The Dynamics of R&D and Innovation in the Short Run and in the Long Run *

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Abstract

In this paper we estimate the dynamic relationship between resources used in R&D by some OECD countries and their innovation output as measured by patent applications. We first estimate a long-run cointegration relation using recently developed tests and panel estimation techniques. We find that the stock of knowledge of a country, its R&D resources and the stock of international knowledge move together in the long run. Then, imposing this long-run relation across variables we analyze the impulse response of new ideas to a shock to R&D or to a shock to innovation by estimating an error correction mechanism. We find that internationally generated ideas have a very significant impact in helping innovation in a country. As a consequence, a positive shock to innovation in a large country as the US has, both in the short and in the long run, a significant positive effect on the innovation of all other countries.

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1 Introduction

Technological change in the form of invention of new goods or discovery of new processes has two main effects on the economic performances of countries. First, as measured in a seminal work by Robert Solow [25] technological progress is, over time, the main determinant of a country's increase in labor productivity. Second, as formulated by Business Cycle theories since their early contributions (such as Prescott [22] or Christiano and Eichenbaum [5]) random technological change is the source of shocks affecting productivity fluctuations and possibly determining business cycles. The first is a phenomenon that reveals its action over the long run, the second is a phenomenon affecting the short and the medium run. Due to a traditional split in the interest of macroeconomists between long run (growth theory) and short run (business cycle theory), there is very scant empirical analysis of technological change that reconciles effects in the short run and in the long run. This paper provides a novel contribution in this area. We focus on a particular but important aspect of technological change, namely how resources devoted to research and development (R&D) generate new ideas that could have productive economic use. We develop an empirical frame and we apply very recent techniques of panel cointegration and dynamic panel estimation to shed light on the process of technological innovation. We are particularly interested in how countries use R&D resources to generate innovation, how such innovation diffuses over time and in the world, and how it is used to generate further innovation. While such processes could be studied at the microeconomic level, focussing on sectors within countries or even on firm-level data, we maintain throughout the paper a decidedly macroeconomic approach, considering OECD countries as units and their aggregate R&D activity and their innovative output, measured as yearly patent applications at the U.S. patent office, for the period 1972-1995.

We assume the existence of a "production function of innovation" relating the amount of new knowledge created to the amount of existing accessible knowledge and to the amount of R&D resources. Within such context a long-run relationship between R&D and stock of ideas exists even if each variable follows a non-stationary process. Assuming that the production of new ideas is approximately log-linear there is a linear combination of R&D and stock of domestic and internationally generated ideas that is stationary, and the three series are cointegrated. The first part of our work explores this long-run relationship by testing cointegration and estimating the cointegration vector between R&D resources and stock of domestic and international non-obsolete ideas. We apply the recent techniques of panel cointegration in order to test the long-run relationship between those three variables and to estimate the cointegration vector. Once we have identified this long-run relation we estimate the short-run dynamics by means of an Error Correction Mechanism panel VAR (VECM). Moreover, as we have several OECD countries innovating at the same time and learning from each other ideas, we estimate the effect of resources and ideas of each country on innovation of other countries too. By including a variable that captures the accessible world stock of knowledge we analyze the "external" impact, due to learning, of the resources of a country on other countries' innovation.

The rest of the paper is organized as follows Section 2 briefly reviews the relevant literature. Section 5 presents the empirical model and describes the estimation techniques. Section 4 describes the data, Section 5 studies the long-run behavior of innovation using panel cointegration analysis and section 6 analyzes the short-run behavior using VAR techniques. Section 7 concludes the paper.

2 Review of the Literature

Panel cointegration techniques have been used in the analysis of R&D externalities since the initial contribution of Coe and Helpman [4]. The idea tested in that paper is that productivity of a country depends on the stock of past accumulated R&D of the country as well as on that of its trading partners. This implies that a long-run relationship exists between the three variables. As techniques for testing panel cointegration improved in the late nineties, several papers after the original Coe and Helpman [4] applied test of panel cointegration and re-estimated the cointegration vector between productivity, internal R&D and external R&D. Keller [15], Kao et al. [14], Funk [7] and Edmond [6] all produced estimates of this cointegration relation using OECD countries for the period 1970-1991. They used recently developed tests of panel unit-root (developed by Im, Peasaran and Shin [11]) and of panel cointegration (developed by Pedroni [18]) to analyze the long run properties of R&D stocks and productivity and their relationship. The first part of our paper is similar to these recent works in the techniques that it uses. However our long run relationship test the comovements of R&D resources and innovation rather than R&D and productivity, as we believe that a stricter relation exists between those two variables than with productivity.

The second part of the paper is concerned with the short-run dynamics of R&D and innovation. Such topic has been much less explored by the dynamic empirical literature than the corresponding long-run dynamics. The reason is that short-run dynamics are considered the realm of "business cycle economists" and are rarely explored by growth-oriented researchers. However, in order to characterize correctly the short-run behavior of a set of non-stationary variables, we need to account for their long run behavior (cointegration). This is why we build on our results of cointegration and we estimate an error correction mechanism that allows to identify a response of R&D and innovation to shocks in the short run. This, to the best of our knowledge, has never been done in the literature. The literature has however addressed in some studies the important issue of identifying technological shocks and estimating their dynamic impact in the short run on aggregate fluctuations. In a very influential paper Jordi Gali [8] analyzed the effect of technological shocks, identified as those shocks with long-run persistence, on the short-run aggregate fluctuations. The paper was not concerned with the causes of TFP shocks but simply tracked the consequences of these shocks on the short run aggregate fluctuations. Similarly, but emphasizing the role of R&D spending and patenting in generating technological shocks, John Shea [24] estimated the effect of these shocks on short run fluctuations for U.S. sectors. Neither paper found a large effect of technological shocks on short run fluctuations. Our paper shares the interest with this literature for analyzing the propagation mechanism and the timing of diffusion of shocks to knowledge creation and innovation. The ECM model developed to analyze long-run relations provides the ideal frame to study these short-run dynamic properties accounting for the long-run linkages across variables.

3 The Model: R&D Resources and New Ideas

The analysis of the process of generating patentable ideas from resources devoted to research and development and the interaction between innovation, growth and R&D is one of the key mechanisms studied in recent models of innovation and growth (such as Romer [23], Aghion and Howitt [1], Grossman and Helpman [10] and all their derivatives). Intuitively new ideas are produced with the contribution of R&D resources and of the existing stock of knowledge. Therefore, in the long run, existing knowledge, new knowledge and R&D resources are linked by a stable relationship. Such a stable production function can be viewed as the relation between the number of ideas patented in country i during year t and the inputs needed to generate this ideas. We can express such relation as follows:

$$Pat_{i,t} = Innovation\left(R\&D_{i,t},\ A_{i,t-1}, A_{ROWi,t-1}\right) \tag{1}$$

Innovation is a mapping that captures the process of producing new ideas from a set of inputs. Pat_{it} is the measure of new ideas generated in country i and patented during year t. Given that the bureaucratic process of obtaining a patent for a new idea may take several years we measure the patents at the moment in which the patenting process begins (application year) rather than when it is concluded (granted year). We assume that resources devoted to research in year t affect patent applications already during year t. $R\&D_{i,t}$ is a measure of the resources used in the private research and development sector of the economy for country i in year t. $A_{i,t-1}$ is the stock of past accumulated knowledge generated by country i up to the end of the previous period, $t-1$. Similarly $A_{ROWi,t-1}$ is the stock of past accumulated knowledge generated by any country in the world other than i up to time $t-1$. Existing ideas are a very important input in the creation of new ideas, this is why we include $A_{i,t-1}$ and $A_{ROWi,t-1}$ as inputs. We allow the domestically generated stock of ideas $A_{i,t-1}$ to have an impact on innovation different from the internationally generated stock of ideas. In spite of being a non-rival good, international ideas are accessible to a country only in their codified content and they need to be learned before they can be used. In this regard they are different from locally generated ideas that are available also in their non-codified components and do not require learning. We construct $A_{ROWi,t-1}$ as the simple sum of the stock of ideas generated in countries other than i by year $t-1$. The choice of a simple sum is driven by three considerations. First, Keller [15] showed that unweighted sum of external R&D works just as well as a trade-weighted sum, when we measure the external effect of research. Second, Edmond [6] has shown that the specification with unweighted sum is more robust to different specifications and estimation methods than the weighted one. Finally Peri [19] found that international flows of ideas are much less localized than trade flows. Weighting the contribution of foreign ideas by trade shares would incorrectly reduce their impact and, to a first approximation, it is better to take simply their unweighted sum.

Stock variables are obtained by accumulating past patented ideas using the perpetual inventory method. In order to capture the fact that new ideas may displace or improve on old ideas and make them obsolete, we assume that the stock of knowledge is continually increased by the addition of new patents but is also continually decreased by a constant depreciation (obsolescence) rate δ. We choose a depreciation rate to be within the range estimated using data on patent-citations (Caballero and Jaffe [2]) and close to what is chosen as depreciation for the R&D stock (Keller [16]). Such rate is set to $\delta = 0.1$[1] The Variable $A_{i,t}$ is constructed by setting the initial value of the knowledge stock at the level A_{it_0}[2], as follows:

$$A_{it_0} = \sum_{i=0}^{-\infty} = \frac{Pat_{it_0}}{(1+\overline{g_i})^i}(1-\delta)^i = \frac{Pat_{i,t_0}}{(\overline{g_i}+\delta)} \tag{2}$$

$\overline{g_i}$, is the growth rate of patenting in country i in the five years between t_0 and t_0+5 and δ is equal to 0.1. This initial stock is at best a rough estimate of initial knowledge in country i. To compute $A_{i,t}$ for the following years we use the recursive formula:

$$A_{i,t} = Pat_{i,t} + (1-\delta)A_{i,t-1} \tag{3}$$

We use $t_0 = 1962$ as initial year to compute the stock of knowledge, while we begin our analysis of cross-country innovation in 1973. This allows us to reduce the effect of any mistake due to an imprecise estimate of the initial stock of knowledge, as the impact of $A_{i,1962}$ on $A_{i,1973}$ is rather small. We calculate the stock of knowledge from the rest of the world as the simple sum of each country stock of knowledge: $A_{ROW\,i,t-1} = \sum_{j \neq i} A_{j,t-1}$.

In order to estimate the relationship defined by (1) we assume that the mapping $innovation(.,.,.)$ could be approximated by a log-linear function. We consider only patents granted by the U.S. patent office[3] and we assume that each country i decides to patent internationally only a share $\varkappa_i$ of its overall patented ideas ($Pat_{i,t}^{TOT}$)so that we can write expression (1) as:

[1] We conduct robustness checks for the case of $\delta = 0.15$, and we do not find any significant variation in the results.

[2] The level A_{it_0} is compatible with balanced growth path in the periods before t_0.

[3] We employ U.S. patents to provide a comparable measure of innovations with substantial commercial importance across the OECD countries in our sample. International establishments obtaining U.S. patent protection for their ideas incur a cost which is approximately equal for foreign inventors from different countries

$$\ln(Pat_{i,t}) = \ln[\varkappa_i Pat_{i,t}^{TOT}] = \ln(\varkappa_i) + \lambda \ln(R\&D_{i,t}) + \phi \ln(A_{i,t-1}) + \xi \ln(\sum_{j \neq i} A_{j,t-1}) \tag{4}$$

Equation (4) states that the level of patenting across countries and over time is a log-linear function of the level of resources used in R&D and of the level of locally and internationally accumulated past patents, net of depreciation. λ captures the impact of R&D resources on patenting, while ϕ and ξ capture, respectively, the effect on patenting of past accumulated ideas generated within the country and learned internationally. Taking into account the recursive relationship between $Pat_{i,t}$ and A_{it}, dividing equation (3) by $A_{i,t-1}$ and re-arranging we obtain:

$$\frac{Pat_{i,t}}{A_{i,t-1}} = g_{Ai,t} + \delta \tag{5}$$

$g_{Ai,t}$ is the growth rate of the stock of knowledge A_i between $t-1$ and t. Taking natural logarithms on both sides and substituting equation (4) into equation (5) we obtain the following linear relation between the time series of $\ln(A_{i,t-1})$, $\ln(R\&D_{i,t})$ and $\ln(A_{ROWi,t-1})$:

$$\ln(g_{i,t} + \delta) - \ln(\varkappa_i) = \lambda \ln(R\&D_{i,t}) + (\phi - 1) \ln(A_{i,t-1}) + \xi \ln(A_{ROWi,t-1}) \tag{6}$$

This equation is valid in each period. If the economy converges to a deterministic Balanced Growth Path $g_{i,t}+\delta$ converges to a (potentially country-specific) constant $g_i+\delta$. Alternatively if the economy converges to a stochastic Balanced Growth Path $g_{i,t}+\delta$ converges to a (trend) stationary stochastic process. The equation in (6) represents the long-run relation between $\ln(R\&D_{i,t})$, $\ln(A_{i,t})$ and $\ln(A_{ROWi,t-1})$. Even if each of the three variables turns out to be non-stationary the above-written equation establishes that if there is convergence to a stochastic balanced growth path there must be a cointegration relation among those three, i.e. a linear combination that is stationary. The cointegration vector, standardizing the coefficient in front of $\ln(A_{i,t-1})$ to minus one is $(-1, \mu, \gamma)$ where $\mu = \lambda/(1-\phi)$ and $\gamma = \xi/(1-\phi)$.

The framework developed above provides a guidance for our empirical analysis. The equation in (6) represents a convenient and useful approximation of the average long-run relation between R&D resources, stock of domestic knowledge and stock of international knowledge. It is our guidance in analyzing the long-run properties of the data. On the other hand, the timing implied by equation

(1) is used to identify and estimate the effect of R&D shocks and "idea' shocks in the short-run. Equation (1) implies that patent applications in period t ($Pat_{i,t}$) are affected by R&D resources employed in the same period, and by knowledge generated within the country $A_{i,t-1}$ or outside of it $A_{ROWi,t-1}$ up to the previous period . However, it is reasonable to assume that the amount of R&D employed in period t depends only on ideas generated up to $t-1$. Given the innovation function represented in (1), even if the resources devoted to research respond to changes in its productivity this only induces a dependence of $R\&D_{i,t}$ from $A_{i,t-1}$ but not from $A_{i,t}$. This assumption on the timing of innovation relative to R&D provides the identifying restriction needed in our Error Correction Mechanism.

4 Data and Time-Series Behavior

4.1 Data Description

Our empirical analysis is performed on fifteen OECD Countries for the period 1973-1995. The fifteen countries considered account for about 90% of the world R&D and for 97-98% of the total U.S. granted patents. R&D resources are measured as the number of hours worked by people employed in the R&D sector from the ANBERD, OECD data set. The data on patents by country are obtained by aggregating more than three million individual patents from the NBER Patent Data set described in detail in the book by Jaffe and Trajtenberg ([12]). We impute the country of residence of the first inventor[4] as the location of the patent to capture the location where the underlying research was carried out rather than the country where its application's paperwork was prepared (headquarters of the company). The dataset includes about 3 million patents granted by the United States patent office between the years 1963 and 1999. However in our analysis we group the patents by application year, in order to approximate at our best the timing of the invention. We use as measure of $Pat_{i,t}$ the total number of patents' applications by residents of country i during year t and we weight each patent by the factor $(1+\mu_3)$ where μ_3 is the average number of yearly citations received by the patent during the first three years after it has been granted[5].This is done because subsequent citations are a measure of the importance of a patent and so doing we account for the "importance" of the idea that a patent represents.

[4]This is routinely done by the literature on patent's location.

[5]For this reason we have restricted our dataset to the patent granted in the period 1963-1995.

Table 1 shows the average values of the variables of interest over the period 1973-1995. Large variation in patenting and R&D resources exists across these countries. Ireland, the smallest innovator in our sample, filed an average of 37 patent applications each year and each of those patents received 0.5 citations per year in the first 3 years. To the other end of the spectrum the U.S. filed more than 45,000 patent applications each year and each of those patents was cited 0.42 times per year during the first three years. Ireland devoted slightly more than 6 million hours of its labor force per year to R&D, the U.S. devoted 1.6 billion hours per year to R&D. Considering total patenting and total resources spent in R&D by the OECD countries over time (not reported), we have a consistent and systematic increase over the considered period of both variables. Total patent applications grew by 2% per year on average and much faster during the period 1983-1989. R&D hours grew more uniformly by an average 4% per year. This is true of the overall patenting and R&D spending but also of most of the single considered countries. Analyzing the behavior of the time series for R&D resources and stock of knowledge is the first goal of our paper. In order to apply the appropriate econometric technique to estimate the long-run and the short-run dynamics of our variables we need to determine the stationarity or lack of it for each variable. While both trending up it is not clear if the two series are trend-stationary or non-stationary and in order to establish this we perform several unit-root tests.

4.2 Test of Unit Root

A change in the stock of knowledge of a country should permanently be incorporated in the future potential for generating new knowledge. At the same time the industrialized world has experienced a persistent and sustained increase of employment in R&D sector. Investments in R&D, which are complementary to ideas in generating innovation, are also driven in this continued upward trend. Our presumption is that both series could exhibit very persistent effects of shocks and a non-stationary behavior. It is well known, though, that unit root and cointegration tests have rather low power. In a short time series (22 years) of yearly data, it is particularly hard to discern non-stationariety. We rely on panel unit roots tests that are more powerful as they exploit both the cross section and the time series dimension of the data. There are several statistics that can be used to test for a unit root in panel data. Specifically we want to test for non stationarity against the alternative of trend stationarity, allowing for different intercept and a common time trend. This is a very general alternative hypothesis and therefore the test of non-stationariety is very demanding. We employ the test by Im, Pesaran and Shin [11] which allows each panel member to have different short time dynamics under the alternative hypothesis of trend stationarity. Their most powerful test in finite samples T, is based on the average of the Augmented Dickey-Fuller (ADF) statistics across all countries, taking into account the differences in the structure of serial correlation. Im Peasaran and Shin [11] provide also the critical values for the panel ADF. The test proposed is:

$$\bar{t}_{iT} = (1/N) \sum_{j=1}^{N} t_{iT}(p_i, \rho_i) \tag{7}$$

where N = 15, number of countries

T= 22, number of periods

p_i = order of the Auto-Regressive process

ρ_i= parameters on lags included in ADF

$t_{iT}(p_i, \rho_i)$ = individual ADF statistics

For each individual series $X_{it}(= \ln(A_{it})$ or $\ln(R\&D_{i,t}))$ we can write:

$$\Delta\widetilde{X}_{it} = \alpha_i + \gamma_i t + \beta_i \widetilde{X}_{it-1} + \sum_{j=1}^{p_i} \phi_{ij} \Delta\widetilde{X}_{it-j} + \epsilon_{it} \tag{8}$$

where $E(\epsilon_{it}\epsilon_{jt}) = 0,\ i \neq j$ for all t and where we define $\widetilde{X}_{it} = X_{it} - (1/N)\sum_{i=1}^{N} X_{it}$, the deviation from the cross-sectional average, as the basic unit of analysis. The null hypothesis of unit roots is $H_0 : \beta_i = 0$ against the alternative $H_0 : \beta_i < 0$. The test procedure requires that the observations are generated independently across countries. The de-meaning procedure [6] removes possible correlation among residuals due to a common time effect that might affect the results of the test.

We construct a balance panel data set for 15 countries in the period 1973-1995. The test is based on the average of the augmented Dicky-Fueller test statistics computed for each country with a lag of two periods to adjust for autocorrelation. The adjusted test statistics are distributed as a N(0,1) under the null hypothesis and large negative values tend to reject the unit root hypothesis in favor of stationarity. The test does not require all the series for all countries to be non stationary

[6]This procedure is not robust to misspecification of time trends or short-run dynamics if the effect of the common component varies across countries

since the value of the test is the average of the ADF individual countries. Table 2 reports our estimated test statistics. Neither for the log series of the domestic knowledge stock, $\ln(A_{i,t})$, nor for the log series of the international knowledge stock $\ln(A_{ROWi,t})$ or for the log of employment in R&D $\ln(R\&D_{i,t})$ we can reject the null of unit root at standard level of significance. Even stronger than that, none of the ADF statistics relative to $\ln(A_{i,t}), \ln(A_{ROWi,t})$ or $\ln(R\&D_{i,t})$ for any country is lower than the threshold for rejecting the unit-root hypothesis. We report in column 1 of Table 2 the test statistics for the variable $\ln(A_{i,t})$. Column 2 reports the test for $\ln(A_{ROWi,t})$ and column 3 for $\ln(R\&D_{i,t})$, the log of R&D employed. The critical 5% value for the statistic proposed by Im, Peasaran and Shin ([11]) is reported in the last row of our table. The average statistic for each variable is well above the threshold and therefore we cannot reject the null of non-stationary series. Overall we confirm our hypothesis of extremely high persistence of shocks to R&D and to domestic or learned stock of ideas and we are comfortable with the idea that they are effectively represented by $I(1)$ processes.

5 The Long-Run Dynamics

Our prior of non stationarity of the variables is confirmed by the unit root tests. We then proceed to analyze whether the long run behavior of R&D resources, domestic knowledge and international knowledge is linked by a cointegration relation. If it is, the dynamic system of national R&D resources and innovation converges to a stochastic balanced growth path. Using very recently developed techniques we estimate the cointegration vector of equation (6) and then we test that the residuals of such regression are stationary (test of cointegration).

5.1 Panel cointegration Relation

We use dynamic ordinary least squares (DOLS) to estimate (6) on the whole panel of 15 countries and 22 years in order to gain degrees of freedom. The environment that we study imposes homogeneity on the cointegration vector across countries but allows for country-specific fixed effects and time trends. As in Phillips and Moon [21], Kao [13] and Pedroni [18] , the errors are assumed to be independent across countries. Therefore, as in the single-equation environment, this estimator sacrifices asymptotic efficiency because it does not take into account the cross-equation dependence in the equilibrium errors[7].

This method of exploiting the cross-section dimension of the data set while respecting the time series properties of the data, without aggregating or pooling, allows us to address the problem of inconsistent estimates in dynamic heterogeneous panels identified by Pesaran and Smith [20] .Finally, the use of DOLS as opposed to other cointegration estimators is justified by recent work by Kao et al. [14] which shows that it performs better than other single-equation cointegration estimators in panels of up to size N=20.

In practical terms, the estimation of the equation by DOLS involves adding leads and lags of the first differences of the I(1) regressors to equation (1). Thus, all nuisance parameters, which represent short-run dynamics, are I(0) and are by construction not correlated with the error term. This procedure corrects for the possible endogeneity of the non-stationary regressors and gives estimates of the cointegration vector which are asymptotically efficient when the error terms are independent across countries. All variables and nuisance parameters corresponding to the dynamic terms are allowed to vary across countries.

In order to estimate the cointegration relation between R&D and stock of ideas we re-write expression (6) adding two lags of the differences variables as follows[8]:

$$\begin{aligned} \ln(A_{it-1}) \quad = \quad & c_i + \theta_t + \mu \log(R\&D_{i,t}) + \sum_{j=1}^{2} \mu_i \Delta \ln(R\&D_{i,t-j}) + \\ & + \gamma \log(A_{ROWi,t-1}) + \sum_{j=1}^{2} \gamma_i \Delta \ln(A_{ROWi,t-1-j}) + \epsilon_{it} \end{aligned} \tag{9}$$

The estimates of parameters μ and γ are reported in Table 3. The variance-covariance matrix of the coefficients is consistently estimated by applying Mark and Sul [17] dynamic panel variance estimator. As different countries may exhibit permanent differences in their innovation generating process we allow for country-specific fixed effects c_i in each specification. Alternatively the time-

[7] In contrast to previous analyses of panel cointegration vector estimators, the asymptotic distribution of panel DOLS under cross-sectional dependence is easy to obtain.Mark and Sul [17] and Kao and Chiang [14] studied the properties of panel dynamic OLS under the assumption of independence across cross-sectional units. Pedroni [18] and Phillips and Moon [21] study a panel fully modified OLS estimator also under cross-sectional independence. Moreover, the asymptotic theory employed in these papers allows both T and N to go to infinity.

[8] The lag length can be determined by Campbell and Perron's [3] top-down t-test approach.

effects θ_t are either omitted (Specification I) or included as a common time-trend (Specification II) or included as a country-specific time trend (Specification III). Specification I implies that in the long run there is a strong positive impact of R&D resources on accumulation of ideas in a country. An increase by 1% in R&D resources generates an increase by 0.36% in the stock of ideas generated by that country. The contribution of learning from foreign ideas is even larger, with a long-run effect on domestic idea of 0.75% per each extra percentage point of international stock of ideas. Such estimates imply that the long-run effect of international learning on domestic innovation is twice as strong as the effect of domestic R&D resources. However, once we allow for a common time-trend in the cointegration relation we obtain that the contribution of R&D and of international knowledge on domestic innovation is similar. Specification II (our preferred one) shows that an increase of 1% in R&D would benefit innovation by 0.30%, while an increase of 1% in the stock of foreign ideas increases innovation by 0.25%. Similar values are estimated in specification III with time-specific trend. Domestic R&D and international learning have a similar impact on domestic innovation. This is consistent with the estimates of Coe and Helpman [4] and of Kao et al. [14] who estimate elasticities of productivity to domestic and international R&D similar to each other. In fact several studies of R&D spillovers (some of them reviewed in Griliches [9]) find that the impact of external R&D on productivity of firms or countries is between half as large and 50% larger than the impact of own R&D. Our estimate of learning externalities of the same order of magnitude as the internal effect of R&D are therefore right in the same ballpark.

5.2 Panel Cointegration Test

The variable ϵ_{it} in the cointegration regression (9) should be a stationary error term. We test such property using an ADF based panel cointegration test from Pedroni [18] which is analogous to the Im, Pesaran ans Shin [11] ADF we used to test the unit-root property of the variables $\ln(A_{i,t})$, $\ln(A_{ROWi,t})$ and $\ln(R\&D_{i,t})$. Last row of Table 3 reports the average over countries of the ADF t-test calculated from the residuals of the regression (9) with a lag length of up to five years. Adjustment parameters to construct the test statistic are from Pedroni [18], which allows for the fact that we are testing residuals from an estimated relationship rather than a true relationship. Large negative values imply stationarity of the residuals and lead to a rejection of no cointegration. In each single case we cannot reject the null of cointegration (i.e. stationarity of the residuals) at the 5% confidence level and for specification I and II we cannot reject it at 1% level of confidence.

We can think of the cointegration relationship as capturing those features on which it is necessary to condition in order for the stock of ideas in a country to be conditionally convergent to those of other countries. Any remaining differences in the production of new ideas across countries would be only transitory. The various terms of the regression account for any mechanism that might possibly lead to permanent differences in the production of ideas across countries, including those elements that might impact countries differently. In nonstationary cointegrated panel fixed effects and the common trend serve to capture a broad class of unobserved mechanisms. Country effects c_i account for different propensity to patent internationally or unobservable institutional inputs to the innovation process. The common time trend θ_t captures a potential common tendency to increase efficiency in the innovation process. On the other hand we assume that the parameters that capture the long-run relation (i.e. the cointegration vector) is common to all countries. This is a strong assumption as Coe and Helpman [4], for instance, found differences in the long-run relations in large (G7) and small countries. We hope that the richer specification and characterization of the panel as well as the use of a more homogeneous phenomenon (patented innovation) across countries account properly for country differences leaving a correct characterization of the long-run relation among variables. Unfortunately the short time dimension of our sample does not allow us to test if the elasticities of the production function differ significantly across countries.

An important advantage of the method used is that we do not need to make any special assumption regarding the dynamics around the steady state. The regressions picks up the long run relationship between the variables in a way that is robust to the presence of short run dynamics. While conventional panel techniques tend to estimate higher frequency relationships among the variables, and they relegate to fixed effects the long run relationship, the reverse happens in panel cointegrated estimation. In this case transitional dynamics have a second order effect on the estimated long run relationship and they can be treated as a nuisance parameters in the estimation and testing procedure. In addition we can relax the exogeneity assumptions that have been required in earlier approaches, without the need for external instruments. Again this stems from the superconsistency properties of the panel cointegration regression which identifies the long run relationship even in the presence of endogeneity. Instead endogeneity can create only a second order effect.

6 The Short-Run Response

6.1 The Error Correction Mechanism VAR

While departure from the cointegration relation between R&D resources and ideas cannot last in the long run, the innovation process is subject to shocks in the short run. There could be shocks to the amount of resources allocated to research or to the productivity of researchers in generating new ideas. In order to analyze the propagation and the impulse response to such shocks in the short run, we adopt an "error correction" representation of our dynamic relationship between $\ln(R\&D_{i,t})$ and $\ln(A_{i,t})$.In particular we consider the change of each variable as depending on the past changes in the other variables as in a VAR in differences but we include a term that captures the deviation from the estimated long-run relationship. Such "disequilibrium" term ensures that we account properly in the short-run dynamics for the convergence to the estimated long-run stochastic balanced growth path. We represent the dynamic behavior of $\Delta\ln(A_{i,t})$ and $\Delta\ln(R\&D_{i,t})$ as follows:

$$\begin{aligned}\Delta\ln(A_{i,t}) &= c_{1i} + d_1\widehat{\epsilon}_{it-1} + \sum_{z=1}^{2}\eta_{1z}\Delta\ln(R\&D_{i,t-z}) + \sum_{z=1}^{2}\eta_{2z}\Delta\ln(A_{it-z}) + \sum_{z=1}^{2}\eta_{3z}\Delta\ln(A_{ROWi,t-z}) + e_{Ait} \\ \Delta\ln(R\&D_{i,t}) &= c_{2i} + d_2\widehat{\epsilon}_{it-1} + \sum_{z=1}^{2}\upsilon_{1z}\Delta\ln(R\&D_{i,t-z}) + \sum_{z=1}^{2}\upsilon_{2z}\Delta\ln(A_{it-z}) + \sum_{z=1}^{2}\upsilon_{3z}\Delta\ln(A_{ROWi,t-z}) + e_{RD}\end{aligned}$$

We only need to specify the dynamics for these two variables as the evolution of the international stock of knowledge for each country $A_{ROWi,t}$ is simply given by the sum of $A_{j,t}$ for all countries other than i. The term $\overset{\wedge}{\epsilon}_{it}$ is the "disequilibrium term" and it is equal to $\ln(A_{it-1}) - \widehat{c}_i - \widehat{\theta}_t - \widehat{\mu}\ln(R\&D_{it}) - \widehat{\gamma}\ln(A_{ROWi,t-1})$. We constructed it using the estimated cointegration relation. It represents the deviation from the equilibrium relation and the coefficients d_1 and d_2 measure how the disequilibrium generates adjustment in order to preserve the long run equilibrium. The Granger representation theorem implies that at least one of the d_i coefficients must be non-zero if a long run relationship between the variables is to hold. The estimates of d_1 and d_2 in our system are equal to -0.011 (s.e. 0.0047) and 0.0034 (s.e 0.072). The first coefficient estimated is significant and negative and it guarantees that the system does actually converge to its stochastic long run relation. The second coefficient, instead, is statistically not different from zero and it tells us that innovations to a country stock of log knowledge has no long run effect on log R&D.

Rather than presenting the estimates of the dynamic coefficients we show the impulse responses of stock of nationally generated ideas and resources used in R&D to shocks to the productivity of resources in generating new ideas (e_{Ait}) and to the amount of resources used in R&D (e_{RDit}).

6.2 Impulse Response

Given our flexible specification that allows for country specific effects and spillover effects through the term $A_{ROWi,t-1}$the impulse response of country i to an innovation of one of the two equations in country j could be different for each couple of i and j. However, the short time length of our sample does not allow for heterogeneity across countries. Therefore, we impose the coefficients $\eta_{1z} - \eta_{3z}$ and $\upsilon_{1z} - \upsilon_{3z}$ equal across countries restricting the impulse responses so that the only real difference across them depends on the impact of that country on the total available world knowledge $A_{ROWi,t-1}$. A shock to a country that provides a relevant contribution to $A_{ROWi,t-1}$ has, through this channel, a non trivial impact on innovation and on the choice of R&D resources for all other countries in the world. A country that contributes only trivially to $A_{ROWi,t-1}$ exhibits mainly effect on its own innovation and R&D as dynamic response to a shock e_{Ait}, e_{RDit}. In order to illustrate this comparison in its most extreme form we choose to report the impulse response of R&D resources, $\ln(R\&D_{i,t})$, and innovation $\ln(A_{it})$ for all the fifteen countries to shocks $e_{Ajt}$and e_{RDjt} that take place in the U.S. (the largest country in the sample) and in Ireland (the smallest country in the sample). Panels 1 trough 8 present the complete set of estimated impulse response functions, along with standard errors bands.

The first four panels (1 to 4) track the 20 years response in each country's innovation activity to shocks originating in the U.S. Depending on which shock we consider ($e_{A,USt}, e_{RD,US,t}$) and which variable we track ($\ln(A_{it}), \ln(R\&D_{i,t})$) we have four combinations of IRs. The long run behavior of the system is driven by the cointegration relation. However the dynamics in the short and medium run allow us to learn something of the process through which this transition takes place. Consider first Panel 1. The dynamic response of the stock of knowledge of other countries to a 1% (0.13) increase in the (ln) stock of US knowledge at the beginning of the period is rather similar across countries: it is significantly positive at any horizon, increasing rapidly during the first five to ten years. The impact of the US shock on other countries flattens on average at +0.10, which corresponds to an increase of 1-1.5% of the average stock of their knowledge in the period considered.

This effect is due to two components. First higher US knowledge increases the stock of world knowledge and this benefits innovation in all countries. Second (see next panel) in the medium-long run, higher world knowledge implies higher investment in R&D resources of countries and this contributes to higher stock of knowledge. The effect of this shock on US innovation itself is much larger and builds up in the short run reaching a peak after 10 years at 0.6% and declining afterwards so that after twenty years it is roughly equal to 0.4, three times higher than the initial shock. Complementing this picture, Panel 2 shows the effect of the same shock on resources employed in R&D across countries. Interestingly, while in the US itself a positive shock to innovation drives more resources into R&D since the first year, in other countries a "substitution" effect prevails at first. During the first four to five years following the shock to US innovation, R&D resources in other countries are slightly decreased as a consequence of more international spillovers (coming from the positive US shock). After this period local R&D resources respond positively and the final result is a permanent increase of about 1-1.4% (+0.12) in R&D resources employed across countries in response to a 1% (0.13) increase in (ln)US stock of knowledge.

We then analyze the impact of a shock to U.S. ln(R&D) resources on US (ln) stock of knowledge (Panel 3) and ln(R&D) resources (Panel 4) of all countries. If we first look at the own U.S. impulse responses (the figures in the lower right corner) we notice that ln(R&D) shocks affect knowledge with a delay as it takes few periods for these resources to generate knowledge. Therefore such positive shocks result in further increasing in R&D resources. The increase in $\ln(A_{US,t})$ stabilizes after 20 years at a level equal to 1% (+0.14) of the average (ln) stock of US Knowledge. The increase in $\ln(R\&D_{US})$ resources stabilizes much earlier (after 5-6 years) at +0.32, a 2.5% higher average (ln)stock of knowledge in the sample. Consistently with the previous finding relative to $e_{A,USt}$ the impact of a shock $e_{RD,US,t}$ on the stock of knowledge of the other countries is positive (an average increase of 2-4%) and is delayed a couple of years as shown in Panel 3. Moreover, the responses of their R&D resources exhibit a delay of about two years and, similarly to Panel 2, an initial "substitution" effect that drives R&D of other countries down for a few years. Eventually the positive effect prevails and the R&D of all countries increases. In the long run an increase in the stock of world knowledge is consistent (due to the cointegration relation) with higher R&D and higher stock of national knowledge for all countries.

Panels 5-8 report the impulse response of knowledge and R&D resources to shocks taking place in Ireland, the smallest country in our sample (in terms of number of weighted patents). The difference between these IRs and the four IRs previously analyzed is mostly driven by the difference between US and Ireland innovation in contributing to world knowledge. The first country is responsible for about half of the world innovation, the second for a negligible share. The impulse response of Irish $\ln(A_{it})$ and $\ln(R\&D_{it})$ to its own shocks $(e_{A,IEt}, e_{RD,IE,t})$, reported in the middle picture (third from above) of the right column in each Panel (5 to8) are similar to the own responses found before (of US variables to US shocks). The response of $\ln(A_{it})$ to $e_{A,IEt}$ is hump shaped with maximum effect after ten years: the initial 1% increase in the stock of Irish knowledge triple after twenty year. However the increase in R&D resources after a shock in knowledge is much lower for the simple reason that the spillovers effect of other countries' world knowledge is now lower. Similar pattern have the other IR functions for Ireland when we look at $e_{R\&D,IEt}$: They show a progressive increase and by the twentieth year they have reached a plateau. To the contrary, the responses of other countries to these shocks are very small and, even in the long run, typically less than a hundredth of a percentage point of the initial shock as we can see by reading the scale in each impulse response. As the impact is so small, some nuisances (such as country effects or lagged effects) also cause the IRs in this case to have different shapes from those generated by US shocks that were dominated by the effect of US knowledge on world knowledge. All in all we can think of the external effect of a small country such as Ireland on the dynamics of other country's innovation and R&D as negligible both in the short and in the long run.

7 Conclusions

Shocks to the innovative activity of a country could be the source of booms in the short run and of improvements in productivity in the long run. Analyzing them in a coherent framework that tracks their consequences at different time horizons is a way of reconciling the short and the long run. Such path of research on innovation has been largely neglected by recent economic analysis. This paper takes a first step in this direction by analyzing one phase of the innovation process, namely the interaction of R&D resources and knowledge to generate new ideas. We apply some recent methods to estimate the cointegration (long-run) relationship between these variables. Moreover we use an error correction mechanism to estimate short and medium run responses. We find that, in the long run, internationally generated knowledge is an important contributor to the innovation of a country. The stock of knowledge of a country responds to international knowledge with roughly the same elasticity as to its own R&D. We then estimate the dynamic response in the short and medium run to this impulse. A large country as the US would have a non negligible impact on other countries' knowledge creation even in the short run. A 1% positive shock to the log of US stock of knowledge increases by 1-1.5% knowledge creation in other countries within five years. As for the impact of this shock on the US it generates a maximum 6% effect after ten years and then declines slightly. Analyzing the impact of a similar shock originating in Ireland we see that such small country has basically no effect on knowledge creation of others.

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Tables

Table 1.
Summary Statistics for Patents, Stock of Knowledge and R&D.

Country	Citation-weighted Patents	Accumulated Stock of Knowledge, Country i	Accumulated Stock of Knowledge, Rest of the World	Total hours worked in R&D
Australia	466	3458	811475	58451
Canada	2047	14531	800401	92267
Germany	8477	64933	749999	393014
Denmark	235	1690	813243	19685
Spain	133	886	814047	46598
Finland	283	1613	813320	22112
France	3282	24642	790290	264272
UK	3420	29954	784979	296468
Ireland	51	297	8146363	6121
Italy	1257	8883	806050	117092
Japan	20978	121472	693461	737808
The Netherlands	1040	7888	807045	61661
Norway	132	938	813995	16918
Sweden	1012	8221	806712	46790
USA	63903	525531	284639	1654718

15 OECD Countries, averages for the period 1972-1995.

Table 2.
Test of Unit Roots for the variables $\ln(A_{it})$, $\ln(A_{ROWit})$ and ln(R&D).

Country	**Ln(A)**	**Ln(A_{ROW})**	**Ln(R&D)**
Australia	-0.0383	-0.6311	-0.2943
Canada	-0.057	-0.6487	-0.9917
Germany	-0.040	-0.6109	-0.7890
Denmark	0.2376	-0.4877	-1.5189
Spain	-0.0387	-0.6057	-0.4141
Finland	-0.04821	-0.6238	-1.1023
France	0.00278	-0.6102	-0.7464
UK	-0.0124	-0.5673	-0.8547
Ireland	-0.0433	-0.6142	-0.3900
Italy	-0.0076	-0.5797	-0.6383
Japan	-0.0584	-1.0157	-1.1289
The Netherlands	-0.0064	-0.5764	1.0729
Norway	-0.0384	-0.60684	-1.10167
Sweden	-0.0285	-0.61193	0.0375
USA	-1.3076	-1.5915	-2.1434
Test Statistic	-0.098	-1.052	-0.73369

The calculated statistic is the average ADF test, proposed by Im Pesaran and Shin (1999).

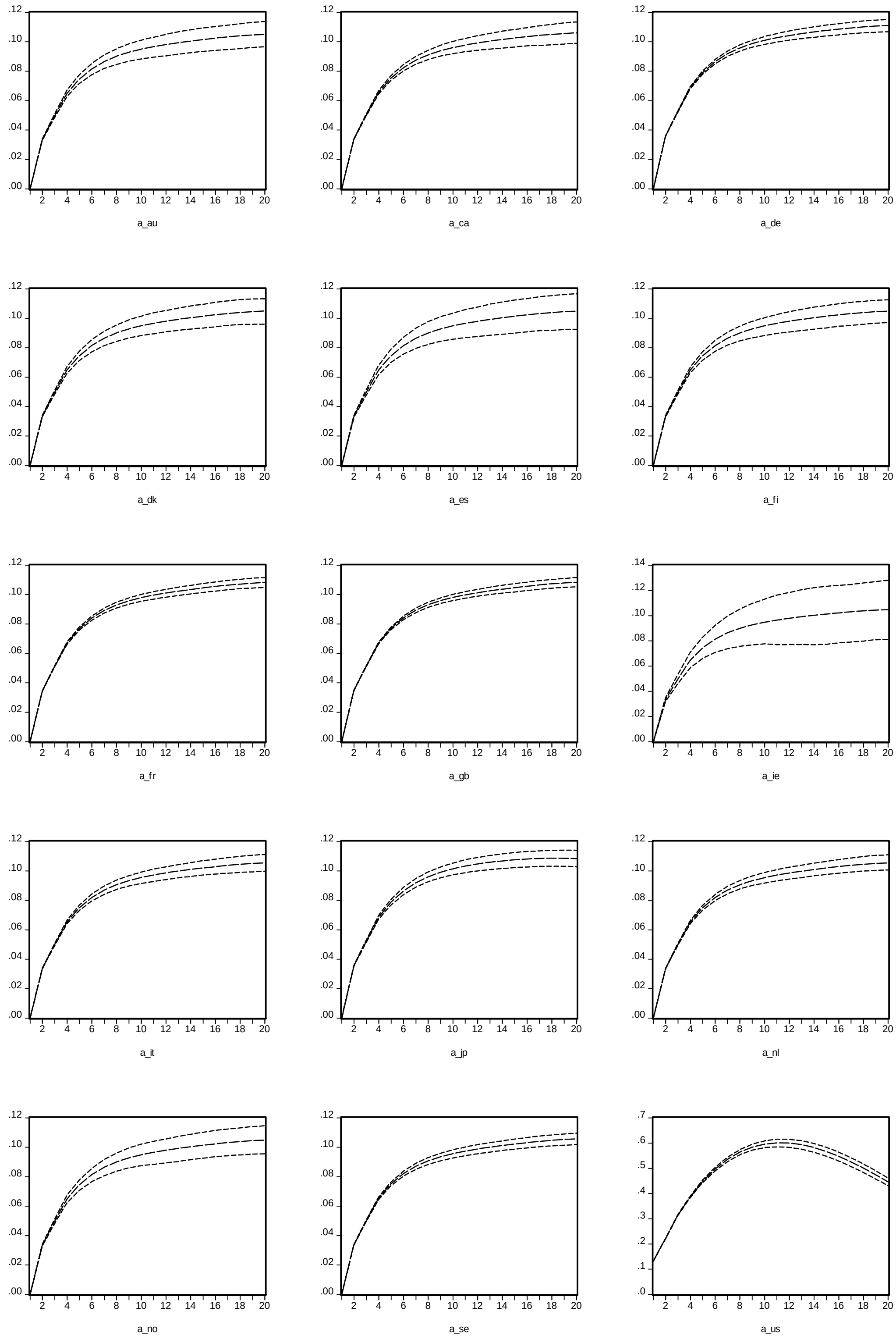
Table 3
Estimates of the Cointegration Vector

	Cointegrating Relation I	**Cointegrating Relation II**	**Cointegrating Relation III**
$Ln(A_{it-1})$	-1	-1	-1
$Ln(R\&D_{it})$	0.359** (0.03)	0.305** (0.03)	0.233** (0.04)
$Ln(A_{ROWt-1})$	0.753** (0.030)	0.247** (0.068)	0.328** (0.044)
Country Fixed Effect	Yes	Yes	Yes
Homogeneous trend		Yes	
Heterogeneous trend			Yes
R^2	0.934	0.943	0.940
Number of Observations	300	300	300
Test of Cointegration Pedroni (1997)	-4.90**	-2.65**	-2.10*

Method of Estimation: Dynamic Ordinary Least Squares
DOLS consistent standard errors in parenthesis
*= significant at 1% confidence level.
**= significant at 1% confidence level.

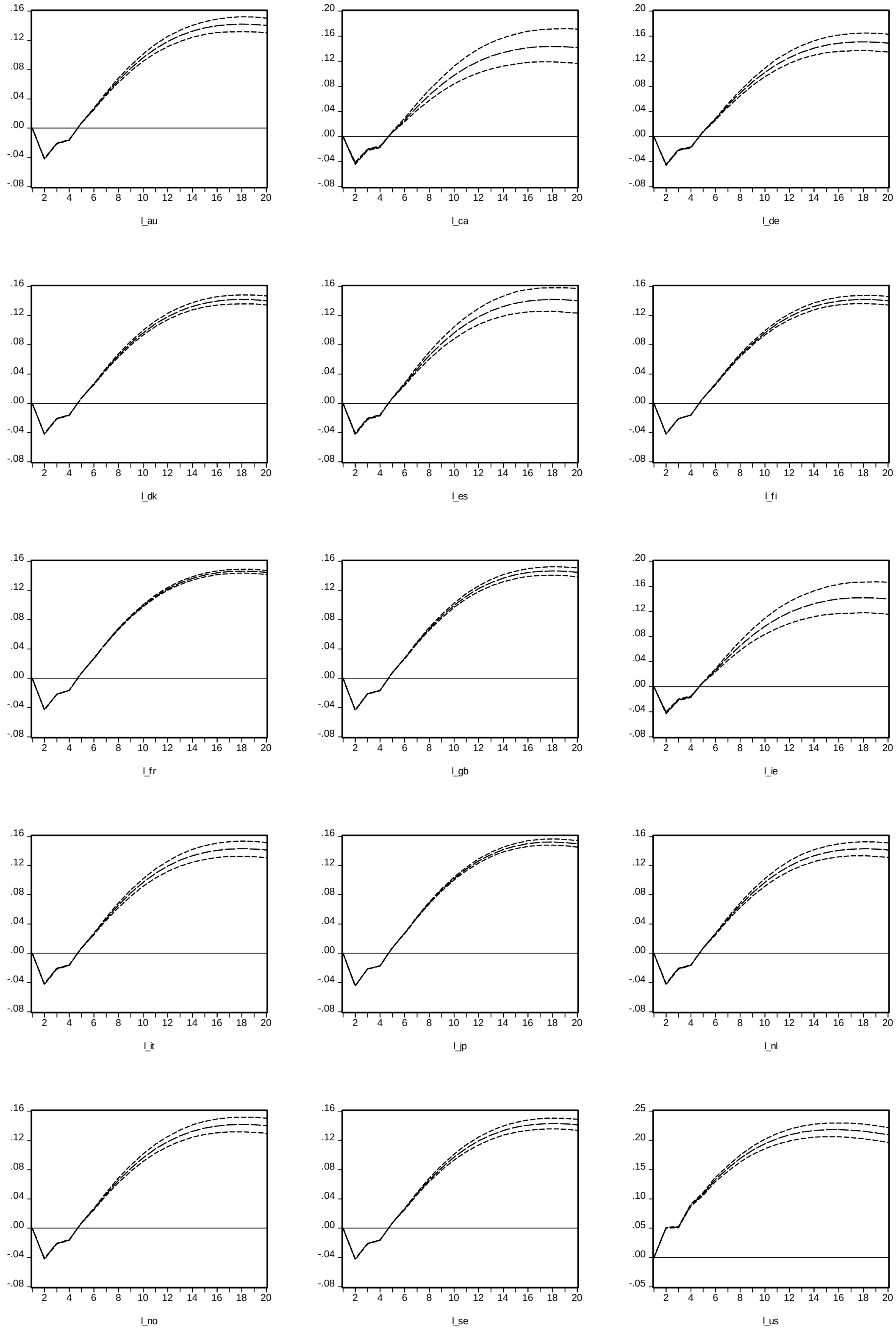
Specification I: Dynamic Ordinary Least Squares with country-specific intercepts and no time-effects.
Specification II: Dynamic Ordinary Least Squares with country-specific intercepts and common time-trend
Specification III: Dynamic Ordinary Least Squares with country-specific intercepts and country-specific time-trend.

Panel 1
IR of ln(A_{it}) for all countries
to $\varepsilon_{A,US,t}$ (shock to innovation in the US)



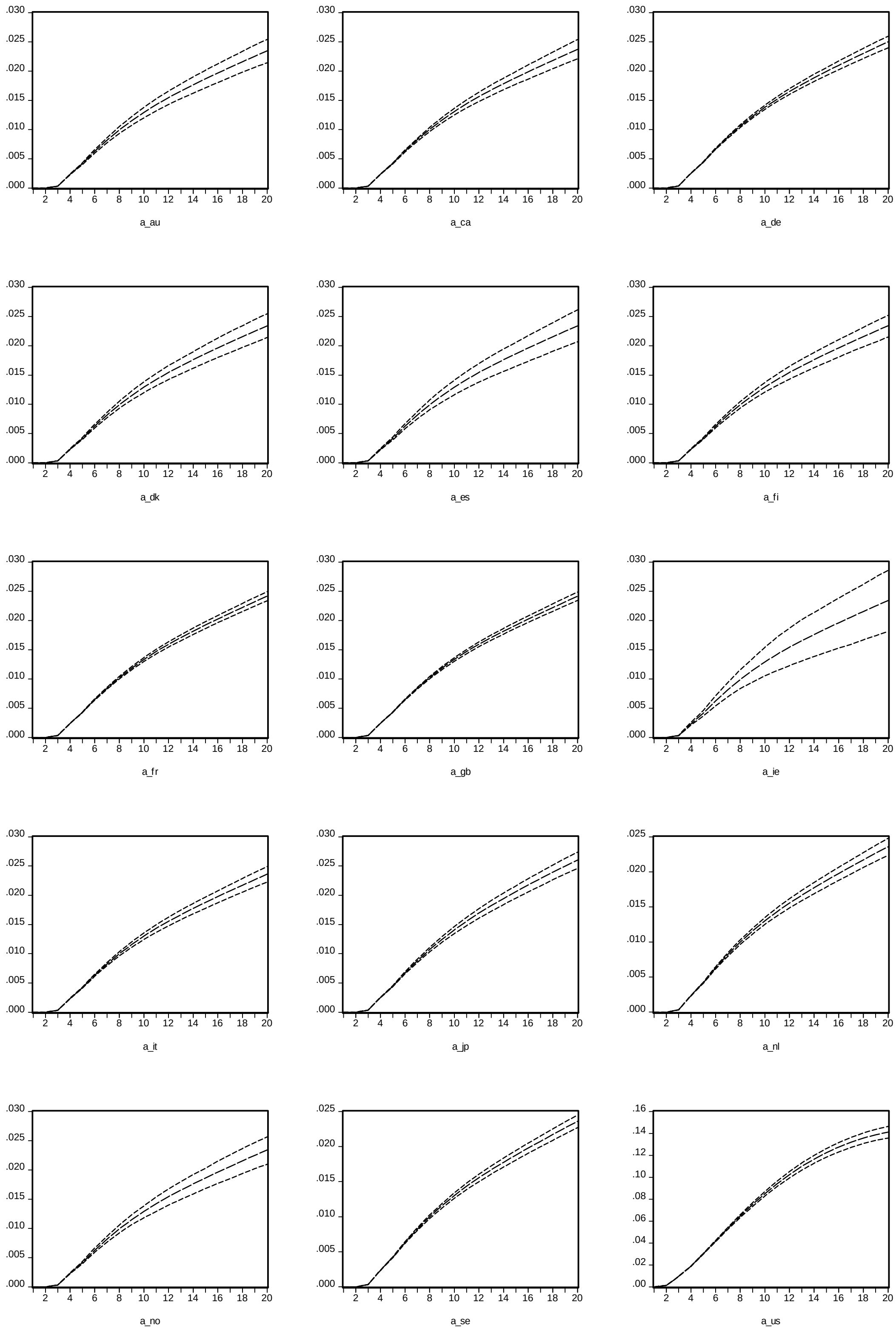
Shock equal to 1% of ln(A_{USt}).

Panel 2
IRs of ln(R&D$_{it}$) for all countries
to $\varepsilon_{A,US,t}$ (shock to innovation in the US)



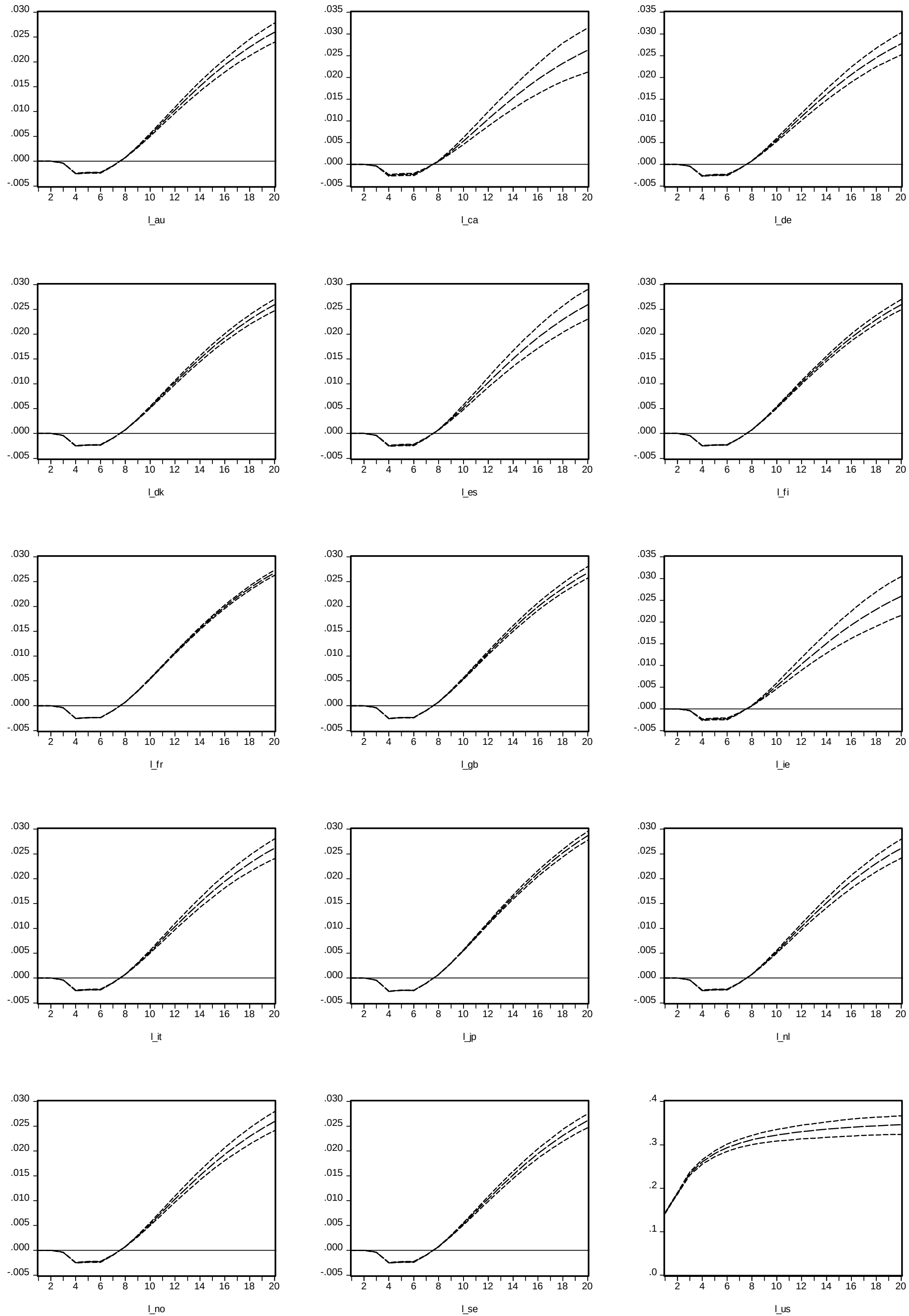
Shock equal to 1% of $\ln(A_{Ust})$.

Panel 3
IR of $\ln(A_{it})$ for all countries
to $\varepsilon_{RD,US,t}$ (shock to R&D resources in the US)



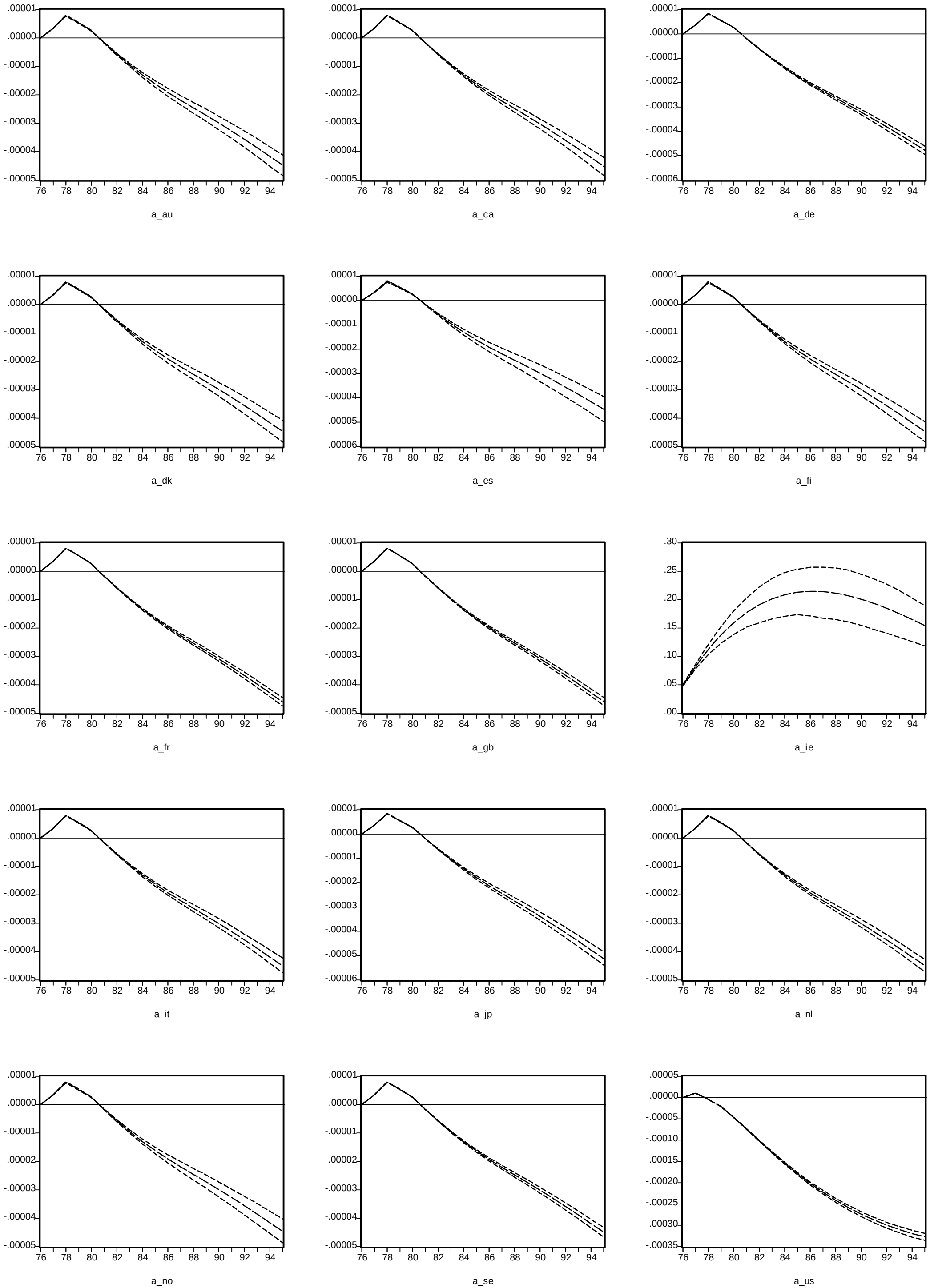
Shock equal to 1% of $\ln(R\&D_{Ust})$.

Panel 4
IRs of $\ln(R\&D_{it})$ for all countries
to $\varepsilon_{RD,US,t}$ (shock to R&D resources in the US)



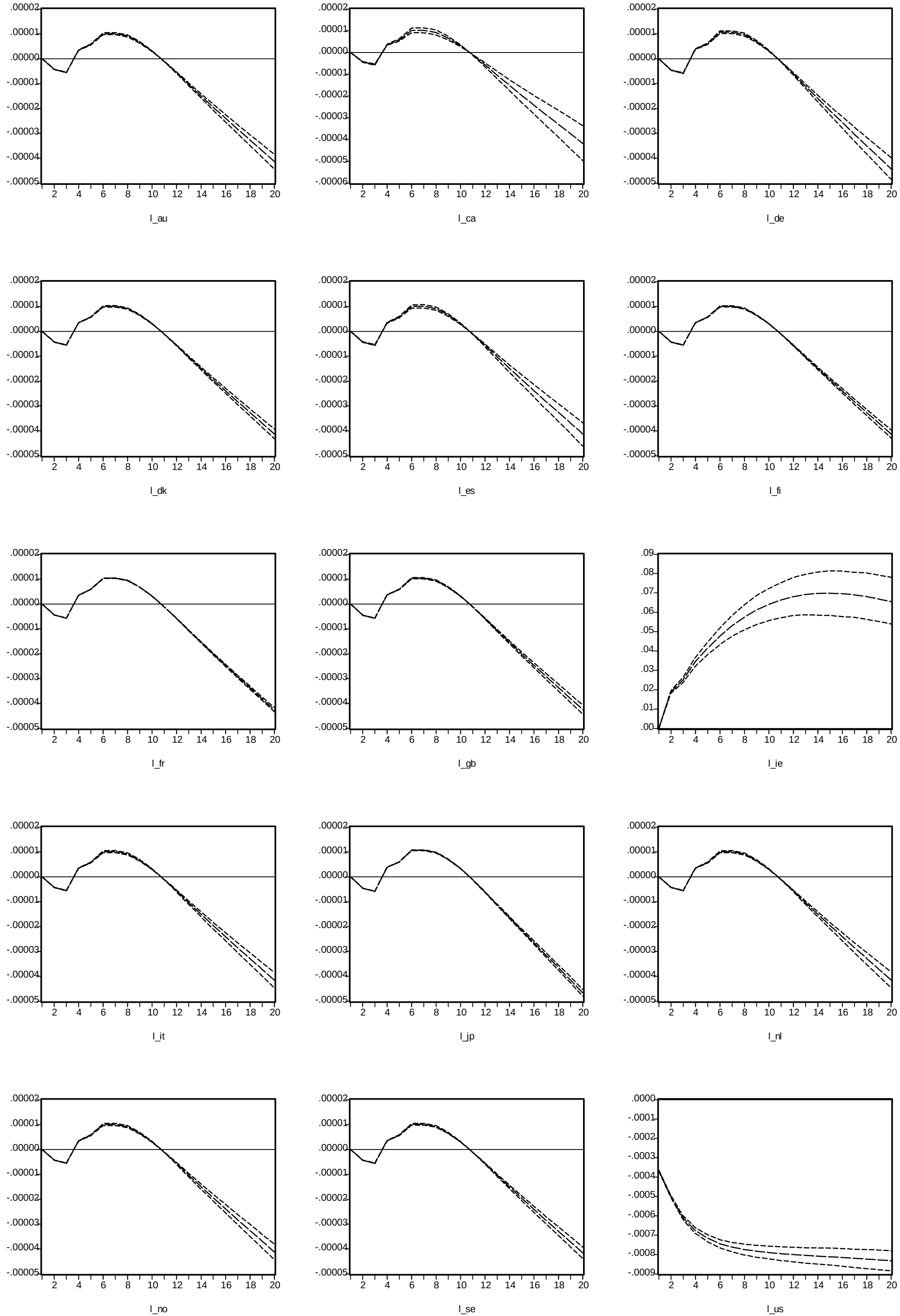
Shock equal to 1% of $\ln(R\&D_{Ust})$.

Panel 5
IR of $\ln(A_{it})$ for all countries
to $\varepsilon_{A,IE,t}$ (shock to innovation in Ireland)



Shock equal to 1% of $\ln(A_{Iet})$.

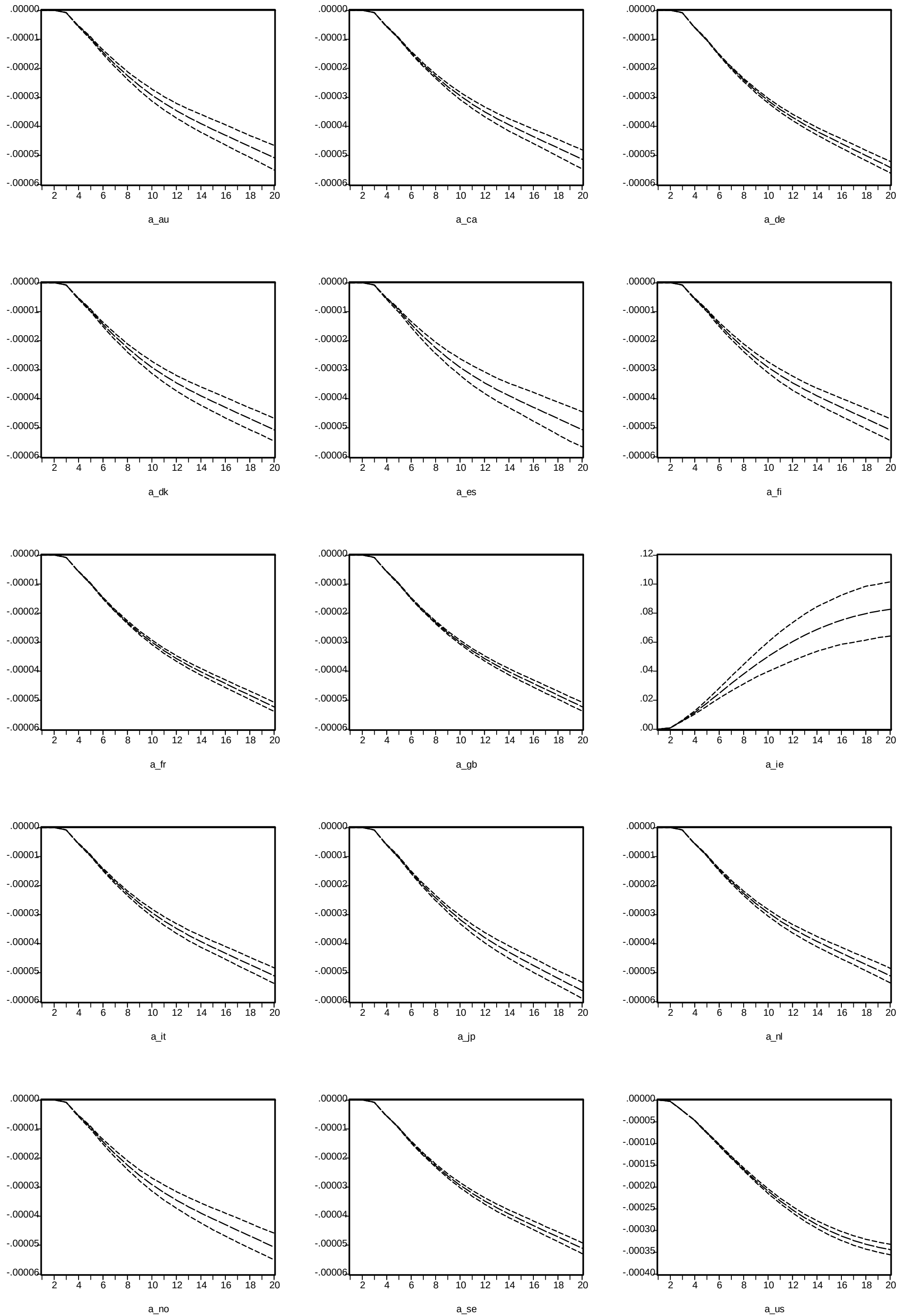
Panel 6
IRs of $\ln(R\&D_{it})$ for all countries
to $\varepsilon_{A,IE,t}$ (shock to innovation in Ireland)



Sho

Shock equal to 1% of $\ln(A_{Iet})$.

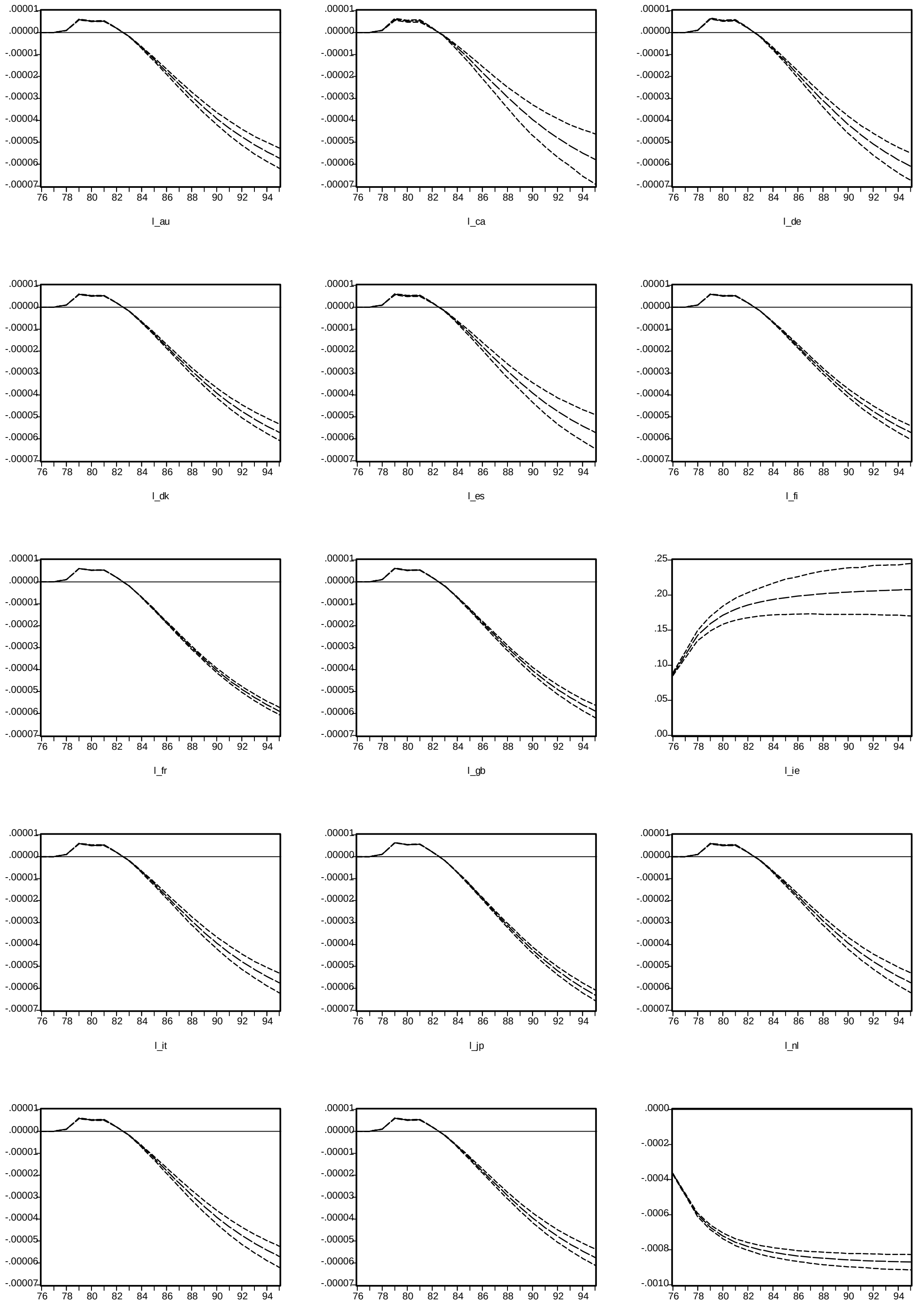
Panel 7
IR of ln(A_{it}) for all countries
to $\varepsilon_{RD,IE,t}$ (shock to R&D resources in the Ireland)



Sho

Shock equal to 1% of ln($R\&D_{Iet}$).

Panel 8
IRs of ln($R\&D_{it}$) for all countries
to $\varepsilon_{RD,IE,t}$ (shock to R&D resources in Ireland)



Sho

Shock equal to 1% of ln($R\&D_{Iet}$).