects of international R&D spillovers are less positive. The international R&D spillovers for Pacific OECD and Latin America are even negative.

Column (4) presents the total effects of trade liberalisation. The picture is diverse. For all regions the international spillovers are lower. This is not the case for the sectoral spillovers, at least, for regions that do not specialize in R&D intensive products. Thus the gains from trade liberalisation are lower for most regions. The exceptions are China and Sub-Saharan Africa. If they where to rely on international R&D spillovers only, the gains from trade liberalisation would be higher, as the positive numbers in column (4) in Table 5.6 show.

Sensitivity to the estimated coefficients

The importance of the sectoral and international spillovers depends on the size of the R&D elasticities in the TFP function, see equation (1). We change these elasticities to get some idea of the sensitivity of changes in these elasticities on the GDP effects of trade liberalisation. In the benchmark simulations our starting point is the estimated elasticities in equation (8) of own R&D, sectoral R&D and international R&D are equal to 0.167, 2.636, and 0.618, see Table 3.5. These elasticities are modified such that the appropriate γs for every sector and region are implemented in the model. As a third sensitivity analysis we assume that the estimated elasticities for the sectoral and international spillovers are equal. We use a value of 1.674, the average of the estimated elasticities. So, the value of the two elasticities together does not change. If this value would change, it is clear beforehand that the GDP effects from trade liberalisation would change. Table 5.8 presents the deviations of the GDP effects of the simulations where the R&D elasticities are modified, compared to the simulations in Table 5.2. As only the GDP effects which are related to the sectoral and international spillovers are modified, Table 5.8 presents only these deviations and the deviations in the total GDP effect.

Table 5.8 Deviations of cumulative GDP effects of trade liberalisation in 2020 R&D elasticities are modified

region	sectoral R&D spillovers (1)	international R&D spillovers (2)	total (3)
United States	-0.1	0.5	0.4
Western Europe	-1.0	0.2	-0.7
Japan	-3.5	0.3	-3.2
Pacific OECD	-0.2	0.4	0.2
Eastern Europe	-0.4	1.1	0.7
Former Soviet Union	-0.1	0.4	0.3
Latin America	-0.3	0.6	0.3
Middle East & N. Africa	-0.2	3.3	3.1
Sub-Saharan Africa	0.1	1.1	1.2
China	0.2	1.4	1.5
South-East Asia	-2.5	1.8	-0.7
South Asia & Rest	-0.2	0.9	0.7

Source: WorldScan simulations. All results are presented in deviation from Table 5.2.

Not surprisingly, Table 5.8 shows that the effects of the sectoral spillovers are smaller, while those of the international spillovers are larger. Some GDP effects of the sectoral spillovers are reduced by 50%. Some GDP effects of international spillovers are more than doubled (compare column (2) of Table 5.8 to column (4) of Table 5.2). As a result, the total effects vary. The bottom line, however, is that the GDP effects of trade liberalisation induced by spillovers are larger for most regions.

The GDP effects are significantly larger for the United States, Former Soviet Union, the Middle East, Sub-Saharan Africa, China and South Asia & Rest. This is also what we expect. These regions acquire the positive R&D spillovers mainly by import as we showed before. The international R&D spillovers are relatively important for these regions. If the elasticity of these spillovers is increased, GDP effects of trade liberalisation also increase. For other regions, as Western Europe, Japan, and South-East Asia the sectoral spillovers are important, because they specialize in R&D-intensive industries. The TFP elasticity with respect to the sectoral spillovers decreases in this analysis whereas the elasticity with respect to international spillovers increases. The latter does not compensate the loss in sectoral spillovers, caused by the former, because those are more important for those regions than the international spillovers. The GDP gains of trade liberalisation are thus lower for these regions.

6. Conclusions

Do R&D and R&D spillovers provide a link between openness and growth? The answer to that question is affirmative according to our analysis. The introduction of R&D in our AGE model always increases the effect of trade liberalisation. The size of the effect depends heavily on specialisation patterns and changes of that pattern due to trade liberalisation. A more intense relation with one sector or region often implies a less intense relation with other sectors or regions. A change in the input of intermediate goods or trade pattern only raises productivity if it is a change towards R&D-intensive sectors or regions.

This is one of the main conclusions of this paper. Although R&D enlarges the benefits from trade liberalisation, the effects are region- and sector specific. Here the value added of our AGE model WorldScan comes in. It allows for regional and sectoral detail. Therefore, we can model inter- and intra-regional spillovers of R&D. Sectors and regions face a trade-off with respect to these spillovers. R&D spillovers can be obtained by producing R&D-intensive and spillover-intensive goods domestically or by importing them. In the former case the intra-regional (sectoral) spillovers are important. Regions which already have a comparative advantage in R&D-intensive sectors rely on this mechanism. As producing R&D-intensive goods turns out skill- and capital-intensive, the intra-regional spillovers are important for Western Europe, Eastern Europe and Japan. Other regions which specialize in Agriculture or that are not skill- and capital-rich obtain the R&D spillovers by the international linkages. For some regions the gains from trade liberalisation are even reduced by negative sectoral spillovers. In the process of trade liberalisation, these regions specialise in R&D-extensive products. As a consequence the R&D-intensive sectors move away to other regions.

This is no reason to restrict trade. The gains from trade liberalisation are still positive. A policy option is stimulating R&D. If regions increase R&D expenditures the negative spillovers of trade liberalisation decrease or even disappear. Our analyses showed that the sectoral spillovers then become more important. A policy which stimulates R&D not necessarily has to be directed to the R&D-intensive sectors. It makes sense to stimulate those sectors which produce goods that are often used as intermediate goods. However, as those goods are often imported, it could make more sense to target R&D-stimulating policy at those sectors which are often used domestically as intermediate goods such as services.

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Appendices

A. R&D data

R&D data for agriculture and mining.

ANBERD (OECD, 1999a) contains a full set of data for manufacturing sectors. The data for services are not completed by estimation. The data for other sectors, Agriculture and Mining are not introduced separately; they are for most countries included in the total industries. So ANBERD contains the sum of the two industries, not the division over the two sectors.

The Basic Science and Technology Statistics (BSTS, see OECD, 1998)) contains the date for both sectors separately (for most countries). The time-series are rather short. We use the 1990 division of the R&D expenditures, and apply that to the total time series available from ANBERD. Table A.1 contains the data for Agriculture and Mining from the BSTS and compares these with the sum of those sectors reported in ANBERD. If the deviation is smaller than 5% we use the BSTS division for ANBERD, otherwise we apply the same R&D intensity to both Agriculture and Mining. The first column of Table A.1 reports the numbers actually used (as far as they are obtained from BSTS).

Table A.1 R&D expenditures for mining and agriculture in BSTS and ANBERD in 1990

	share R&D in L to L and G	Agriculture (L) in BSTS	Mining (G) in BSTS	Sum of L and G in BSTS	Relative deviation of BSTS to ANBERD	Sum of L and G in ANBERD
Canada	0.19	29.8	124.5	154.3	0.1	154.2
Denmark[a]	--	0	0	0	--	-0.5
Finland	0	13.4	10.1	23.5	-446.1	128.3
France	0.78	925.7	265.2	1190.9	0	1191
W. Germany	0	48	344	392	-13.5	445
Italy[b]	1	3196		3196	0	3196
Japan	0.27	10880	29712	40592	-0.3	40700.2
Norway	0	87.2	647.3	734.5	-59.8	1173.4
Sweden	0	223.7	79.1	302.8	29	215
United Kingdom	0.37	67	115	182	0	182
Usa[c]	--			0	--	0

[a] Mining (=G) is estimated to be zero, agriculture (=L) is included in services

[b] In both databases 1990 has zeros for Agriculture and Mining

[c] Both Mining and Agriculture is included in services

Sectoral R&D data for OECD countries

Table A.2 R&D intensities for various countries at a sectoral level in 1990 (ISIC2 classification)

sectoral R&D	Agriculture	Raw Materials	Food, tobacco	Textiles	Wood	Paper
Canada	0.18	0.46	0.48	0.73	0.65	0.76
Denmark	0.50	0.00	1.40	0.43	0.26	0.23
Finland	0.42	0.42	2.71	1.17	0.90	2.05
France	0.42	0.88	0.94	0.40	0.17	0.27
Germany	0.93	0.93	0.43	0.64	0.67	0.34
Italy	0.00	0.00	0.26	0.04	0.04	0.01
Japan	0.10	2.65	1.91	3.52	0.00	2.57
Norway	0.97	0.97	1.46	0.89	0.75	0.68
Sweden	0.54	0.54	1.61	1.21	0.18	2.14
United Kingdom	0.75	1.01	1.32	0.27	0.33	0.34
United States	0.53	0.53	1.27	0.57	0.52	0.88

sectoral R&D	Chemicals. Rubbers, plas.	Stone and Clay	Basic Metals	Fabricated Metals	Other Man.	services
Canada	4.59	0.51	3.01	7.07	0.96	0.41
Denmark	8.92	1.95	4.69	5.65	13.36	0.50
Finland	9.10	2.06	3.79	7.75	0.68	0.32
France	7.61	1.59	2.52	11.08	0.89	0.17
Germany	8.12	1.63	1.02	9.34	1.29	0.12
Italy	5.80	0.24	1.58	5.89	0.27	0.13
Japan	12.88	4.92	4.70	10.64	0.36	0.12
Norway	7.44	0.00	6.87	8.78	0.28	0.34
Sweden	13.44	1.65	3.74	14.04	3.13	0.44
United Kingdom	12.09	1.28	0.63	11.06	0.69	0.48
United States	9.37	2.46	1.72	15.22	2.99	0.53

Source: OECD (1999a, 1999b) and own calculations.

Sectoral R&D intensities in WorldScan for the non-OECD

Table A.3 Sectoral R&D intensities in WorldScan for the non-OECD as ratio of sectoral value added

sectoral R&D intensities	Agriculture	Raw Material	Consumer Goods	Energy Goods	Capital Goods	Services	average
Eastern Europe	0.11	0.16	0.22	1.26	2.79	0.07	0.42
Former Soviet Union	0.12	0.19	0.25	1.45	3.22	0.08	0.49
Latin America	0.04	0.06	0.08	0.48	1.07	0.03	0.16
Middle East	0.08	0.12	0.16	0.94	2.10	0.05	0.32
Sub-Saharan Africa	0.08	0.12	0.17	0.96	2.13	0.05	0.32
China	0.05	0.07	0.10	0.58	1.29	0.03	0.19
South-East Asia	0.23	0.35	0.48	2.77	6.13	0.16	0.93
South Asia & Rest	0.05	0.07	0.09	0.55	1.21	0.03	0.18

Source: UNESCO (1998, 1999), OECD (1999a, 1999b) and own calculations.

Trend in R&D expenditures

In WorldScan we model the R&D stock as a capital stock: the current R&D stock in the previous period (corrected for depreciation) plus the outlays in the current period. These outlays are derived from an exogenous ratio of value added to R&D investment. Our analysis of the UNESCO (1998) data shows that low-income countries spend relatively less on R&D than high-income countries. Figure A.1 shows the correlation between the R&D expenditures /GDP ratio and log GNP per capita (Worldbank, 1997) for about 85 countries in 1995.

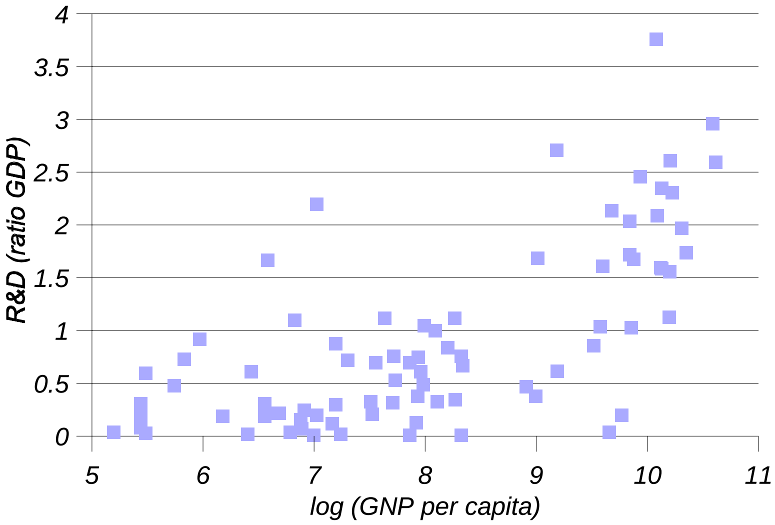

Figure A.1. R&D intensity and income per capita

From this figure we see a positive relationship between economic development (measured by GNP per capita) and expenditures on R&D. This relationship follows also from a simple OLS regression:

RD/GDP = -2.13 + 0.38 log (GNP per capita)
(0.41) (0.05)

This regression clearly shows that if GNP per capita doubles, the R&D-GDP ratios increases by 0.38% points.[32] So if low-income countries develop, their R&D-GDP ratio will increase substantially. We use this result in the sensitivity analysis reported on in the main text.

[32] Standard errors are reported between parenthesis. The adjusted R^2 is 0.45.

B. Sensitivity analysis for the regression results

This appendix contains two tables with regression results to corroborate the robustness of the findings in the main text. First, we present analogous regressions to those in the main text, but now for manufacturing only. The second table includes some regressions in 'levels'.

We re-evaluate the results for the manufacturing sectors only as we are mainly interested in international spillovers and the bulk of the international trade concerns the manufacturing sectors.[33]

Table B.1 OLS estimation results manufacturing. Dependent variable is ($\hat{TFP}$).†

Variable	(I) *Direct effect*	(II) *Direct + indirect effect*	(III) *Domestic and Total*	(IV) *Domestic and Foreign*
DD_M	$.158^{**}$	$.124^{*}$	0.096	$.162^{**}$
	[.069]	[.07]	[.073]	[.079]
ID_M		2.408^{**}	2.943^{***}	3.797^{***}
		[1.045]	[1.11]	[1.175]
TF_M			0.541	
			[.386]	
DF_M				0.107
				[.436]
IF_M				10.627^{**}
				[4.844]
R^2 (adjusted)	0.02	0.04	0.05	0.06
N	216	216	216	216

† Sample period is 1974-1991, 3 sectors and 4 regions. All regressions include a constant. The explanatory variables are lagged by one year. Standard errors are given in parentheses under the estimates. *, **, and *** denote statistical significance at the 10% level, the 5% level, and the 1% level, respectively.

[33] Excluding the Agriculture and Raw Materials sector too, is motivated by the fact that the R&D data for these results are far less reliable.

The results are not dramatically different from those in the main text, Surprisingly, the regression in column (IV) in Table B.1 indicates that for manufacturing sectors the indirect foreign spillovers are only important.

In Table B.2 we present analogous regressions to those in the main text, but now estimated in levels.

Table B.2 OLS estimation results aggregate model. Dependent variable is ln(TFP).†

Variable	(I) *Direct effect*	(II) *Direct + indirect effect*	(III) *Domestic and Foreign*
DD	.189***	.184***	.159***
	[.026]	[.025]	[.027]
ID		1.14***	1.538***
		[.378]	[.411]
TF			.410**
			[.173]
R^2 (adjusted)	0.78	0.78	0.78
N	456	456	456

† Sample period is 1973-1991, 6 sectors and 4 regions. All regressions include sector-specific constants and a time trend. Standard errors are given in parentheses under the estimates. *, **, and *** denote statistical significance at the 10% level, the 5% level, and the 1% level, respectively.

Columns (I) to (III) in Table B.2 are analogous to columns (I) to (III) in Table 3.5 in the main text. The estimations are based on: the integrated version of equation (8):

$$logF_{ikt} = ct + \beta^{DD}\sum_{\tau=0}^{t}\frac{RD_{ik\tau}}{Y_{ik\tau}} + \beta^{ID}\sum_{j\neq i}^{I}\omega_{ijk}\sum_{\tau=0}^{t}\frac{RD_{jk\tau}}{Y_{jk\tau}} + \beta^{F}\sum_{l\neq k}^{K}\sum_{i}^{I}n_{ijkl}\sum_{\tau=0}^{t}\frac{RD_{jk\tau}}{Y_{jk\tau}} + u_{ikt} \quad \text{(B.11)}$$

This is an expression in ‘levels’. Given our aim, we do not extensively discuss econometric issues related to the estimation of equations in levels with variables that are non-stationary.[34] The elasticities estimated here are somewhat lower than those in the main text. The coefficient on foreign R&D is now significant.

The results in the main text are not very sensitive for the lag structure – one year– we impose. We do not report these regressions. These are available upon request.

[34] Estimating variables that are individually non-stationary is possible if the combination of variables is cointegrating. That is, if a linear combination of the variables exists which, in a regression, yields a stationary error term. The t-statistics should however be interpreted with caution. Moreover, the robustness of the Coe and Helpman results to the estimation method is established by Engelbrecht (1997). Estimations in log difference yields similar and significant results to the estimation of the cointegrated relations. Kao, Chiang and Chen (1999) use modern panel cointegration techniques to redo the Coe and Helpman estimations and confirm most findings; most t-statistics turn out considerably lower (some are reduced by half).

C. Calibration

We want to introduce equation (1) in the model. Hence, we need to integrate equation (8) as we have estimated in growth rates and theory requires an implementation in levels.[35] Rewrite the right-hand side of equation (5) for the indirect spillovers as follows:

$$\frac{\sum_{h\neq i}^{I} \eta_{jik}\,\omega_{hik}\,R_{hk}}{R_{ik}^{ID}} \sum_{j\neq i}^{I} \frac{\eta_{jik}\omega_{jik}\,R_{jk}}{\sum_{h\neq i}^{I} \eta_{jik}\,\omega_{hik}\,R_{hk}} \hat{R}_{jk} \;, \tag{C.1}$$

and integrate this expression and substitute the result in (1) to obtain:

$$F_{ikt} = A_{ikt}\left(R_{ikt}^{DD}\right)^{\gamma_{ik}^{DD}} \left(\sum_{j\neq i}^{I} \eta_{jik}\omega_{jikt}\,R_{jkt} \right)^{\gamma_{ik}^{ID}} \left(R_{ikt}^{F}\right)^{\gamma_{ik}^{F}} . \tag{C.2}$$

The corrected estimated coefficient is sector specific, namely:

$$\gamma_{ik}^{ID} = \beta^{ID} \frac{\sum_{h\neq i}^{I} \eta_{jik}\,\omega_{hik}\,R_{hk}}{R_{ik}^{ID}} = \beta^{ID} \sum_{h\neq i}^{I} \omega_{hik}\,\frac{R_{hk}}{Y_{hl}}. \tag{C.3}$$

One can follow an analogous procedure for the own R&D stock and the foreign R&D stock.

[35] We use the equation in levels to allow for effective spillovers that are affected by changing trade patterns. In practice, we do allow the international trade pattern to vary in the simulations. The IO relations, relevant for R&D spillovers, are kept at the baseline level in the policy experiments.

D. Simulations results without deprecation of the R&D stock

Table D.1 Cumulative GDP effects of trade liberalisation in 2020 without depreciation

region	own R&D (2)	sectoral R&D spillovers (3)	international R&D spillovers (4)	relative GDP increase due to R&D (5)
United States	0.1	0.5	0.7	83.6
Western Europe	0.6	3.1	0.2	227.5
Japan	1.4	10.5	0.3	524.2
Pacific OECD	0.3	0.6	-0.4	13.0
Eastern Europe	0.3	1.3	1.2	55.2
Former Soviet Union	0.2	0.3	0.4	53.8
Latin America	0.4	0.9	-0.1	12.7
Middle East & N. Africa	0.4	0.6	5.0	125.1
Sub-Saharan Africa	0.1	-0.4	0.8	11.4
China	0.2	-0.7	1.2	4.4
South-East Asia	1.8	7.8	2.7	82.5
South Asia & Rest	0.2	0.4	0.8	9.0

Source: WorldScan simulations.

If one compares the results in Table D.1 with Table 5.2 in the main text it follows that the GDP effects of trade liberalisation are in general larger. This is in particular the case for those regions in which the extra effects of incorporating R&D are fairly large in the benchmark simulation; the ones with large sectoral R&D spillovers.

E. Regional and sectoral concordances for WorldScan

Regions	Sectors
1 United States 2 Japan 3 Western Europe United Kingdom, Germany, Denmark, Sweden, Finland, Rest of European Union, EFTA 4 Pacific OECD Australia, New Zealand, Canada 5 Eastern Europe 6 Former Soviet Union 7 Middle East and North Africa Turkey, Rest of Middle East, Morocco, Rest of North Africa 8 Sub-Saharan Africa South African Customs Union, Rest of Southern Africa, Rest of Sub-Saharan Africa 9 Latin America Central America and Carribean, Mexico, Argentina, Brazil, Chile, Uruguay, Venezuela, Colombia, Rest of South America 10 China China, Hong Kong 11 South-East Asia Republic of Korea, Indonesia, Malaysia, Philippines, Singapore, Thailand, Taiwan, Vietnam 12 South Asia & Rest India, Sri Lanka, Rest of South Asia, Rest of the World	1 Agriculture and food production Paddy rice, Wheat, Grains, Cereal Grains, Non grain crops, Vegetables, Oil seeds, Sugar cane Plant-based fibres, Crops, Bovine cattle, Animal products, Raw milk, Wool, Forestry, Fisheries, 2 Raw Materials Oil, Gas, Coal, Minerals 3 Consumer goods Processed rice, Meat products, Vegetable Oils, Dairy products, Sugar, Other food products, Beverages and tobacco, Textiles, Wearing Apparels, Leather etc, Wood products, Rest of manufacturing 4 Energy-intensive goods Pulp paper, Petroleum and coal, Nonmetallic minerals, Ferrous metals, Nonferrous metals, Chemical, rubbers and plastics 5 Capital goods Fabricated metal products, Transport industries, Machinery and equipment, Electronic equipment, Motor vehicles and parts. 6 Services Electricity, Gas manufacture and distribution, Water, Construction, Financial, business and recreational services, Public administration, education and health, Dwellings 7 Trade and Transport Trade and Transport

Abstract

Research and development (R&D) raises not only the own technology levels, but also that in other sectors and abroad. We examine the trade-related diffusion of R&D in three steps. First, using OECD and UNESCO data we provide an overview of global R&D expenditures. Second, we estimate the relation between sectoral R&D expenditures and growth. Finally, these R&D linkages are incorporated in WorldScan: a dynamic applied general equilibrium model for the world economy. We simulate trade liberalisation and analyse the effects on GDP in different regions. We find that the GDP effects of trade liberalisation are magnified considerably for some regions - - notably Japan and South-East Asia - - where for others - - for example China and Sub-Saharan Africa - - the GDP effects are not blown up at all. These findings can be traced back to changing specialization patterns and changing import patterns. A region either specialises in R&D-intensive sectors or imports R&D-intensive goods. Some regions import the knowledge-intensive goods from knowledge-poor regions. Such a ‘double unfortunate’ trade and production pattern explains the results for Sub-Saharan Africa and China.