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GROWTH AND THE INTERNATIONAL TRANSMISSION OF BUSINESS CYCLES*

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Two-country single-good real business cycle models predict that the cross-country correlation of output is smaller than the cross-country correlations of consumption and productivity, in contrast to the evidence in historical samples. The objective of this paper is to reproduce the observed empirical evidence in a two-country real business cycle model with endogenous growth. Central features of the model include a nonmarket sector and international externalities in production. The model generates realistic cross-country correlations for output, consumption, and productivity with standard parameter values.

1. INTRODUCTION

Two-country single-good real business cycle models, such as those presented in Backus et al. (1992) and Baxter and Crucini (1993), predict that the cross-country correlation of output is smaller than the cross-country correlations of consumption and productivity. This is contrary to the evidence found in postwar samples for industrialized economies. This counterfactual ranking of cross-country correlations suggests that single-good models possess the wrong mechanism for transmitting shocks across countries.

The objective of this paper is to explain the international transmission of shocks and the observed ranking of cross-country correlations in a two-country endogenous growth model. The two central features of the model are, 1) international externalities in production that are large enough to generate sustained growth, and 2) nontraded goods in the form of household or nonmarket production.

The study of the international transmission of shocks in this framework is interesting for two reasons. First, the model provides a natural detrending mechanism: the model produces difference stationary processes and, accordingly, the

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analysis uses log-differenced data (growth rates). Second, and more importantly, the model permits the study of spillovers from the international mobility of knowledge. The model is akin to Romer (1986) in that knowledge is a byproduct of accumulated investment and research activities, and is an external benefit of the production process. Grossman and Helpman (1991) suggest that the international flow of knowledge is a central factor in the determination of worldwide growth. This paper suggests that the international flow of knowledge is a central factor in explaining the existence of worldwide productivity shocks.

The model also introduces a second and nontraded sector to the single-good model. The specific form of nontraded goods comes from household or nonmarket production, as in Benhabib et al. (1991). This form is worth studying for at least three reasons. First, Benhabib et al. (1991) demonstrate that this addition to the closed-economy model reduces the volatility of investment, which tends to be too large in two-country models. Second, nonmarket production is not recorded in national accounts, and thus provides the structure underlying the concept of taste shocks used in Stockman and Tesar (1995) to explain low cross-country consumption correlations. Finally, Benhabib et al. (1991) show that the substitutability between market and nonmarket activities explains many features of observed labor markets. The inability of single-good models to predict cross-country correlations that are larger for output than for productivity can be attributed to labor markets, because single-good models generate cross-country employment correlations that are negative.

Simulation results suggest that the substitutability between market and nonmarket activities is responsible for an international synchronization of labor markets. Following a productivity shock in the domestic market sector, mobile factors of production are reallocated across sectors and countries. This reallocation affects knowledge, so that shocks are internationally transmitted via the market productive externality, even if these shocks are internationally uncorrelated. The sectoral reallocation from nonmarket to market sectors in each country negates the international reallocation from foreign to domestic country, such that employment is highly positively correlated across countries. The model thus generates positive cross-country correlations of output, productivity, and employment. The cross-country correlation of output is larger than the cross-country correlation of productivity, because employment is positively correlated across countries. Finally, shocks to nonmarket production greatly reduce the cross-country correlation of consumption.

The model involves externalities and nontraded goods, which are standard elements in growth theory and international economics. These are relevant elements in industrialized economies. First, empirical evidence can be found in Caballero and Lyons (1990, 1992) for externalities in production, and in Eisner (1988) for nonmarket production. Results in Caballero and Lyons (1990, 1992) suggest the presence of external economies in industry-level productions for the United States and for four European countries.[2] Studies reviewed in Eisner (1988) for the United States

[2] Cohen (1990) criticizes those studies on the ground that only external economies that are internal to country boundaries are considered; he argues that these external effects transcend country boundaries.

suggest that the nonmarket sector represents 20 to 50 percent of market gross national product (GNP). Second, these elements have been included in closed-economy real business cycle models by Baxter and King (1991) for productive externalities, and by Benhabib et al. (1991) for nonmarket production. These studies show that productive externalities and nonmarket production improve the standard model along several directions and that the resulting models generate more accurate business cycle predictions. Finally, knowledge spillovers and nonmarket goods share characteristics with other elements used in studies of two-country models. Knowledge spillovers associated with productive externalities give rise to interdependencies that are similar to those considered in Canova (1992), Costello and Praschnik (1993), and Head (1993). In these studies, trade in productive inputs is used to explain cross-country output correlations. Nonmarket goods are similar to nontraded goods, as in Leme (1984), Backus and Smith (1993), Tesar (1993), and Stockman and Tesar (1995). In these studies, nontraded goods are used to explain cross-country consumption correlations.

The rest of the paper is organized as follows. Section 2 compares the ranking of cross-country correlations produced in standard two-country single-good real business cycle models to the ranking observed in postwar samples from eight OECD economies. Section 3 introduces the two-country endogenous growth model with a nonmarket sector and discusses its benchmark calibration. Section 4 presents the evaluation method and compares the simulated cross-country correlations generated from the benchmark model to those from a single-good model and a standard nontraded goods model. Section 5 concludes.

2. CROSS-COUNTRY CORRELATIONS

Two-country single-good real business cycle models with complete international financial markets, such as those presented in Backus et al. (1992) and Baxter and Crucini (1993), are plagued by a cross-country correlation puzzle. This puzzle refers to the difference between the ranking of cross-country correlations produced in theoretical economies and those observed in historical samples: cross-country correlations of output are smaller than cross-country correlations of consumption and productivity in theoretical economies while being larger in historical samples.

Table 1 presents cross-country correlations for annual growth rates of output, consumption, productivity, employment, and investment between the United States and seven industrialized countries over the 1960–1991 period. Productivity is computed as in Backus et al. (1992).[3] The observed cross-country correlations of output are larger than those of consumption in six of the seven cases and larger than those of productivity in three of the seven cases. Similar evidence is reported in Devereux et al. (1992) for consumption and in Costello (1993) for productivity.[4]

This evidence contrasts with predictions from two-country single-good real business cycle models. First, these models typically produce simulated cross-country

[3] Details are given in the Appendix.

[4] This evidence is robust to detrending methods: Backus et al. (1992) reach similar conclusions using Hodrick-Prescott filtered data.

TABLE 1
CROSS-COUNTRY CORRELATIONS OF ANNUAL GROWTH RATES*

	Correlation with Same U.S. Variable				
Country	Output	Consumption	Productivity	Employment	Investment
Canada	0.84	0.66	0.82	0.70	0.30
Germany	0.48	0.31	0.48	0.28	0.29
France	0.54	0.50	0.47	0.31	0.34
U.K.	0.62	0.48	0.52	0.49	0.42
Italy	0.34	−0.03	0.43	−0.14	0.10
Japan	0.34	0.41	0.44	−0.04	0.24
Sweden	0.23	0.21	0.33	0.12	0.25

* Data are from the *OECD National Accounts Volume I: Main Economic Indicators*, and the *Bureau of Labor Statistics: Comparative Labor Statistics*. Sample period is 1960–1991. Entries refer to log-differenced per capita data. For details, consult the Appendix.

consumption correlations that are much larger than simulated cross-country output correlations, because international financial markets are assumed to be complete. These financial markets ensure a high degree of international risk sharing: consumers engage in assets trade until their marginal utilities of consumption are equated. If consumption and leisure choices are separable, consumption variations are perfectly correlated across countries. For reasonable nonseparabilities between consumption and leisure, the cross-country correlation of consumption is very large: the benchmark calibration produces a cross-country consumption correlation of 0.88 in Backus et al. (1992) and of 0.97 in Baxter and Crucini (1993).[5]

Second, these models generate cross-country productivity correlations that are systematically larger than cross-country output correlations, because of an international reallocation of resources. For example, a positive technology shock in the domestic economy induces an increase in (expected) domestic returns, wage rate and rental rate, and stimulates domestic employment and investment. If shocks are imperfectly correlated across countries, foreign employment and investment are reduced in favor of domestic employment and investment, because expected returns are higher in the domestic economy. The negative cross-country employment correlation then ensures that productivity is more correlated across countries than output.

This account suggests some extensions to the two-country single-good model. First, different transmission mechanisms for shocks across countries must be identified and, second, the solution must involve labor market elements. These extensions must also be consistent with low cross-country consumption correlation. The model developed in the next section attempts to include some of these elements. It introduces an endogenous transmission of technology shocks across countries via productive externalities. Also, it uses nonmarket production to explain low cross-country consumption correlation and give a better account of labor markets.

[5] Devereux et al. (1992) use nonseparabilities between consumption and leisure in a model of unbalanced growth to explain low cross-country consumption correlations; they obtain a consumption correlation of 0.24. Unbalanced growth models, however, are uncommon in this literature.

3. A TWO-COUNTRY MODEL OF ENDOGENOUS GROWTH

3.1. *The Model.* The analysis uses a two-country version of the stochastic growth model. The model has two main features. One, the model has endogenous growth as in Romer (1986) and Hercowitz and Sampson (1991). Two, the model contains a nonmarket production sector as in Benhabib et al. (1991).

Each country is inhabited by a large number of identical households and identical firms. Populations of both countries are equal and constant. Each country can thus be represented by a single identical and infinitely-lived consumer. Each country produces the same set of goods; a market-oriented output and a nonmarket output. The technology to produce these goods is identical in both countries up to country-specific shocks in both production technologies. Labor and installed capital are mobile across sectors, but immobile across countries. The countries are labelled 1 and 2, and indexed by i.

Preferences. Following Benhabib et al. (1991), preferences in country i are represented by the following expected lifetime utility function:

$$E_0 \sum_{t=0}^{\infty} \beta^t U\left(C_{mt}^i, C_{nt}^i, N_{mt}^i, N_{nt}^i\right), \tag{1}$$

where C_{mt}^i and C_{nt}^i are consumption of market and nonmarket goods, and N_{mt}^i and N_{nt}^i are time devoted to market and nonmarket activities. Momentary utility takes the following functional form:

$$U\left(C_{mt}^i, C_{nt}^i, N_{mt}^i, N_{nt}^i\right) = \omega \ln\left(C_t^i\right) + (1-\omega)\ln\left(L_t^i\right), \tag{2}$$

where C_t^i is a composite consumption good and L_t^i is leisure. The composite C_t^i is a constant elasticity of substitution (CES) aggregate over consumption of market and nonmarket goods:

$$C_t^i = \left(\lambda C_{mt}^{i\mu} + (1-\lambda) C_{nt}^{i\mu}\right)^{1/\mu}. \tag{3}$$

Leisure has the usual definition:

$$L_t^i = 1 - N_{mt}^i - N_{nt}^i. \tag{4}$$

Production technologies. Two technologies are used; one for production in the market sector and one for production in the nonmarket sector. The market sector production function is Cobb-Douglas:

$$\begin{aligned} Y_t^i &= F\left(K_{mt}^i, H_{mt}^i N_{mt}^i; A_{mt}^i\right), \\ &= A_{mt}^i \left(K_{mt}^i\right)^{\alpha} \left(H_{mt}^i N_{mt}^i\right)^{1-\alpha}, \end{aligned} \tag{5}$$

where K_{mt}^i is the level of physical capital used in market production, H_{mt}^i is an index of the specific knowledge used in this industry, so that $H^i_{mt}N^i_{mt}$ represents the effective labor input or the human capital of the market sector, and A^i_{mt} is a technology shock.

The nonmarket sector technology uses the same functional form:

$$X^i_t = G\left(K^i_{nt}, H^i_{nt}N^i_{nt}, A^i_{nt}\right), \tag{6}$$

$$= A^i_{nt}\left(K^i_{nt}\right)^{\eta}\left(H^i_{nt}N^i_{nt}\right)^{1-\eta},$$

where K^i_{nt} and $H^i_{nt}N^i_{nt}$ are the level of physical and human capital used in nonmarket production, and A^i_{nt} is a technology shock.

Technology shocks are described by the following stochastic structure:

$$A^i_{jt} = A_j \exp\left(\theta^i_{jt}\right),$$

where $j = m$ or n. The stochastic parts are assumed to follow a first-order autoregressive process:

$$\theta_{t+1} = \Gamma\theta_t + \epsilon_{t+1}, \tag{7}$$

where $\theta_t = (\theta^1_{mt}, \theta^2_{mt}, \theta^1_{nt}, \theta^2_{nt})'$. The vector ϵ_t is i.i.d. normal with variance Σ.

Knowledge. Knowledge is assumed to be sector-specific. The motivation for this assumption is that the market sector enjoys links with the rest of the world that are not shared by the nonmarket sector. Following Romer (1986), knowledge in the market sector grows proportionally to the level of physical capital used in that industry, as a byproduct of the investment and production activities, and is equal to the average physical capital stock across firms in that industry. For example, knowledge in the market sector of country 1 is a weighted sum of physical capital applied to market production in both countries:

$$H^1_{mt} = \tau K^1_{mt} + (1-\tau)K^2_{mt}, \tag{8}$$

where τ describes knowledge spillovers across countries. Knowledge in the nonmarket sector is country-specific and is proportional to the physical capital stock used in that sector:

$$H^i_{nt} = K^i_{nt}. \tag{9}$$

Investment. Investment is a market activity; the physical capital stock is built using market goods only. Nonmarket production is nonstorable and, consequently, is not considered for investment. As in Benhabib et al. (1991), physical capital is mobile between market and nonmarket activities:[6]

$$K^i_t = K^i_{mt} + K^i_{nt}. \tag{10}$$

[6] An alternative assumption is that capital be immobile across sectors. However, a considerable reallocation of capital is achieved by not replacing depreciated capital (see Benhabib et al. 1991).

The aggregate physical capital stock evolves according to the usual accumulation function:

$$K_{t+1}^{i} = I_t^{i} + (1-\delta)K_t^{i}, \tag{11}$$

where δ is a depreciation rate.

International financial markets. International financial markets offer a complete set of contingent claims that allows consumers in each country to insure their income against adverse realizations of productivity shocks before they are known. For simplicity, international financial markets offer one-step ahead state-contingent securities. Denote $B^i(S_{t+1})$ to be the net amount of period $t+1$ market goods that the consumer purchased at t, for a price of $P(S_{t+1}, S_t)$, contingent on the economy being in state S_{t+1} next period.

Market clearing. Finally, markets must clear. The feasibility of the allocations of labor and physical capital is ensured by (4) and (10). Market clearing of market sectors requires that output is either consumed or invested:

$$\sum_{i=1}^{2} Y_t^{i} = \sum_{i=1}^{2} C_{mt}^{i} + \sum_{i=1}^{2} I_t^{i}. \tag{12}$$

Market clearing of the nonmarket sector in both countries requires that output is consumed:

$$C_{nt}^{i} = X_t^{i}. \tag{13}$$

Finally, market clearing for financial markets requires that for all states, what one consumer borrows another lends:

$$\sum_{i=1}^{2} B^{i}(S_t) = 0. \tag{14}$$

3.2. *The Competitive Equilibrium.* The model has knowledge as an externality to the production process, so that the competitive equilibrium will not be Pareto efficient. To solve for the competitive equilibrium, the complete choices of households and firms in both countries must be specified.[7]

The competitive equilibrium consists of an allocation

$$\{C_{mt}^{i}, C_{nt}^{i}, N_{mt}^{i}, N_{nt}^{i}, K_{mt}^{i}, K_{nt}^{i}, B^{i}(S_t)\}$$

and prices

$$\{W_t^{i}, R_t^{i}, P(S_t, S_{t-1})\}$$

[7] Greenwood and Huffman (1992) give proofs of existence and uniqueness of the competitive equilibrium for the type of economies considered here.

such that:

(i) Households in both countries choose how much to consume of every good, how to allocate hours and capital to both activities, how much to invest, and how many claims to buy to maximize their expected lifetime utility, taking the dynamic evolution of knowledge and prices as given;
(ii) Firms choose how much to use of capital and labor to maximize profits, taking knowledge and prices as given;
(iii) Goods, factors, and loans markets clear.

Solutions to the consumer's problem and to the firm's problem are presented in the Appendix. The model is solved numerically using log-linear approximations of the first-order conditions, as in King et al. (1987).

3.3. *Benchmark Calibration.* The benchmark calibration is based on the deterministic balanced growth path of the symmetric equilibrium of the model. The method of calibration follows that of Benhabib et al. (1991). The model has been calibrated to reflect the properties of annual growth rates during 1960–1991, as reported in Table A1 of the Appendix.

Along the balanced growth path, the steady-state values of the gross output growth rate, g, and the gross risk free rate, R^f, are related by $g = \beta R^f$, because of logarithmic preferences. The net output growth rate is calibrated using output growth rates presented in Table A1: the average net output growth rate is 2.80 percent. The steady-state risk free rate is calibrated using the United States real returns for the period 1800 to 1990 documented in Siegel (1992). He estimates the real long return, using bonds that have a maturity ranging from 2 to 20 years, to be between 3.36 percent (geometric mean) and 3.71 percent (arithmetic mean). He also estimates the real short return, using 90 day commercial paper, to be between 2.95 percent (geometric mean) and 3.13 percent (arithmetic mean). For the benchmark calibration, the gross output growth rate and the gross risk free rate have been fixed at $g = 1.0280$ and $R^f = 1.0336$: this implies a value for the subjective discount factor of $\beta = 0.995$.

Production in the nonmarket sector occupies between 25 and 28 percent of a worker's discretionary time, according to data from the Michigan Time Use Survey (see Benhabib et al. 1991, and Greenwood et al. 1995). In comparison, production in the market sector occupies 33 percent of discretionary time. Preference parameters are endogenously set to $\lambda = 0.43$ and $\omega = 0.58$ to ensure that $N_m = 0.33$ and $N_n = 0.25$ along the balanced growth path.

The main parameters in the production function are the Cobb-Douglas shares of capital; α and η. The value of α is chosen to be 0.36 to facilitate comparison with other studies (see Benhabib et al. 1991 and Backus et al. 1992). Choosing a value for η is more problematic, because there is no real evidence on which to base that parameter. Benhabib et al. (1991) choose to interpret the stock of capital in the nonmarket sector as household equipment and furniture: a value of $\eta = 0.08$ is used to obtain that 12 percent of a country's capital stock is in the nonmarket sector.[8] The benchmark calibration also uses a value of $\eta = 0.08$.

With a depreciation rate of 10 percent per annum, the level parameter A_m is set to ensure the equality between real returns and marginal product of capital: $R^f = \alpha A_m N_m^{1-\alpha} + 1 - \delta$, where the implied value for A_m is 0.75. The level parameter A_n is set to reproduce the observed relative size of the nonmarket sector. Results documented in Eisner (1988) suggest that production of the nonmarket sector represents 20 to 50 percent of measured market gross national product (GNP). Benhabib et al. (1991) calibrate their model such that output from the nonmarket sector is 26 percent of market GNP. This share is used for the benchmark calibration: a value of $A_n = 2.95$ ensures that output of the nonmarket sector is 26 percent of market GNP along the balanced growth path.

The values for μ that describes the substitutability between consumption of market and nonmarket goods, for τ that describes the international mobility of knowledge, and for the matrices Γ and Σ that describe the stochastic structure of technology shocks are discussed below. Generally, the matrices of parameters Γ and Σ are set to reproduce the stochastic structure of observed Solow residuals. Productivity in the nonmarket sector, however, is difficult to assess, and, because of productive externalities, technology shocks in the present model do not coincide with standard notions of Solow residuals. The elasticity of substitution and the correlation of within-country sectoral shocks must be calibrated jointly, because the importance of the nonmarket sector depends on the opportunities for substitution between market and nonmarket activities. Similarly, the spillovers in productive externalities and the cross-country correlation of shocks must be calibrated jointly, because the importance of international spillovers depends on the international mobility of knowledge and the existence of worldwide technology shocks.

To parametrize the within-country stochastic structure of sectoral shocks, a sensible approach is to follow Benhabib et al. (1991). They assume that market and nonmarket sectors are subject to shocks of similar amplitudes. Shocks are represented by

$$\theta_{j,t+1} = \rho_j \theta_{j,t} + \epsilon_{j,t+1},$$

with $j = m$ or n and where $\epsilon_{j,t+1}$ is i.i.d. normal with standard deviation σ_j. They set the autocorrelation coefficients to $\rho_m = \rho_n = 0.95$ and the standard deviations to $\sigma_m = \sigma_n = 0.007$. Also, the elasticity of substitution between consumption of market and nonmarket goods, $1/(1-\mu)$, and the correlation between sectoral innovations, $\gamma = \text{corr}(\epsilon_m, \epsilon_n)$, are parametrized as follows: first, a high degree of substitutability is assumed, $\mu = 0.8$, and second, a large innovation correlation is assumed, $\gamma = 0.67$. Finally, off-diagonal within-country elements of Γ are set to 0.

[8] Greenwood et al. (1995) interpret the nonmarket capital stock more broadly to include residential structures and, thus, use a value of $\eta = 0.32$. This definition is not adopted for the benchmark calibration, because this reduces the share of consumption from 62 to 41 percent of market output.

These values are adopted for the benchmark calibration with the following changes. First, formal estimations in Benhabib et al. (1991) and in McGrattan et al. (1993) obtain values of $\mu = 0.6$ and $\mu = 0.4$: μ is set to 0.5, the average of these estimates. Second, the empirical evidence in McGrattan et al. (1993) suggests that the correlation between market and nonmarket shocks is much lower than 0.67 and could be null. Benhabib et al. (1991) argue that their results are robust to changes in this correlation; they consider a range of 0.5 to 0.75. For the benchmark calibration, γ is set at the lower bound of the range considered by Benhabib et al. (1991): $\gamma = 0.5$.[9]

To parametrize the cross-country stochastic structure of shocks, an extension of Benhabib et al. (1991) is considered. First, the off-diagonal cross-country elements of Γ are set to 0, as the off-diagonal within-country elements have already been set to 0. Second, to emphasize the innovation of this paper, only spillovers coming from the international mobility of knowledge are considered: the cross-country correlation of shocks to the market sector is restricted to $\psi = \text{corr}(\epsilon_m^1, \epsilon_m^2) = 0$. The purpose is to obtain a high cross-country correlation for productivity and output using only the endogenous transmission mechanism offered by the externality. A sensible point of departure is to assume perfect mobility of knowledge, such that knowledge to produce market goods is identical in both countries: $\tau = 0.5$. Finally, off-diagonal cross-country elements of Σ are set to 0.

4. SIMULATION RESULTS

4.1. *The Evaluation Method.* The method used to describe and evaluate the model is taken from Gregory and Smith (1991). The model is a completely defined data generating process that can be used to compute the distribution of a vector of moments ϑ. To approximate the sampling distribution of ϑ, R samples of length N are drawn, and for each sample $\hat{\vartheta}_N$ is computed. If R is sufficiently large, the empirical distribution of the vector of simulated moments can be used to approximate the necessary sample distribution.

The analysis is concerned with testing the ability of the model to explain the observed ranking of cross-country correlations. Using simulated samples of size equal to observed samples ($N = T$), the probability that the model replicates the observed ranking of cross-country correlations is computed as the proportion of samples for which the model produces cross-country correlations of output that are larger than the cross-country correlations of consumption and productivity. Calculations are based on $N = T = 30$ and $R = 1000$.

4.2. *Simulation Results*: *Cross-Country Correlations*. Table 2 presents the simulated cross-country correlations of output, consumption, productivity, employment, and investment. It also reports the probability (p-value) that the ranking of

[9] In Section 4, a parallel is drawn between the nonmarket sector and a standard nontraded sector. In the nontraded goods literature, shocks to traded and nontraded sectors are assumed to be positively correlated. For example, Stockman and Tesar (1995) use a correlation of 0.46, which is close to the value of 0.50 used here.

TABLE 2
SIMULATED CROSS-COUNTRY CORRELATIONS OF GROWTH RATES*

Model	Output	Consumption	Productivity	Employment	Investment	p-value
Single-Good Models						
Worldwide shocks	−0.44	1.00	−0.24	−0.69	−0.97	0.00
Perfect mobility	−0.68	1.00	−0.54	−0.84	−0.99	0.00
Nonmarket Goods Models						
Substitutes						
Worldwide shocks	0.48	0.56	0.33	0.59	−0.59	0.01
Perfect mobility⁺	0.50	0.53	0.27	0.65	−0.97	0.39
Investment costs	0.52	0.50	0.44	0.60	−0.48	0.64
Complements						
Worldwide shocks	0.22	0.74	0.45	−0.31	−0.09	0.00
Perfect mobility	−0.26	0.26	−0.03	−0.62	−0.69	0.00
Nontraded Goods Models						
Substitutes						
Worldwide shocks	0.23	1.00	0.24	0.36	−0.59	0.00
Perfect mobility	0.11	1.00	0.19	−0.12	−0.97	0.00
Complements						
Worldwide shocks	0.40	1.00	0.51	−0.13	−0.09	0.00
Perfect mobility	−0.11	1.00	0.02	−0.59	−0.69	0.00

* Statistics are based on log-differenced data. Entries are the average over 1000 simulations of 30 periods each. p-value is the proportion of samples that replicate the observed ranking of the cross-country correlations of consumption, output, and productivity.

⁺Benchmark calibration. Parameters for the alternative economies are as in the benchmark case with the following changes: single-good models, $\mu = \eta = N_n = A_n = 0.0001$; worldwide shocks, $\tau = 0.999$ and $\psi = 0.60$; complements, $\mu = -1.00$; and investment costs, $\xi = 0.067$ and $A_i = 0.87$.

the simulated cross-country correlations of consumption, output, and productivity replicates the observed ranking.[10] Table 2 presents these statistics for three different models; a single-good model, a nonmarket goods model, and a nontraded goods model. Unless otherwise indicated, these models use the general parameters of the benchmark calibration discussed in Section 3. The benchmark calibration corresponds to the nonmarket goods model with perfect knowledge mobility and is highlighted with a ⁺ in the table.

For all three models, simulation results are reported for two mechanisms to internationally transmit market technology shocks. The first mechanism is based on worldwide market technology shocks, as in Backus et al. (1992), and the second is based on perfect knowledge mobility, as in the benchmark case. Worldwide shocks cases assume immobile knowledge ($\tau = 1$) with cross-country correlated technology shocks to the market sector.[11] Perfect mobility cases assume perfect knowledge

[10] Other moments of interest appear in the Appendix, Table A2.

[11] When $\tau = 1$, production technologies are homogeneous to degree 1 in domestic capital and of degree 0 in foreign capital, so that the marginal product of capital is independent of capital. Then, the equalization of expected returns from capital accumulation does not ensure a determinate distribution of capital across countries. To ensure a determinate distribution of capital, τ is set at 0.999.

mobility ($\tau = 0.5$) with internationally uncorrelated technology shocks to the market sector. For worldwide shocks cases, the cross-country correlation of market technology shocks, $\psi = \text{corr}(\epsilon_m^1, \epsilon_m^2)$, is chosen to generate a cross-country productivity correlation close to the one obtained in the benchmark case. A value of $\psi = 0.60$ in the nonmarket goods model with worldwide shocks generates an average cross-country productivity correlation of 0.33, while the benchmark case generates an average correlation of 0.27.

For the nonmarket goods and the nontraded goods models, simulation results are also reported for different elasticities of substitution between consumption of market and nonmarket goods. Market and nonmarket (nontraded) goods can be substitutes, as in the benchmark case, or complements, as in Stockman and Tesar (1995). Substitutes cases assume that $\mu = 0.5$, so that goods from different sectors are imperfect substitutes (with an elasticity of substitution of 2). Complements cases assume that $\mu = -1.00$, so that goods from different sectors are complements (with an elasticity of substitution of 1/2).

Single-good model. The single-good model considers only market production in each country. Benhabib et al. (1991) show that a model with a nonmarket sector replicates a single-good model when consumption of market and nonmarket goods are separable and all productive factors are allocated to the market sector. This corresponds to $\mu = \eta = N_n = A_n = 0$ and implies $\lambda = \phi = 1$.[12]

Single-good versions of the model highlight the anomaly: the simulated cross-country correlation of output is systematically smaller than the simulated cross-country correlations of consumption and productivity.[13] The poor performance of the single-good model is attributable to the following effects. First, the cross-country consumption correlation is unity, and thus above the cross-country output correlation, because of perfect international risk-sharing and separability between consumption and leisure. Second, spillovers, whether from worldwide shocks or perfect knowledge mobility, are insufficient to significantly transmit shocks across countries and to create positive cross-country correlations for output and productivity. Third, cross-country correlations for output, productivity, employment, and investment are all negative; a result of factors of production moving to the highest return location in response to technology shocks. Finally, the cross-country productivity correlation is larger than the cross-country output correlation, because the cross-country employment correlation is negative.

Nonmarket goods model. The nonmarket goods model also considers market production in each country, because nonmarket production is not recorded in national accounts. However, nonmarket production plays a crucial role in the determination of cross-country correlations.

[12] To prevent divisions by 0, the parameters are set to $\mu = \eta = N_n = A_n = 0.001$.

[13] The impact of the externality on the marginal product of physical capital is responsible for a highly volatile investment, as is shown in Table A2. First, note that the more complex externality created by knowledge spillovers leads to more volatile investment. Second, using adjustment costs to investment would reduce the volatility of investment. This avenue is not pursued in the single-goods model, because adding adjustment costs would not solve the cross-country correlations puzzle.

Table 2 presents, first, cases with imperfect substitutability between consumption of market and nonmarket goods and, second, cases with complementarity. The benchmark case is not rejected by the cross-country correlations-ranking criterion: simulated cross-country correlations replicate the observed ranking in 39 percent of simulated samples.

The success of the benchmark model comes from consumption of nonmarket goods and its effect on the cross-country consumption correlation and from two endogenous transmission mechanisms, which are strong enough to generate positive cross-country correlations for output and productivity. First, consumption of market and nonmarket goods are nonseparable, so that shocks to the nonmarket sector act as taste shocks. This greatly reduces the cross-country correlation of consumption. Second, the transmission mechanisms are knowledge spillovers and countercyclical trade balance (see Appendix Table A2). For example, a positive technology shock in the market sector of country 1 triggers a reallocation of resources, employment and capital, toward its market sector; the substitutability between market and nonmarket activities promotes this reallocation. The reallocation improves knowledge in the market sector and is transmitted as a positive shock to country 2 via the externality. Also in country 1, the increase in consumption of the market good and the large increase in investment induce a deterioration of the trade balance, thus increasing the relative price of market goods in country 2. In country 2, higher exports of market goods and higher knowledge in the market sector trigger a similar sectoral reallocation from nonmarket to market sector. Market sector output, productivity, and employment then are positively correlated across countries. Productivity is less correlated than output, because employment is highly positively correlated.

The model with worldwide shocks possesses only one transmission mechanism: the cross-country correlation of market technology shocks. In this case, a positive technology shock to the market sector of country 1 has large spillovers that promote an increase of output, productivity, and employment in the market sector of both countries. It has the potential to solve the anomaly, because the reallocation between market and nonmarket activities creates highly correlated employment across countries. However, it also generates a procyclical trade balance and the cross-country consumption correlation is larger than the cross-country output correlation.

A puzzling feature of the benchmark case is that investment is extremely volatile and negatively correlated across countries. The relative volatility of investment is 10.53 for the benchmark case and 2.90 for the worldwide shocks case. In comparison, the relative volatility of investment is 2.85 for the United States (Appendix Table A1). Also, the simulated cross-country correlation of investment is -0.97 in the benchmark case. In comparison, this correlation is positive for the OECD countries documented in Table 1.

To correct this puzzling feature of investment, the addition of adjustment costs is considered. Physical capital now evolves according to the following accumulation equation:

$$K_{t+1}^{i} = Q(K_t^i, I_t^i),$$

$$= A_i K_t^{i\xi} I_t^{i^{1-\xi}} + (1-\delta) K_t^i.$$

An adjustment cost parameter of $\xi = 0.067$ and a value for the level parameter of $A_i = 0.87$ (to ensure that the steady state is respected) are chosen to reflect small adjustment costs as in Baxter and Crucini (1993).[14]

The addition of adjustment costs reduces the relative volatility of investment to 2.49 and only improves the cross-country correlation of investment to -0.48.[15] Other cross-country correlations are affected only marginally, and the qualitative impacts of shocks is similar.

Finally, the case of complementarity in consumption produces samples that replicate the anomaly found in single-good models. The importance of the nonmarket sector depends on the opportunities for substitution between market and nonmarket activities. Under complementarity, technology shocks do not promote large reallocations between these activities, because an increase in consumption of market goods must be accompanied by an increase in consumption of nonmarket goods. This version of the model generates a procyclical trade balance and a negative cross-country employment correlation.

In related research, Canova (1992) studies the transmission of shocks through production interdependencies that are similar to those exploited here. He shows that common disturbances give a better account of the propagation of shocks across countries because there exists a stochastic process for technology shocks that can reproduce any transmission through production interdependencies. Costello and Praschnik (1993) analyze a model with trade in intermediate goods as the source of production interdependencies. Although trade in intermediate goods is an effective transmission mechanism, cross-country output correlations are larger than productivity correlations in their simulation results. Finally, Head (1993) presents a model with increasing returns to the worldwide variety of internationally traded intermediate goods that predicts the observed ranking for the cross-country correlations of output and productivity.

Nontraded goods model. The nontraded goods model considers the nonmarket sector as a standard nontraded sector. To aggregate traded and nontraded productions, a price is required. The price of nontraded goods in country i is computed from the ratio of marginal utilities evaluated at the equilibrium allocation:

$$P_{nt}^i = \frac{U_2(C_{mt}^i, C_{nt}^i, N_{mt}^i, N_{nt}^i)}{U_1(C_{mt}^i, C_{nt}^i, N_{mt}^i, N_{nt}^i)}.$$

Aggregate output and aggregate consumption are $Y_t^i + P_{nt}^i X_t^i$ and $C_{mt}^i + P_{nt}^i C_{nt}^i$, and aggregate employment is $N_{mt}^i + N_{nt}^i$. Finally, productivity is computed using aggregate output and employment instead of market output and employment.

Nontraded goods versions of the model are rejected by the cross-country correlations ranking criterion. First, the cross-country correlation of aggregate consumption

[14] The empirical work in Hercowitz and Sampson (1991) suggests a value of $\xi = 0.66$. However, their estimation does not consider partial depreciation which might explain a large dependence on past capital stocks.

[15] Similar conclusions are reached in Baxter and Crucini (1993).

is unity, and thus much larger than the cross-country correlation of aggregate output, because consumption and leisure are separable.[16] Second, the cross-country correlation of productivity is larger than the cross-country correlation of aggregate output, because aggregating both sectors employment reduces the cross-country correlation of employment.

Nonseparabilities between consumption and leisure would reduce the cross-country correlation of consumption. However, for reasonable nonseparabilities, such as those considered in Stockman and Tesar (1995), the nontraded goods model generates consumption correlations that are larger than output correlations. To further reduce the consumption correlation, Stockman and Tesar (1995) invoke taste shocks. These have little influence on the cross-country correlation of output and productivity, and would not solve the cross-country correlations puzzle.[17]

5. CONCLUSION

This paper studies the inability of single-good international real business cycle models to generate cross-country correlations that are higher for output than for consumption and productivity. The paper presents a two-country model of growth and cycle with a nonmarket sector that can explain the observed ranking of cross-country correlations.

To explain the observed cross-country correlations ranking, the model must possess transmission mechanisms that produce a positive cross-country correlation of employment. Two elements related to employments are analyzed. First, the model introduces international externalities in production that are sufficient to generate sustained growth. These externalities are related to knowledge and, thus, to human capital. Second, the model introduces nonmarket production; substitutability between market and nonmarket activities affects employment.

The model presented in this paper is not suited to analyze the potential impact of the international flow knowledge on growth, as in Romer and Rivera-Batiz (1992). An interesting extension would be to analyze the effects of economic integration on both the international transmission of technology shocks and the worldwide growth rate.

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APPENDIX

A. *Solution to the Competitive Equilibrium.* To solve for the competitive equilibrium and use the computational technique, the model is restated to obtain a stationary steady-state; growing variables are normalized using a stationarity-inducing transformation and are expressed as lower-case variables. As in Hercowitz and

[16] A formal proof of the unit cross-country consumption correlation is given in the Appendix.

[17] The benchmark case without taste shocks of Stockman and Tesar (1995) produces cross-country correlations of 0.64 for output and 0.78 for consumption. The case where taste shocks are added produces cross-country correlations of 0.63 for output and 0.68 for consumption.

Sampson (1991), the transformation involves dividing growing variables by the world stock of knowledge, $H_t = \Sigma_{i=1}^2 (H_{mt}^i + H_{nt}^i)$: $z_t = Z_t / H_t$, for $Z = C_m, C_n, I, K_m, K_n, H_m, H_n, \ldots$. In equilibrium, $H_t = K_t$ (the world capital stock), so that $\Sigma_{i=1}^2 k_t^i = 1$.

The consumer chooses how much to consume of both goods, how to allocate time and capital to both activities, how much to invest, and how many claims to buy to solve the consumer's problem:

$$\max \kappa + E_0 \sum_{t=0}^{\infty} \beta^t U(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i), \tag{A.1}$$

subject to

$$c_{mt}^i + i_t^i + \int P(s_{t+1}, s_t) b^i(s_{t+1})\, ds_{t+1} = R_t^i k_{mt}^i + w_t^i N_{mt}^i + b^i(s_t), \tag{A.2}$$

$$c_{nt}^i = G(k_{nt}^i, h_{nt}^i N_{nt}^i; A_{nt}^i), \tag{A.3}$$

$$k_t^i = k_{mt}^i + k_{nt}^i, \tag{A.4}$$

$$g_{t+1} k_{t+1}^i = Q(k_t^i, i_t^i), \tag{A.5}$$

where $g_{t+1} = H_{t+1}/H_t$ and $\kappa = E_0 \Sigma_{t=0}^{\infty} \beta^t \omega \ln(H_t)$.

The consumer takes as given the returns to labor and physical capital, w_t^i and R_t^i, and the dynamic evolution of externalities and world capital stock. The state of the world, s_t, follows a Markov process with transition probability density $f(s_{t+1}, s_t)$.

The first-order necessary conditions are:

$$w_t^i = \frac{U_3(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i)}{U_1(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i)}, \tag{A.6}$$

$$G_2(k_{nt}^i, h_{nt}^i N_{nt}^i; A_{nt}^i) h_{nt}^i = \frac{U_4(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i)}{U_2(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i)}, \tag{A.7}$$

$$\frac{R_t^i}{G_1(k_{nt}^i, h_{nt}^i N_{nt}^i; A_{nt}^i)} = \frac{U_2(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i)}{U_1(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i)}, \tag{A.8}$$

$$P(s_{t+1}, s_t) = \beta \frac{U_1(c_{mt+1}^i, c_{nt+1}^i, N_{mt+1}^i, N_{nt+1}^i)}{U_1(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i)} f(s_{t+1}, s_t), \tag{A.9}$$

(A.10)

$$\beta E_t \left\{ \frac{Q_2(k_t^i, i_t^i)}{g_{t+1}} \frac{U_1(c_{mt+1}^i, c_{nt+1}^i, N_{mt+1}^i, N_{nt+1}^i)}{U_1(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i)} \left[R_{t+1}^i + \frac{Q_1(k_{t+1}^i, i_{t+1}^i)}{Q_2(k_{t+1}^i, i_{t+1}^i)} \right] \right\} = 1,$$

$$\lim_{t \to \infty} \beta^t E_0 \{ U_1(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i) k_{t+1}^i \} = 0, \tag{A.11}$$

$$\lim_{t \to \infty} \beta^t E_0 \left\{ U_1(c_{mt}^i, c_{nt}^i, N_{mt}^i, N_{nt}^i) \int P(s_{t+1}, s_t) b^i(s_{t+1})\, ds_{t+1} \right\} = 0. \tag{A.12}$$

The asset market condition (A.9) ensures that ex-post intertemporal marginal rates of substitutions are equalized across consumers of either country. Assuming initial conditions such that no consumer has initial debt, the asset market condition (A.9) is rewritten as a perfectly pooled condition (see Lucas 1982):

$$U_1\left(c_{mt}^1, c_{nt}^1, N_{mt}^1, N_{nt}^1\right) = U_1\left(c_{mt}^2, c_{nt}^2, N_{mt}^2, N_{nt}^2\right).$$

The firm chooses how much capital and labor to employ to solve the firm's problem:

$$\max F\left(k_{mt}^i, h_{mt}^i N_{mt}^i; A_{mt}^i\right) - R_t^i k_{mt}^i - w_t^i N_{mt}^i. \tag{A.13}$$

The firm takes as given prices and externalities. The first-order necessary conditions are:

$$R_t^i = F_1\left(k_{mt}^i, h_{mt}^i N_{mt}^i; A_{mt}^i\right), \tag{A.14}$$

$$w_t^i = F_2\left(k_{mt}^i, h_{mt}^i N_{mt}^i; A_{mt}^i\right) h_{mt}^i. \tag{A.15}$$

B. *Nontraded Goods and Aggregation.* Nontraded goods prices are computed from the ratio of marginal utilities evaluated at the equilibrium allocation:

$$P_{nt}^i = \frac{U_2\left(C_{mt}^i, C_{nt}^i, N_{mt}^i, N_{nt}^i\right)}{U_1\left(C_{mt}^i, C_{nt}^i, N_{mt}^i, N_{nt}^i\right)},$$

$$= \left(\frac{1-\lambda}{\lambda}\right)\left(\frac{C_{mt}^i}{C_{nt}^i}\right)^{1-\mu}.$$

Aggregate consumption levels are equalized across countries:

$$C_{mt}^1 + P_{nt}^1 C_{nt}^1 = C_{mt}^1 + \left(\frac{1-\lambda}{\lambda}\right)\left(\frac{C_{mt}^1}{C_{nt}^1}\right)^{1-\mu} C_{nt}^1,$$

$$= (1/\lambda) C_{mt}^{1^{1-\mu}}\left(\lambda C_{mt}^{1^{\mu}} + (1-\lambda) C_{nt}^{1^{\mu}}\right)$$

$$= \omega / U_1\left(C_{mt}^1, C_{nt}^1, N_{mt}^1, N_{nt}^1\right),$$

$$= \omega / U_1\left(C_{mt}^2, C_{nt}^2, N_{mt}^2, N_{nt}^2\right),$$

$$= C_{mt}^2 + P_{nt}^2 C_{nt}^2.$$

C. *Data Sources.* Cross-country correlations of annual growth rates documented in Table 1 are based on two data sources: *OECD National Accounts Volume I: Main Aggregates*, and *Bureau of Labor Statistics: Comparative Labor Statistics*. The sample covers the period 1960–1991.

TABLE A1

WITHIN-COUNTRY MOMENTS OF ANNUAL GROWTH RATES*

			Relative Volatility		Correlation	
Country	Mean Output	Volatility Output	Consumption to Output	Investment to Output	Trade Balance and Output	Saving and Investment
Canada	2.59	2.43	0.93	2.18	−0.36	0.14
Germany	2.34	2.05	1.01	2.40	−0.42	0.07
France	3.06	1.60	0.94	2.50	−0.38	0.31
U.K.	1.98	2.11	1.10	2.71	−0.46	0.17
Italy	3.29	2.28	0.94	2.31	−0.48	0.09
Japan	5.16	3.16	0.87	2.12	−0.31	0.44
Sweden	2.20	1.93	1.01	2.35	−0.23	0.18
U.S.A.	1.76	2.22	0.84	2.85	−0.45	0.46

* Data are from *OECD National Accounts Volume I: Main Economic Indicators*, and the *Bureau of Labor Statistics: Comparative Labor Statistics*. Sample period is 1960–1991. Entries refer to log-differenced per capita data. For details, consult the Appendix.

TABLE A2

SIMULATED WITHIN-COUNTRY MOMENTS OF GROWTH RATES*

		Relative Volatility		Correlation	
Model	Volatility Output	Consumption to Output	Investment to Output	Trade Balance and Output	Saving and Investment
Single-Good Models					
Worldwide shocks	1.64	0.20	9.75	0.74	−0.78
Perfect mobility	1.72	0.15	27.61	0.16	−0.13
Nonmarket Goods Models					
Substitutes					
Worldwide shocks	4.29	0.69	2.90	0.15	−0.15
Perfect mobility⁺	3.17	0.70	10.53	−0.25	−0.20
Investment costs	2.77	0.75	2.49	−0.78	0.65
Complements					
Worldwide shocks	1.07	0.26	2.67	0.22	−0.06
Perfect mobility	1.11	0.26	3.55	0.56	−0.50
Nontraded Goods Models					
Substitutes					
Worldwide shocks	1.45	0.55	8.60	0.32	−0.07
Perfect mobility	1.21	0.49	27.72	0.03	0.03
Complements					
Worldwide shocks	0.86	0.35	3.31	0.04	0.01
Perfect mobility	0.86	0.27	4.59	0.45	−0.45

* Statistics are based on log-differenced data. Entries are the average over 1000 simulations of 30 periods each.

⁺Benchmark calibration. Parameters for the alternative economies are as in the benchmark case with the following changes: single-good models, $\mu = \eta = N_n = A_n = 0.0001$; worldwide shocks, $\tau = 0.999$ and $\psi = 0.60$; complements, $\mu = -1.00$; and investment costs $\xi = 0.067$ and $A_i = 0.87$.

From the *OECD National Accounts Volume I: Main Aggregates*, the series are output (Gross Domestic Product), consumption (Private Final Consumption), investment (Gross Fixed Capital Formation), and population. Except for population, the series are real 1985 prices. Employment (civilian employment) is from the *Comparative Labor Statistics*.

To obtain growth rates for the construction of Table 1 and Table A1, per capita variables are log-differenced. Following Backus et al. (1992), growth rates of productivity are computed using growth rates of output y and employment N: $y-(1-\alpha)N$, where $1-\alpha=0.64$ is the labor share. The trade balance is computed as $y-c-i$ and saving as $y-c$, where c and i are growth rates of consumption and investment.

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