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INTERNATIONAL R&D SPILLOVERS: AN APPLICATION OF ESTIMATION AND INFERENCE IN PANEL COINTEGRATION

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I. INTRODUCTION

In this paper, we consider the application of recent results on the estimation and inference in panel cointegration to the study of empirical economic growth. The emergence of endogenous growth theory in the 1980s has led to a resurgence of interest in the sources of economic growth. Coe and Helpman (1995), among other researchers, state that commercially oriented innovation efforts which respond to economic incentives are the major engine of technological progress and productivity growth. Coe and Helpman argue that, in a global economy, a country's productivity depends on its own R&D efforts as well as the R&D efforts of its trading partners. Using data from 21 OECD countries plus Israel during 1971-1990, they find that both domestic and foreign R&D capital stocks have important effects on total factor productivity (TFP). We intend to re-examine the econometric foundation of Coe and Helpman's paper.

Coe and Helpman (1995) discovered that all of their data exhibit a clear trend, and unit root tests on these data indicate that the *TFP* and both the domestic and foreign R&D capital stocks are non-stationary. They then confirm the presence of cointegration for *TFP* and the domestic and foreign R&D capital stocks by testing for a unit root in the residuals. In other words, although all the variables are individually non-stationary, there exists a linear combination of these variables so that the regression containing these variables has a stationary error term.

Coe and Helpman's use of a cointegrating regression enables us to exploit the relationship among the variables in levels, without transforming the data, such as differencing, to avoid the spurious regression problem. Unfortunately, at the time of their article the econometrics of panel cointegra-

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tion had not yet been resolved. Among the various issues that now need to be addressed are two directly associated with Coe and Helpman's empirical interpretations. First, we need to know the asymptotic distribution of the estimated cointegrating vector in panel data. It is well known that the asymptotic distributions of estimators in pure time series regression are dramatically affected by the presence of unit roots and the cointegration. Accordingly, we expect that the asymptotic distributions of estimators in panel regression might also be affected by the presence of unit roots and cointegration. Indeed, Coe and Helpman chose not to report the t-statistic, because the asymptotic distribution of the t-statistic was unknown. Given that the estimated coefficients are relatively small, we are not sure whether these estimators are significantly different from zero. Second, although it is well known that the time series regression estimates are super-consistent, it has been found that the estimation bias may remain substantial for moderate sample sizes. We have no reason to presume that this bias will become negligible in panel regression due to the introduction of the cross-section dimension. Given that the estimated coefficients in Coe and Helpman are relatively small in magnitude, one even wonders whether those estimates are correctly signed after the bias correction. The issues presented above cast serious doubts on Coe and Helpman's conclusion that *TFP* is closely linked to domestic and foreign R&D.

Recently, Kao and Chiang (1998) found that the limiting distributions of *OLS* estimators are normally distributed with non-zero means and proposed fully-modified (*FM*) and dynamic *OLS* (*DOLS*) estimators in panel data. While the limiting distribution of the *OLS* estimator is normal with a non-zero mean, the *FM* and *DOLS* estimators are asymptotically normal with zero means. Therefore, we apply Kao and Chiang's result to Coe and Helpman's international R&D spillover regressions, and we compare the empirical consequences of the different estimation approaches.

The paper is organized as follows. Section 2 briefly reviews Coe and Helpman's model. Section 3 reviews the asymptotic theory developed by Kao and Chiang. Section 4 presents the empirical results. Concluding remarks are made in Section 5.

II. COE AND HELPMAN'S THEORY AND MODEL

Coe and Helpman's model is built on recent theories of innovation-driven growth (e.g., Grossman and Helpman, 1991). Contrary to most cross-country studies of economic growth that focus on explaining output growth as determined by the accumulation of labor, capital, and some additional economic and political variables, Coe and Helpman choose to focus on the growth of *TFP*, which is the component of output growth that is not attributable to the accumulation of inputs. By this account, in an economy with two factors of production, the log of *TFP* is measured as

$$\log TFP = \log Y - \theta \log K - (1-\theta)\log L, \tag{1}$$

where Y is final output, L is the available labor force, K is the capital accumulation, and θ is the share of capital in *GDP*.

In a simple closed economy, the production function of final output is assumed to be a linearly homogenous function in the employed inputs. Because a country's R&D investment either expands the measure of available inputs or improves the qualities of inputs, one can establish a linkage between the *TFP* and the domestic R&D capital stock. International trade in intermediate goods enables a country to gain access to all inputs available in the rest of the world. From this aspect, the foreign R&D capital stocks of a country's trading partners become relevant to this country's *TFP*:

$$\log TFP_i = \alpha_{0i} + \alpha_d \log S_{di} + \alpha_f \log S_{fi}, \tag{2}$$

where i is the country index, S_{di} represents the domestic R&D capital stock, and S_{fi} represents the foreign R&D capital stocks defined as the import-share-weighted average of the domestic R&D capital stocks of trade partners. Note that this specification allows the constant α_{0i} to differ across countries to account for country-specific effects. However, the specification may not capture the role of international trade. Although the foreign R&D capital stocks S_{fi} have been weighted by import shares, these weights are fractions that add up to one and, therefore, do not properly reflect the level of imports. Whenever two countries have the same composition of imports and face the same composition of R&D capital stocks among trade partners, the country that imports more relative to its *GDP* may benefit more from foreign R&D. Therefore, a modified specification of (2) that accounts for the interaction between the foreign R&D capital stocks and the level of international trade may be preferable:

$$\log TFP_i = \alpha_{0i} + \alpha_d \log S_{di} + \alpha_f (m_i \log S_{fi}), \tag{3}$$

where m_i stands for the fraction of imports relative to *GDP* for country i.

One salient feature that distinguishes Coe and Helpman's work from most other empirical works on economic growth is that Coe and Helpman pay close attention to the time series behavior of the data set. They detect that *TFP* and domestic and foreign R&D capital stocks all exhibit a clear upward trend over time. The unit root tests on the panel data confirm that all the variables are non-stationary with unit roots. To avoid the 'spurious' correlation problem, they conduct cointegration tests on the estimation equations. Even though those tests tend to suggest the presence of cointegration, Coe and Helpman fail to interpret their estimation results within a cointegration framework. As already noted, while they report the estimated coefficients, they do not discuss the accuracy of the results and whether those estimates are statistically significant. Consequently, the results do not strongly support the argument that domestic and foreign R&D capital stocks are closely linked to *TFP*, even though the estimated parameters seem to be plausible and consistent with the theoretical model. For example, the estimates have the expected sign, and estimated elasticities of *TFP* with respect to the domestic R&D stock are in the range of 0.06 and 0.1 which are typically found in single country studies. Coe and Helpman simply did not have appropriate econometric foundation available for them to draw such a conclusion.

For this reason, the role of the asymptotic theory of panel cointegrating regressions becomes important. Kao and Chiang's work enables us to estimate and make inference on the cointegrating vector in Coe and Helpman's regression.

III. PANEL COINTEGRATION TESTS AND ESTIMATION

3.1. A Review of OLS, *FM*, and *DOLS* in Panel Data

In this section, we provide a brief review of the *OLS*, *FM*, and *DOLS* estimation methods with cointegration discussed by Kao and Chiang (1998). Phillips and Moon (1999) and Pedroni (1996) also obtained similar results for the *OLS* and *FM* estimators. The reader is referred to the cited papers for further details and discussions.

Consider the following fixed-effect panel regression:

$$y_{i,t} = \alpha_i + x'_{i,t}\beta + u_{i,t},\ i = 1, \ldots, N,\ t = 1, \ldots, T, \tag{4}$$

where $\{y_{i,t}\}$ are 1×1, β is an $M \times 1$ vector of the slope parameters, $\{\alpha_i\}$ are the intercepts, and $\{u_{i,t}\}$ are the stationary disturbance terms. We assume that $\{x_{i,t}\}$ are $M \times 1$ integrated processes of order one for all i, where $x_{i,t} = x_{i,t-1} + \varepsilon_{i,t}$. Under these specifications, (4) describes a system of cointegrated regressions, i.e. $y_{i,t}$ is cointegrated with $x_{i,t}$. With the assumptions that $\{y_{i,t}, x_{i,t}\}$ are independent across cross-sectional units and $w_{i,t} = (u_{i,t}, \varepsilon'_{i,t})'$ is a linear process that satisfies the assumptions in Kao and Chiang (1998). Then, the long-run covariance matrix, Ω, of $\{w_{i,t}\}$ can be expressed as

$$\begin{aligned}\Omega &= \sum_{j=-\infty}^{\infty} E(w_{ij}w'_{i0}) \\ &= \Sigma + \Gamma + \Gamma' \\ &= \begin{bmatrix} \Omega_u & \Omega_{u\varepsilon} \\ \Omega_{\varepsilon u} & \Omega_{\varepsilon} \end{bmatrix},\end{aligned}$$

where

$$\Gamma = \sum_{j=1}^{\infty} E(w_{ij}w'_{i0}) = \begin{bmatrix} \Gamma_u & \Gamma_{u\varepsilon} \\ \Gamma_{\varepsilon u} & \Gamma_{\varepsilon} \end{bmatrix} \tag{5}$$

and

$$\Sigma = E(w_{i0}w'_{i0}) = \begin{bmatrix} \Sigma_u & \Sigma_{u\varepsilon} \\ \Sigma_{\varepsilon u} & \Sigma_\varepsilon \end{bmatrix} \tag{6}$$

are partitioned conformably with $w_{i,t}$. We then define the one-sided long-run covariance

$$\Delta = \Sigma + \Gamma$$
$$= \sum_{j=0}^{\infty} E(w_{ij}w'_{i0}),$$

with

$$\Delta = \begin{bmatrix} \Delta_u & \Delta_{u\varepsilon} \\ \Delta_{\varepsilon u} & \Delta_\varepsilon \end{bmatrix}.$$

Kao and Chiang derive limiting distributions for the *OLS*, *FM*, and *DOLS* estimators in a cointegrated regression and show they are asymptotically normal. Kao and Chiang also investigate the finite sample proprieties of the *OLS*, *FM*, and *DOLS* estimators. They find that (i) the *OLS* estimator has a non-negligible bias in finite samples, (ii) the *FM* estimator does not improve over the *OLS* estimator in general, and (iii) the *DOLS* estimator may be more promising than *OLS* or *FM* estimators in estimating the cointegrated panel regressions.

The *OLS* estimator of β is

$$\hat{\beta}_{OLS} = \left[\sum_{i=1}^{N}\sum_{t=1}^{T}(x_{i,t} - \overline{x}_i)(x_{i,t} - \overline{x}_i)'\right]^{-1}\left[\sum_{i=1}^{N}\sum_{t=1}^{T}(x_{i,t} - \overline{x}_i)(y_{i,t} - \overline{y}_i)\right], \tag{7}$$

where $\overline{x}_i = (1/T)\sum_{t=1}^{T} x_{i,t}$ and $\overline{y}_i = (1/T)\sum_{t=1}^{T} y_{i,t}$. The *FM* estimator is constructed by making corrections for endogeneity and serial correlation to the *OLS* estimator $\hat{\beta}_{OLS}$ in (7). Let $\hat{\Omega}_{\varepsilon u}$ and $\hat{\Omega}_\varepsilon$ be consistent estimates of $\Omega_{u\varepsilon}$ and Ω_ε. Define

$$\hat{y}^+_{i,t} = y_{i,t} - \hat{\Omega}_{u\varepsilon}\hat{\Omega}_\varepsilon^{-1}\varepsilon_{i,t}.$$

The endogeneity correction is achieved by modifying the variable $y_{i,t}$ in (4) with the transformation

$$\hat{y}^+_{i,t} = y_{i,t} - \hat{\Omega}_{u\varepsilon}\hat{\Omega}_\varepsilon^{-1}\varepsilon_{i,t}$$
$$= \alpha_i + x'_{i,t}\beta + u_{i,t} - \hat{\Omega}_{u\varepsilon}\hat{\Omega}_\varepsilon^{-1}\varepsilon_{i,t}.$$

The serial correlation correction term has the form

$$\hat{\Delta}^{+}_{\varepsilon u} = (\hat{\Delta}_{\varepsilon u} \ \ \hat{\Delta}_{\varepsilon})\begin{pmatrix} 1 \\ -\hat{\Omega}_{\varepsilon}^{-1}\hat{\Omega}_{\varepsilon u} \end{pmatrix}$$

$$= \hat{\Delta}_{\varepsilon u} - \hat{\Delta}_{\varepsilon}\hat{\Omega}_{\varepsilon}^{-1}\hat{\Omega}_{\varepsilon u},$$

where $\hat{\Delta}_{\varepsilon u}$ and $\hat{\Delta}_{\varepsilon}$ are kernel estimates of $\Delta_{\varepsilon u}$ and Δ_{ε}. Therefore, the *FM* estimator is

$$\hat{\beta}_{FM} = \left[\sum_{i=1}^{N}\sum_{t=1}^{T}(x_{i,t} - \overline{x}_i)(x_{i,t} - \overline{x}_i)'\right]^{-1}\left[\sum_{i=1}^{N}\left(\sum_{t=1}^{T}(x_{i,t} - \overline{x}_i)\hat{y}^{+}_{i,t} - T\hat{\Delta}^{+}_{\varepsilon u}\right)\right]. \tag{8}$$

Finally, the *DOLS* estimator, $\hat{\beta}_D$, can be obtained by running the following regression:

$$y_{i,t} = \alpha_i + x'_{i,t}\beta + \sum_{j=-q_1}^{q_2} c_{ij}\Delta x_{i,t+j} + v_{i,t}. \tag{9}$$

Accordingly, Kao and Chiang (1998) show that the asymptotic distributions of estimators using the *OLS*, *FM*, and *DOLS* are as follows:

(a) $\sqrt{N}T(\hat{\beta}_{OLS} - \beta) - \sqrt{N}\delta_{NT} \Rightarrow N(0,\, 6\Omega_{\varepsilon}^{-1}\Omega_{u.\varepsilon})$,

(b) $\sqrt{N}T(\hat{\beta}_{FM} - \beta) \Rightarrow N(0,\, 6\Omega_{\varepsilon}^{-1}\Omega_{u.\varepsilon})$,

(c) $\sqrt{N}T(\hat{\beta}_{D} - \beta) \Rightarrow N(0,\, 6\Omega_{\varepsilon}^{-1}\Omega_{u.\varepsilon})$,

where

$$\Omega_{u.\varepsilon} = \Omega_u - \Omega_{u\varepsilon}\Omega_{\varepsilon}^{-1}\Omega_{\varepsilon u},$$

$\Rightarrow$ denotes convergence in distribution,

$$\delta_{NT} = \left[\frac{1}{N}\sum_{i=1}^{N}\frac{1}{T^2}\sum_{t=1}^{T}(x_{i,t} - x_{i,t})(x_{i,t} - \overline{x}_i)'\right]^{-1}$$
$$\times \left[\frac{1}{N}\sum_{i=1}^{N}\Omega_{\varepsilon}^{1/2}\left(\int_0^1 \tilde{W}_i(r)dW'_i(r)\right)\Omega_{\varepsilon}^{-1/2}\Omega_{\varepsilon u} + \Delta_{\varepsilon u}\right],$$

$W_i(r)$ is a standard Brownian motion, and

$$\tilde{W}_i(r) = W_i(r) - \int_0^1 W_i(r)dr.$$

Remark 1. *Kao (1999) has shown that*

$$\hat{\beta}_{OLS} \xrightarrow{p} \Omega_{\varepsilon}^{-1}\Omega_{u\varepsilon}$$

and

$$\sqrt{N}(\hat{\beta}_{OLS} - \Omega_{\varepsilon}^{-1}\Omega_{u\varepsilon}) \Rightarrow N(0, \tfrac{2}{5}\Omega_{\varepsilon}^{-1}\Omega_{u.\varepsilon})$$

if $u_{i,t}$ is $I(1)$, i.e., (4) is not cointegrated. It follows that under $H_0: \beta = 0$ in (4)

$$\sqrt{N}(\hat{\beta}_{OLS}) \Rightarrow N(0, \tfrac{2}{5}\Omega_{\varepsilon}^{-1}\Omega_{u.\varepsilon})$$

if $u_{i,t}$ is $I(1)$.

3.2. A Review of Panel Cointegration Tests

While a number of cointegration tests are documented in the time series literature, there are few cointegration tests developed in panel data. Here, we employed cointegration tests proposed by Kao (1999) and Pedroni (1995) to test whether the cointegration relationship exists in the estimated equations.[1]

Kao (1999) presents two types of cointegration tests in panel data, the Dickey–Fuller (*DF*) and augmented Dickey–Fuller (*ADF*) types. The *DF*-type tests from Kao (1999) can be calculated from the estimated residuals as:

$$\hat{e}_{i,t} = \gamma\hat{e}_{i,t-1} + v_{i,t}, \tag{10}$$

where $\hat{e}_{i,t}$ is the estimated residuals from the estimated equation. In order to test the null hypothesis of no cointegration, the null can be written as $H_0: \gamma = 1$. In addition, the *OLS* estimate of γ can be given as:

$$\hat{\gamma} = \frac{\sum_{i=1}^{N}\sum_{t=2}^{T}\hat{e}_{i,t}\hat{e}_{i,t-1}}{\sum_{i=1}^{N}\sum_{t=2}^{T}\hat{e}_{i,t}^{2}}. \tag{11}$$

Accordingly, four *DF*-type tests are constructed as follows:

1. $DF_{\gamma} = \frac{\sqrt{N}T(\hat{\gamma}-1)+3\sqrt{N}}{\sqrt{10.2}}$,
2. $DF_t = \sqrt{1.25}t_{\gamma} + \sqrt{1.875}N$,

[1]Editorial Note: In the context of this volume, it should be noted that the Kao (1999) and Pedroni (1995) tests given here apply to the somewhat restrictive scenario of β being the same across all units i since this is maintained in (4) above. In his paper in this Special Issue, Pedroni generalizes the analysis to allow for heterogeneous β_i (and endogeneity of the regressors) as described also in Section 4 of the editorial overview.

3. $DF_{\gamma}^{*} = \frac{\sqrt{N}T(\hat{\gamma}-1)+(3\sqrt{N}\hat{\sigma}_{v}^{2}}{\hat{\sigma}_{0v}^{2})/\sqrt{3+(7.2\hat{\sigma}_{v}^{4}/\hat{\sigma}_{0v}^{4})}}$,
4. $DF_{t}^{*} = \frac{t_{\gamma}+(\sqrt{6N}\hat{\sigma}_{v}}{2\hat{\sigma}_{0v})/\sqrt{(\hat{\sigma}_{0v}^{2}/2\hat{\sigma}_{v}^{2})+(3\hat{\sigma}_{v}^{2}/10\hat{\sigma}_{0v}^{2})}}$,

where $\hat{\sigma}_{v}^{2} = \Sigma_{u} - \Sigma_{u\varepsilon}\Sigma_{\varepsilon}^{-1}$ and $\hat{\sigma}_{0v}^{2} = \Omega_{u} - \Omega_{u\varepsilon}\Omega_{\varepsilon}^{-1}$. While DF_{γ} and DF_{t} are based on assuming strict exogeneity of the regressors with respect to the errors in the equation, DF_{γ}^{*} and DF_{t}^{*} are for cointegration with endogenous regressors. For the *ADF* test, we can run the following *ADF* regression:

$$\hat{e}_{i,t} = \gamma\hat{e}_{i,t-1} + \sum_{j=1}^{p} \vartheta_{j}\Delta\hat{e}_{i,t-j} + v_{i,tp}. \tag{12}$$

With the null hypothesis of no cointegration, the *ADF* test statistics can be constructed as:

$$ADF = \frac{t_{ADF} + (\sqrt{6N}\hat{\sigma}_{v}/2\hat{\sigma}_{0v})}{\sqrt{(\hat{\sigma}_{0v}^{2}/2\hat{\sigma}_{v}^{2}) + (3\hat{\sigma}_{v}^{2}/10\hat{\sigma}_{0v}^{2})}},$$

where t_{ADF} is the *t*-statistic of γ in (12). The asymptotic distributions of DF_{γ}, DF_{t}, DF_{γ}^{*}, DF_{t}^{*}, and *ADF* converge to a standard normal distribution $N(0, 1)$. Building up on the assumption that the regressors are strictly exogenous, Pedroni (1995) provides a pooled Phillips and Perron-type test.[2] First, under the null hypothesis of no cointegration, the panel autoregressive coefficient estimator, $\hat{\gamma}_{N,T}$, can be constructed as follows:

$$\hat{\gamma}_{N,T} - 1 = \frac{\sum_{i=1}^{N}\sum_{t=2}^{T}(\hat{e}_{i,t-1}\Delta\hat{e}_{i,t} - \hat{\lambda}_{i})}{\left(\sum_{i=1}^{N}\sum_{t=2}^{T}\hat{e}_{i,t-1}^{2}\right)}, \tag{13}$$

where $\hat{\lambda}_{i}$ acts as a scalar equivalent to the correlation matrix, Γ, and corrects for any correlation effect. Hence, Pedroni provides the limiting distributions of two test statistics:

1. $PC_{1} = \frac{T\sqrt{N}(\hat{\gamma}_{N,T}-1)}{\sqrt{2}} \Rightarrow N(0, 1)$,
2. $PC_{2} = \frac{\sqrt{NT(T-1)}(\hat{\gamma}_{N,T}-1)}{\sqrt{2}} \Rightarrow N(0, 1)$.

IV. DATA AND ESTIMATION RESULTS

We use annual data for 22 countries listed in Coe and Helpman (1995) from 1971 to 1990. The variables include *TFP*, domestic R&D capital stocks

[2] But see footnote 1 above.

(S_d), foreign R&D capital stocks (S_f), and the fraction of imports in *GDP* (m). See Coe and Helpman's appendix for the definition and construction of these variables.

Table 1 is simply a reproduction of Table 3 of Coe and Helpman, except that we augment it by adding regression (iv). In regression (iv), the estimated coefficient on the domestic R&D capital stocks is constrained to be the same for all countries and the foreign R&D capital stocks are interacted with the ratio of imports to *GDP* for allowing country-specific and time-varying elasticities on foreign R&D capital stocks. The rationale for this specification is obvious since it is explicitly suggested by equation (3). All regressions include unreported country-specific effects. The conventional t-statistics are shown in parentheses.

Before looking at the estimation results, we need to confirm whether estimated equations are actually cointegrated. Table 2 reports cointegration test results using panel cointegration tests of Kao (1999) and Pedroni (1995). All test statistics are significant so that the null of no cointegration is strongly rejected. Therefore, the cointegration relationship among variables for all equations is supported.

Although the estimated coefficients reported in Table 1 have the expected signs and the values of all the t-statistics are significantly large, as shown in the previous section, these *OLS* estimates are generally biased due to endogeneity in variables. Hence, the corresponding t-statistics do not have

TABLE 1
TFP Estimation Results using OLS

	(i)	*(ii)*	*(iii)*	*(iv)*
$\log S_d$	0.097 (10.98)	0.090 (10.86)	0.078 (10.32)	0.105 (13.24)
$G7 \cdot \log S_d$		0.135 (8.58)	0.157 (10.71)	
$\log S_f$	0.092 (6.00)	0.060 (4.06)		
$m \cdot \log S_f$			0.289 (7.23)	0.266 (5.94)
R^2	0.558	0.622	0.650	0.558

Notes: (a) Estimations are based on pooled data from 1971–1990 for 22 countries (440 observations). The dependent variable is log *TFP*. All regressions include unreported, country-specific constants. The conventional t-statistics are reported in parentheses. Note that our estimated coefficients in regression (iii) are slightly different from Coe and Helpman's.
(b) S_d = domestic R&D capital stock, beginning of the year.
(c) S_f = foreign R&D capital stock, beginning of the year.
(d) $G7$ = dummy variable equal to 1 for the seven major countries and equal to 0 for the other 15 countries.
(e) m = ratio of imports of goods and services to *GDP*, both in the previous year.

TABLE 2
The Cointegration Tests

	(i)	*(ii)*	*(iii)*	*(iv)*
DF_{ρ}	−2.896	−3.204	−3.44	−2.648
	(0.002)	(0.000)	(0.000)	(0.004)
DF_t	23.282	23.112	22.989	23.486
	(0.000)	(0.000)	(0.000)	(0.000)
DF^*_{ρ}	−5.45	−5.927	−6.235	−5.073
	(0.000)	(0.000)	(0.000)	(0.000)
DF^*_t	−2.249	−2.36	−2.441	−2.116
	(0.012)	(0.009)	(0.007)	(0.017)
ADF	−2.366	−2.389	−2.627	−2.248
	(0.009)	(0.008)	(0.004)	(0.012)
PC_1	−12.367	−12.897	−13.879	−12.129
	(0.000)	(0.000)	(0.000)	(0.000)
PC_2	−12.054	−12.57	−13.527	−11.882
	(0.000)	(0.000)	(0.000)	(0.000)

Note:(a) The critical probabilities are reported in parentheses.
(b) Cointegration test statistics are calculated through the residuals from the *OLS* estimation.

usual t-distributions. Consequently, it is unwise to place too much confidence in the estimation results of Table 1.

Tables 3, 4, and 5 present the coefficient estimates based upon the *OLS* with bias correction, the *FM*, and the *DOLS* estimators respectively (with their t-statistics in parentheses). Observe that the coefficient estimators by the *OLS* with bias correction are similar to those of the *FM* estimator. That might result from the fact that *FM* estimation corrects the dependent variable using the long-run covariance matrices for the purpose of removing the nuisance parameters and applies the usual *OLS* estimation method to the corrected variables. On the other hand, the estimated coefficients of the *DOLS* estimator are quite different from those of the *FM* estimator, even though the limiting distributions of the *DOLS* estimator is the same as of the *FM* estimator as shown in Kao and Chiang (1998). The *DOLS* estimator includes lead and lag terms to correct the nuisance parameter in order to obtain coefficient estimates with nice limiting distribution properties.

First, we would like to examine the magnitude of the estimation bias by the *OLS* in comparison with those of the biascorrection method. At first glance, the estimated elasticities on the domestic and the foreign R&D capital stocks are correctly signed for all regressions in Table 1 and Tables 3–5. However, the estimated elasticities on the domestic and the foreign R&D capital stocks vary considerably with the different methods. It is interesting to see that the estimation bias with *OLS* may be upward or

TABLE 3
TFP Estimation Results with Bias-Corrected OLS

	(i)	*(ii)*	*(iii)*	*(iv)*
$\log S_d$	0.084 (4.571)**	0.078 (4.533)**	0.065 (4.199)**	0.095 (5.715)**
$G7 \cdot \log S_d$		0.131 (3.653)**	0.163 (4.874)**	
$\log S_f$	0.125 (4.071)**	0.090 (3.1103)**		
$m \cdot \log S_f$			0.395 (5.285)**	0.358 (4.153)*
R^2	0.558	0.622	0.641	0.551

Notes: (a) Estimations are based on the pooled data from 1971–1990 for 22 countries (440 observations). The dependent variable is log *TFP*. All regressions include unreported, country-specific constants. The bias-corrected *t*-statistics are reported in parentheses. *(**) denotes that the coefficient is significantly different from zero at a 10 percent (5 percent) level.
(b) S_d = domestic R&D capital stock, beginning of the year.
(c) S_f = foreign R&D capital stock, beginning of the year.
(d) $G7$ = dummy variable equal to 1 for the seven major countries and equal to 0 for the other 15 countries.
(e) m = ratio of imports of goods and services to *GDP*, both in the previous year.

TABLE 4
TFP Estimation Results using FM *Estimator*

	(i)	*(ii)*	*(iii)*	*(iv)*
$\log S_d$	0.084 (4.372)**	0.077 (4.27)**	0.072 (4.451)**	0.100 (5.72)**
$G7 \cdot \log S_d$		0.127 (3.378)**	0.156 (4.449)**	
$\log S_f$	0.103 (3.184)**	0.075 (2.452)**		
$m \cdot \log S_f$			0.264 (3.354)**	0.244 (2.696)*
R^2	0.506	0.574	0.581	0.494

Notes: (a) Estimations are based on pooled data from 1971–1990 for 22 countries (440 observations). The dependent variable is log *TFP*. All regressions include unreported, country-specific constants. The *t*-statistics are reported in parentheses. * (**) denotes that the coefficient is significantly different from zero at a 10 percent (5 percent) level.
(b) S_d = domestic R&D capital stock, beginning of the year.
(c) S_f = foreign R&D capital stock, beginning of the year.
(d) $G7$ = dummy variable equal to 1 for the seven major countries and equal to 0 for the other 15 countries.
(e) m = ratio of imports of goods and services to *GDP*, both in the previous year.

TABLE 5
TFP Estimation Results using DOLS *Estimator*

	(i)	*(ii)*	*(iii)*	*(iv)*
$\log S_d$	0.107	0.091	0.091	0.124
	(4.672)**	(4.248)**	(4.705)**	(5.957)**
$G7 \cdot \log S_d$		0.116	0.135	
		(2.597)**	(3.221)**	
$\log S_f$	0.056	0.044		
	(1.450)	(1.215)		
$m \cdot \log S_f$			0.145	0.068
			(1.555)	(0.633)
R^2	0.511	0.572	0.579	0.502

Notes: (a) Estimations are based on the pooled data 1971–1990 for 22 countries with one lead and tow lags of first differenced independent variables, 440 observations. The dependent variable is log *TFP*. All regressions include unreported, country-specific constants. The *t*-statistics are reported in parentheses. *(**) denotes that the coefficient is significantly different from zero at a 10 percent (5 percent) level.
(b) S_d = domestic R&D capital stock, beginning of the year.
(c) S_f = foreign R&D capital stock, beginning of the year.
(d) $G7$ = dummy variable equal to 1 for the seven major countries and equal to 0 for the other 15 countries.
(e) m = ratio of imports of goods and services to *GDP*, both in the previous year.

downward, depending on which method you use to make the comparison. The *OLS* estimator gives us a higher elasticity on the domestic R&D capital stocks in comparison with the estimators of the *OLS* with bias correction and the *FM* methods. On the other hand, the *OLS* estimator indicates a lower elasticity on the domestic R&D capital stocks than the *DOLS*'s estimator. Overall, the bias remains within the range of 20 percent. The estimation bias of the elasticity on the foreign R&D capital stocks spreads even wider among different estimation methods. For example, the estimated coefficient on ($m \log S_f$) by the *OLS* is 0.266, but 0.068 by the *DOLS* based on regression (iv).

It is more troublesome when we turn to inferences made by *OLS*. As can be seen from the tables, showing the values of *t*-statistics in all the *OLS* estimators with bias correction, the *FM* and the *DOLS* estimators are significantly reduced in comparison with those in the *OLS* without bias corrections. All the estimations confirm that the elasticity on the domestic R&D capital stocks is significant at a 5 percent level. In addition, the estimated coefficient on the domestic R&D capital stocks with the G7 dummy ($G7 \log S_d$) in all regressions is significant at a 5 percent level, which supports the argument that the impact of the domestic R&D differs between the largest seven economies and the remaining 15 small countries. However, these methods disagree on the impact of foreign R&D capital stocks. The *OLS* with bias correction and the *FM* estimators confirm that the impact of the foreign R&D capital stock is significant at a 5 percent level, but the *DOLS* indicates that the impact is statistically insignificant even at a 10 percent level. The Monte Carlo simulations in Kao and Chiang suggest that the *DOLS* estimator outperforms the *OLS* and *FM* estimators. Kao and Chiang pointed out that the *FM* estimator could be inferior to the *OLS* in some cases and they suggest using the *DOLS* estimator in practice to avoid the potential problem of estimating the nuisance parameters in the *FM* approach. The *FM* estimator is complicated by the dependence of the correction terms upon the preliminary estimator (here we use *OLS*), which may be biased in finite samples. The *DOLS* differs from the *FM* estimator in that the *DOLS* requires no initial estimation and no non-parametric correction. It is true that a major difficulty of using the *DOLS* estimator is how to choose the lags and leads. However, it seems from the Monte Carlo experiments in Kao and Chiang that the failure of the non-parametric correction for the *FM* could be more serious. In this paper, for the *DOLS* we chose the same lags and leads for all i. The issue of how to choose different lags and leads in the panel cointegration is an interesting question, but it goes beyond the scope of this paper. Consequently, we lean to rejecting the linkage between *TFP* and the foreign R&D via trade in Coe and Helpman (1995).

Our finding is in line with recent criticisms of Coe and Helpman's results. Lichtenberg and van Pottesberghe (1998) suggest that Coe and Helpman's functional form of how foreign R&D affects domestic productivity via imports is probably incorrect. They claim the construction of foreign R&D capital stocks in Coe and Helpman is subject to the aggregation bias. Using an improved measure of foreign R&D capital stock, Lichtenberg and van Pottesberghe were able to produce improved results. Keller (1998) argues that Coe and Helpman's results are not sufficient to support their hypothesis that international R&D spillovers are trade related. Using the same model as Coe and Helpman used, Keller found large international R&D spillovers by randomly generating bilateral trade shares to construct foreign R&D capital stocks. However, they were silent about the non-stationarity of the variables in their regressions. Applying Kao and Chiang (1998) to their models may provide further insight of the relationship of foreign R&D and *TFP*. However, this goes beyond the scope of this paper.

Although inferences about the impact of foreign R&D capital stocks are different between the *FM* and the *DOLS* methods, the impact of foreign R&D capital stocks on the *TFP* is still of interest to us. Tables 6 and 7 compute the estimated elasticities[3] of *TFP* with respect to the foreign R&D capital stocks based on regression (iii) of the *FM* and the *DOLS* methods, respectively. The estimated impacts of foreign R&D capital stocks increase

[3]The estimated elasticities of total factor productivity with respect to the foreign R&D capital stocks are calculated as the product of the estimated coefficient of $m \log S_f$ and the import share.

TABLE 6
Country-Specific, Time-Varying Estimates of the Impact of Foreign Research and Development Capital Stocks on TFP *using* FM *Estimators: Based on Regression (iii) in Table 4*

	1971	*1980*	*1990*
United States	0.015	0.027	0.030
Japan	0.025	0.033	0.024
West Germany	0.051	0.064	0.069
France	0.040	0.054	0.060
Italy	0.041	0.060	0.052
United Kingdom	0.057	0.072	0.073
Canada	0.053	0.070	0.067
Australia	0.039	0.044	0.049
Austria	0.081	0.095	0.103
Belgium	0.116	0.162	0.233
Denmark	0.082	0.085	0.082
Finland	0.071	0.079	0.067
Greece	0.045	0.056	0.085
Ireland	0.111	0.161	0.148
Israel	0.132	0.139	0.137
Netherlands	0.119	0.131	0.142
New Zealand	0.067	0.077	0.060
Norway	0.120	0.112	0.099
Portugal	0.089	0.105	0.118
Spain	0.039	0.039	0.056
Sweden	0.060	0.078	0.083
Switzerland	0.103	0.095	0.101

from 1971 to 1980 as found by Coe and Helpman (1995). Most of the 15 small countries have larger impacts generated from changes of foreign capital stocks than G7 countries, which confirms that the small countries with open economy benefit more than large countries. As expected, the magnitudes of estimated impacts are much smaller in Table 7 than in Table 6.

Tables 8 and 9 present the estimates of the international R&D spillovers[4] from the *FM* and the *DOLS* methods, respectively. While the conclusions drawn from these tables are basically consistent with conclusions made by Coe and Helpman qualitatively, one can observe some quantitative differences. Tables 8 and 9 confirm that international R&D spillovers from the major countries (USA, Japan) are the largest.

[4]The estimated elasticities of total factor productivity with respect to R&D capital stocks in the G7 countries are calculated using the formula: $m^j \alpha_f m_i^j S_{di} / \Sigma_{k \neq j} m_k^j S_{dk}$, where m^j is country j's import share and m_i^j is the fraction of j's imports from country i.

TABLE 7
Country-Specific, Time-Varying Estimates of the Impact of Foreign Research and Development Capital Stocks on TFP *using DOLS Estimators: Based on Regression (iii) in Table 5*

	1971	*1980*	*1990*
United States	0.008	0.015	0.016
Japan	0.014	0.018	0.013
West Germany	0.028	0.035	0.038
France	0.022	0.030	0.033
Italy	0.023	0.033	0.028
United Kingdom	0.031	0.040	0.040
Canada	0.029	0.039	0.037
Australia	0.021	0.024	0.027
Austria	0.045	0.052	0.057
Belgium	0.064	0.089	0.128
Denmark	0.045	0.047	0.045
Finland	0.039	0.043	0.037
Greece	0.025	0.031	0.047
Ireland	0.061	0.089	0.082
Israel	0.073	0.076	0.076
Netherlands	0.066	0.072	0.078
New Zealand	0.037	0.043	0.033
Norway	0.066	0.061	0.055
Portugal	0.049	0.058	0.065
Spain	0.021	0.021	0.031
Sweden	0.033	0.043	0.046
Switzerland	0.057	0.052	0.056

Tables 10 and 11 show estimates of the average own rate of return[5] from investment in R&D in 1990. The average own returns from investment in R&D are 120 (118) percent in the G7 countries and 79 (99) percent in the remaining 15 countries. While these estimates are a little smaller than those in Coe and Helpman, they indicate that the R&D capital investment in G7 countries generates higher rates of return than in smaller countries. In addition, the spillover effect of R&D capital investment in G7 countries through trades is 29 (16) percent assuring that G7 countries contribute larger proportions to its trade partners.

[5]The average own rate of return for a group, N, is computed as $\rho_{NN} = \sum_{j\in N}\rho_j S_{dj}/(\sum_{i\in N} S_{di})$, where ρ_j is calculated as $\sum_i \rho_{ij} = \alpha_j Y/S_{dj}$ in which $Y = \sum_i Y_i$ is a aggregate *GDP* and $\alpha_j = \sum_i \alpha_{ij} Y_i / Y$ is the *GDP* weighted average elasticity of output with respect to country *j*'s R&D capital stock. α_{ij} represents the elasticity of country *i*'s output with respect to *j*'s domestic R&D capital stock.

TABLE 8

Elasticities of TFP *with Respect to Research and Development Capital Stocks in G7 Countries in 1990 using* FM *Estimators: Based on Regression (iii) in Table 4*

	US	*Japan*	*Germany*	*France*	*Italy*	*UK*	*Canada*
United States	...	0.0196	0.0035	0.0012	0.0005	0.0022	0.0022
Japan	0.0228	...	0.0007	0.0003	0.0001	0.0003	0.0001
West Germany	0.0417	0.0087	...	0.0073	0.0022	0.0054	0.0001
France	0.0331	0.0044	0.0140	...	0.0022	0.0044	0.0001
Italy	0.0228	0.0024	0.0149	0.0068	...	0.0029	0.0001
United Kingdom	0.0475	0.0062	0.0117	0.0042	0.0010	...	0.0002
Canada	0.0643	0.0017	0.0005	0.0002	0.0001	0.0005	...
Australia	0.0367	0.0082	0.0017	0.0004	0.0002	0.0016	0.0001
Austria	0.0270	0.0092	0.0548	0.0036	0.0030	0.0027	0.0001
Belgium	0.0834	0.0104	0.0728	0.0304	0.0035	0.0206	0.0004
Denmark	0.0403	0.0056	0.0224	0.0033	0.0011	0.0059	0.0001
Finland	0.0320	0.0092	0.0148	0.0024	0.0011	0.0047	0.0001
Greece	0.0260	0.0124	0.0258	0.0058	0.0051	0.0063	0.0001
Ireland	0.0926	0.0084	0.0085	0.0026	0.0007	0.0339	0.0001
Israel	0.1066	0.0040	0.0109	0.0027	0.0015	0.0074	0.0001
Netherlands	0.0746	0.0067	0.0386	0.0075	0.0014	0.0101	0.0002
New Zealand	0.0415	0.0117	0.0018	0.0004	0.0002	0.0032	0.0002
Norway	0.0577	0.0075	0.0166	0.0029	0.0010	0.0086	0.0005
Portugal	0.0486	0.0084	0.0264	0.0140	0.0044	0.0115	0.0003
Spain	0.0321	0.0042	0.0088	0.0054	0.0016	0.0033	0.0001
Sweden	0.0445	0.0082	0.0183	0.0032	0.0010	0.0062	0.0001
Switzerland	0.0406	0.0072	0.0359	0.0077	0.0029	0.0051	0.0001
Average elasticity of foreign *TFP*	0.0379	0.0124	0.0081	0.0029	0.0009	0.0030	0.0010

V. CONCLUDING REMARKS

We have re-examined Coe and Helpman's international R&D spillover regressions by applying different estimation methods of cointegrating regressions in panel data proposed by Kao and Chiang (1998). Our empirical results indicate that the estimated coefficients in Coe and Helpman's regressions are subject to estimation bias. However, in all cases the estimates are correctly signed.

All estimations confirm the existence of the linkage between TFP and domestic capital stock. In addition, there exists strong evidence supporting Coe and Helpman's argument that the impact of the domestic R&D capital stocks on *TFP* differs between the G7 countries and the other small countries. However, these estimations do not seem to agree on the impact of the foreign R&D capital stocks on *TFP*. The *OLS* with bias correction and the *FM* support the idea that foreign R&D is related to *TFP*. However, the

TABLE 9

Elasticities of TFP *with Respect to Research and Development Capital Stocks in G7 Countries in 1990 using* DOLS *Estimators: Based on Regression (iii) in Table 5*

	US	*Japan*	*Germany*	*France*	*Italy*	*UK*	*Canada*
United States	. . .	0.0108	0.0019	0.0007	0.0003	0.0012	0.0012
Japan	0.0126	. . .	0.0004	0.0002	0.0001	0.0002	0.0001
West Germany	0.0230	0.0048	. . .	0.0040	0.0012	0.0030	0.0001
France	0.0182	0.0024	0.0077	. . .	0.0012	0.0024	0.0001
Italy	0.0126	0.0013	0.0082	0.0038	. . .	0.0016	0.0001
United Kingdom	0.0262	0.0034	0.0065	0.0023	0.0006	. . .	0.0001
Canada	0.0354	0.0010	0.0003	0.0001	0.0001	0.0003	. . .
Australia	0.0202	0.0045	0.0010	0.0002	0.0001	0.0009	0.0001
Austria	0.0149	0.0051	0.0302	0.0020	0.0016	0.0015	0.0001
Belgium	0.0459	0.0057	0.0401	0.0168	0.0019	0.0114	0.0002
Denmark	0.0222	0.0031	0.0124	0.0018	0.0006	0.0033	0.0001
Finland	0.0176	0.0051	0.0081	0.0013	0.0006	0.0026	0.0001
Greece	0.0143	0.0068	0.0142	0.0032	0.0028	0.0035	0.0001
Ireland	0.0510	0.0046	0.0047	0.0014	0.0004	0.0187	0.0001
Israel	0.0587	0.0022	0.0060	0.0015	0.0009	0.0041	0.0001
Netherlands	0.0411	0.0037	0.0212	0.0041	0.0008	0.0056	0.0001
New Zealand	0.0228	0.0064	0.0010	0.0002	0.0001	0.0018	0.0001
Norway	0.0318	0.0041	0.0091	0.0016	0.0006	0.0047	0.0003
Portugal	0.0268	0.0046	0.0145	0.0077	0.0024	0.0063	0.0002
Spain	0.0177	0.0023	0.0049	0.0030	0.0009	0.0018	0.0001
Sweden	0.0245	0.0045	0.0101	0.0018	0.0005	0.0034	0.0001
Switzerland	0.0224	0.0040	0.0198	0.0042	0.0016	0.0028	0.0001
Average elasticity of foreign *TFP*	0.0209	0.0068	0.0045	0.0016	0.0005	0.0016	0.0006

TABLE 10

Rates of Return on Investment in Research and Development in 1990 using FM *Estimator: Based on Regression (iii) in Table 4*

Average own return of research and development investment	
in G7 countries	1.20
in the remaining 15 OECD countries	0.79
worldwide	1.17
Average worldwide return of research and development investment in G7 countries	1.49

DOLS method suggests that the impact of foreign R&D on *TFP* is insignificant. Given the superiority of the *DOLS* over the *FM* as suggested by Kao and Chiang, we lean to rejecting Coe and Helpman's hypothesis that international R&D spillovers are trade related.

TABLE 11
Rates of Return on Investment in Research and Development in 1990 using DOLS *Estimator: Based on Regression (iii) in Table 5*

Average own return of research and development investment	
in G7 countries	1.18
in the remaining 15 OECD countries	0.99
worldwide	1.17
Average worldwide return of research and development investment in G7 countries	1.34

We also remeasured the magnitude of international R&D spillovers, and found the small countries benefit more from international R&D spillovers than the larger countries do. In addition, international R&D spillovers from the major countries (USA and Japan) are the largest, which means that R&D in the largest countries may lead the world trend. Our estimates suggest that the rates of return on R&D capital stock are very high, both in terms of domestic and international spillovers, although not so large as Coe and Helpman's estimates.

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