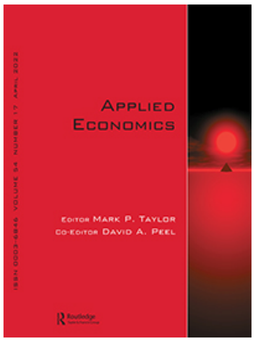

Applied Economics

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/raec20

Fourier DF unit root test for R&D intensity of G7 countries

Yifei Cai & Jamel Saadaoui

To cite this article: Yifei Cai & Jamel Saadaoui (2022): Fourier DF unit root test for R&D intensity of G7 countries, Applied Economics, DOI: 10.1080/00036846.2022.2038776

To link to this article: https://doi.org/10.1080/00036846.2022.2038776

Published online: 20 Feb 2022.

APPLIED ECONOMICS
https://doi.org/10.1080/00036846.2022.2038776

Fourier DF unit root test for R&D intensity of G7 countries

Yifei Cai[a] and Jamel Saadaoui[b]

[a]International Business School, Jilin International Studies University, Changchun, China; [b]BETA, CNRS, University of Strasbourg, Strasbourg, France

ABSTRACT
According to the Schumpeterian endogenous growth theory, the efficacy of R&D is lowered by the proliferation of products. To be consistent with empirical data, the ratio between innovative activity and product variety (also called R&D intensity) must be stationary. From this perspective, our contribution investigates whether the R&D intensity series is stationary when structural breaks are considered. Our sample of G7 countries is examined over the period spanning from 1870 to 2016. Our results indicate that traditional unit root tests (ADF, DF-GLS and KPSS) conclude that the R&D intensity series are non-stationary, in contradiction with the Schumpeterian endogenous growth theory. The conclusions of these traditional unit root tests may be misleading, as they ignore the presence of structural breaks. Indeed, we use several types of Fourier Dickey-Fuller tests to consider the presence of structural breaks. In the Fourier Dickey-Fuller unit root tests using double frequency and fractional frequency, the R&D intensity is significantly stationary at least at the 5% level for Canada, France, Germany, Italy and Japan when a deterministic trend is included in the tests. Nevertheless, the R&D intensity is non-stationary for the US, even when we consider structural breaks.

KEYWORDS
R&D intensity; Schumpeterian growth model; double frequency; Fourier Dickey-Fuller unit root test

JEL CLASSIFICATION
C12; C22; O30; O40

I. Introduction

According to the standard neoclassical growth model (Solow 1956; Swan 1956), the assumption of constant returns to scale in production technology implies a decreasing marginal product of capital. The *real per capita GDP* is constant in the steady state in the Solow-Swan model. Indeed, economic growth is only possible during the transition to the steady state, but is not sustainable. In this theory, the only source of long-run economic growth is technological progress, since it allows the steady state to be increased. In line with the empirical evidence for the first part of the 20th century for the United States (Solow 1957), a large part of productivity growth is due to technical change during this period, rather than factor accumulation. In the Solow-Swan model, technological progress is not properly explained in the equations and, thus, is considered to be exogenous. During the Golden Age era (1945–1971), the pace of technological progress was very high. Thus, this assumption of exogenous technological progress may reflect this historical context.

After the end of the Golden Age, the pace of technological progress slowed down, according to Gordon (2016). In this new context, the assumption of exogenous technological progress has become increasingly questionable. Consequently, the exogenous growth model (i.e. the Solow-Swan model) was replaced by a new generation of endogenous growth models at the beginning of the 1990s (Romer 1990; Aghion and Howitt 1992). In these growth models, technological progress is explicitly modelled. After the Jones‘ critiques (Jones 1995a, 1995b), the proposition of scale effects in ideas production has been invalidated. Afterwards, two kinds of theories have been developed to resolve this contradiction between theory and data. First, the semi-endogenous growth theory predicts that innovative activity must grow continuously to sustain productivity growth. Second, the Schumpeterian growth theory predicts that if the ratio of innovative activity and product variety remains stable, growth will be sustainable.

The aim of our study is to provide robust empirical evidence of the Schumpeterian growth theory for the G7 countries over a period spanning

CONTACT Jamel Saadaoui jamelsaadaoui@gmail.com BETA, CNRS, University of Strasbourg, Strasbourg 67000, France

from 1870 to 2016. To this end, we use the historical database introduced by Madsen, Islam, and Doucouliagos (2018). Indeed, testing the stationarity of R&D intensity constitutes an empirical test of the Schumpeterian growth theory. We found that traditional unit root tests may result in misleading conclusions, as they do not detect the presence of unit root in the R&D intensity series. Fourier Dickey-Fuller unit root tests with double frequency have better power performance in the case of smooth structural breaks. They indicate that R&D intensity is stationary in all countries, except in the US.

Studying the unit root properties of R&D intensity series has important implications in terms of economic theory and in terms of economic policy. Firstly, in terms of economic theory, the investigation of the unit root properties of R&D intensity series allows us to discriminate between the semi-endogenous growth theory and the Schumpeterian theory. Indeed, the growth effect of R&D intensity is transitory in semi-endogenous growth theory and permanent in the Schumpeterian theory. Secondly, in terms of economic policy, the stationarity of R&D intensity series may indicate that the Schumpeterian theory is not rejected. In this case, investing in knowledge activities can offer sustained productivity growth. In semi-endogenous growth theory, investing in knowledge can offer temporary growth spurts at best.

In Section II, we survey the literature that provides integration analyses of second endogenous growth theories. In Section III, we present the econometric methodology. In Section IV, we briefly describe the dataset. We discuss the empirical findings in Section V. Section VI concludes.

II. Literature review

In the first generation of endogenous growth models, the new ideas are proportional to the stock of knowledge (Romer 1990; Aghion and Howitt 1992). In these models, we postulate that there are scale effects in ideas production. This last assumption is not supported by empirical evidence (Jones 1995a, 1995b). Consequently, the literature has followed two different directions, the first branch abandoning the hypothesis of scale effects in ideas production by postulating diminishing returns to the stock of R&D. Thus, R&D has to continuously increase to sustain positive TFP growth. The second branch of the literature has followed a different path. To keep the hypothesis of scale effects in ideas production, the effectiveness of R&D is assumed to be diluted due to the proliferation of products as the economy expands. As shown by Ang and Madsen (2011), the Schumpeterian growth model predicts that the ratio between the logarithm of R&D intensity and the product variety can follow a stationary process. The R&D intensity may have a positive growth effect, but this positive effect is counterbalanced by the negative effect of product variety. Alternatively, the log of R&D intensity and the log of the product variety can be co-integrated with a (1,-1) vector.

Indeed, we can recall that the knowledge production function can be written as follows (Ha and Howitt 2007; Madsen 2008):

$$\frac{\dot{A}}{A} = \lambda\left(\frac{X}{Q}\right)^{\sigma} A^{\phi-1}, \tag{1}$$

$$Q \propto L^{\beta}$$

where $\dot{A}$ stands for the number of newly generated ideas, A is the stock of knowledge, λ is a R&D research parameter, X is innovative activities, Q represents product variety, σ is a duplication parameter (0 if all innovations are duplication and 1 if there are no duplications), ϕ is the return to scale in knowledge, L stands for population or employment and β is the parameter of product proliferation.

The empirical counterpart of the knowledge production function described in Equation (1) is the following (Ang and Madsen 2011):

$$\Delta \ln A_t = \ln\lambda + \sigma\left[\ln X_t - \ln Q_t + \left(\frac{\phi-1}{\sigma}\right)\ln A_t\right] + \varepsilon_t \tag{2}$$

If the left-hand side term is stationary in Equation (2), then the term in square brackets must also be stationary, since the λ parameter is a constant. On the one hand, in the Schumpeterian growth theory, we have constant return to knowledge ($\phi = 1$) and the presence of product variety

($\beta = 1$). Then, testing the existence of a long-run relationship between $\ln X$ and $\ln Q$ can be seen as an empirical test of the theory, as the third term in the square brackets disappears according to the assumptions of scale effect and product variety effect. The long-run relationship can be written as follows: $v_t = \ln X_t - \ln Q_t$. The cointegration vector between the logarithm of R&D effort and the logarithm of the product variety is equal to $(1; -1)$. We have the following nested equation:

$$\Delta \ln A_t = \ln \lambda + \sigma[\ln X_t - \ln Q_t] + \varepsilon_t \qquad (3)$$

On the other hand, in the semi-endogenous growth theory, there are diminishing returns to knowledge ($\phi < 1$) and no product variety effect ($\beta = 0$). The second term in square brackets disappears. The long-run relation relationship must be written as follows: $\zeta_t = \ln X_t + [(\phi - 1)/\sigma] \ln A_t$. The cointegration vector between the logarithm of R&D effort and the logarithm of the stock of knowledge is equal to $(1; (\phi - 1)/\sigma)$, where the second term is strictly negative. We have the following nested equation:

$$\Delta \ln A_t = \ln \lambda + \sigma \left[\ln X_t + \left(\frac{\phi - 1}{\sigma} \right) \ln A_t \right] + \varepsilon_t \qquad (4)$$

In their integration analysis, Ang and Madsen (2011) investigate a sample of six Asian economies over a period spanning from 1953 to 2006. It uses several first- and second-generation unit root tests. It is found that the logarithm of the ratio between R&D expenditures and GDP is stationary in all the tests. They also found evidence in favour of stationarity when structural breaks are considered (Lee and Strazicich 2003). These findings are in line with other measure of R&D intensities like the number of R&D workers in total employment. In addition, they found that TFP and R&D are not integrated at the same order as predicted by the semi-endogenous growth models. In their cointegration analysis, the logarithm of R&D and the logarithm of GDP are cointegrated. The tests mostly reject the null of no cointegration. The error-correction term is statistically significant. More importantly, the cointegration vector is equal to (1,-1.093). The values of the cointegration vector are consistent with the theoretical predictions, as shown in Equation (3). The authors conclude that these tests support the Schumpeterian theory in this sample, whereas the evidence does not support cointegration between TFP and R&D. Consequently, there is limited support for semi-endogenous growth theory in this sample of Asian economies, as we can see in Equation (4).

Ha and Howitt (2007) offer a Schumpeterian critique of the semi-endogenous growth theory. They investigated the trends in productivity and R&D in the U.S. and in the G5 countries during the second half of the 20th century. During this period, they note that the growth rate of R&D intensity has fallen more than three-fold without inducing a dramatic decrease in the TFP growth in the U.S. This trend is in contradiction with the semi-endogenous growth theory that postulates diminishing returns to knowledge and the absence of proliferation effects. Indeed, if TFP growth does not require sustained growth in R&D labour, then the central proposition of semi-endogenous growth theory appears less relevant. On the contrary, Schumpeterian growth theory postulates constant returns to knowledge and the presence of proliferation effects. These hypotheses imply an absence of trends in the R&D intensity. In the U.S. and in the G5 countries, they do not detect any trends (deterministic or stochastic) in the various measures of R&D intensity. In their integration analysis, they find no strong empirical support for the semi-endogenous growth theory, which predicts a cointegration relationship between log productivity and log of R&D input with a $(1; (\phi - 1)/\sigma)$ vector where the second term is strictly negative. Whereas, they find empirical support for the Schumpeterian growth theory in seven measures of adjusted R&D input. They reject the presence of unit root in these series, as this last theory predicts a cointegration relationship between the log of R&D input and the log of the GDP with a (1, −1) vector.

Madsen (2008) investigates whether second-generation endogenous theory can explain TFP growth or not. His study explores the impact of technological spillovers at the international level. In this respect, he is able to explore variations in TFP growth across countries and through time thanks to historical data. Along with several measures of research intensity, the granted patents and the stock of trademarks are used to capture the long-run effects of innovative activities and the long-run effects of the product variety, respectively. In his sample of 21 OECD countries, innovative activities are observed over a period spanning from 1898 to 2004 for the patents. The estimation period is shorter for the R&D expenditures (1965–2004). In the cointegration analysis, he uses the dynamic ordinary least square (DOLS) estimator to ensure that the long-run coefficients are unbiased in the panel estimations (Kao and Chiang 2001). He uses the Dickey-Fuller test suggested by Kao (1999) to test the existence of a long-run relationship. For the semi-endogenous growth theory, the results are consistent with those of Ha and Howitt (2007). The null hypothesis of no-cointegration between TFP growth and R&D expenditures is not rejected in three out of four cases. Besides, the null hypothesis of no cointegration between TFP growth and patents is rejected in the majority of cases, but the coefficients in patents are insignificant in seven estimates out of eight.[1] For the Schumpeterian growth theory, the null hypothesis of no-cointegration is rejected in all the models. The long-run coefficients are close (but superior) to those predicted by the theory in the model that relates R&D expenditures to the GDP.[2] Besides, he uses long-run expenditures R&D data because the average value of patents may have changed considerably over the past 100 years. For the U.S., Australia, Germany and Spain, there is evidence of a cointegration relationship between R&D expenditures and the GDP, but only at the 10% level. These results support the prediction of the Schumpeterian growth theory. The long-run evidence with these historical data of R&D, however, does not support the semi-endogenous growth theory, especially when product dilution variables are included.

In the following paragraphs, we discuss several recent studies that share some common features with our empirical investigation, especially when integration and cointegration analyses are conducted.[3] Laincz and Peretto (2006) provide some empirical evidence supporting Schumpeterian growth theory with disaggregated data. The disaggregated framework helps to understand the respective roles of scale effects and product proliferation. Indeed, the development of a new product line fragments the economy into smaller submarkets[4] and reduces the incentives to do R&D. Consequently, R&D employment is scale invariant. For the U.S. economy, their dataset includes the number of establishments, the total employment, the R&D personnel and the population over the period spanning from 1964 to 2001 (to 1997 for the R&D employees). The graphical analysis shows that all the four aforementioned variables grow at the same rate. The main implication of this last observation is that the share of R&D personnel in total employment does not seem to exhibit any trends. Simultaneously, the employment per establishment and the R&D personnel per establishment do not exhibit any persistent trend. The authors conduct integration analyses on the R&D workers per establishment and on the employees per establishment. Their Augmented Dickey-Fuller tests do not include a time trend and find that the null hypothesis of unit root cannot be rejected for the employees per establishment and for R&D personnel in the total employment at the 5% level. However, the R&D personnel in total employment is stationary at the 10% level.[5] In the KPSS tests, the null of stationarity cannot be rejected for both series at the 10% level. In their cointegration analysis, they cannot reject the null of the absence of a cointegration relationship between employees and R&D workers at the 5% level. Nevertheless, they cannot reject the hypothesis that at most one cointegration relationship exists at the 5% level. According to their results, the average size of establishment and number of R&D workers per establishment are probably stationary, but the level of these variables (R&D workers, number of establishments) is non-stationary.

The work of Madsen, Ang, and Banerjee (2010) analyses the case of the Indian economy with time-series data over a period spanning from 1950 to

[1]This evidence is robust to the removal of fixed effect dummies in the regressions including granted patents and patents applied for.
[2]Again, this evidence is robust to the removal of fixed effect dummies in the regressions that include granted patent and patent applied for. We can note that the long-run coefficients are close to one in these regressions, as predicted by the Schumpeterian growth theory.
[3]We build on Herzer (2020) who provides a critical review of the literature.
[4]As the speed of market fragmentation is superior to the population growth.
[5]The p-value for the ADF test is equal to 0.06.

2005. Besides, they use panel data for a sample of 590 firms observed over a period spanning from 1993 to 2005. Indeed, the use of disaggregated data allows for a better understanding of the underlying causal mechanisms, as argued by Laincz and Peretto (2006). For the time-series data, these authors use the unit root test of Ng and Perron (2001) to consider the presence of structural breaks. In their integration tests, they found that various measures of R&D intensity are stationary, including the ratio between R&D expenditures and GDP. In their cointegration tests, they find that the logarithm of R&D expenditures and the logarithm of GDP are cointegrated. The Johansen cointegration tests give a (1, −1.9) cointegration vector for the pre-reform sample. For the full sample, the cointegration vector is not in the range predicted by the Schumpeterian growth theory. On the whole, these authors conclude that aggregate evidence provide empirical support for the Schumpeterian growth theory. Regarding the semi-endogenous growth theory, the cointegration tests between TFP and R&D do not report consistent values for the cointegration vector.[6] For the panel data, they use the panel unit root test of Breitung (2001). The logarithm of the ratio of R&D to GDP is stationary for this sample of firms over the investigated period, in accordance with Schumpeterian growth theory. Moreover, the series of R&D expenditures is stationary, in contradiction with the prediction of the semi-endogenous growth theory since TFP is I(1) in this sample. In the cointegration analysis, the panel tests of Pedroni (2004) clearly support the prediction of the Schumpeterian theory. All the tests reject the null hypothesis of no-cointegration at the 1% level. The cointegration vector has statistically significant values, which are very close (1, −1.2) to the prediction of the theory.[7]

Madsen, Ang, and Banerjee (2010) explore the respective roles of population and innovation over the long run in the British economy (England and Wales). Their work aims at disentangling the different influences of population growth and innovative activities in the transition from the Malthusian Trap to the post-Malthusian growth regime. They use annual data over a period spanning from 1620 to 2006 in integration and cointegration analyses. In their graphical analysis, they underline that the research intensity (domestic patent to the labour force) stabilized after 1890. On the whole, the graphical evidence does not support semi-endogenous growth theory. As we face different growth regimes, the integration analysis considers the possibility of structural breaks. Augmented Dickey-Fuller and Zivot and Andrews (2002) tests indicate that the research intensity is stationary in level at the 1% level and the 5% level, respectively. Furthermore, the Zivot–Andrews tests produce an endogenous break point in 1884 for the research intensity in level. On the contrary, the patent applications are non-stationary in level. Thus, the unit root results support the Schumpeterian growth theory. In the cointegration analysis, the Johansen (1988) procedure gives inconsistent results for the semi-endogenous growth theory. The coefficients have the wrong signs and there are multiple-cointegration vectors, whereas the results are more supportive regarding the Schumpeterian growth theory. There is a unique cointegration vector between the number of patents and the labour force, besides the error-correction terms are negative, besides the range of values for the cointegration vector is consistent with the Schumpeterian theory. Moreover, the long-run relationship between product variety and innovative activities is stable over time.

Saunoris and Payne (2011) recall that economic growth does not depend on the research intensity in semi-endogenous growth theory. The growth effect of R&D expenditures would only be transitory, and thus knowledge creation is not an engine of long-run economic growth. On the contrary, the Schumpeterian theory predicts that policies that impact R&D expenditures will impact long-run economic growth. In their empirical investigation, they used annual data for the U.S. over a period spanning from 1960 to 2007. We conduct integration and cointegration to test the main predictions of these endogenous growth theories. For the unit root tests, they use the Dickey and Fuller (1979) and the Phillips and Perron (1988) tests. They

[6]We can recall that we expect a negative and significant value in the long-run relationship between R&D and TFP reflecting diminishing returns to knowledge.
[7]We can recall that the Schumpeterian growth theory predicts a (1, −1) vector for the long-run relationship between the log of innovative activities and the log of product variety.

found evidence of unit roots since TFP, R&D and GDP are both stationary in first-difference and non-stationary in level. Engle and Yoo (1987) cointegration tests provide empirical support for the Schumpeterian theory. The values of the cointegration vector are in line with those predicted by the theory for several measures of R&D intensity. For product proliferation, the long-run coefficient is not statistically different from the one at the 1% level for each measure of R&D intensity. For returns to knowledge, the long-run coefficient is not statistically different from zero at the 1% level for each measure of R&D intensity. Interestingly, they concede that diminishing returns to knowledge could play a larger role at the regional level in the case of rural areas, for instance.

Venturini (2012) examines the evidence of endogenous growth in 20 manufacturing industries in the U.S. over a period spanning from 1975 to 1996. In his note, he considers the technological level of the industry (low-tech. versus high-tech.). Besides, he focuses on the quality of the R&D output (patent backward citations, forward citations, claims). In this panel dataset, the author uses the panel DOLS estimator (Mark and Sul 2003) to estimate the cointegration relationship between the innovation output (total patent application, quality-adjusted patents), R&D input (stock of real expenditures in R&D), product proliferation (real GDP) and the level of innovation output. The results of the unit root tests are not provided in his empirical investigation. On the whole and without distinction between technological levels, the hypothesis of constant returns to knowledge is supported by the disaggregated data in contrast with the semi-endogenous theory. The existence of proliferation effects is supported in the data, especially when quality adjusted measures are considered, in accordance with the Schumpeterian theory.[8]

Barcenilla-Visús, López-Pueyo, and Sanaú-Villarroya (2014) explore the validity of second-generation endogenous growth theories for six developed countries (namely, Finland, France, Italy, the United States, Canada and Spain) and 10 manufacturing industries over a period spanning from 1979 to 2001. In their sectoral approach, they use several measures of research intensity (namely, R&D expenditures divided by (i) labour-adjusted TFP, (ii) value added, (iii) total employment and (iv) hours worked) to test the predictions of these competing growth theories. They use the empirical modelling approach found in Ha and Howitt (2007). Thus, in their cointegration analyses, they estimate the long-run relationship between research effort, product variety and stock knowledge in the panel data framework as underlined by Madsen (2008). On the one hand, the Schumpeterian growth theory predicts that the cointegration vector between the logarithm of the research effort and the logarithm of the product variety is equal to $(1; -1)$. Consequently, the research effort adjusted by the product variety (or product proliferation) must be stationary. On the other hand, the semi-endogenous theory predicts the cointegration vector between the logarithm of the research effort and the logarithm of the stock of knowledge is equal to a $(1; (\phi - 1)/\sigma)$ vector where the second term is strictly negative. In their integration analyses, they used the panel unit root tests of Pesaran (2007) to detect the presence of cross-sectional dependence in the series. In their sample, the research intensity is stationary in the first difference, but has a unit root in the level. The cointegration tests of Pedroni (1999) and Westerlund (2007) and the long-run estimation (Kao and Chiang 2001) provide mixed results for both Schumpeterian growth theory and semi-endogenous growth theory.

Fedderke and Liu (2016) investigated the nature and the source of productivity growth for the South African manufacturing sectors from an international perspective. They want to explore the relative explanatory power of the second generation endogenous models in panel data and in time series. Indeed, they recall that determining which theory (semi-endogenous or Schumpeterian) holds is essential. If productivity growth is semi-endogenous, then investing in knowledge can offer temporary growth spurts at best. The *real per capita GDP* will revert to a stable value defined by the steady state of the economy. Whereas, if productivity growth is Schumpeterian, then investing in knowledge can offer sustained productivity

[8]We can note that evidence is more mixed when the technological level of the industry is considered.

growth. The *real per capita GDP* will be permanently lifted if the innovative capacities of the economy are increased. They argue that panel data evidence could be unreliable due to the heterogeneity between the individuals in the panel (countries or industries). In the panel data analyses, they use three distinct datasets. The first sample includes 13 countries over a period spanning from 1996 to 2010. The second one includes 25 manufacturing sectors for the South African economy over the period 1973–1993. The third sample includes 10 manufacturing sectors in 6 OECD countries over a period spanning from 1979 to 2001 (Barcenilla-Visús, López-Pueyo, and Sanaú-Villarroya 2014). In the time-series analyses, they investigate the 25 manufacturing sectors in South Africa and 10 sectors in OECD countries. The R&D expenditures are normalized by the TFP. They use several measures of product variety, namely the total employment, total working hours, country GDP or sectoral VA and the patents applied for by the residents of the country. In the panel integration analyses, they use the Hadri (2000) test. It is found that the productivity growth is stationary in level and all the measures of R&D intensity are non-stationary in level. The panel evidence is mixed for both theories. In the time-series analyses, they use the Perron (1989) test to deal with structural breaks. On the whole, the integration and cointegration analyses in time series indicate that the Schumpeterian effects are more concentrated in a few sectors in South Africa. Besides, the Schumpeterian effects are more frequent in North American economies.

The work of Minniti and Venturini (2017) tries to answer the following questions for the U.S. economy: Do public policies that influence the R&D activities affect growth? Are these potential effects long-lasting? To this end, the investigated sample includes 20 manufacturing industries over a period spanning from 1975 to 2000. They consider two policy variables, namely the R&D tax credit and the share of federal funding in the business R&D expenditures, along with explanatory variables recommended by the Schumpeterian growth theory. The R&D intensity is measured as the share of labour allocated to R&D in total employment. In their integration and cointegration analyses, they found that the R&D intensity is stationary, thanks to the Pesaran (2007) test.[9] Besides, they use the estimator of Chudik et al. (2016) to estimate long-run relationships and control for cross-sectional dependencies. The cointegration tests of Westerlund (2007) reject the null of no cointegration between the growth rate of productivity and the explanatory variables.[10] In the long-run, an increase of 10% in R&D tax credit generates a permanent increase in the growth rate of labour productivity of 0.4% per year. They conclude that public policies that influence the R&D activities do affect growth, and these effects are long-lasting.

III. Econometric model

Perron (1989) first showed that structural breaks can be important factors, which significantly deteriorate the testing power of traditional unit root tests. Following his groundbreaking work, many econometricians have developed various unit root tests by considering structural breaks (Zivot and Andrews 2002; Lee and Strazicich 2003; Enders and Lee 2012a, 2012b). In this study, we utilize the Fourier Dickey-Fuller unit root test proposed by Enders and Lee (2012a) to examine the unit root properties of R&D intensity in 7 OECD countries. Beyond that, we extend their model by allowing Fourier type deterministic trends generated by double frequencies. Indeed, we will be able to investigate whether the historical series of R&D intensity are truly stationary, in accordance with the Schumpeterian growth theory. Over a period spanning from 1870 to 2016, the R&D intensity and the pace of productivity have been known in several regimes, as noted by Gordon (2016). Consequently, our econometric methodology is well suited to investigate the unit root properties of R&D intensity.

To begin with, the Fourier Dickey-Fuller unit root test can be expressed as follows,

[9]They include three or four-year lags to control serial correlation.
[10]Except specifications that include policy variables when knowledge growth is approximated by the patenting rate or R&D intensity.

$$y_t = c + \alpha \sin\left(\frac{2\pi kt}{T}\right) + \beta \cos\left(\frac{2\pi kt}{T}\right) + \theta y_{t-1} + \varepsilon_t \tag{5}$$

where y_t is the R&D intensity. ε_t denotes a *i.i.d.* normal disturbance. T represents the sample size. The representation above is known for its single frequency method. To estimate Equation (5), we should know the frequencies k beforehand. Based on a data-driven method suggested by Enders and Lee (2012a), we determine the optimal frequency k^* which minimizes the sum of squared residuals in Equation (5). Enders and Lee (2012a) further extend Equation (5) by using a cumulative frequency approach, as follows in Equation (6),

$$y_t = c + \sum_{i=1}^{n} \alpha_i \sin\left(\frac{2\pi k_i t}{T}\right) + \sum_{i=1}^{n} \beta_i \cos\left(\frac{2\pi k_i t}{T}\right) + \theta y_{t-1} + \varepsilon_t \tag{6}$$

where n is the cumulative frequency, which is widely determined as 2 to achieve better estimating precision and avoid testing power loss. The methods above are mainly suggested to use integer frequency, however Omay (2015) presents that using fractional values of the frequency in Equation (5) can achieve better estimating precision and elevate testing power. Specifically, the approach considered by Omay (2015) can be shown as follows in Equation (7),

$$y_t = c + \alpha \sin\left(\frac{2\pi k^{fra} t}{T}\right) + \beta \cos\left(\frac{2\pi k^{fra} t}{T}\right) + \theta y_{t-1} + \varepsilon_t \tag{7}$$

where k^{fra} denotes fractional frequency. Similar to Enders and Lee (2012a), Omay (2015) extends the data-driven method by setting a maximum searching range and a searching precision. Cai and Omay (2021) further extend the traditional model by using double frequency, the model can be presented as follows in Equation (8),

$$y_t = c + \alpha \sin\left(\frac{2\pi k_s t}{T}\right) + \beta \cos\left(\frac{2\pi k_c t}{T}\right) + \theta y_{t-1} + \varepsilon_t \tag{8}$$

where k_s and k_c are determined by minimizing the SSR of Equation (8) through an updated data-driven method. k_s and k_c can be either integer or fractional values. To test for the unit root, we utilize the traditional t test as follows,

$$\tau = \frac{\hat{\theta} - 1}{\sigma_{\hat{\theta}}} \tag{9}$$

IV. Dataset

The measurement of R&D intensity is the ratio of nominal R&D expenditure to nominal gross domestic production[11] proposed by Madsen, Islam, and Doucouliagos (2018). The complete methodology describing the construction of the R&D historical series is provided in Section 1.2 of the online appendix.[12] The dataset is yearly, which covers the period from 1870 to 2016. Thus, we have 147 observations for each country. The G7 countries include Canada, France, Germany, Italy, Japan, the United Kingdom and the United States.

In Table 1, we provide some descriptive statistics for the R&D intensity series. We can see that France and the United Kingdom have the highest means and standard deviations in the G7 countries. Canada, Germany, Japan and the United States share common features. Italy has the lowest mean and standard deviation. We plot the R&D intensity of G7 countries in Figure 1, which is shown to have a deterministic trend in its original path.[13]

V. Empirical findings

In this section, we utilize various unit root tests to examine the integrating property of R&D intensity of G7 countries. Commonly, if the series is tested to reject the unit root hypothesis (i.e. the series is stationary), this may indicate that the

[11] Barlevy (2007) underlines that the use of an overall price index to deflate R&D expenditures may lead to spurious fluctuations in R&D.
[12] The historical series of R&D expenditures is extended by using the World Development Indicator (WDI) dataset, as in Churchill, Inekwe, and Ivanovski (2019) for example.
[13] Other measures of R&D input like the granted patents are available, but the value of a patent is not stable through time. Besides, the patent regulation has changed through time.

Table 1. Descriptive statistics on R&D intensity series as percentage of GDP.

	Obs.	Mean	SD	Min	Max
Canada	147	1.258	0.672	0.223	2.544
France	147	2.455	1.443	0.549	6.282
Germany	147	1.348	0.915	0.199	2.930
Italy	147	0.450	0.438	0.031	1.380
Japan	147	1.318	1.132	0.108	3.400
United Kingdom	147	2.305	1.382	0.498	5.865
United States	147	1.492	1.067	0.171	3.260

Note: The series have been updated using World Development Indicators. Authors' calculations.

nature of economic growth is Schumpeterian as explained in Section II. Thus, public policies that affect innovative activities may have a long-run impact on economic growth. Otherwise, the failure to reject the unit root hypothesis (i.e. the series is non-stationary) may indicate that the Schumpeterian growth theory is not supported by the data.

Traditional unit root tests

We first test for the unit root hypothesis of R&D intensity by using traditional methods including the ADF test (Dickey and Fuller 1981), DF-GLS (Elliott, Rothenberg, and Stock 1996) and KPSS (Kwiatkowski et al. 1992). The null hypothesis of ADF and DF-GLS tests is a unit root process, however the null of KPSS test is stationarity. We consider different cases by including only a constant and a constant and a trend, respectively. Concerning the ADF and DF-GLS unit root tests, we find that R&D intensity of Germany is stationary when including both intercept and trend. In the remaining cases, however, the R&D intensity should be viewed as a unit root process. By using KPSS tests, we are confident that the stationary hypothesis is rejected for all countries. Therefore, overwhelming evidence supports that R&D intensity of G7 countries should be

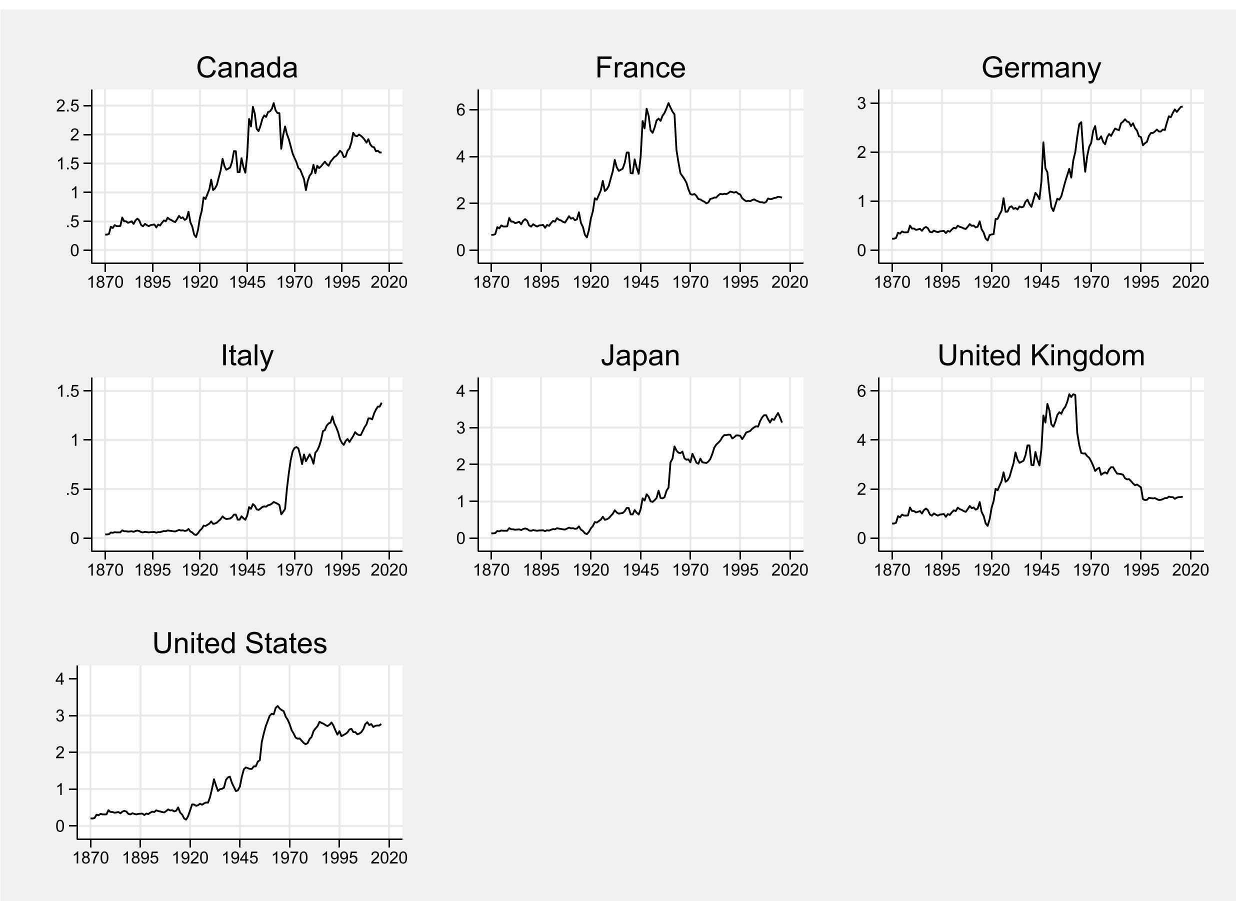

Figure 1. Plots of R&D intensity of G7 countries as percentage of GDP. **Note**: The construction of R&D historical series is described in the online appendix of Madsen, Islam, and Doucouliagos (2018).

modelled as a unit root processes. Based on traditional unit root tests, the integration analysis may indicate that the Schumpeterian growth theory is not supported by the data in this sample. However, these traditional unit root tests do not consider the presence of structural breaks. The choice of econometric modelling may have important consequences in terms of economic interpretation. These tests may lead to deceptive conclusions about the Schumpeterian growth theory.

The groundbreaking work of Perron (1989) suggests that the failure to reject the unit root hypothesis can be attributed to the ignorance of structural breaks. Previous studies, which aim to approximate structural breaks can be divided into two strands. The first strand uses time dummies (Perron 1989; Zivot and Andrews 2002; Lee and Strazicich 2003; Lumsdaine and Papell 1997), and the second method suggests the use of smooth functions (Leybourne, Mills, and Newbold 1998; Enders and Lee 2012a, 2012b). In this study, we focus on using Fourier functions to approximate structural breaks in R&D intensity of G7 countries.

Fourier Dickey-Fuller unit root test with single frequency

As proposed by Enders and Lee (2012a) and Omay (2015), Fourier Dickey-Fuller unit root tests have better power performance.[14] Both studies of Enders and Lee (2012a) and Omay (2015) all use single frequencies in trig functions. Therefore, we follow their methods to re-examine the unit root in R&D intensity of G7 countries. The optimal frequency is selected over the maximum frequency $k_{max} = 5$. The lags are determined by using Akaike Information Criterion (AIC) with the maximum lags of 12. The test statistics τ_{DF} are not significant for all countries, with the inclusion of intercept only. After taking both constant and intercept into account, the unit root hypothesis is rejected for Germany and Japan, as we can see in Table 3.

Omay (2015) updates the method proposed by Enders and Lee (2012a) by using fractional frequencies in trig functions. The simulation results shown by Omay (2015) suggest that employing a fractional method can gain more power than a traditional integer frequency method. To make comparisons, the optimal fractional frequency is selected by setting the maximum frequency $k_{max} = 5$. With the inclusion of intercept only, τ_{DF} is significant for France, Germany, Italy, Japan and the United Kingdom. After including both intercept and trend, the unit root hypothesis is rejected for Germany and Japan, as we can see in Table 4.

Fourier Dickey-Fuller unit root test with double frequency

Cai and Omay (2021) suggest that using double frequency in Fourier Dickey-Fuller unit root test can significantly elevate the testing power and increase the estimating precision. They proposed a modified Fourier DF unit root test, which has better power performance when structural breaks are smooth, and located at the beginning and the end of the sample.[15] Table 5 reports empirical results using double integer frequency, with maximum search range $k_{max} = 5$. Regarding the results by incorporating intercept only, the test statistics τ_{DF} are not significant for all countries. After taking the time trend into account, for the R&D series of Germany, Italy and Japan, we reject the unit root hypothesis.[16] Although we consider double frequency, the unit root hypothesis is only rejected for three out of seven countries when only integer frequencies are considered.

Next, we follow the conclusions of Omay (2015) who suggests using fractional frequencies in the Fourier DF unit root test. To find the optimal frequencies k_s and k_c, we set the searching precision to $\Delta k = 0.1$.[17] The results are presented in Table 6. The undefined test statistics are significantly stationary for all countries except the United States. Therefore, this evidence may support the Schumpeterian growth theory for six out

[14]Omay (2015) suggests using a fractional frequency to approximate structural breaks, which can gain more power than the test proposed by Enders and Lee (2012a).
[15]As noted by Gordon (2016), the pace of life-altering innovative activities was considerably higher during the period 1870–1970.
[16]To be noted, the R&D series of Canada rejects the unit root hypothesis when including intercept only. The selected double frequencies in trig functions are $k_s = k_c = 2$, which are the same as the results in Table 2. This finding implies that using double frequency does not ignore the case of using single frequency.
[17]We also shrink the searching precision $\Delta k = 0.01$, the empirical results are unchanged.

Table 2. Traditional unit root tests.

	ADF		DF-GLS		KPSS	
	c	*c, t*	*c*	*c, t*	*c*	*c, t*
Canada	−1.517 [0]	−1.635 [0]	−0.378 [0]	−1.680 [0]	1.020 [10]***	0.187 [10]**
France	−1.730 [1]	−1.513 [1]	−1.022 [1]	−1.419 [1]	0.454 [10]*	0.244 [10]***
Germany	−0.006 [0]	−3.533 [1]**	1.258 [0]	−3.108 [0]*	1.375 [10]***	0.203 [10]**
Italy	0.808 [1]	−1.762 [1]	1.717 [1]	−1.064 [1]	1.297 [10]***	0.330 [9]***
Japan	0.665 [0]	−2.182 [0]	1.201 [0]	−1.116 [0]	1.351 [10]***	0.312 [9]***
United Kingdom	−1.642 [0]	−1.325 [0]	−1.015 [0]	−1.261 [0]	0.484 [10]**	0.272 [10]***
United States	−0.870 [1]	−2.092 [1]	0.195 [1]	−1.972 [1]	1.290 [10]***	0.154 [9]**

Note: For all unit root tests, we consider both intercept and intercept and trend, respectively. The numbers in brackets of augmented Dickey-Fuller (ADF) test (Dickey and Fuller 1981), Dickey-Fuller generalized least square (DF-GLS) test (Elliott, Rothenberg, and Stock 1996) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Kwiatkowski et al. 1992) represent optimal lags (determined by Schwarz Information Criterion) and bandwidth (determined by Newey-West automatic using Bartlett kernel), respectively. The symbols ***, ** and * correspond to statistical significance at 1, 5 and 10%, respectively. Here, statistical significance amounts to stationarity in the case of ADF and DF-GLS tests. Statistical significance corresponds to non-stationarity in the case of KPSS tests. Authors‘ calculations.

Table 3. Fourier Dickey-Fuller unit root tests using single frequency (Enders and Lee 2012a).

	Single frequency ($\Delta k = 1, k_{max} = 5$)											
	c						*c, t*					
	k	τ_{DF}	10%	5%	1%	lags	k	τ_{DF}	10%	5%	1%	lags
Canada	2	−2.078	−2.952	−3.327	−4.049	1	2	−1.568	−3.783	−4.127	−4.844	1
France	2	−2.096	−2.954	−3.322	−4.061	1	2	−1.369	−3.774	−4.134	−4.834	1
Germany	1	−2.191	−3.549	−3.887	−4.548	1	1	−5.043**	−4.126	−4.460	−5.123	1
Italy	3	0.458	−2.698	−3.050	−3.791	1	3	−2.104	−3.497	−3.823	−4.524	1
Japan	1	−1.493	−3.550	−3.891	−4.507	1	1	−4.614**	−4.138	−4.449	−5.090	2
United Kingdom	1	−2.823	−3.569	−3.888	−4.545	1	1	−2.789	−4.165	−4.486	−5.169	1
United States	5	−0.979	−2.598	−2.930	−3.582	1	5	−1.837	−3.229	−3.567	−4.242	1

Note: For all unit root tests, we consider both intercept and intercept and trend, respectively. The numbers in brackets of augmented Dickey-Fuller (ADF) test (Dickey and Fuller 1981), Dickey-Fuller generalized least square (DF-GLS) test (Elliott, Rothenberg, and Stock 1996) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Kwiatkowski et al. 1992) represent optimal lags (determined by Schwarz Information Criterion) and bandwidth (determined by Newey-West automatic using Bartlett kernel), respectively. The symbol ** corresponds to statistical significance at 5%, respectively. Here, statistical significance amounts to stationarity. Authors‘ calculations.

of seven countries. However, our integration analysis may indicate that the Schumpeterian growth theory is not supported by the data in the case of the United States.

VI. Concluding remarks

This empirical investigation is aimed at determining whether the Schumpeterian growth theory is supported by the data in a sample of seven industrialized countries over a period spanning from 1870 to 2016. On the whole, in the traditional unit root tests (ADF, DF-GLS and KPSS), we cannot reject the null hypothesis of unit root for the R&D intensity in contradiction with the Schumpeterian growth theory. These findings of non-stationarity for the R&D intensity may be deceptive, as these traditional tests do not consider the presence of structural breaks.

To consider structural breaks, we use Fourier Dickey-Fuller tests. In the Fourier Dickey-Fuller unit root tests using single frequency and integer (or fractional) frequency, the R&D intensity is significantly stationary at the 5% level for Germany and Japan when deterministic trends are included in the tests. Besides, in the Fourier Dickey-Fuller unit root tests using double frequency and integer frequency, the R&D intensity is significantly stationary at least at the 5% level for Italy, Germany and Japan when deterministic trends are included in the tests. Furthermore, in the Fourier Dickey-Fuller unit root tests using double

Table 4. Fourier Dickey-Fuller unit root tests using single frequency (Omay 2015).

	Single frequency ($\Delta k = 0.1, k_{max} = 5$)											
	c						c, t					
	k	τ_{DF}	10%	5%	1%	lags	k	τ_{DF}	10%	5%	1%	lags
Canada	2.1	−1.978	−2.885	−3.283	−4.035	1	1.6	−3.072	−4.035	−4.352	−5.032	1
France	1.6	−3.107*	−3.096	−3.443	−4.170	1	1.5	−3.262	−4.091	−4.419	−5.088	1
Germany	0.6	−4.906***	−3.705	−4.010	−4.660	1	1.3	−5.097**	−4.144	−4.468	−5.117	1
Italy	0.5	−4.197**	−3.692	−4.017	−4.636	2	3.2	−2.253	−3.414	−3.766	−4.522	1
Japan	0.6	−4.468**	−3.721	−4.029	−4.634	2	1	−4.614**	−4.155	−4.504	−5.115	2
United Kingdom	1.4	−3.572*	−3.253	−3.636	−4.329	1	1.4	−3.888	−4.119	−4.451	−5.111	1
United States	5	−0.979	−2.580	−2.897	−3.563	1	5	−1.837	−3.243	−3.586	−4.240	1

Note: We determine the searching precision $\Delta k = 0.1$ with the maximum searching range $k_{max} = 5$. c and c, t represent the inclusions of intercept and intercept and trend, respectively. The lags are determined by using AIC. The critical values are generated by using stochastic simulations with 20,000 replications. The symbols ***, ** and * correspond to statistical significance at 1, 5 and 10%, respectively. Here, statistical significance amounts to stationarity. Authors' calculations.

Table 5. Fourier Dickey-Fuller unit root tests using double frequency (Cai and Omay 2021).

	Double frequency ($\Delta k = 1, k_{max} = 5$)													
	c							c,t						
	k_s	k_c	τ_{DF}	10%	5%	1%	lags	k_s	k_c	τ_{DF}	10%	5%	1%	lags
Canada	2	2	−2.078	−2.934	−3.308	−4.022	1	4	2	−2.572	−3.657	−4.042	−4.816	1
France	5	2	−2.310	−2.810	−3.200	−3.948	1	5	2	−1.958	−3.571	−3.937	−4.732	1
Germany	1	3	−2.298	−3.356	−3.725	−4.446	1	1	1	−5.043**	−4.148	−4.462	−5.103	1
Italy	1	3	−0.880	−3.348	−3.724	−4.445	1	3	1	−5.382***	−4.058	−4.416	−5.110	2
Japan	1	5	−1.987	−3.256	−3.620	−4.360	1	1	1	−4.614**	−4.132	−4.459	−5.085	2
U.K.	5	1	−2.967	−3.147	−3.511	−4.263	1	5	1	−2.671	−3.857	−4.214	−4.863	1
U.S.	1	5	−2.578	−3.248	−3.604	−4.274	1	2	5	−3.391	−3.664	−4.022	−4.737	1

Note: We determine the searching precision $\Delta k = 1$ with the maximum searching range $k_{max} = 5$. c and c, t represent the inclusions of intercept and intercept and trend, respectively. The lags are determined by using AIC. The critical values are generated by using stochastic simulations with 20,000 replications. The symbols ***, ** and * correspond to statistical significance at 1, 5 and 10%, respectively. Here, statistical significance amounts to stationarity. Authors' calculations.

Table 6. Fourier Dickey-Fuller unit root tests using double frequency (Cai and Omay 2021).

	Double frequency ($\Delta k = 0.1, k_{max} = 5$)													
	c							c,t						
	k_s	k_c	τ_{DF}	10%	5%	1%	lags	k_s	k_c	τ_{DF}	10%	5%	1%	lags
Canada	2.4	0.7	−4.563***	−3.525	−3.879	−4.533	1	2.4	0.8	−4.881**	−4.166	−4.514	−5.178	1
France	1.5	2.9	−4.188**	−3.129	−3.547	−4.335	1	1.4	2.8	−5.090**	−4.111	−4.478	−5.199	1
Germany	1.9	0.4	−5.254***	−3.656	−4.017	−4.668	1	3.2	1.3	−5.733***	−3.958	−4.379	−5.090	1
Italy	3.1	0.2	−4.099**	−3.369	−3.726	−4.469	2	3.1	1.1	−5.329***	−4.040	−4.393	−5.096	2
Japan	0.8	0.5	−4.508**	−3.720	−4.028	−4.632	2	3.6	1.3	−4.633**	−3.909	−4.294	−5.016	2
U.K.	2.3	0.9	−4.740***	−3.386	−3.816	−4.625	1	1.4	2.9	−4.813**	−4.040	−4.416	−5.122	1
U.S.	1.5	5	−0.913	−3.039	−3.405	−4.132	1	1.2	5	−3.311	−3.818	−4.175	−4.898	1

Note: We determine the searching precision $\Delta k = 0.1$ with the maximum searching range $k_{max} = 5$. c and c, t represent the inclusions of intercept and intercept and trend, respectively. The lags are determined by using AIC. The critical values are generated by using stochastic simulations with 20,000 replications. The symbols ***, ** and * correspond to statistical significance at 1, 5 and 10%, respectively. Here, statistical significance amounts to stationarity. Authors' calculations.

frequency and fractional frequency, the R&D intensity is significantly stationary at least at the 5% level for Canada, France, Germany, Italy and Japan when deterministic trends are included in the tests. Nevertheless, the R&D intensity is non-stationary for the US, even when we consider structural breaks.

These empirical results may lead to a better understanding of the nature of economic growth. Indeed, integration analyses aimed at discriminating between competing theories of endogenous growth should be careful with the presence of structural breaks. Especially when historical data are used, traditional unit root tests may lead to erroneous economic interpretations. Here, traditional unit root tests do not support Schumpeterian growth theory. However, the conclusion is reversed, except for the US, when structural breaks are considered in the Fourier Dickey-Fuller unit root tests. Thus, this evidence may indicate that public policy affecting innovative activities will affect long-run economic growth.

We conclude that our empirical investigation may lead us to explore the existence of structural breaks in the long-run relationships between innovative activities, product variety and productivity. This could produce more reliable empirical tests for the second generation of endogenous growth theory and help to formulate sound policy recommendations.

Our results may indicate that there is scope for public policies that influence the R&D activities in a large majority of G7 countries. When we consider structural breaks with smooth functions, we find that R&D intensity is stationary in the G7 countries, with the notable exception of the U.S. Thus, we do not reject the Schumpeterian growth theory. Our policy recommendation would be to invest in knowledge to sustain productivity growth. This means that investing in knowledge activities could probably influence long-run productivity growth in Canada, France, Germany, Italy and Japan. Our study contributes to the empirical debates about the true nature of economic growth (semi-endogenous or Schumpeterian), but further empirical investigations (cointegration analyses, error-correction model) that consider structural breaks need to be done. We leave this to future research.

Acknowledgment

The authors are grateful to Remy Guichardaz for fruitful discussions and to Katharina Priedl for proofreading.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Yifei Cai http://orcid.org/0000-0002-4389-2948
Jamel Saadaoui http://orcid.org/0000-0003-1143-4480

References

Aghion, P., and P. Howitt. 1992. “A Model of Growth Through Creative Destruction.” *Econometrica* 60 (2): 323–351. doi:10.2307/2951599.

Ang, J. B., and J. B. Madsen. 2011. “Can Second-Generation Endogenous Growth Models Explain the Productivity Trends and Knowledge Production in the Asian Miracle Economies?” *The Review of Economics and Statistics* 93 (4): 1360–1373. doi:10.1162/REST_a_00126.

Barcenilla-Visús, S., C. López-Pueyo, and J. Sanaú-Villarroya. 2014. “Semi-Endogenous versus Fully Endogenous Growth Theory: A Sectoral Approach.” *Journal of Applied Economics* 17 (1): 1–30. doi:10.1016/S1514-0326(14)60001-5.

Barlevy, G. 2007. “On the Cyclicality of Research and Development.” *The American Economic Review* 97 (4): 1131–1164. doi:10.1257/aer.97.4.1131.

Breitung, J. 2001. ”The Local Power of Some Unit Root Tests for Panel Data.” In *Nonstationary Panels, Panel Cointegration, and Dynamic Panels, Volume 15 of Advances in Econometrics*, edited by B. H. Baltagi, T. B. Fomby, and R. C. Hill, 161–177. Bingley: Emerald Group Publishing Limited.

Cai, Y., and T. Omay. 2021. “Using Double Frequency in Fourier Dickey–fuller Unit Root Test.” *Computational Economics* X (X): x–x.

Chudik, A., K. Mohaddes, M. H. Pesaran, and M. Raissi. 2016. ”Long-Run Effects in Large Heterogeneous Panel Data Models with Cross-Sectionally Correlated Errors.” In *Essays in Honor of Aman Ullah, Volume 36 of Advances in Econometrics*, edited by G.-G. Rivera, R. C. Hill, and T.-H. Lee, 85–135. Bingley: Emerald Group Publishing Limited.

Churchill, S. A., J. Inekwe, and K. Ivanovski. 2019. “Convergence of R&D Intensity in OECD Countries: Evidence Since 1870.” *Empirical Economics* 59 (1): 295–306. doi:10.1007/s00181-019-01628-1.

Dickey, D. A., and W. A. Fuller. 1979. “Distribution of the Estimators for Autoregressive Time Series with a Unit Root.” *Journal of the American Statistical Association* 74 (366): 427–431.

Dickey, D. A., and W. A. Fuller. 1981. “Likelihood Ratio Statistics for Autoregressive Time Series with a Unit Root.” *Econometrica* 49 (4): 1057–1072. doi:10.2307/1912517.

Elliott, G., T. J. Rothenberg, and J. H. Stock. 1996. “Efficient Tests for an Autoregressive Unit Root.” *Econometrica* 64 (4): 813–836. doi:10.2307/2171846.

Enders, W., and J. Lee. 2012a. “The Flexible Fourier Form and Dickey–fuller Type Unit Root Tests.” *Economics Letters* 117 (1): 196–199. doi:10.1016/j.econlet.2012.04.081.

Enders, W., and J. Lee. 2012b. "A Unit Root Test Using a Fourier Series to Approximate Smooth Breaks." *Oxford Bulletin of Economics and Statistics* 74 (4): 574–599. doi:10.1111/j.1468-0084.2011.00662.x.

Engle, R. F., and B. S. Yoo. 1987. "Forecasting and Testing in Co-Integrated Systems." *Journal of Econometrics* 35 (1): 143–159. doi:10.1016/0304-4076(87)90085-6.

Fedderke, J. W., and Y. Liu. 2016. "Schumpeterian and Semi-Endogenous Productivity Growth Explanations." *Economics of Transition* 25 (1): 111–137. doi:10.1111/ecot.12114.

Gordon, R. J. 2016. *The Rise and Fall of American Growth*. Princeton, New Jersey: Princeton University Press.

Ha, J., and P. Howitt. 2007. "Accounting for Trends in Productivity and R&D: A Schumpeterian Critique of Semi-Endogenous Growth Theory." *Journal of Money, Credit, and Banking* 39 (4): 733–774. doi:10.1111/j.1538-4616.2007.00045.x.

Hadri, K. 2000. "Testing for Stationarity in Heterogeneous Panel Data." *The Econometrics Journal* 3 (2): 148–161. doi:10.1111/1368-423X.00043.

Herzer, D. 2020. "Semi-Endogenous versus Schumpeterian Growth Models: A Critical Review of the Literature and New Evidence." MPRA Paper 100383. Germany: University Library of Munich.

Johansen, S. 1988. "Statistical Analysis of Cointegration Vectors." *Journal of Economic Dynamics & Control* 12 (2–3): 231–254. doi:10.1016/0165-1889(88)90041-3.

Jones, C. I. 1995a. "R & D-Based Models of Economic Growth." *The Journal of Political Economy* 103 (4): 759–784. doi:10.1086/262002.

Jones, C. I. 1995b. "Time Series Tests of Endogenous Growth Models." *The Quarterly Journal of Economics* 110 (2): 495–525. doi:10.2307/2118448.

Kao, C. 1999. "Spurious Regression and Residual-Based Tests for Cointegration in Panel Data." *Journal of Econometrics* 90 (1): 1–44. doi:10.1016/S0304-4076(98)00023-2.

Kao, C., and M.-H. Chiang. 2001. "On the Estimation and Inference of a Cointegrated Regression in Panel Data." In *Nonstationary Panels, Panel Cointegration, and Dynamic Panels, Volume 15 of Advances in Econometrics*, edited by B. H. Baltagi, T. B. Fomby, and R. C. Hill, 179–222. Bingley: Emerald Group Publishing Limited.

Kwiatkowski, D., P. C. Phillips, P. Schmidt, Y. Shin, et al. 1992. "Testing the Null Hypothesis of Stationarity Against the Alternative of a Unit Root." *Journal of Econometrics* 54 (1–3): 159–178. doi:10.1016/0304-4076(92)90104-Y.

Laincz, C. A., and P. F. Peretto. 2006. "Scale Effects in Endogenous Growth Theory: An Error of Aggregation Not Specification." *Journal of Economic Growth* 11 (3): 263–288. doi:10.1007/s10887-006-9004-9.

Lee, J., and M. C. Strazicich. 2003. "Minimum Lagrange Multiplier Unit Root Test with Two Structural Breaks." *The Review of Economics and Statistics* 85 (4): 1082–1089. doi:10.1162/003465303772815961.

Leybourne, S. J., T. C. Mills, and P. Newbold. 1998. "Spurious Rejections by Dickey–fuller Tests in the Presence of a Break Under the Null." *Journal of Econometrics* 87 (1): 191–203. doi:10.1016/S0304-4076(98)00014-1.

Lumsdaine, R. L., and D. H. Papell. 1997. "Multiple Trend Breaks and the Unit-Root Hypothesis." *The Review of Economics and Statistics* 79 (2): 212–218. doi:10.1162/003465397556791.

Madsen, J. B. 2008. "Semi-Endogenous versus Schumpeterian Growth Models: Testing the Knowledge Production Function Using International Data." *Journal of Economic Growth* 13 (1): 1–26. doi:10.1007/s10887-007-9024-0.

Madsen, J. B., J. B. Ang, and R. Banerjee. 2010. "Four Centuries of British Economic Growth: The Roles of Technology and Population." *Journal of Economic Growth* 15 (4): 263–290. doi:10.1007/s10887-010-9057-7.

Madsen, J. B., M. R. Islam, and H. Doucouliagos. 2018. "Inequality, Financial Development and Economic Growth in the OECD, 1870–2011." *European Economic Review* 101: 605–624. doi:10.1016/j.euroecorev.2017.11.004.

Madsen, J. B., S. Saxena, and J. B. Ang. 2010. "The Indian Growth Miracle and Endogenous Growth." *Journal of Development Economics* 93 (1): 37–48. doi:10.1016/j.jdeveco.2009.06.002.

Mark, N. C., and D. Sul. 2003. "Cointegration Vector Estimation by Panel DOLS and Long-Run Money Demand." *Oxford Bulletin of Economics and Statistics* 65 (5): 655–680. doi:10.1111/j.1468-0084.2003.00066.x.

Minniti, A., and F. Venturini. 2017. "The Long-Run Growth Effects of R&D Policy." *Research Policy* 46 (1): 316–326. doi:10.1016/j.respol.2016.11.006.

Ng, S., and P. Perron. 2001. "Lag Length Selection and the Construction of Unit Root Tests with Good Size and Power." *Econometrica* 69 (6): 1519–1554. doi:10.1111/1468-0262.00256.

Omay, T. 2015. "Fractional Frequency Flexible Fourier Form to Approximate Smooth Breaks in Unit Root Testing." *Economics Letters* 134: 123–126. doi:10.1016/j.econlet.2015.07.010.

Pedroni, P. 1999. "Critical Values for Cointegration Tests in Heterogeneous Panels with Multiple Regressors." *Oxford Bulletin of Economics and Statistics* 61 (s1): 653–670. doi:10.1111/1468-0084.61.s1.14.

Pedroni, P. 2004. "Panel Cointegration: Asymptotic and Finite Sample Properties of Pooled Time Series Tests with an Application to the PPP Hypothesis." *Econometric Theory* 20 (03): 597–625. doi:10.1017/S0266466604203073.

Perron, P. 1989. "The Great Crash, the Oil Price Shock, and the Unit Root Hypothesis." *Econometrica* 57 (6): 1361–1401. doi:10.2307/1913712.

Pesaran, M. H. 2007. "A Simple Panel Unit Root Test in the Presence of Cross-Section Dependence." *Journal of Applied Econometrics* 22 (2): 265–312. doi:10.1002/jae.951.

Phillips, P. C. B., and P. Perron. 1988. "Testing for a Unit Root in Time Series Regression." *Biometrika* 75 (2): 335–346. doi:10.1093/biomet/75.2.335.

Romer, P. M. 1990. "Endogenous Technological Change." *The Journal of Political Economy* 98 (5, Part 2): 71–102. doi:10.1086/261725.

Saunoris, J. W., and J. E. Payne. 2011. "An Empirical Note on R&D Growth Models with Regional Implications." *Journal of Regional Analysis and Policy* 41 (1): 1–6.

Solow, R. M. 1956. "A Contribution to the Theory of Economic Growth." *The Quarterly Journal of Economics* 70 (1): 65. doi:10.2307/1884513.

Solow, R. M. 1957. "Technical Change and the Aggregate Production Function." *The Review of Economics and Statistics* 39 (3): 312. doi:10.2307/1926047.

Swan, T. W. 1956. "Economic Growth and Capital Accumulation." *The Economic Record* 32 (2): 334–361. doi:10.1111/j.1475-4932.1956.tb00434.x.

Venturini, F. 2012. "Product Variety, Product Quality, and Evidence of Endogenous Growth." *Economics Letters* 117 (1): 74–77. doi:10.1016/j.econlet.2012.04.037.

Westerlund, J. 2007. "Testing for Error Correction in Panel Data." *Oxford Bulletin of Economics and Statistics* 69 (6): 709–748. doi:10.1111/j.1468-0084.2007.00477.x.

Zivot, E., and D. W. K. Andrews. 2002. "Further Evidence on the Great Crash, the Oil-Price Shock, and the Unit-Root Hypothesis." *Journal of Business & Economic Statistics* 20 (1): 25–44. doi:10.1198/073500102753410372.