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Agricultural Productivity and Convergence: Europe and the United States

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Abstract: This paper applies the Window Malmquist Index (*WMI*) approach to measure changes in agricultural total factor productivity (*TFP*) for the United States and a sample of nine European countries for the period 1973 to 1993. The data set used in this paper is obtained from Ball et al. (2001). The *WMI* is constructed by combining Data Envelopment Analysis (*DEA*) window analysis with the Malmquist index approach. Furthermore, the "Kruskal and Wallis rank test" is used for testing frontier shifts among observed periods. The paper also explores the question of convergence in *TFP* across the countries under consideration, by testing for β- and σ-convergence, as well as for *stochastic or long-run* convergence. The results show wide variation in the rate of *TFP* growth across countries with an average trend growth rate of 1.62%. The results indicate the presence of β-convergence but the absence of σ-convergence for the full period under consideration but the presence of both β- and σ-convergence for the sub-period 1983-1993. Finally, a wide spectrum of panel unit root test results support the presence of long-run convergence among the sample countries.

JEL classification: O13; C23

Keywords: Window Malmquist Index, convergence, panel unit root tests.

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1. Introduction

In the last decade there has been an enormous increase in research investigating cross-country differences in agricultural productivity and convergence. With the aim of analyzing better the process of convergence, most of these studies has concentrated in investigating the hypothesis of catching-up in agricultural productivity among countries. The catching-up hypothesis states that the poorest countries, i.e. lowest productivity level countries, growing at a rate higher than the richest countries, i.e. highest productivity level countries, so that they are catching-up.

The objective of the present paper is to measure agricultural total factor productivity growth for the United States and nine European countries, i.e. Germany, France, Italy, the Netherlands, Belgium, the United Kingdom, Ireland, Denmark and Greece, over the period 1973 to 1993 and then test for convergence. To this end, the paper utilizes exactly the same output and input data as the paper by Ball et al. (2001) but uses a different analytical approach in calculating *TFP* and testing for convergence.[1]

The empirical approach used in this paper in calculating *TFP* growth relies on the Window Malmquist Index (*WMI*) proposed by Sueyoshi and Aoki (2001). Thore et al. (1994) and Goto and Tsutsui (1998) proposed a "new Malmquist type productivity index" by combining Data Envelopment Analysis (*DEA*) window analysis with the conventional Malmquist index approach. The *DEA*-window analysis (Bowling, 1987) examines how much a *DEA* efficiency score changes by shifting a combination of adjacent periods referred to as "a window". Unfortunately, this new Malmquist type productivity index did not provide a statistical basis regarding which periods should be combined together to form a "window". In order to overcome this shortcoming, Sueyoshi and Aoki (2001) proposed a nonparametric rank sum test, referred to as the "Kruskal and Wallis rank test", which combined it with the *DEA*-window analysis and the conventional Malmquist index approach to create the *WMI* used in the present study.

Having measured *TFP* growth for the United States and the nine European countries, the present study investigates convergence as described by the neo-classical growth model (Barro and Sala-i-Martin, 1995; Bernard and Durlauf, 1996). In this paper both cross-section and time series techniques are used for testing convergence. Cross section analyses have concentrated in the transition to equilibrium growth paths. Convergence is then focused on the narrowing of initial differences in productivity, either defined as labor productivity, income per capita or total factor productivity, over some time horizon, i.e. poorer countries grow faster than richer ones (*β-convergence*), or the decrease of cross-country variance of productivity (*σ-convergence*), although one does not necessarily indicate the other. Time series analysis examines long-run behavior of differences in productivity across countries. This approach assumes convergence (*stochastic convergence*) if these differences are transitory, in the sense that they are *approaching zero* in the long run. The time series analyses use recently developed panel unit-root tests for testing stochastic convergence.

Several studies have examined agricultural productivity and convergence for various countries or regions around the world. Such studies are the paper by Paci (1997) for European Union regions; the papers by Ball et al. (2001), Gutierrez (2000), and Rezitis (2005) for the United States and the European Union; the paper by Suhariyanto and Thirtle (2001) for Asian countries; the paper by Mukherjee and Kuroda (2003) for Indian states; the paper by McErlean and Wu (2003) for Chinese regions; and the paper by Thirtle et al. (2003) for Botswana regions. The present paper differs from the previous studies in terms of the empirical approach used in measuring agricultural productivity and testing convergence. In particular, the papers by Suhariyanto and Thirtle (2001) and Thirtle et al. (2003) calculate Malmquist index with respect to the sequential frontier, which is formed without any statistical basis; the papers of Ball et al. (2001) and Mukherjee and Kuroda (2003) use Divisia indices to measure *TFP*, which in the words of Grosskopf (1993) ignores efficiency; the papers by Paci (1997), Gutierrez (2000) and McErlean and Wu (2003) use labor productivity for examining convergence. With regard to the approach used for testing convergence only four of the previous studies, i.e. Suhariyanto and Thirtle (2001), Thirtle *et al.* (2003), Mukherjee and Kuroda (2003) and Rezitis (2005), use time series techniques while the rest of them use cross-section. It should be noted, however, that the present paper uses a wider spectrum of panel unit root tests than previous papers with the exception of the paper by Rezitis (2005) which uses the same unit root tests. The difference between the present study and the paper by Rezitis (2005) is that the latter one tests for convergence by using exactly the same *TFP* data as the study by Ball *et al.* (2001). Note however that the *TFP* data set of Ball *et al.* (2001) ignores efficiency (Grosskopf, 1993) while the *TFP* data set created in the present study takes efficiency effects into account. An additional difference between the present paper and the paper by Rezitis (2005) is that the former one tests for *β*- and *σ*- convergence as well as for *stochastic* convergence while the latter one tests only for *stochastic* convergence. In spite of the aforementioned differences it would be interesting to compare the empirical results of the present paper and the paper by Rezitis (2005).

The rest of the paper is organized as follows. Section 2 discusses methodological issues of the *WMI* index and presents *TFP* growth estimates for the United States and the nine European countries under consideration. In Section 3, the issue of convergence is discussed and tested, based on both cross section and time series techniques. Finally, Section 4 summarizes the paper.

2. Agricultural *TFP* growth in European countries and the US

2.1. Window Malmquist Index (WMI)

Several studies have used the Malmquist Productivity Index (*MPI*) to examine agricultural *TFP* differences between countries, e.g. Thirtle et al. (1995), Fulginiti and Perrin (1997, 1998) and Arnade (1998) among others. As discussed by Fare et al. (1994) an important aspect of the Malmquist approach is to construct an index with respect to a *contemporaneous* frontier technology by using nonparametric methods to create the *best practice frontier* and then measure the distance functions of each country in the sample from this frontier. It should be noted that data on inputs and outputs from all of the countries in the sample are used to construct the *best practice* production frontier that represents the minimum level of inputs required to produce a given level of output (see Coelli, 1995 for a survey of studies used the *MPI*).

Following Sueyoshi and Aoki (2001), Figure 1 illustrates an output-based *MPI* measurement with two outputs and fixed input. The figure shows one DUM, *d*, which is observed at two different time periods, i.e. at the base period (*b*) and at the current period (*t*). Thus, the production position of the DUM in the base period is depicted by d^b and in the current period by d^t. Note that $d_b^{\,b}$ ($d_b^{\,t}$) and $d_t^{\,b}$ ($d_t^{\,t}$) are the projections of d^b (d^t) onto the base and current frontiers respectively. The *MPI* between the *b*th period and the *t*th period *is* given by

$$\mathrm{MPI}_b^t = \left[\frac{\dfrac{0d_t^b}{0d^b}\,\dfrac{0d_t^t}{0d^t}}{\dfrac{0d_b^b}{0d^b}\,\dfrac{0d_b^t}{0d^t}}\right]^{1/2} \qquad (1)$$

The sub-components of (1) can be measured by the Data Envelopment Analysis (*DEA*) and thus by using *DEA* terminology equation (1) can be written as

$$MPI_b^t = \left[\frac{TSE^b}{IEI^{b \to t}} \frac{IEI^{t \to b}}{TSE^t} \right]^{1/2} \tag{2}$$

where, *TSE* represents Technical and Scale Efficiency while *IEI* stands for the Intertemporal Efficiency Index which indicates the level of production change due to a shift on the frontier from one period to another.[2] The efficiency measured by *TSE* takes values between 0 and 1 while the measurement *IEI* may take values greater than or less than unity. The measurement $IEI^{t \to b}$ is obtained in a manner that the production of a DMU in the *t*th (future) period is radially projected onto the efficiency frontier of the *b*th (base) period and then the magnitude of $IEI^{t \to b}$ is estimated by measuring its projected distance from the efficiency frontier. When the DUM exhibits technological progress, its performance in the *t*th period is better than that of the *b*th period. Thus, the magnitude of $IEI^{t \to b}$ becomes greater than unity. The opposite takes place when no technology progress is identified.

Sueyoshi and Aoki (2001) proposed a non-parametric rank sum test, i.e. a Kruskal-Wallis rank test (1952), to investigate statistically whether a frontier shift occurs or not. The Kruskal-Wallis test provides a statistical basis regarding which periods should be combined together to form a “window”. Figure 2 depicts a no frontier shift in the form of a frontier cross-over occurring between the *t*-1th and the *t*th periods and indicates that DUMs in these two periods belong to the same group, i.e. they form a “window”. In this case the *TSE* and *IEI* measurements of all DUMs belonging to the “window” are calculated with regard to d_{t-1}^1- d_{t-1}^2- d_t^2- d_t^3- d_t^4 efficiency frontier. Thus the Window Malmquist Index (*WMI*) proposed by Sueyoshi and Aoki (2001) is given by[3]

$$WMI_b^t = \left[\frac{TSE^b}{IEI^{b \to t-1 \cup t}} \frac{IEI^{t \to b}}{TSE^{t-1 \cup t}} \right]^{1/2} \tag{3}$$

Note that value of $IEI^{b \to t-1 \cup t}$ is obtained in a way that the production of a DMU in the *b*th (base) period is radially projected onto the efficiency frontier constructed of the combined two consecutive periods, i.e. the *t-1*th and *t*th periods, and then the magnitude of $IEI^{b \to t-1 \cup t}$ is evaluated by measuring its projected distance from the efficiency frontier.

Assuming a dynamic process from the *b*th period to the *t*th period where each time period is specified by p (=b, b+1, ..., t-1, t) the Kruskal-Wallis rank statistic in a *DEA* framework is computed as follows: 1) The efficiency frontier of each time period, i.e. from the *b*th to the *t*th, are calculated and the related DUM projections are obtained in each period. 2) TSE scores are calculated for the whole set of all projected DUMs obtained in the previous step. This set contains N [=$n(t$-b+1)] DUMs, where t-b+1 is the length of observed periods and n is the number of DUMs per period. 3) All the projected DUMs are ranked (R_j) in a single series. 4) The Kruskal-Wallis rank statistic is given by

$$H=\left[\frac{12}{N(N+1)}\sum_{p=b}^{t}\frac{W_p^2}{n}\right]-3(N+1) \tag{4}$$

where $W_p=\sum_{j\in J_p}R_j$ and J_p indicates a whole set of DUMs for the *p*th period. The H statistic is approximately distributed as the χ^2 with t-b degrees-of-freedom. The null hypothesis tested by H is that a frontier shift does not occur among the observed periods. In the case of ties the H statistic is adjusted and the corrected Kruskal-Wallis rank statistic is used, which is given by

$$H^c=H/\left[1-\frac{\sum(\tau^3-\tau)}{N^3-N}\right] \tag{5}$$

where τ is the number of tied DUMs in a tied group of TSE scores. 5) If the null hypothesis of the previous step is rejected, then the periods between which a frontier shift does not occur, should be identified. In order to specify the periods, the following one-to-one period identification rank sum test statistic is used

$$H^{\#}=\left|\frac{W_p-W_{p'}}{n}\right|/\sqrt{\frac{N(N+1)(N-1-H)}{6n(N-t+b-1)}} \tag{6}$$

The $H^{\#}$ statistic is approximately distributed as the t with N-t+b-1 degrees-of-freedom. The null hypothesis tested by (6) is that a frontier shift does not occur between, for example, the *p*th and *p'*th period.

2.2. TFP results

The Kruskal-Wallis rank statistic (H), calculated by (4), equals 154.65 while the corrected statistic (H^c), calculated by (5), equals 155.12. Since both H and H^c are greater than the χ^2 (=31.41) with 20 degrees-of-freedom, the null hypothesis that a frontier shift does not occur among the observed periods is rejected at the 5% level of significance.

In order to exactly specify the periods which a frontier shift occurs or not, the one-to-one period identification statistic ($H^{\#}$) is calculated by (6). This statistic ($H^{\#}$) is compared with the *t*-score (=1.976) of both-sided 5% level of significance and 189 degrees-of-freedom. The null hypothesis that a frontier shift does not occur is tested for any adjacent annuls observations. Table 1 presents the results of the $H^{\#}$ statistic. The results indicate that the null hypothesis is rejected for any adjacent annul observations of the periods 1973-1980, 1982-1983 and 1988-1991. While it is not rejected for any adjacent annual observations of the periods 1980-1982, 1983-1984, 1984-1987, 1991-1992 and 1992-1993. In addition, the findings of the $H^{\#}$ statistic indicate that the length of the annual periods to be combined together to form a window, varies from 2 to 4 years. For example a two-year window is formed by the periods 1980-1981, 1983-1984, 1984-1985, 1991-1992 and 1992-1993, a three-year window is formed by the periods 1980-1982 and 1984-1986, and a four-year window is formed by the period 1984-1987.

Table 2 presents the estimates on *WMI* for the countries under consideration and Fig. 3 plots these estimates for convenience of exposition. The year 1973 (=1.00) is used as the base period. The results indicate that there has been a wide variation in the rate of *TFP* growth across countries over the period 1973-1993 with an average trend growth rate of about 1.62%.[4] The countries with the highest trend growth rate are the Netherlands (1.95%), the United Kingdom (1.90%), and Belgium (1.84%), while those with the lowest are Denmark (1.38%) and the United States (1.30%).

A closer examination of Fig. 3 reveals that the whole period can be divided into two subperiods across countries. In the first period from 1973 to 1982 the average trend growth rate is about 1.78% while in the second period from 1983 to 1993, the average rate is about 2.02%. In the first period, countries presenting the highest productivity growth are the United Kingdom (2.48%), Greece (2.15%), the United States (2.14%) and Denmark (1.81%) while those showing the lowest growth are Italy (1.29%) and France (0.98%). During the second period countries with the highest performance are Belgium (2.79%), France (2.58%), the Netherlands (2.17%), Germany (2.10%) and Italy (2.08%) while those with the lowest growth are Denmark (1.41%) and the United States (1.41%).

Table 3 shows estimates of the four sub-components of the *WMI* for each country under examination for the period 1973-1993. These estimates indicate that the TSE^{73} (the base year) and other *TSEs* (from 1974 to 1993) of Greece exhibit 100% efficiency. The average *TSE* score for all the countries in the sample for the period 1973-1993 is about 89.99% and among the countries, besides Greece, exhibiting the highest average *TSE* score during this period are the Netherlands (97.07%), Italy (94.60%), the United Kingdom (93.92%), Belgium (92.40%) and Germany (90.84%).

A comparison of the $IEI^{t\rightarrow 73}$ scores (t=1974-1993) indicates that there is a considerable difference among countries in attaining more than 100% in these scores. For example, as indicated by TSE^{73}, only Greece and the United Kingdom attained the efficiency frontier as the most efficient countries in 1973. Next, the Netherlands, Belgium, Germany and Ireland reached the level of the efficiency frontier (1973) in 1977, Italy reached it in 1978, Denmark and the United States in 1980 and France in 1981.

3. Convergence in agricultural *TFP* across European countries and the US

Three empirical approaches of testing convergence have been used extensively in the literature. Two of these, known as *beta (β)* and *sigma (σ)* convergence, are based on cross-section techniques, while the third, known as *stochastic or long-run* convergence is based on time series techniques.

3.1. Beta and Sigma convergence

β-Convergence implies that countries with relatively low initial level of productivity, defined for example either as labor productivity, income per capita or total factor productivity, grow relatively faster than high-productivity countries. To test for β-convergence, the productivity growth rate of each country in the cross section is regressed on its own initial level of productivity and if the coefficient is negative, then there is said to be β-convergence. In other words, a test of β-convergence is conducted by estimating the following regression

$$\hat{TFP}^{i}_{t} = \alpha + \beta \ln TFP^{i}_{t} + \varepsilon_{it} \qquad (7)$$

where *TFP* is the productivity level at the beginning of each period, the circumflexes (^) denote time derivatives or relative rate of change, α and β are parameters and ε_{it} is an error term with zero mean and finite variance. β-Convergence occurs if the value of β is negative and statistically significant. Regression (7) is estimated for the whole period, i.e. 1973-1993, and also for the two sub-periods, i.e. 1973-1982 and 1983-1993. The regression results are reported in Table 4 and indicate that the estimated parameter β is negative and statistically significant for the whole period. However, convergence is more pronounced in the second sub-period, i.e. 1983-1993, when β is highly statistically significant at about 1% level of significance. In the first sub-period, i.e. 1973-1982, β is still negative, but statistically significantly different than zero at low confidence level, i.e. at about 10% level of significance. Thus, although convergence becomes less clear in the first sub-period than in the second one, in general, the results indicate convergence in agricultural productivity among the sample countries. In other words, countries with low level of productivity at the beginning of the period, grow more rapidly than high productivity countries.

For σ-convergence to occur across countries, a sufficient condition is that the cross-sectional dispersion in *TFP* growth declines over time (Lichtenberg, 1994). To test for σ-convergence, the following regression should be estimated

$$StdDev(\ln TFP) = \phi_1 + \phi_2 t + \varepsilon_t \tag{8}$$

where *StdDev* stands for standard deviation, ϕ_1 and ϕ_2 are parameters and ε_t is an error term with zero mean and finite variance. A sufficient condition for σ-convergence, i.e. for convergence to the same *TFP* level for all countries, is that ϕ_2 is negative and statistically significant. Regression (8) is estimated for the whole period, i.e. 1973-1993, and for the two sub-periods, i.e. 1973-1982 and 1983-1993. Table 5 presents the regression results. In addition, Figures 4, 5 and 6 show the actual and fitted values of the dependent variable of regression (8) for the full period and the two sub-periods, respectively. For the full period, the estimated parameter ϕ_2, in Table 5, is positive and statistically insignificant. Figure 4 also shows a slight positive slope for the fitted values. In addition, a visual inspection of the actual values, while, indicates too much fluctuation and an increase of the standard deviation of the sample productivities during the first sub-period, it shows, however, a decline of these values for the second sub-period. In Table 5, the estimated parameter ϕ_2, in the first sub-period, is positive and statistically significant at the 5% level, while in the second sub-period, it is negative and statistically significant at the 1% level. Figure 5 shows a positive slope for the fitted values of the standard deviation of the sample productivities for the first sub-period and Figure 6 shows a negative slope of the fitted values for the second sub-period. Thus, σ-convergence test results indicate that while *TFP* growth rates across countries diverge during the 1973-1982 sub-period, they however converge during the 1983-1993 sub-period.

The empirical results of the cross-section tests of convergence indicate the present of β-convergence for the full period under consideration but the absence of σ-convergence for the same period. It is worth stating that although β- and σ-convergence are based on different tests, they are related. A necessary condition for σ-convergence is the presence of β-convergence. Note, however, that β-convergence is a necessary but not a sufficient condition for σ-convergence to exist (Sala-i-Martin, 1996). In other words, there could be high intra-distribution mobility that leads to β-convergence but still this does not generate a reduction in the distribution dispersion itself. Considering the first sub-period, the empirical results indicate weak β-convergence but the absence of σ-convergence. Finally, during the second sub-period, the empirical results support the presence of both β- and σ-convergence.

3.2. Stochastic or long-run convergence

The stochastic convergence approach uses nonstationary time series tools to examine the issue of convergence. In this case, the issue of convergence is examined by testing whether the long-run forecasts of *TFP* differences *approach zero* as the forecasting horizon tends to infinity. In other words, this long-run convergence is related to the productivity equality. The stochastic convergence approach uses recently developed panel data unit-root tests that can provide improvements in statistical power, compared to performing a separate unit root test for each individual series. In addition, Goddard and Wilson (2001) showed that a panel estimator outperforms both the cross-sectional and pooled OLS estimators in the presence of heterogeneous individual effects.

The basic model

The neoclassical growth model without technology asserts convergence in output per worker for similar, closed economics based on the accumulation of capital. However, if the exogenous technology process follows different long-run paths across countries, there will be no tendency for convergence. Analogously, this study examines whether the agricultural sectors of the sample countries under consideration have managed to narrow their technology gap. This paper follows the study by

Bernard and Jones (1996) and considers a simple model of sectoral output in which convergence in output occurs due to the improvement in *TFP*. In this model convergence in *TFP* across countries may occur if relatively backward countries can grow more rapidly by efficiently using the same technologies that are available to the more advanced countries. Thus, following Bernard and Jones (1996) a Cobb-Douglas production function with constant returns to scale is given as

$$\ln Y_{i,t} = \ln A_{i,t} + \alpha \ln K_{i,t} + (1-\alpha)\ln L_{i,t} \tag{9}$$

where $\ln Y_{i,t}$ is the log of the output in agriculture in country *i* at time *t*, $A_{i,t}$ is an exogenous technology process, $K_{i,t}$ is the capital stock, and $L_{i,t}$ is the number of workers in the sector. It is assumed that $A_{i,t}$ is given, according to

$$\ln A_{i,t} = \gamma_i + \lambda \ln \frac{A_{m,t-1}}{A_{i,t-1}} + \ln A_{i,t-1} + \varepsilon_{i,t} \tag{10}$$

where γ_i is the asymptotic rate of growth of agriculture in country *i*, the parameter λ represents the speed of catch-up, which is a function of productivity differential in agriculture in country *i* from that of the sample average of the countries under consideration, A_m, and $\varepsilon_{i,t}$ is the country-specific productivity shock, i.e the error term. Eq. (10) implies that *TFP* growth in country *i* may potentially grow either due to a sector-specific growth or because of technology transfer. In the case of the sample average Eq. (10) becomes

$$\ln A_{m,t} = \gamma_m + \ln A_{m,t-1} + \varepsilon_{m,t} \tag{11}$$

Combining Eqs. (10) and (11), the following model for the time path of *TFP* is obtained as

$$\ln \frac{A_{i,t}}{A_{m,t}} = (\gamma_i - \gamma_m) + (1-\lambda)\ln \frac{A_{i,t-1}}{A_{m,t-1}} + \hat{\varepsilon}_{i,t} \tag{12}$$

where $\hat{\varepsilon}_{i,t}$ are iid error terms. If 1>λ>0, the difference between the productivity levels between the country *i* and the sample average level will be stationary, indicating evidence of convergence and implying that productivity differences should vanish in the long run. Alternatively, if λ=0, productivity levels would grow at different rates permanently and show no tendency to converge. In that case the difference between the productivity in country *i* and the sample average will be nonstationary.

Estimation procedures

Earlier studies have tested for convergence in panel data models using the methodology proposed by Levin and Lin (1992). Recently, testing for convergence in panel data models is becoming more common, given both the ongoing theoretical investigation and the development of testing procedures (Banerjee, 1999; Chiang and Kao, 2002; Harris and Sollis, 2003). In this paper, several panel unit root tests are considered. Such tests are those suggested by Levin and Lin –LL- (1992, 1993) and Im, Pesaran and Shin –IPS- (1997) together with more recent extensions and developments such as the tests by Harris and Tzavalis –HT- (1999), Breitung (2000) and Hardi (2000). All these tests, except the last one, test the null hypothesis of nonstationarity, i.e. the presence of a unit root, against the alternative of stationarity. In contrast, Hardi (2000) tests the null of stationarity against the alternative of nonstationarity.

During the remainder of this paper, the notation $y_{i,t}$ will be used to refer to the variable $\ln\frac{A_{i,t}}{A_{m,t}}$ of Eq. 12, for facilitating the presentation of the panel unit root tests. The general structure of the Levin and Lin (1992) approach may be summarized as follows

$$\Delta y_{i,t} = \rho y_{i,t-1} + z_{it}^{'}\gamma + e_{it} \tag{13}$$

where e_{it} ~iid$(0,\sigma_e^2)$, i represents cross sectional units, i.e. i=1,2…N, and t represents time periods, i.e. t=1,2…T. Table 6 presents the seven forms of the Levin and Lin (1992) test (LL_1-LL_7) which are considered in this paper. The first test (LL_1) sets $z_{it} = 0$, i.e. without intercept and time trend; the second (LL_2) sets $z_{it} = \delta_0$, i.e. with intercept and no time trend; the third (LL_3) sets $z_{it} = \delta_0 + \delta_i t$, i.e. with intercept and time trend; the forth (LL_4) sets $z_{it} = v_t$, i.e. without intercept and time trend but with time specific effect; the fifth (LL_5) sets $z_{it} = \alpha_i$, i.e. without intercept and time trend, but with individual specific effect; the sixth (LL_6) sets $z_{it} = \alpha_i + \eta_i t$, i.e. with individual specific effect and individual time trend; and the seventh (LL_7) sets $z_{it} = 0$, i.e. without intercept and time trend, but with serial correlation across time period. In all cases, the null is H_0: $\rho=0$ for all i against the alternative H_1: $\rho<0$ for all i, with auxiliary assumptions under the null also being required about the coefficients relating to the deterministic components (Table 6). Thus, under the null hypothesis all i series in the panel contain a unit root, while the alternative hypothesis is that all individual series are stationary. Levin and Lin (1992) showed that as $N \to \infty$ and $T \to \infty$ the panel regression unit root *t-statistic* converges to the standard normal distribution *N(0,1)*, which makes possible statistical inferences about the value and significance of the parameter ρ.

Levin and Lin (1993) developed panel unit root tests that resolve the problems of heteroscedasticity and autocorrelation that are present in the Levin and Lin (1992) tests. The general structure of the Levin and Lin (1993) model may be presented as follows

$$\Delta y_{it} = \rho y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + z_{it}^{'} \gamma + u_{it} \qquad (14)$$

Eq. (14) indicates that the Levin and Lin (1993) approach allows the presence of different lags for each cross sectional series while the Levin and Lin (1992), Eq. (13), does not. Table 6 presents the three forms of the Levin and Lin (1993) test (LL_8-LL_10) which are considered in this paper. The first test (LL_8) sets $z_{it} = 0$, i.e. without individual specific effect and individual time trend; the second (LL_9) sets $z_{it} = \alpha_i$, i.e. with individual specific effect, but without time trend; and the third (LL_10) sets $z_{it} = \alpha_i + \eta_i t$, i.e. with individual specific effect and individual time trend. The Levin and Lin (1993) approach, as the Levin and Lin (1992), tests the null hypothesis that all *i* series in the panel contain a unit root, while the alternative hypothesis is that all individual series are stationary. The unit root *t-statistic* is, also, asymptotically distributed under the standard normal distribution.

Harris and Tzavalis – HT- (1999) indicated that the assumption that $T \to \infty$ of the LL tests yields a test with poor power to reject the null when it is actually false. Harris and Tzavalis (1999) created a test based on the assumption that *T* is fixed and they found that this had better power properties when *T* was small. In this paper three forms of this test, which is based on Eq. (13), are considered. The first test (HT_1) sets $z_{it} = 0$, i.e. without intercept and time trend, and corresponds to LL_1 test; the second (HT_2) sets $z_{it} = a_i$, i.e. without intercept and time trend but with individual specific effect, and corresponds to LL_5 test; and the third (HT_3) sets $z_{it} = \alpha_i + \delta_i t$, i.e. with individual specific effect and individual time trend and corresponds to LL_6 test.

Breitung (2000) showed that the methods used to estimate panel models with fixed effects for performing the Levin and Lin tests suffer from a sever loss of power. As a result Breitung (2000) suggested a test –UB- with a constant and without fixed effects in the model and showed that this test is more powerful than the Levin and Lin tests.

The Im, Pesaran and Shin (1997) test allows the coefficient ρ in Eq. (14) to be free to vary across each cross sectional series in the panel. This test also permits different lags for each cross section as in the case of Levin and Lin (1993). Thus, this test uses the following model:

$$\Delta y_{it} = \rho_i y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + z_{it}^{'} \gamma + u_{it} \tag{15}$$

The null hypothesis is that all i series in the panel contain a unit root, while the alternative hypothesis is that at least one of the individual series is stationary. The Im, Pesaran and Shin (1997) approach averages all the ADF individual unit root test statistics which are obtained from estimating (15) for each individual cross sectional series. Im, Pesaran and Shin (1997) showed that their test statistic (IPS97) follows the standard normal distribution. Two forms of this test (IPS97_1 and IPS97_2) are considered in this paper. The first test (IPS97_1) sets $z_{it} = \alpha_i$, i.e. with individual specific effect but without time trend; and the second (IPS97_2) sets $z_{it} = \alpha_i + \eta_i t$, i.e. with individual specific effect and individual time trend. Im, Pesaran and Shin (1997) also proposed an LM test based on a lagrange multiplier test rather than t-statistics. Again, two forms of this test (IPSLM_1 and IPSLM_2) are considered in this paper. The first test (IPSLM_1) sets $z_{it} = \alpha_i$, i.e. with individual specific effect but without time trend; and the second (IPSLM_2) sets $z_{it} = \alpha_i + \eta_i t$, i.e. with individual specific effect and individual time trend.

Finally, Hadri (2000) proposed a residual-based LM test for a null that the time series for each cross section are stationary around a deterministic trend, against the alternative of a unit root in the panel. In this paper two forms of the Hadri (2000) –H- test are considered, one (H_1) with individual specific effect, without time trend and the other (H_2) with individual specific effect and individual time trend.

Estimation Results

Table 7 presents the results of the tests for convergence, i.e. panel unit root tests, discussed in the previous subsection.[5] All the panel unit root tests, except the Hadri (2000) tests, reject the null hypothesis of non-stationarity for the whole period, i.e. 1973-1993, as well as for the two sub-periods, i.e 1973-1982 and 1983-1993. Moreover, the Hadri (2000) test based on the null of stationarity yields ambiguous results. In particular, for the whole period, the H_1 test does not reject the null of stationarity at the 5% level but it rejects the null at the 10% level. The H_2 test, however, rejects the null of stationarity at any conventional level of significance. For the sub-period 1973-1982 (1983-1993) the H_1 tests rejects (does not reject) the null while the H_2 test does not reject (rejects) the null. A comparison of the results obtained in the present study with those of the study by Rezitis (2005) indicates stronger support of long-run convergence across the sample countries. This is because, while in the paper by Rezitis (2005), the IPSLM_2 test does not support any convergence for the first sub-period, it however supports convergence for the same sub-period in the present paper.

It should be stated that although the samples under consideration consist of small number of years and countries, i.e. N and T are relatively small; all panel unit root tests (except for the Hadri test) provide clear-cut evidence for rejecting unit roots in the series. Thus the results indicate that the *TFP* difference as measured by the distance of each country's productivity level from the countries' sample average is stationary. In other words, there is evidence of long-run convergence. This result is robust to specifications that take account country specific effects, year specific effects and time trend.

4. Conclusions

This paper constructs window Malmquist TFP indices from 1973 to 1993, for the agricultural sectors of the United States and nine European countries and tests for convergence in TFP using both cross-section and time-series techniques.

The results indicate that there has been a wide variation in the rate of *TFP* growth across countries over the period under consideration with an average trend growth rate of about 1.62%. The convergence analysis, on the other hand, indicates the presence of β-convergence, but the absence of σ-convergence for the countries under consideration. When the two sub-periods are considered, i.e 1973-1982 and 1983-1993, the convergence results indicate the presence of weak β-convergence and the absence of σ-convergence for the first sub-period, while the results indicate the presence of both β- and σ-convergence for the second sub-period. Finally, all panel unit root test results (except for the Hardi tests) support the presence of stationarity in the series, i.e. stochastic convergence, for the full period and for the two sub-periods. Thus, the majority of the convergence test results indicate the presence of convergence of the countries under examination for the full period and the two sub-periods but with stronger evidence for the second sub-period.

The findings of the present study are supported by other papers examining convergence for the United States and Europe. Such studies are the paper by Paci (1997) which found that for several European regions the catching-up process appeared stronger in the second part of 1980s, when there was an increase in the trade liberalization due to the inclusion of other southern members in the European Community; the paper by Ball et al. (2001) which found evidence that those countries that lagged far behind the technology leaders experienced the most rapid productivity convergence; the paper by Gutierrez (2000) which found strong evidence for convergence in agriculture across all US states and eleven EU countries during 1970-1992; the paper by Rezitis (2005) which support convergence among EU countries and the USA. Finally, the findings of studies examining convergence for other countries or regions around the world are mixed. For example, the paper by Suhariyanto and Thirtle (2001) which examined convergence between Asian countries found that less productive countries are falling further behind, rather than catching-up. The study of Thirtle et al. (2003) found no evidence for convergence between several agricultural districts of Botswana. On the other hand the paper by McErlean and Wu (2003) found regional divergence in China between 1985 and 1992 and convergence between 1992 and 2000. While the study by Mukherjee and Kuroda (2003) found no evidence for σ-convergence between Indian states but strong evidence for stochastic convergence.

Endnotes

[1] The output and input data are obtained from the Appendix A (Ball et. al., 2001). In particular, the output data are obtained from Table A.2 (pp.23), the capital input data from Table A.4 (pp.24), the land input data from Table A.6 (pp.25), the labor input data from Table A.8 (pp.26) and the intermediate input data from Table A.10 (pp. 27).

[2] The study by Sueyoshi and Aoki (2001) provides the *DEA* models to calculate *IEIs* and *TSEs* measures.

[3] The study by Sueyoshi and Aoki (2001) provides the *DEA* models to measure $IEI^{b \to t-1 \cup t}$ and $TSE^{t-1 \cup t}$.

[4] In estimating *TFP* trend growth rates presented in Table 2 the following regression model is used: $Ln(TFP) = intercept + GROWTHRATE * time$.

[5] The panel unit root tests presented in Table 7 were estimated using the GAUSS econometric package and the subroutines from Chiang and Kao (2002).

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Table 1. One-to-one Period Identification Rank Sum Test

p	p'	H#
73	74	3.0119*
74	75	4.935*
75	76	5.397*
76	77	5.007*
77	78	4.015*
78	79	3.474*
79	80	4.976*
80	81	0.865
80	82	0.138
80	83	4.084*
81	82	1.003
81	83	3.219*
82	83	4.221*
83	84	1.568
83	85	2.932*
84	85	1.365
84	86	1.806
84	87	0.644
84	88	5.548*
85	86	0.441
85	87	0.720
85	88	4.184*
86	87	1.161
86	88	3.742*
87	88	4.903*
88	89	2.964*
89	90	12.378*
90	91	12.219*
91	92	1.216
91	93	2.602*
92	93	1.385

*Indicates 5% significance.

Table 2. Results of the Window Malmquist Total Factor Productivity Index (Base Year 1973=1.00)

	Germany	France	Italy	Netherlands	Belgium	United Kingdom	Ireland	Denmark	Greece	United States	AVERAGE
WPI_{73}^{74}	1.023	1.026	0.999	0.962	0.961	1.030	1.007	1.024	0.997	1.034	1.003
WPI_{73}^{75}	1.095	1.015	0.990	0.995	1.026	1.106	0.998	1.072	1.042	1.124	1.044
WPI_{73}^{76}	1.055	1.011	0.981	0.934	0.998	1.126	1.013	1.044	1.030	1.141	1.029
WPI_{73}^{77}	1.013	0.925	0.923	0.956	0.971	1.091	0.957	0.983	0.961	1.072	0.984
WPI_{73}^{78}	1.104	1.020	1.001	0.994	1.048	1.190	1.086	1.071	1.048	1.165	1.070
WPI_{73}^{79}	1.065	0.988	0.955	1.007	1.008	1.144	1.028	1.035	1.005	1.120	1.033
WPI_{73}^{80}	1.142	1.060	1.032	1.001	1.065	1.233	1.078	1.138	1.094	1.226	1.101
WPI_{73}^{81}	1.152	1.077	1.070	1.070	1.110	1.256	1.112	1.164	1.182	1.242	1.143
WPI_{73}^{82}	1.163	1.092	1.104	1.091	1.130	1.284	1.145	1.194	1.202	1.263	1.166
WPI_{73}^{83}	1.110	1.002	1.024	1.092	1.040	1.256	1.086	1.116	1.056	1.178	1.094
WPI_{73}^{84}	1.140	1.053	1.074	1.126	1.106	1.289	1.118	1.153	1.204	1.220	1.152
WPI_{73}^{85}	1.162	1.077	1.103	1.136	1.137	1.312	1.132	1.175	1.224	1.243	1.173
WPI_{73}^{86}	1.177	1.134	1.110	1.168	1.153	1.337	1.187	1.226	1.243	1.293	1.203
WPI_{73}^{87}	1.222	1.155	1.135	1.185	1.184	1.361	1.218	1.255	1.273	1.324	1.231
WPI_{73}^{88}	1.236	1.172	1.150	1.195	1.208	1.391	1.237	1.262	1.194	1.317	1.234
WPI_{73}^{89}	1.318	1.239	1.226	1.297	1.309	1.491	1.253	1.294	1.244	1.330	1.300
WPI_{73}^{90}	1.175	1.113	1.084	1.171	1.171	1.319	1.121	1.141	1.079	1.207	1.157
WPI_{73}^{91}	1.371	1.290	1.230	1.342	1.357	1.524	1.290	1.310	1.307	1.362	1.339
WPI_{73}^{92}	1.381	1.315	1.280	1.346	1.387	1.534	1.307	1.323	1.407	1.395	1.373
WPI_{73}^{93}	1.350	1.318	1.310	1.355	1.405	1.521	1.316	1.308	1.396	1.404	1.374
						Trend Growth Rates (%)					
73-82	1.45^{**}	0.98	1.29^{*}	1.53^{***}	1.75^{***}	2.48^{***}	1.72^{***}	1.81^{**}	2.15^{**}	2.14^{***}	1.78^{***}
83-93	2.10^{***}	2.58^{***}	2.08^{***}	2.17^{***}	2.79^{***}	1.97^{***}	1.72^{***}	1.41^{***}	1.74^{**}	1.41^{***}	2.02^{***}
73-93	1.43^{***}	1.49^{***}	1.49^{***}	1.95^{***}	1.84^{***}	1.9^{***}	1.49^{***}	1.38^{***}	1.62^{***}	1.3^{***}	1.62^{***}

***Indicates 1% significance, **Indicates 5% significance, *Indicates 10% significance.

Table 3. Components of Window Malmquist Index

	Germany	France	Italy	Netherlands	Belgium	UK	Ireland	Denmark	Greece	US	AVERAGE
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{74}	0.849	0.723	0.877	1.000	0.966	1.000	0.852	0.757	1.000	0.676	0.870
IEI$^{73\rightarrow 74}$	0.836	0.177	0.881	0.984	0.981	0.975	0.770	0.681	1.041	0.692	0.802
IEI$^{74\rightarrow 73}$	0.869	0.740	0.886	0.962	0.929	1.035	0.835	0.775	1.034	0.700	0.877
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{75}	0.789	0.702	0.926	0.920	0.832	0.941	0.930	0.659	1.000	0.680	0.838
IEI$^{73\rightarrow 75}$	0.781	0.178	0.897	0.951	0.947	0.904	0.769	0.649	1.040	0.635	0.775
IEI$^{75\rightarrow 73}$	0.864	0.708	0.935	0.916	0.880	1.040	0.894	0.705	1.130	0.763	0.884
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{76}	0.832	0.682	0.890	0.994	0.842	0.920	0.850	0.677	1.000	0.679	0.837
IEI$^{73\rightarrow 76}$	0.810	0.185	0.933	1.013	1.009	0.888	0.799	0.675	1.081	0.624	0.802
IEI$^{76\rightarrow 73}$	0.878	0.709	0.918	0.929	0.898	1.036	0.874	0.714	1.147	0.772	0.888
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{77}	0.880	0.747	0.879	1.000	0.866	0.920	0.822	0.733	1.000	0.735	0.858
IEI$^{73\rightarrow 77}$	0.816	0.193	0.975	1.007	1.026	0.867	0.835	0.705	1.130	0.646	0.820
IEI$^{77\rightarrow 73}$	1.023	0.824	0.987	1.051	1.035	1.129	1.016	0.850	1.240	0.901	1.006
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{78}	0.915	0.815	0.981	1.000	0.902	0.962	0.861	0.789	1.000	0.828	0.905
IEI$^{73\rightarrow 78}$	0.876	0.205	1.035	1.028	1.080	0.920	0.887	0.749	1.200	0.686	0.867
IEI$^{78\rightarrow 73}$	1.063	0.896	1.065	1.103	1.049	1.158	1.012	0.908	1.213	0.997	1.046
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{79}	0.860	0.762	0.966	1.000	0.850	0.901	0.833	0.724	1.000	0.706	0.860
IEI$^{73\rightarrow 79}$	0.836	0.194	0.978	1.068	1.070	0.896	0.838	0.707	1.142	0.648	0.838
IEI$^{79\rightarrow 73}$	1.097	0.913	1.157	1.132	1.094	1.227	1.017	0.951	1.366	0.961	1.092
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{80}	0.848	0.749	0.935	1.000	0.868	0.890	0.806	0.742	1.000	0.773	0.861
IEI$^{73\rightarrow 80}$	0.835	0.194	0.978	1.000	1.000	0.887	0.838	0.707	1.000	0.648	0.809
IEI$^{80\rightarrow 73}$	1.100	0.926	1.203	1.211	1.134	1.245	1.047	1.020	1.398	1.080	1.136
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE$^{81\cup 80}$	0.927	0.817	0.915	1.000	0.877	0.923	0.840	0.791	1.000	0.767	0.886
IEI$^{73\rightarrow 81\cup 80}$	0.834	0.194	0.978	1.000	1.000	0.877	0.838	0.707	1.000	0.648	0.808
IEI$^{81\rightarrow 73}$	1.222	1.039	1.254	1.259	1.188	1.334	1.157	1.144	1.445	1.109	1.215
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE$^{82\cup 81\cup 80}$	0.955	0.880	1.000	1.000	0.961	0.948	0.905	0.794	1.000	0.699	0.914
IEI$^{73\rightarrow 82\cup 81\cup 80}$	0.907	0.215	1.084	1.020	1.070	0.888	0.929	0.784	1.256	0.718	0.887
IEI$^{82\rightarrow 73}$	1.248	1.044	1.307	1.286	1.179	1.327	1.243	1.113	1.401	0.974	1.212
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{83}	0.982	0.880	0.974	1.000	0.963	1.000	0.953	0.875	1.000	0.801	0.943
IEI$^{73\rightarrow 83}$	0.884	0.209	1.000	1.000	1.000	0.878	0.902	0.761	1.000	0.698	0.833
IEI$^{83\rightarrow 73}$	1.320	1.120	1.292	1.341	1.250	1.458	1.349	1.270	1.450	1.164	1.301

TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE$^{84\cup83}$	0.930	0.907	0.970	0.996	0.945	0.945	0.926	0.881	1.000	0.875	0.938
IEI$^{73\rightarrow84\cup83}$	0.875	0.208	1.000	1.000	1.000	0.870	0.896	0.757	1.000	0.693	0.830
IEI$^{84\rightarrow73}$	1.286	1.202	1.356	1.358	1.295	1.416	1.333	1.320	1.499	1.311	1.338
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE$^{85\cup84}$	0.977	0.908	0.985	1.000	0.978	0.944	0.915	0.896	1.000	0.908	0.951
IEI$^{73\rightarrow85\cup84}$	0.863	0.197	1.000	1.000	1.000	0.862	0.848	0.716	1.000	0.661	0.815
IEI$^{85\rightarrow73}$	1.367	1.263	1.395	1.443	1.378	1.455	1.371	1.384	1.545	1.403	1.400
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE$^{86\cup85\cup84}$	0.918	0.931	1.000	0.959	0.938	0.928	0.915	0.843	1.000	0.896	0.933
IEI$^{73\rightarrow86\cup85\cup84}$	0.860	0.197	1.000	1.000	1.000	0.856	0.848	0.716	1.000	0.661	0.814
IEI$^{86\rightarrow73}$	1.378	1.345	1.482	1.423	1.394	1.472	1.445	1.365	1.620	1.452	1.438
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE$^{87\cup86\cup85\cup84}$	0.949	0.908	0.974	0.941	0.935	0.895	0.890	0.896	1.000	0.840	0.923
IEI$^{73\rightarrow87\cup86\cup85\cup84}$	0.854	0.203	1.021	1.037	1.033	0.864	0.875	0.739	1.184	0.677	0.849
IEI$^{87\rightarrow73}$	1.448	1.391	1.511	1.473	1.494	1.496	1.494	1.514	1.689	1.379	1.489
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{88}	0.893	0.874	0.915	0.884	0.895	0.863	0.802	0.862	1.000	0.895	0.888
IEI$^{73\rightarrow88}$	0.850	0.202	1.016	0.970	0.966	0.808	0.871	0.735	1.178	0.673	0.827
IEI$^{88\rightarrow73}$	1.542	1.489	1.607	1.525	1.572	1.551	1.377	1.523	1.824	1.491	1.550
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{89}	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
IEI$^{73\rightarrow89}$	0.982	0.233	1.174	1.095	1.091	0.912	1.006	0.849	1.361	0.778	0.948
IEI$^{89\rightarrow73}$	1.586	1.586	1.586	1.586	1.586	1.586	1.586	1.586	1.586	1.586	1.586
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{90}	0.884	0.863	0.941	0.901	0.941	0.902	0.877	0.874	1.000	0.899	0.908
IEI$^{73\rightarrow90}$	0.861	0.204	1.030	0.942	0.939	0.785	0.882	0.745	1.193	0.682	0.826
IEI$^{90\rightarrow73}$	1.674	1.610	1.686	1.615	1.725	1.645	1.615	1.603	2.038	1.590	1.680
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{91}	0.937	0.920	0.958	0.918	0.995	0.934	0.921	0.854	1.000	0.955	0.939
IEI$^{73\rightarrow91}$	0.861	0.204	1.000	0.927	0.931	0.772	0.882	0.745	1.000	0.682	0.800
IEI$^{91\rightarrow73}$	1.800	1.784	1.805	1.630	1.889	1.696	1.742	1.598	1.980	1.772	1.770
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE$^{92\cup91}$	0.985	0.905	0.970	0.925	1.000	0.922	0.884	0.944	1.000	0.912	0.945
IEI$^{73\rightarrow92\cup91}$	0.874	0.207	1.000	0.922	0.938	0.771	0.895	0.755	1.000	0.692	0.805
IEI$^{92\rightarrow73}$	1.834	1.789	1.912	1.655	1.963	1.645	1.720	1.749	1.949	1.739	1.796
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE$^{93\cup92}$	0.985	0.905	0.970	0.925	1.000	0.922	0.884	0.944	1.000	0.912	0.945
IEI$^{73\rightarrow93\cup92}$	0.874	0.207	1.000	0.922	0.938	0.771	0.895	0.755	1.000	0.692	0.805
IEI$^{93\rightarrow73}$	1.834	1.789	1.912	1.655	1.963	1.645	1.720	1.749	1.949	1.739	1.796

Table 4. Testing for Beta Convergence

Period	Variable	Coefficient	Std. Error	t-statistics	p-value	R^2
1973-1982	α β	0.0258 -0.1514	0.0068 0.0796	3.80 -1.90	0.000 0.061	0.044
1983-1993	α β	0.0607 -0.2372	0.0148 0.0697	4.09 -3.40	0.000 0.001	0.097
1973-1993	α β	0.0332 -0.1278	0.0067 0.0396	4.90 -3.23	0.000 0.001	0.053

Table 5. Testing for Sigma Convergence

Period	Variable	Coefficient	Std. Error	t-statistics	p-value	R^2
1973-1982	ϕ_1 ϕ_2	-0.1728 0.0029	0.0946 0.0012	-1.83 2.41	0.110 0.047	0.453
1983-1993	ϕ_1 ϕ_2	0.1787 -0.0013	0.0212 0.0002	8.42 -5.71	0.000 0.000	0.784
1973-1993	ϕ_1 ϕ_2	0.0358 0.0002	0.0286 0.0003	1.250 0.718	0.226 0.482	0.028

Table 6. Levin and Lin (1992, 1993) Panel unit Root Tests

Test Name	Model	Hypothesis
LL_1	$\Delta y_{it} = \rho y_{i,t-1} + e_{it}$	$H_0: \rho = 0;\quad H_1: \rho < 0;$
LL_2	$\Delta y_{it} = \rho y_{i,t-1} + \delta_0 + e_{it}$	$H_0: \rho = \delta_0 = 0;\quad H_1: \rho < 0;$
LL_3	$\Delta y_{it} = \rho y_{i,t-1} + \delta_0 + \delta_i t + e_{it}$	$H_0: \rho = \delta_i = 0;\quad H_1: \rho < 0;\quad \delta_i \in R$ for all i
LL_4	$\Delta y_{it} = \rho y_{i,t-1} + v_t + e_{it}$	$H_0: \rho = 0;\quad H_1: \rho < 0;$
LL_5	$\Delta y_{it} = \rho y_{i,t-1} + \alpha_i + e_{it}$	$H_0: \rho = \alpha_i = 0;\quad H_1: \rho < 0;\quad \alpha_i \in R$ for all i
LL_6	$\Delta y_{it} = \rho y_{i,t-1} + \alpha_i + \eta_i t + e_{it}$	$H_0: \rho = \eta_i = 0;\quad H_1: \rho < 0;\quad \eta_i \in R$ for all i
LL_7	$\Delta y_{it} = \rho y_{i,t-1} + e_{it}$, with serial correlation	$H_0: \rho = 0;\quad H_1: \rho < 0;$
LL_8	$\Delta y_{it} = \rho y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + u_{it}$	$H_0: \rho = 0;\quad H_1: \rho < 0;$
LL_9	$\Delta y_{it} = \rho y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + \alpha_i + u_{it}$	$H_0: \rho = \alpha_i = 0;\quad H_1: \rho < 0;\quad \alpha_i \in R$ for all i
LL_10	$\Delta y_{it} = \rho y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + \alpha_i + \eta_i t + u_{it}$	$H_0: \rho = \eta_i = 0;\quad H_1: \rho < 0;\quad \eta_i \in R$ for all i

Note: A similar table summarizing LL(1992, 1993) panel unit roots tests can be found in Harris and Sollis (2003) page 194.

Table 7. Panel Unit Root Test Results

Test Name[1, 2]	Deterministic Components	Test statistic[3] [Significance level for rejection]		
		Period: 1973-1993	Period: 1973-1982	Period: 1983-1993
LL_1		-10.909 [0.000]	-10.805 [0.000]	-11.378 [0.000]
LL_2	δ_0	-15.197 [0.000]	-15.073 [0.000]	-15.472 [0.000]
LL_3	$\delta_0 + \delta_i t$	-15.158 [0.000]	-15.064 [0.000]	-15.454 [0.000]
LL_4	v_t	-13.927 [0.000]	-13.771 [0.000]	-13.435 [0.000]
LL_5	α_i	-12.761 [0.000]	-12.720 [0.000]	-13.283 [0.000]
LL_6	$\alpha_i + \eta_i t$	-12.025 [0.000]	-11.725 [0.000]	-12.933 [0.000]
LL_7		-538.367 [0.000]	-508.760 [0.000]	-550.944 [0.000]
LL_8		49.677 [0.000]	49.677 [0.000]	52.662 [0.000]
LL_9	α_i	2,924.608 [0.000]	2,465.928 [0.000]	2,384.374 [0.000]
LL_10	$\alpha_i + \eta_i t$	2,000.211 [0.000]	2,405.131 [0.000]	1,786.622 [0.000]
HT_1		-34.364 [0.000]	-33.535 [0.000]	-35.086 [0.000]
HT_2	α_i	-20.918 [0.000]	-20.597 [0.000]	-21.010 [0.000]
HT_3	$\alpha_i + \eta_i t$	-11.423 [0.000]	-11.091 [0.000]	-11.493 [0.000]
UB	δ_0	-7.168 [0.000]	-9.100 [0.000]	-10.498 [0.000]
IPS97_1	α_i	-10.788 [0.000]	-11.149 [0.000]	-10.819 [0.000]
IPS97_2	$\alpha_i + \eta_i t$	-9.0246 [0.00]	-9.310 [0.00]	-9.323 [0.00]
IPSLM_1	α_i	10.387 [0.000]	10.368 [0.000]	10.639 [0.000]
IPSLM_2	$\alpha_i + \eta_i t$	6.529 [0.000]	6.512 [0.000]	6.741 [0.000]
H_1	α_i	-1.571 [0.058]	-1.937 [0.026]	-1.028 [0.152]
H_2	$\alpha_i + \eta_i t$	2.670 [0.004]	0.656 [0.256]	2.925 [0.0002]

[1] Where applicable lag length is set at 1.
[2] LL stands for the Levin and Lin (1992, 1993) test statistics, HT stands for the Harris and Tzavalis (1999) test statistics, UB stands for the Breitung (2000) test statistic, IPS stands for the Im, Pesaran and Shin (1997) test statistics, and H stands for the Hadri (2000) test statistics.
[3] All tests are (asymptotically or exactly) distributed under the standard normal distribution.

Figure 1. Shift of the frontier from the *b*th to the *t*th period

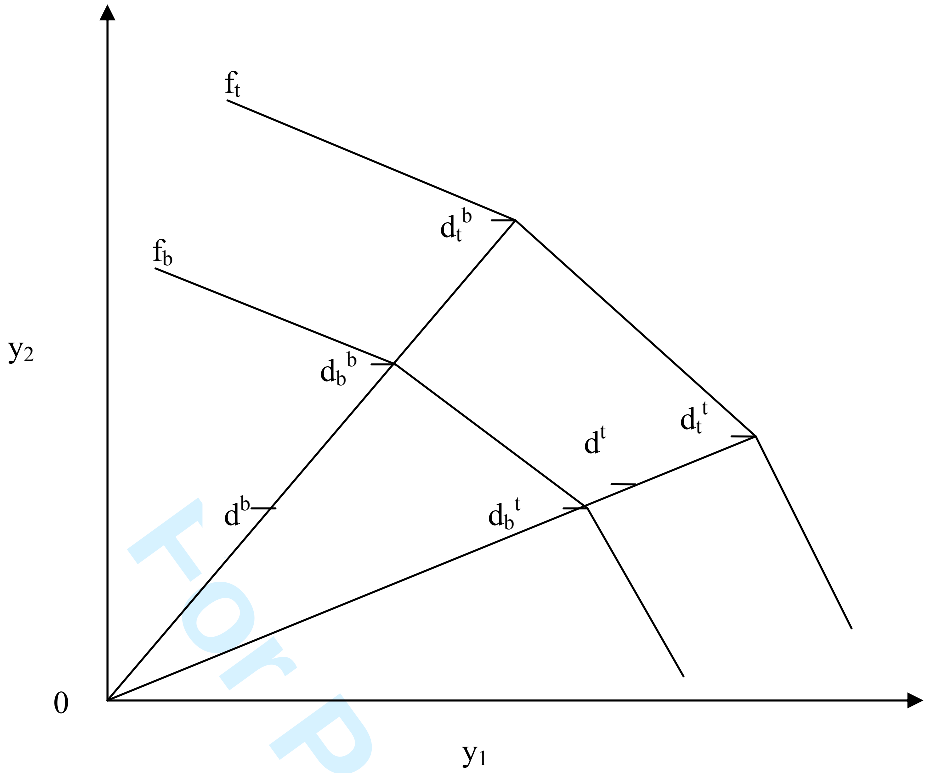


Figure 2. A cross-over among two frontiers

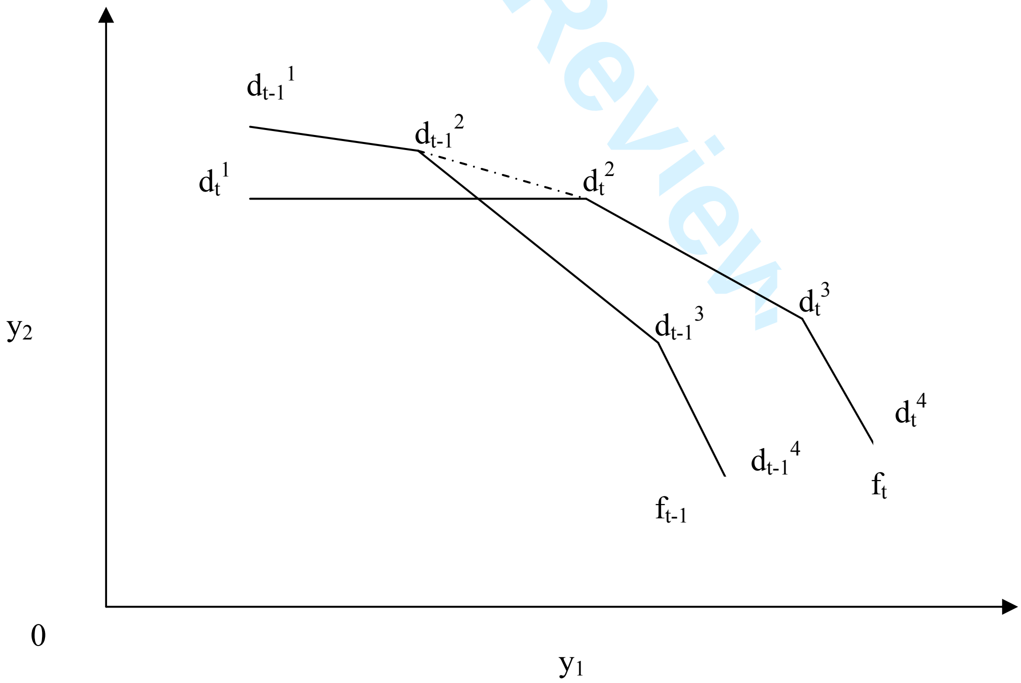


Figure 3. *TFP* Growth Rates for Nine EU countries and the US

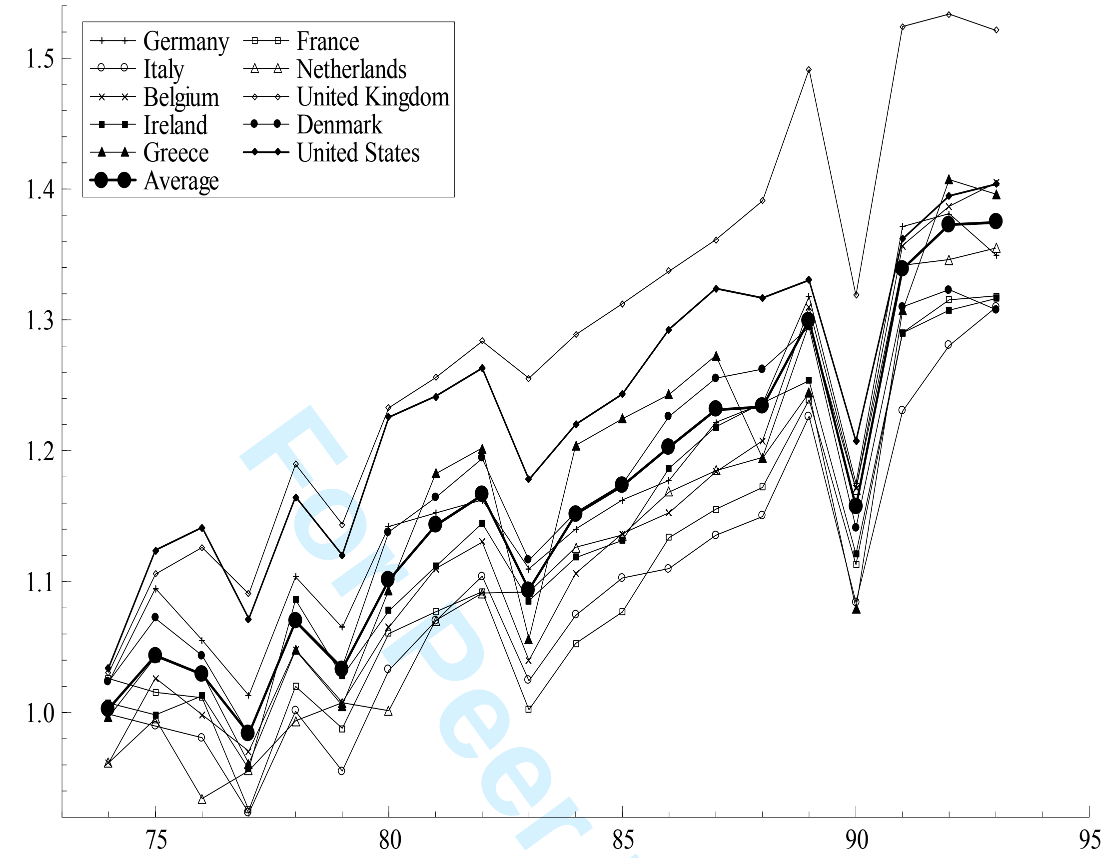


Figure 4. Standard Deviation of ln(*TFP*) for the period 1973-1993

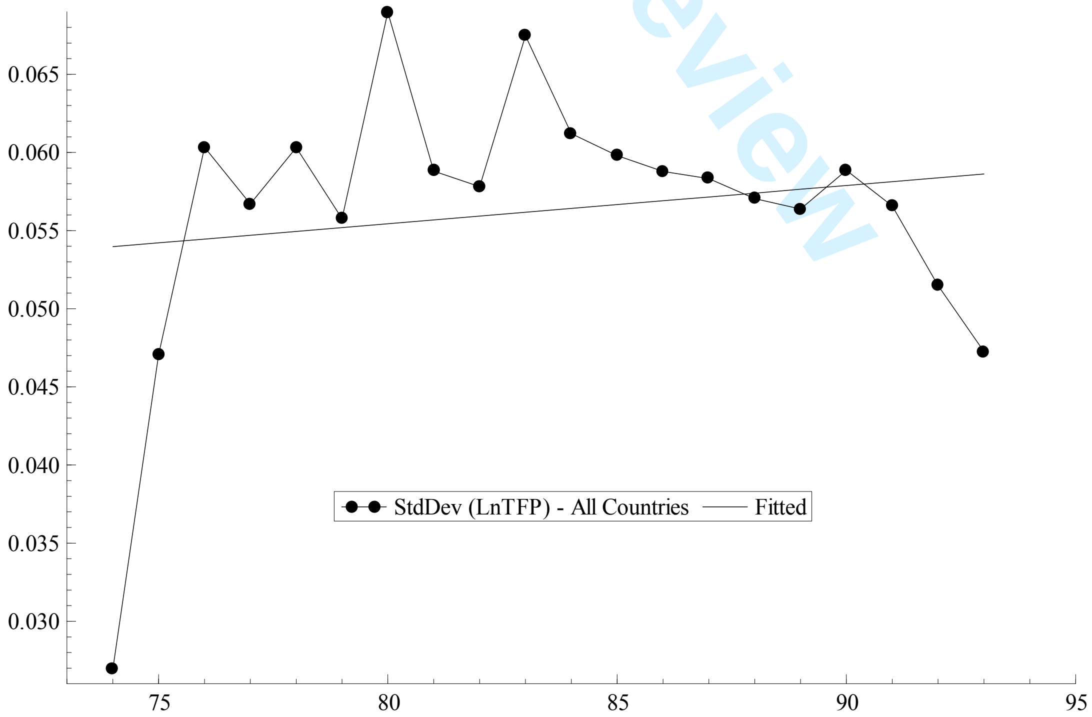


Figure 5. Standard Deviation of ln(*TFP*) for the period 1973-1982

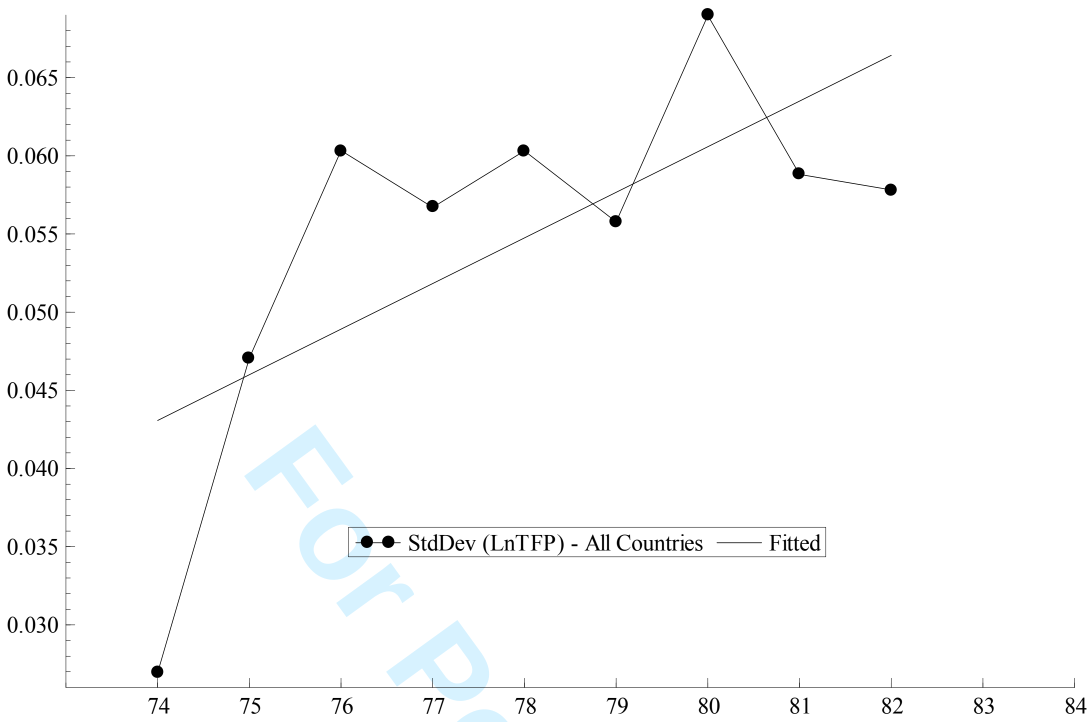
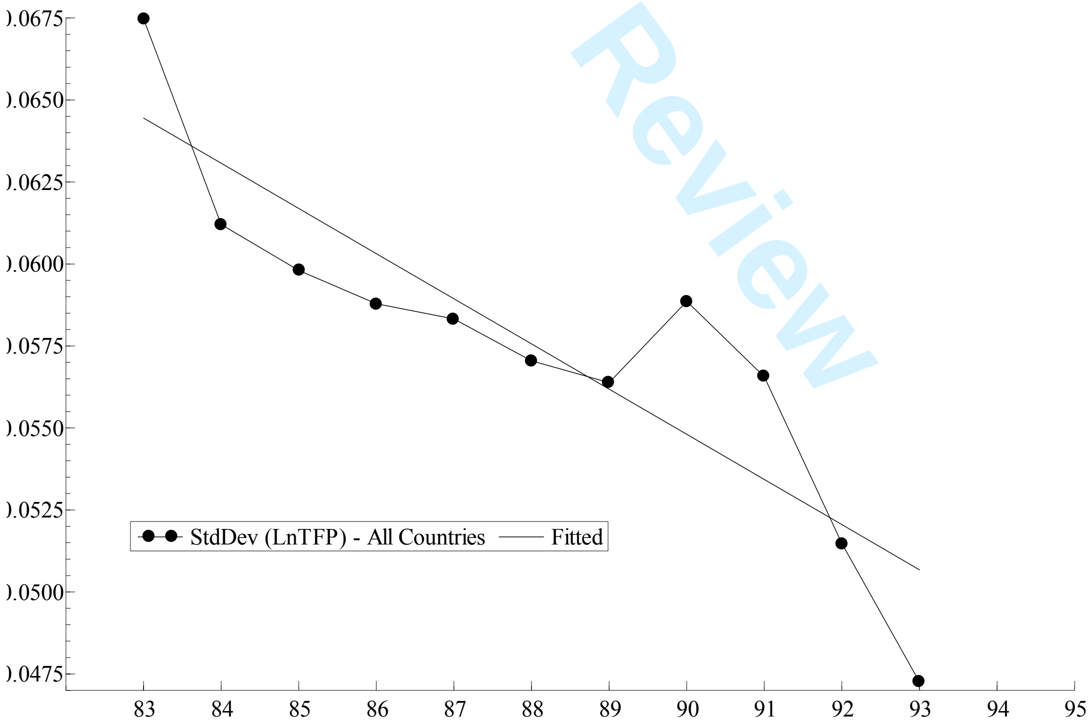


Figure 6. Standard Deviation of Ln(*TFP*) for the period 1983-1993



Agricultural Productivity and Convergence: Europe and the United States

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Abstract: This paper applies the Window Malmquist Index (*WMI*) approach to measure changes in agricultural total factor productivity (*TFP*) for the United States and a sample of nine European countries for the period 1973 to 1993. The data set used in this paper is obtained from Ball et al. (2001). The *WMI* is constructed by combining Data Envelopment Analysis (*DEA*) window analysis with the Malmquist index approach. Furthermore, the "Kruskal and Wallis rank test" is used for testing frontier shifts among observed periods. The paper also explores the question of convergence in *TFP* across the countries under consideration, by testing for β- and σ-convergence, as well as for *stochastic or long-run* convergence. The results show wide variation in the rate of *TFP* growth across countries with an average trend growth rate of 1.62%. The results indicate the presence of β-convergence but the absence of σ-convergence for the full period under consideration but the presence of both β- and σ-convergence for the sub-period 1983-1993. Finally, a wide spectrum of panel unit root test results support the presence of long-run convergence among the sample countries.

JEL classification: O13; C23

Keywords: Window Malmquist Index, convergence, panel unit root tests.

1. Introduction

In the last decade there has been an enormous increase in research investigating cross-country differences in agricultural productivity and convergence. With the aim of analyzing better the process of convergence, most of these studies has concentrated in investigating the hypothesis of catching-up in agricultural productivity among countries. The catching-up hypothesis states that the poorest countries, i.e. lowest productivity level countries, growing at a rate higher than the richest countries, i.e. highest productivity level countries, so that they are catching-up.

The objective of the present paper is to measure agricultural total factor productivity growth for the United States and nine European countries, i.e. Germany, France, Italy, the Netherlands, Belgium, the United Kingdom, Ireland, Denmark and Greece, over the period 1973 to 1993 and then test for convergence. To this end, the paper utilizes exactly the same output and input data as the paper by Ball et al. (2001) but uses a different analytical approach in calculating *TFP* and testing for convergence.[1] There are three main reasons why the sample period of the present paper was restricted over the period 1973-1993. Firstly, the output and input data used in the preset paper are taken from the same published source, i.e. the paper by Ball et al. (2001), and all of them are well constructed. Secondly, the empirical results of the preset paper can be directly compared to those obtained by Ball et al. (2001). Thirdly, and most importantly, there is a structural break in the year of 1994 because of the first major Common Agricultural Policy (CAP) reform proposed in 1992 and implemented in 1994 which reduced the level of support prices and increased direct payments.[2] The presence of a structural break in 1994 implies that the assumption of parameters being exactly the same before and after 1994 is probably unrealistic. Thus, due to the above three aforementioned reasons, it was necessary to confine the analysis of the present paper over the period 1973-1993.

The empirical approach used in this paper in calculating *TFP* growth relies on the Window Malmquist Index (*WMI*) proposed by Sueyoshi and Aoki (2001). Thore et al. (1994) and Goto and Tsutsui (1998) proposed a "new Malmquist type productivity index" by combining Data Envelopment Analysis (*DEA*) window analysis with the conventional Malmquist index approach. The *DEA*-window analysis (Bowling, 1987) examines how much a *DEA* efficiency score changes by shifting a combination of adjacent periods referred to as "a window". Unfortunately, this new Malmquist type productivity index did not provide a statistical basis regarding which periods should be combined together to form a "window". In order to overcome this shortcoming, Sueyoshi and Aoki (2001) proposed a nonparametric rank sum test, referred to as the "Kruskal and Wallis rank test", which combined it with the *DEA*-window analysis and the conventional Malmquist index approach to create the *WMI* used in the present study.

Having measured *TFP* growth for the United States and the nine European countries, the present study investigates convergence as described by the neo-classical growth model (Barro and Sala-i-Martin, 1995; Bernard and Durlauf, 1996). In this paper both cross-section and time series techniques are used for testing convergence. Cross section analyses have concentrated in the transition to equilibrium growth paths. Convergence is then focused on the narrowing of initial differences in productivity, either defined as labor productivity, income per capita or total factor productivity, over some time horizon, i.e. poorer countries grow faster than richer ones (*β-convergence*), or the decrease of cross-country variance of productivity (*σ-convergence*), although one does not necessarily indicate the other. Time series analysis examines long-run behavior of differences in productivity across countries. This approach assumes convergence (*stochastic convergence*) if these differences are transitory, in the sense that they are *approaching zero* in the long run. The time series analyses use recently developed panel unit-root tests for testing stochastic convergence. Thus, a stationary log-difference of two productivity series entails stochastic convergence, i.e. the absence of a unit root, in the sense that stochastic shocks have only temporary effects. Productivity in the two countries is then driven by a common stochastic trend (Bruggemann and Trenkler, 2007). It is worth stating that the present paper applies recently developed panel unit-root tests, e.g. Levin and Lin (1992, 1993), Im *et al.* (1997) among others, which allow investigation of convergence issues even for short time periods. The paper by Lima and Resende (2007) provides examples of studies applying panel unit-root tests on short time periods. It should also be noted that long-run convergence does not imply nor is implied by *σ-convergence*. This is because when long-run convergence takes place, the cross-sectional dispersion, i.e. *σ-convergence tends* to be constant (Proietti, 2005).

Several studies have examined agricultural productivity and convergence for various countries or regions around the world. Such studies are the paper by Paci (1997) for European Union regions; the papers by Ball et al. (2001), Gutierrez (2000), and Rezitis (2005) for the United States and the European Union; the paper by

Suhariyanto and Thirtle (2001) for Asian countries; the paper by Mukherjee and Kuroda (2003) for Indian states; the paper by McErlean and Wu (2003) for Chinese regions; and the paper by Thirtle et al. (2003) for Botswana regions. The present paper differs from the previous studies in terms of the empirical approach used in measuring agricultural productivity and testing convergence. In particular, the papers by Suhariyanto and Thirtle (2001) and Thirtle et al. (2003) calculate Malmquist index with respect to the sequential frontier, which is formed without any statistical basis; the papers of Ball et al. (2001) and Mukherjee and Kuroda (2003) use Divisia indices to measure *TFP*, which in the words of Grosskopf (1993) ignores efficiency; the papers by Paci (1997), Gutierrez (2000) and McErlean and Wu (2003) use labor productivity for examining convergence. With regard to the approach used for testing convergence only four of the previous studies, i.e. Suhariyanto and Thirtle (2001), Thirtle *et al.* (2003), Mukherjee and Kuroda (2003) and Rezitis (2005) use time series techniques while the rest of them use cross-section. It should be noted, however, that the present paper uses a wider spectrum of panel unit root tests than previous papers with the exception of the paper by Rezitis (2005) which uses the same unit root tests. The difference between the present study and the paper by Rezitis (2005) is that the latter one tests for convergence by using exactly the same *TFP* data as the study by Ball *et al.* (2001). Note however that the *TFP* data set of Ball *et al.* (2001) ignores efficiency (Grosskopf, 1993) while the *TFP* data set created in the present study takes efficiency effects into account. An additional difference between the present paper and the paper by Rezitis (2005) is that the former one tests for β- and σ- convergence as well as for *stochastic* convergence while the latter one tests only for *stochastic* convergence. In spite of the aforementioned differences it would be interesting to compare the empirical results of the present paper and the paper by Rezitis (2005). Finally, the present paper, in terms of the methodological approach used, is situated in the research field of regional and country convergence which appear in a series of recent papers published in Applied Economics Journals, e.g. Bruggemann and Trenkler (2007), Lima and Resende (2007), Galvao and Gomes (2007), Chang et al. (2006), Cunado and Perez de Gracia (2006), Costantini and Arbia (2006), Proietti (2005), Kim (2005), among others.

The rest of the paper is organized as follows. Section 2 discusses methodological issues of the *WMI* index and presents *TFP* growth estimates for the United States and the nine European countries under consideration. In Section 3, the issue of convergence is discussed and tested, based on both cross section and time series techniques. Finally, Section 4 summarizes the paper.

2. Agricultural *TFP* growth in European countries and the US

2.1. Window Malmquist Index (WMI)

Several studies have used the Malmquist Productivity Index (*MPI*) to examine agricultural *TFP* differences between countries, e.g. Thirtle et al. (1995), Fulginiti and Perrin (1997, 1998) and Arnade (1998) among others. As discussed by Fare et al. (1994) an important aspect of the Malmquist approach is to construct an index with respect to a *contemporaneous* frontier technology by using nonparametric methods to create the *best practice frontier* and then measure the distance functions of each country in the sample from this frontier. It should be noted that data on inputs and outputs from all of the countries in the sample are used to construct the *best practice* production frontier that represents the minimum level of inputs required to produce a given level of output (see Coelli, 1995 for a survey of studies used the *MPI*).

Following Sueyoshi and Aoki (2001), Figure 1 illustrates an output-based *MPI* measurement with two outputs and fixed input. The figure shows one DUM, d, which is observed at two different time periods, i.e. at the base period (b) and at the current period (t). Thus, the production position of the DUM in the base period is depicted by d^b and in the current period by d^t. Note that $d_b^{\,b}$ ($d_b^{\,t}$) and $d_t^{\,b}$ ($d_t^{\,t}$) are the projections of d^b (d^t) onto the base and current frontiers respectively. The *MPI* between the bth period and the tth period *is* given by

$$\mathrm{MPI}_b^t = \left[\frac{\dfrac{0d_t^b}{0d^b} \dfrac{0d_t^t}{0d^t}}{\dfrac{0d_b^b}{0d^b} \dfrac{0d_b^t}{0d^t}} \right]^{1/2} \tag{1}$$

The sub-components of (1) can be measured by the Data Envelopment Analysis (*DEA*) and thus by using *DEA* terminology equation (1) can be written as

$$MPI_b^t = \left[\frac{TSE^b}{IEI^{b\to t}} \frac{IEI^{t\to b}}{TSE^t} \right]^{1/2} \tag{2}$$

where, *TSE* represents Technical and Scale Efficiency while *IEI* stands for the Intertemporal Efficiency Index which indicates the level of production change due to a shift on the frontier from one period to another.[3] The efficiency measured by *TSE* takes values between 0 and 1 while the measurement *IEI* may take values greater than or less than unity. The measurement $IEI^{t \to b}$ is obtained in a manner that the production of a DMU in the *t*th (future) period is radially projected onto the efficiency frontier of the *b*th (base) period and then the magnitude of $IEI^{t \to b}$ is estimated by measuring its projected distance from the efficiency frontier. When the DUM exhibits technological progress, its performance in the *t*th period is better than that of the *b*th period. Thus, the magnitude of $IEI^{t \to b}$ becomes greater than unity. The opposite takes place when no technology progress is identified.

Sueyoshi and Aoki (2001) proposed a non-parametric rank sum test, i.e. a Kruskal-Wallis rank test (1952), to investigate statistically whether a frontier shift occurs or not. The Kruskal-Wallis test provides a statistical basis regarding which periods should be combined together to form a "window". Figure 2 depicts a no frontier shift in the form of a frontier cross-over occurring between the *t*-1th and the *t*th periods and indicates that DUMs in these two periods belong to the same group, i.e. they form a "window". In this case the *TSE* and *IEI* measurements of all DUMs belonging to the "window" are calculated with regard to d_{t-1}^1- d_{t-1}^2- d_t^2- d_t^3- d_t^4 efficiency frontier. Thus the Window Malmquist Index (*WMI*) proposed by Sueyoshi and Aoki (2001) is given by[3]

$$WMI_b^t = \left[\frac{TSE^b}{IEI^{b \to t-1 \cup t}} \frac{IEI^{t \to b}}{TSE^{t-1 \cup t}} \right]^{1/2} \tag{3}$$

Note that value of $IEI^{b \to t-1 \cup t}$ is obtained in a way that the production of a DMU in the *b*th (base) period is radially projected onto the efficiency frontier constructed of the combined two consecutive periods, i.e. the *t-1*th and *t*th periods, and then the magnitude of $IEI^{b \to t-1 \cup t}$ is evaluated by measuring its projected distance from the efficiency frontier.

Assuming a dynamic process from the *b*th period to the *t*th period where each time period is specified by *p* (=*b*, *b*+1, ..., *t*-1, *t*) the Kruskal-Wallis rank statistic in a *DEA* framework is computed as follows: 1) The efficiency frontier of each time period, i.e. from the *b*th to the *t*th, are calculated and the related DUM projections are obtained in each period. 2) TSE scores are calculated for the whole set of all projected DUMs obtained in the previous step. This set contains *N* [=*n*(*t*-*b*+1)] DUMs, where *t*-*b*+1 is the length of observed periods and *n* is the number of DUMs per period. 3) All the projected DUMs are ranked (R_j) in a single series. 4) The Kruskal-Wallis rank statistic is given by

$$H = \left[\frac{12}{N(N+1)} \sum_{p=b}^{t} \frac{W_p^2}{n} \right] - 3(N+1) \tag{4}$$

where $W_p = \sum_{j \in J_p} R_j$ and J_p indicates a whole set of DUMs for the *p*th period. The *H* statistic is approximately distributed as the χ^2 with *t-b* degrees-of-freedom. The null hypothesis tested by *H* is that a frontier shift does not occur among the observed periods. In the case of ties the *H* statistic is adjusted and the corrected Kruskal-Wallis rank statistic is used, which is given by

$$H^c = H \Big/ \left[1 - \frac{\sum (\tau^3 - \tau)}{N^3 - N} \right] \tag{5}$$

where τ is the number of tied DUMs in a tied group of TSE scores. 5) If the null hypothesis of the previous step is rejected, then the periods between which a frontier shift does not occur, should be identified. In order to specify the periods, the following one-to-one period identification rank sum test statistic is used

$$H^{\#} = \left| \frac{W_p - W_{p'}}{n} \right| \Big/ \sqrt{\frac{N(N+1)(N-1-H)}{6n(N-t+b-1)}} \tag{6}$$

The $H^{\#}$ statistic is approximately distributed as the *t* with *N-t+b-1* degrees-of-freedom. The null hypothesis tested by (6) is that a frontier shift does not occur between, for example, the *p*th and *p'*th period.

2.2. TFP results

The Kruskal-Wallis rank statistic (*H*), calculated by (4), equals 154.65 while the corrected statistic (H^c), calculated by (5), equals 155.12. Since both *H* and H^c are greater than the χ^2 (=31.41) with 20 degrees-of-freedom, the null hypothesis that a frontier shift does not occur among the observed periods is rejected at the 5% level of significance.

In order to exactly specify the periods which a frontier shift occurs or not, the one-to-one period identification statistic ($H^{\#}$) is calculated by (6). This statistic ($H^{\#}$) is compared with the *t*-score (=1.976) of both-sided 5% level of significance and 189 degrees-of-freedom. The null hypothesis that a frontier shift does not occur is tested for any adjacent annuls observations. Table 1 presents the results of the $H^{\#}$ statistic.

The results indicate that the null hypothesis is rejected for any adjacent annul observations of the periods 1973-1980, 1982-1983 and 1988-1991. While it is not rejected for any adjacent annual observations of the periods 1980-1982, 1983-1984, 1984-1987, 1991-1992 and 1992-1993. In addition, the findings of the $H^{\#}$ statistic indicate that the length of the annual periods to be combined together to form a window, varies from 2 to 4 years. For example a two-year window is formed by the periods 1980-1981, 1983-1984, 1984-1985, 1991-1992 and 1992-1993, a three-year window is formed by the periods 1980-1982 and 1984-1986, and a four-year window is formed by the period 1984-1987.

Table 2 presents the estimates on *WMI* for the countries under consideration and Fig. 3 plots these estimates for convenience of exposition. The year 1973 (=1.00) is used as the base period. The results indicate that there has been a wide variation in the rate of *TFP* growth across countries over the period 1973-1993 with an average trend growth rate of about 1.62%.[5] The countries with the highest trend growth rate are the Netherlands (1.95%), the United Kingdom (1.90%), and Belgium (1.84%), while those with the lowest are Denmark (1.38%) and the United States (1.30%).

A closer examination of Fig. 3 reveals that the whole period can be divided into two subperiods across countries. In the first period from 1973 to 1982 the average trend growth rate is about 1.78% while in the second period from 1983 to 1993, the average rate is about 2.02%. In the first period, countries presenting the highest productivity growth are the United Kingdom (2.48%), Greece (2.15%), the United States (2.14%) and Denmark (1.81%) while those showing the lowest growth are Italy (1.29%) and France (0.98%). During the second period countries with the highest performance are Belgium (2.79%), France (2.58%), the Netherlands (2.17%), Germany (2.10%) and Italy (2.08%) while those with the lowest growth are Denmark (1.41%) and the United States (1.41%).

Table 3 shows estimates of the four sub-components of the *WMI* for each country under examination for the period 1973-1993. These estimates indicate that the TSE^{73} (the base year) and other *TSEs* (from 1974 to 1993) of Greece exhibit 100% efficiency. The average *TSE* score for all the countries in the sample for the period 1973-1993 is about 89.99% and among the countries, besides Greece, exhibiting the highest average *TSE* score during this period are the Netherlands (97.07%), Italy (94.60%), the United Kingdom (93.92%), Belgium (92.40%) and Germany (90.84%).

A comparison of the $IEI^{t\rightarrow 73}$ scores (t=1974-1993) indicates that there is a considerable difference among countries in attaining more than 100% in these scores. For example, as indicated by TSE^{73}, only Greece and the United Kingdom attained the efficiency frontier as the most efficient countries in 1973. Next, the Netherlands, Belgium, Germany and Ireland reached the level of the efficiency frontier (1973) in 1977, Italy reached it in 1978, Denmark and the United States in 1980 and France in 1981.

3. Convergence in agricultural *TFP* across European countries and the US

Three empirical approaches of testing convergence have been used extensively in the literature. Two of these, known as *beta (β)* and *sigma (σ)* convergence, are based on cross-section techniques, while the third, known as *stochastic or long-run* convergence is based on time series techniques.

3.1. Beta and Sigma convergence

The economic convergence literature, e.g. Costantini and Arbia (2006) and Miller and Upadhyay (2002) among others, identifies two (beta and sigma) convergence hypotheses: (i) unconditional (absolute) convergence hypothesis, which indicates that each country converges toward the same stead-state productivity level and (ii) conditional convergence hypothesis, which suggests that each country possesses its own stead-state productivity level when it is converging. It should be stated that the steady state in each country is conditional on the state of its economy. In this paper the hypothesis of unconditional (absolute) convergence is investigated.

β-Convergence implies that countries with relatively low initial level of productivity, defined for example either as labor productivity, income per capita or total factor productivity, grow relatively faster than high-productivity countries. To test for β-convergence, the productivity growth rate of each country in the cross section is regressed on its own initial level of productivity and if the coefficient is negative, then there is said to be β-convergence. In other words, a test of β-convergence is conducted by estimating the following regression

$$\hat{TFP}^{i}_{t} = \alpha + \beta \ln TFP^{i}_{t} + \varepsilon_{it} \qquad (7)$$

where TFP is the productivity level at the beginning of each period, the circumflexes (^) denote time derivatives or relative rate of change, α and β are parameters and ε_{it} is an error term with zero mean and finite variance. β-Convergence occurs if the value of β is negative and statistically significant. Regression (7) is estimated for the whole period, i.e. 1973-1993, and also for the two sub-periods, i.e. 1973-1982 and 1983-1993. The regression results are reported in Table 4 and indicate that the estimated parameter β is negative and statistically significant for the whole period. However, convergence is more pronounced in the second sub-period, i.e. 1983-1993, when β is highly statistically significant at about 1% level of significance. In the first sub-period, i.e. 1973-1982, β is still negative, but statistically significantly different than zero at low confidence level, i.e. at about 10% level of significance. Thus, although convergence becomes less clear in the first sub-period than in the second one, in general, the results indicate convergence in agricultural productivity among the sample countries. In other words, countries with low level of productivity at the beginning of the period, grow more rapidly than high productivity countries.

For σ-convergence to occur across countries, a sufficient condition is that the cross-sectional dispersion in *TFP* growth declines over time (Lichtenberg, 1994). To test for σ-convergence, the following regression should be estimated

$$StdDev(\ln TFP) = \phi_1 + \phi_2 t + \varepsilon_t \qquad (8)$$

where *StdDev* stands for standard deviation, ϕ_1 and ϕ_2 are parameters and ε_t is an error term with zero mean and finite variance. A sufficient condition for σ-convergence, i.e. for convergence to the same *TFP* level for all countries, is that ϕ_2 is negative and statistically significant. Regression (8) is estimated for the whole period, i.e. 1973-1993, and for the two sub-periods, i.e. 1973-1982 and 1983-1993. Table 5 presents the regression results. In addition, Figures 4, 5 and 6 show the actual and fitted values of the dependent variable of regression (8) for the full period and the two sub-periods, respectively. For the full period, the estimated parameter ϕ_2, in Table 5, is positive and statistically insignificant. Figure 4 also shows a slight positive slope for the fitted values. In addition, a visual inspection of the actual values, while, indicates too much fluctuation and an increase of the standard deviation of the sample productivities during the first sub-period, it shows, however, a decline of these values for the second sub-period. In Table 5, the estimated parameter ϕ_2, in the first sub-period, is positive and statistically significant at the 5% level, while in the second sub-period, it is negative and statistically significant at the 1% level. Figure 5 shows a positive slope for the fitted values of the standard deviation of the sample productivities for the first sub-period and Figure 6 shows a negative slope of the fitted values for the second sub-period. Thus, σ-convergence test results indicate that while *TFP* growth rates across countries diverge during the 1973-1982 sub-period, they however converge during the 1983-1993 sub-period.

The empirical results of the cross-section tests of convergence indicate the present of β-convergence for the full period under consideration but the absence of σ-convergence for the same period. It is worth stating that although β- and σ-convergence are based on different tests, they are related. A necessary condition for σ-convergence is the presence of β-convergence. Note, however, that β-convergence is a necessary but not a sufficient condition for σ-convergence to exist (Sala-i-Martin, 1996). In other words, there could be high intra-distribution mobility that leads to β-convergence but still this does not generate a reduction in the distribution dispersion itself. Considering the first sub-period, the empirical results indicate weak β-convergence but the absence of σ-convergence. Finally, during the second sub-period, the empirical results support the presence of both β- and σ-convergence.

3.2. Stochastic or long-run convergence

The stochastic convergence approach uses nonstationary time series tools to examine the issue of convergence. In this case, the issue of convergence is examined by testing whether the long-run forecasts of *TFP* differences *approach zero* as the forecasting horizon tends to infinity. In other words, this long-run convergence is related to the productivity equality. The stochastic convergence approach uses recently developed panel data unit-root tests that can provide improvements in statistical power, compared to performing a separate unit root test for each individual series. In addition, Goddard and Wilson (2001) showed that a panel estimator outperforms both the cross-sectional and pooled OLS estimators in the presence of heterogeneous individual effects. Most importantly, panel unit-root tests are particularly useful for identifying nonstationarities when data sets used *are* characterized by a short time dimension (Lima and Resende, 2007; Banerjee, 1999; Maddala and Wu, 1999).

The basic model

The neoclassical growth model without technology asserts convergence in output per worker for similar, closed economics based on the accumulation of capital.

However, if the exogenous technology process follows different long-run paths across countries, there will be no tendency for convergence. Analogously, this study examines whether the agricultural sectors of the sample countries under consideration have managed to narrow their technology gap. This paper follows the study by Bernard and Jones (1996) and considers a simple model of sectoral output in which convergence in output occurs due to the improvement in *TFP*. In this model convergence in *TFP* across countries may occur if relatively backward countries can grow more rapidly by efficiently using the same technologies that are available to the more advanced countries. Thus, following Bernard and Jones (1996) a Cobb-Douglas production function with constant returns to scale is given as

$$\ln Y_{i,t} = \ln A_{i,t} + \alpha \ln K_{i,t} + (1-\alpha)\ln L_{i,t} \tag{9}$$

where $\ln Y_{i,t}$ is the log of the output in agriculture in country i at time t, $A_{i,t}$ is an exogenous technology process, $K_{i,t}$ is the capital stock, and $L_{i,t}$ is the number of workers in the sector. It is assumed that $A_{i,t}$ is given, according to

$$\ln A_{i,t} = \gamma_i + \lambda \ln \frac{A_{m,t-1}}{A_{i,t-1}} + \ln A_{i,t-1} + \varepsilon_{i,t} \tag{10}$$

where γ_i is the asymptotic rate of growth of agriculture in country i, the parameter λ represents the speed of catch-up, which is a function of productivity differential in agriculture in country i from that of the sample average of the countries under consideration, A_m, and $\varepsilon_{i,t}$ is the country-specific productivity shock, i.e the error term. Eq. (10) implies that *TFP* growth in country i may potentially grow either due to a sector-specific growth or because of technology transfer. In the case of the sample average Eq. (10) becomes

$$\ln A_{m,t} = \gamma_m + \ln A_{m,t-1} + \varepsilon_{m,t} \tag{11}$$

Combining Eqs. (10) and (11), the following model for the time path of *TFP* is obtained as

$$\ln \frac{A_{i,t}}{A_{m,t}} = (\gamma_i - \gamma_m) + (1-\lambda)\ln \frac{A_{i,t-1}}{A_{m,t-1}} + \hat{\varepsilon}_{i,t} \tag{12}$$

where $\hat{\varepsilon}_{i,t}$ are iid error terms. If 1>λ>0, the difference between the productivity levels between the country i and the sample average level will be stationary, indicating evidence of convergence and implying that productivity differences should vanish in the long run. Alternatively, if λ=0, productivity levels would grow at different rates permanently and show no tendency to converge. In that case the difference between the productivity in country *i* and the sample average will be nonstationary.

Estimation procedures

Earlier studies have tested for convergence in panel data models using the methodology proposed by Levin and Lin (1992). Recently, testing for convergence in panel data models is becoming more common, given both the ongoing theoretical investigation and the development of testing procedures (Banerjee, 1999; Chiang and Kao, 2002; Harris and Sollis, 2003). In this paper, several panel unit root tests are considered. Such tests are those suggested by Levin and Lin –LL- (1992, 1993) and Im, Pesaran and Shin –IPS- (1997) together with more recent extensions and developments such as the tests by Harris and Tzavalis –HT- (1999), Breitung (2000) and Hardi (2000). All these tests, except the last one, test the null hypothesis of nonstationarity, i.e. the presence of a unit root, against the alternative of stationarity. In contrast, Hardi (2000) tests the null of stationarity against the alternative of nonstationarity.

During the remainder of this paper, the notation $y_{i,t}$ will be used to refer to the variable $\ln\frac{A_{i,t}}{A_{m,t}}$ of Eq. 12, for facilitating the presentation of the panel unit root tests. The general structure of the Levin and Lin (1992) approach may be summarized as follows

$$\Delta y_{i,t} = \rho y_{i,t-1} + z_{it}^{'}\gamma + e_{it} \qquad (13)$$

where e_{it} ~iid$(0,\sigma_e^2)$, *i* represents cross sectional units, i.e. *i*=1,2…*N*, and *t* represents time periods, i.e. *t*=1,2…*T*. Table 6 presents the seven forms of the Levin and Lin (1992) test (LL_1-LL_7) which are considered in this paper.[6] In all cases, the null is H_0: $\rho=0$ for all *i* against the alternative H_1: $\rho<0$ for all *i*, with auxiliary assumptions under the null also being required about the coefficients relating to the deterministic components (Table 6). Thus, under the null hypothesis all *i* series in the panel contain a unit root, while the alternative hypothesis is that all individual series are stationary. Levin and Lin (1992) showed that as $N \to \infty$ and $T \to \infty$ the panel regression unit root *t-statistic* converges to the standard normal distribution *N(0,1)*, which makes possible statistical inferences about the value and significance of the parameter ρ.

Levin and Lin (1993) developed panel unit root tests that resolve the problems of heteroscedasticity and autocorrelation that are present in the Levin and Lin (1992) tests. The general structure of the Levin and Lin (1993) model may be presented as follows

$$\Delta y_{it} = \rho y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + z_{it}^{'} \gamma + u_{it} \quad (14)$$

Eq. (14) indicates that the Levin and Lin (1993) approach allows the presence of different lags for each cross sectional series while the Levin and Lin (1992), Eq. (13), does not. Table 6 presents the three forms of the Levin and Lin (1993) test (LL_8-LL_10) which are considered in this paper.[7] The Levin and Lin (1993) approach, as the Levin and Lin (1992), tests the null hypothesis that all *i* series in the panel contain a unit root, while the alternative hypothesis is that all individual series are stationary. The unit root *t-statistic* is, also, asymptotically distributed under the standard normal distribution.

Harris and Tzavalis – HT- (1999) indicated that the assumption that $T \to \infty$ of the LL tests yields a test with poor power to reject the null when it is actually false. Harris and Tzavalis (1999) created a test based on the assumption that T is fixed and they found that this had better power properties when T was small. This test is based on Eq. (13) and three forms of this test (HT_1-HT_3) are considered in this paper.[8]

Breitung (2000) showed that the methods used to estimate panel models with fixed effects for performing the Levin and Lin tests suffer from a sever loss of power. As a result Breitung (2000) suggested a test –UB- with a constant and without fixed effects in the model and showed that this test is more powerful than the Levin and Lin tests.

The Im, Pesaran and Shin (1997) test allows the coefficient ρ in Eq. (14) to be free to vary across each cross sectional series in the panel. This test also permits different lags for each cross section as in the case of Levin and Lin (1993). Thus, this test uses the following model:

$$\Delta y_{it} = \rho_i y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + z_{it}^{'} \gamma + u_{it} \quad (15)$$

The null hypothesis is that all *i* series in the panel contain a unit root, while the alternative hypothesis is that at least one of the individual series is stationary. The Im, Pesaran and Shin (1997) approach averages all the ADF individual unit root test statistics which are obtained from estimating (15) for each individual cross sectional series. Im, Pesaran and Shin (1997) showed that their test statistic (IPS97) follows the standard normal distribution. Two forms of this test (IPS97_1 and IPS97_2) are considered in this paper.[9] Im, Pesaran and Shin (1997) also proposed an LM test based on a lagrange multiplier test rather than *t*-statistics. Again, two forms of this test (IPSLM_1 and IPSLM_2) are considered in this paper.[10]

Finally, Hadri (2000) proposed a residual-based LM test for a null that the time series for each cross section are stationary around a deterministic trend, against the alternative of a unit root in the panel. In this paper two forms of the Hadri (2000) –H- test are considered, one (H_1) with individual specific effect, without time trend and the other (H_2) with individual specific effect and individual time trend.

Estimation Results

Table 7 presents the results of the tests for convergence, i.e. panel unit root tests, discussed in the previous subsection.[11] All the panel unit root tests, except the Hadri (2000) tests, reject the null hypothesis of non-stationarity for the whole period, i.e. 1973-1993, as well as for the two sub-periods, i.e 1973-1982 and 1983-1993. Moreover, the Hadri (2000) test based on the null of stationarity yields ambiguous results. In particular, for the whole period, the H_1 test does not reject the null of stationarity at the 5% level but it rejects the null at the 10% level. The H_2 test, however, rejects the null of stationarity at any conventional level of significance. For the sub-period 1973-1982 (1983-1993) the H_1 tests rejects (does not reject) the null while the H_2 test does not reject (rejects) the null. A comparison of the results of this study with those by Rezitis (2005), which applies the unit root tests of the present study to the *TFP* data of Ball *et al.* (2001), indicates stronger support of long-run convergence across the sample countries. This is because, while in the paper by Rezitis (2005), the IPSLM_2 test does not support any convergence for the first sub-period, it however supports convergence for the same sub-period in the present paper.

In general, the findings of the present study are supported by other papers examining convergence for the United States and Europe. Such studies are the paper by Paci (1997) which found that for several European regions the catching-up process appeared stronger in the second part of 1980s, when there was an increase in the trade liberalization due to the inclusion of other southern members in the European Community; the paper by Ball et al. (2001) which found evidence that those countries that lagged far behind the technology leaders experienced the most rapid productivity convergence; the paper by Gutierrez (2000) which found strong evidence for convergence in agriculture across all US states and eleven EU countries during 1970-1992; the paper by Rezitis (2005) which support convergence among EU countries and USA. Finally, the findings of studies examining convergence for other countries or regions around the world are mixed. For example, the paper by Suhariyanto and Thirtle (2001) which examined convergence between Asian countries found that less productive countries are falling further behind, rather than catching-up. The study of Thirtle et al. (2003) found no evidence for convergence between several agricultural districts of Botswana. On the other hand the paper by McErlean and Wu (2003) found regional divergence in China between 1985 and 1992 and convergence between 1992 and 2000. While the study by Mukherjee and Kuroda (2003) found no evidence for σ-convergence between Indian states but strong evidence for stochastic convergence.

It should be stated that although the samples under consideration consist of small number of years and countries, i.e. N and T are relatively small; all panel unit root tests (except for the Hadri test) provide clear-cut evidence for rejecting unit roots in the series. Thus the results indicate that the *TFP* difference as measured by the distance of each country's productivity level from the countries' sample average is stationary. In other words, there is evidence of long-run convergence. This result is robust to specifications that take account country specific effects, year specific effects and time trend.

4. Conclusions

This paper constructs window Malmquist TFP indices from 1973 to 1993, for the agricultural sectors of the United States and nine European countries and tests for convergence in TFP using both cross-section and time-series techniques.

The results indicate that there has been a wide variation in the rate of *TFP* growth across countries over the period under consideration with an average trend growth rate of about 1.62%. The convergence analysis, on the other hand, indicates the presence of β-convergence, but the absence of σ-convergence for the countries under consideration. When the two sub-periods are considered, i.e 1973-1982 and 1983-1993, the convergence results indicate the presence of weak β-convergence and the absence of σ-convergence for the first sub-period, while the results indicate the presence of both β- and σ-convergence for the second sub-period. Finally, all panel unit root test results (except for the Hardi tests) support the presence of stationarity in the series, i.e. stochastic convergence, for the full period and for the two sub-periods. Thus, the majority of the convergence test results indicate the presence of convergence of the countries under examination for the full period and the two sub-periods but with stronger evidence for the second sub-period.

Possible routes for future research include the expansion of the time horizon of the data set used. This is of a particular importance because the investigation of TFP convergence (and especially stochastic convergence) for the period after 1994 will provide results for comparing convergence before and after 1994, i.e. the implementation of the first major CAP reform, evaluating the first CAP reform as well as the subsequent reforms. If convergence is found to prevail after 1994, then an additional research step would be the investigation of the speed of convergence among periods which would further shed light on the evaluation of the first CAP reform as well as on the subsequent reforms. As a final note, it should be stated that it is important to analyze convergence adopting different European country groups and different sample periods (Costantini and Arbia, 2007) because the period after 1994 involves the European Union (EU) enlargement as well as more than one CAP reforms, e.g. Agenda 2000 reform and 2003-CAP reform among others.

Endnotes

[1] The output and input data are obtained from the Appendix A (Ball et. al., 2001). In particular, the output data are obtained from Table A.2 (pp.23), the capital input data from Table A.4 (pp.24), the land input data from Table A.6 (pp.25), the labor input data from Table A.8 (pp.26) and the intermediate input data from Table A.10 (pp. 27).
[2] This reform has been the basis of all subsequent CAP reforms. In particular a subsequent major CAP reform constitute the Agenda 2000 reform agreed in March 1999 to cover the 2000-2006 period but mandated a mid-term review (MTR) in 2003. Note that the MTR sets out the CAP framework until 2013 but it is unlikely to be the last CAP reform because the level of direct payments will be subject to the decision on the EU's Financial Perspective (or medium-term budget) over the period 2007-2013 which will determine the resources available for CAP expenditures.
[3] The study by Sueyoshi and Aoki (2001) provides the *DEA* models to calculate *IEIs* and *TSEs* measures.
[4] The study by Sueyoshi and Aoki (2001) provides the *DEA* models to measure $IEI^{b\to t-1\cup t}$ and $TSE^{t-1\cup t}$.
[5] In estimating *TFP* trend growth rates presented in Table 2 the following regression model is used: $Ln(TFP) = intercept + GROWTHRATE * time$.
[6] The first test (LL_1) sets $z_{it} = 0$, i.e. without intercept and time trend; the second (LL_2) sets $z_{it} = \delta_0$, i.e. with intercept and no time trend; the third (LL_3) sets $z_{it} = \delta_0 + \delta_i t$, i.e. with intercept and time trend; the forth (LL_4) sets $z_{it} = v_t$, i.e. without intercept and time trend but with time specific effect; the fifth (LL_5) sets $z_{it} = \alpha_i$, i.e. without intercept and time trend, but with individual specific effect; the sixth (LL_6) sets $z_{it} = \alpha_i + \eta_i t$, i.e. with individual specific effect and individual time trend; and the seventh (LL_7) sets $z_{it} = 0$, i.e. without intercept and time trend, but with serial correlation across time period.
[7] The first test (LL_8) sets $z_{it} = 0$, i.e. without individual specific effect and individual time trend; the second (LL_9) sets $z_{it} = \alpha_i$, i.e. with individual specific effect, but without time trend; and the third (LL_10) sets $z_{it} = \alpha_i + \eta_i t$, i.e. with individual specific effect and individual time trend.
[8] The first test (HT_1) sets $z_{it} = 0$, i.e. without intercept and time trend, and corresponds to LL_1 test; the second (HT_2) sets $z_{it} = a_i$, i.e. without intercept and time trend but with individual specific effect, and corresponds to LL_5 test; and the third (HT_3) sets $z_{it} = \alpha_i + \delta_i t$, i.e. with individual specific effect and individual time trend and corresponds to LL_6 test.
[9] The first test (IPS97_1) sets $z_{it} = \alpha_i$, i.e. with individual specific effect but without time trend; and the second (IPS97_2) sets $z_{it} = \alpha_i + \eta_i t$, i.e. with individual specific effect and individual time trend.
[10] The first test (IPSLM_1) sets $z_{it} = \alpha_i$, i.e. with individual specific effect but without time trend; and the second (IPSLM_2) sets $z_{it} = \alpha_i + \eta_i t$, i.e. with individual specific effect and individual time trend.
[11] The panel unit root tests presented in Table 7 were estimated using the GAUSS econometric package and the subroutines from Chiang and Kao (2002).

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Table 1. One-to-one Period Identification Rank Sum Test

p	p'	H#
73	74	3.0119*
74	75	4.935*
75	76	5.397*
76	77	5.007*
77	78	4.015*
78	79	3.474*
79	80	4.976*
80	81	0.865
80	82	0.138
80	83	4.084*
81	82	1.003
81	83	3.219*
82	83	4.221*
83	84	1.568
83	85	2.932*
84	85	1.365
84	86	1.806
84	87	0.644
84	88	5.548*
85	86	0.441
85	87	0.720
85	88	4.184*
86	87	1.161
86	88	3.742*
87	88	4.903*
88	89	2.964*
89	90	12.378*
90	91	12.219*
91	92	1.216
91	93	2.602*
92	93	1.385

*Indicates 5% significance.

Table 2. Results of the Window Malmquist Total Factor Productivity Index (Base Year 1973=1.00)

	Germany	France	Italy	Netherlands	Belgium	United Kingdom	Ireland	Denmark	Greece	United States	AVERAGE
WPI_{73}^{74}	1.023	1.026	0.999	0.962	0.961	1.030	1.007	1.024	0.997	1.034	1.003
WPI_{73}^{75}	1.095	1.015	0.990	0.995	1.026	1.106	0.998	1.072	1.042	1.124	1.044
WPI_{73}^{76}	1.055	1.011	0.981	0.934	0.998	1.126	1.013	1.044	1.030	1.141	1.029
WPI_{73}^{77}	1.013	0.925	0.923	0.956	0.971	1.091	0.957	0.983	0.961	1.072	0.984
WPI_{73}^{78}	1.104	1.020	1.001	0.994	1.048	1.190	1.086	1.071	1.048	1.165	1.070
WPI_{73}^{79}	1.065	0.988	0.955	1.007	1.008	1.144	1.028	1.035	1.005	1.120	1.033
WPI_{73}^{80}	1.142	1.060	1.032	1.001	1.065	1.233	1.078	1.138	1.094	1.226	1.101
WPI_{73}^{81}	1.152	1.077	1.070	1.070	1.110	1.256	1.112	1.164	1.182	1.242	1.143
WPI_{73}^{82}	1.163	1.092	1.104	1.091	1.130	1.284	1.145	1.194	1.202	1.263	1.166
WPI_{73}^{83}	1.110	1.002	1.024	1.092	1.040	1.256	1.086	1.116	1.056	1.178	1.094
WPI_{73}^{84}	1.140	1.053	1.074	1.126	1.106	1.289	1.118	1.153	1.204	1.220	1.152
WPI_{73}^{85}	1.162	1.077	1.103	1.136	1.137	1.312	1.132	1.175	1.224	1.243	1.173
WPI_{73}^{86}	1.177	1.134	1.110	1.168	1.153	1.337	1.187	1.226	1.243	1.293	1.203
WPI_{73}^{87}	1.222	1.155	1.135	1.185	1.184	1.361	1.218	1.255	1.273	1.324	1.231
WPI_{73}^{88}	1.236	1.172	1.150	1.195	1.208	1.391	1.237	1.262	1.194	1.317	1.234
WPI_{73}^{89}	1.318	1.239	1.226	1.297	1.309	1.491	1.253	1.294	1.244	1.330	1.300
WPI_{73}^{90}	1.175	1.113	1.084	1.171	1.171	1.319	1.121	1.141	1.079	1.207	1.157
WPI_{73}^{91}	1.371	1.290	1.230	1.342	1.357	1.524	1.290	1.310	1.307	1.362	1.339
WPI_{73}^{92}	1.381	1.315	1.280	1.346	1.387	1.534	1.307	1.323	1.407	1.395	1.373
WPI_{73}^{93}	1.350	1.318	1.310	1.355	1.405	1.521	1.316	1.308	1.396	1.404	1.374
						Trend Growth Rates (%)					
73-82	1.45**	0.98	1.29*	1.53***	1.75***	2.48***	1.72***	1.81**	2.15**	2.14***	1.78***
83-93	2.10***	2.58***	2.08***	2.17***	2.79***	1.97***	1.72***	1.41***	1.74**	1.41***	2.02***
73-93	1.43***	1.49***	1.49***	1.95***	1.84***	1.9***	1.49***	1.38***	1.62***	1.3***	1.62***

***Indicates 1% significance, **Indicates 5% significance, *Indicates 10% significance.

Table 3. Components of Window Malmquist Index

	Germany	France	Italy	Netherlands	Belgium	UK	Ireland	Denmark	Greece	US	AVERAGE
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{74}	0.849	0.723	0.877	1.000	0.966	1.000	0.852	0.757	1.000	0.676	0.870
$IEI^{73\to 74}$	0.836	0.177	0.881	0.984	0.981	0.975	0.770	0.681	1.041	0.692	0.802
$IEI^{74\to 73}$	0.869	0.740	0.886	0.962	0.929	1.035	0.835	0.775	1.034	0.700	0.877
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{75}	0.789	0.702	0.926	0.920	0.832	0.941	0.930	0.659	1.000	0.680	0.838
$IEI^{73\to 75}$	0.781	0.178	0.897	0.951	0.947	0.904	0.769	0.649	1.040	0.635	0.775
$IEI^{75\to 73}$	0.864	0.708	0.935	0.916	0.880	1.040	0.894	0.705	1.130	0.763	0.884
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{76}	0.832	0.682	0.890	0.994	0.842	0.920	0.850	0.677	1.000	0.679	0.837
$IEI^{73\to 76}$	0.810	0.185	0.933	1.013	1.009	0.888	0.799	0.675	1.081	0.624	0.802
$IEI^{76\to 73}$	0.878	0.709	0.918	0.929	0.898	1.036	0.874	0.714	1.147	0.772	0.888
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{77}	0.880	0.747	0.879	1.000	0.866	0.920	0.822	0.733	1.000	0.735	0.858
$IEI^{73\to 77}$	0.816	0.193	0.975	1.007	1.026	0.867	0.835	0.705	1.130	0.646	0.820
$IEI^{77\to 73}$	1.023	0.824	0.987	1.051	1.035	1.129	1.016	0.850	1.240	0.901	1.006
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{78}	0.915	0.815	0.981	1.000	0.902	0.962	0.861	0.789	1.000	0.828	0.905
$IEI^{73\to 78}$	0.876	0.205	1.035	1.028	1.080	0.920	0.887	0.749	1.200	0.686	0.867
$IEI^{78\to 73}$	1.063	0.896	1.065	1.103	1.049	1.158	1.012	0.908	1.213	0.997	1.046
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{79}	0.860	0.762	0.966	1.000	0.850	0.901	0.833	0.724	1.000	0.706	0.860
$IEI^{73\to 79}$	0.836	0.194	0.978	1.068	1.070	0.896	0.838	0.707	1.142	0.648	0.838
$IEI^{79\to 73}$	1.097	0.913	1.157	1.132	1.094	1.227	1.017	0.951	1.366	0.961	1.092
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{80}	0.848	0.749	0.935	1.000	0.868	0.890	0.806	0.742	1.000	0.773	0.861
$IEI^{73\to 80}$	0.835	0.194	0.978	1.000	1.000	0.887	0.838	0.707	1.000	0.648	0.809
$IEI^{80\to 73}$	1.100	0.926	1.203	1.211	1.134	1.245	1.047	1.020	1.398	1.080	1.136
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
$TSE^{81\cup 80}$	0.927	0.817	0.915	1.000	0.877	0.923	0.840	0.791	1.000	0.767	0.886
$IEI^{73\to 81\cup 80}$	0.834	0.194	0.978	1.000	1.000	0.877	0.838	0.707	1.000	0.648	0.808
$IEI^{81\to 73}$	1.222	1.039	1.254	1.259	1.188	1.334	1.157	1.144	1.445	1.109	1.215
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
$TSE^{82\cup 81\cup 80}$	0.955	0.880	1.000	1.000	0.961	0.948	0.905	0.794	1.000	0.699	0.914
$IEI^{73\to 82\cup 81\cup 80}$	0.907	0.215	1.084	1.020	1.070	0.888	0.929	0.784	1.256	0.718	0.887
$IEI^{82\to 73}$	1.248	1.044	1.307	1.286	1.179	1.327	1.243	1.113	1.401	0.974	1.212
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{83}	0.982	0.880	0.974	1.000	0.963	1.000	0.953	0.875	1.000	0.801	0.943
$IEI^{73\to 83}$	0.884	0.209	1.000	1.000	1.000	0.878	0.902	0.761	1.000	0.698	0.833
$IEI^{83\to 73}$	1.320	1.120	1.292	1.341	1.250	1.458	1.349	1.270	1.450	1.164	1.301

TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
$TSE^{84\cup 83}$	0.930	0.907	0.970	0.996	0.945	0.945	0.926	0.881	1.000	0.875	0.938
$IEI^{73\rightarrow 84\cup 83}$	0.875	0.208	1.000	1.000	1.000	0.870	0.896	0.757	1.000	0.693	0.830
$IEI^{84\rightarrow 73}$	1.286	1.202	1.356	1.358	1.295	1.416	1.333	1.320	1.499	1.311	1.338
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
$TSE^{85\cup 84}$	0.977	0.908	0.985	1.000	0.978	0.944	0.915	0.896	1.000	0.908	0.951
$IEI^{73\rightarrow 85\cup 84}$	0.863	0.197	1.000	1.000	1.000	0.862	0.848	0.716	1.000	0.661	0.815
$IEI^{85\rightarrow 73}$	1.367	1.263	1.395	1.443	1.378	1.455	1.371	1.384	1.545	1.403	1.400
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
$TSE^{86\cup 85\cup 84}$	0.918	0.931	1.000	0.959	0.938	0.928	0.915	0.843	1.000	0.896	0.933
$IEI^{73\rightarrow 86\cup 85\cup 84}$	0.860	0.197	1.000	1.000	1.000	0.856	0.848	0.716	1.000	0.661	0.814
$IEI^{86\rightarrow 73}$	1.378	1.345	1.482	1.423	1.394	1.472	1.445	1.365	1.620	1.452	1.438
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
$TSE^{87\cup 86\cup 85\cup 84}$	0.949	0.908	0.974	0.941	0.935	0.895	0.890	0.896	1.000	0.840	0.923
$IEI^{73\rightarrow 87\cup 86\cup 85\cup 84}$	0.854	0.203	1.021	1.037	1.033	0.864	0.875	0.739	1.184	0.677	0.849
$IEI^{87\rightarrow 73}$	1.448	1.391	1.511	1.473	1.494	1.496	1.494	1.514	1.689	1.379	1.489
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{88}	0.893	0.874	0.915	0.884	0.895	0.863	0.802	0.862	1.000	0.895	0.888
$IEI^{73\rightarrow 88}$	0.850	0.202	1.016	0.970	0.966	0.808	0.871	0.735	1.178	0.673	0.827
$IEI^{88\rightarrow 73}$	1.542	1.489	1.607	1.525	1.572	1.551	1.377	1.523	1.824	1.491	1.550
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{89}	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
$IEI^{73\rightarrow 89}$	0.982	0.233	1.174	1.095	1.091	0.912	1.006	0.849	1.361	0.778	0.948
$IEI^{89\rightarrow 73}$	1.586	1.586	1.586	1.586	1.586	1.586	1.586	1.586	1.586	1.586	1.586
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{90}	0.884	0.863	0.941	0.901	0.941	0.902	0.877	0.874	1.000	0.899	0.908
$IEI^{73\rightarrow 90}$	0.861	0.204	1.030	0.942	0.939	0.785	0.882	0.745	1.193	0.682	0.826
$IEI^{90\rightarrow 73}$	1.674	1.610	1.686	1.615	1.725	1.645	1.615	1.603	2.038	1.590	1.680
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
TSE^{91}	0.937	0.920	0.958	0.918	0.995	0.934	0.921	0.854	1.000	0.955	0.939
$IEI^{73\rightarrow 91}$	0.861	0.204	1.000	0.927	0.931	0.772	0.882	0.745	1.000	0.682	0.800
$IEI^{91\rightarrow 73}$	1.800	1.784	1.805	1.630	1.889	1.696	1.742	1.598	1.980	1.772	1.770
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
$TSE^{92\cup 91}$	0.985	0.905	0.970	0.925	1.000	0.922	0.884	0.944	1.000	0.912	0.945
$IEI^{73\rightarrow 92\cup 91}$	0.874	0.207	1.000	0.922	0.938	0.771	0.895	0.755	1.000	0.692	0.805
$IEI^{92\rightarrow 73}$	1.834	1.789	1.912	1.655	1.963	1.645	1.720	1.749	1.949	1.739	1.796
TSE^{73}	0.855	0.182	0.870	0.946	0.943	1.000	0.797	0.697	1.000	0.715	0.801
$TSE^{93\cup 92}$	0.985	0.905	0.970	0.925	1.000	0.922	0.884	0.944	1.000	0.912	0.945
$IEI^{73\rightarrow 93\cup 92}$	0.874	0.207	1.000	0.922	0.938	0.771	0.895	0.755	1.000	0.692	0.805
$IEI^{93\rightarrow 73}$	1.834	1.789	1.912	1.655	1.963	1.645	1.720	1.749	1.949	1.739	1.796

Table 4. Testing for Beta Convergence

Period	Variable	Coefficient	Std. Error	t-statistics	p-value	R^2
1973-1982	α β	0.0258 -0.1514	0.0068 0.0796	3.80 -1.90	0.000 0.061	0.044
1983-1993	α β	0.0607 -0.2372	0.0148 0.0697	4.09 -3.40	0.000 0.001	0.097
1973-1993	α β	0.0332 -0.1278	0.0067 0.0396	4.90 -3.23	0.000 0.001	0.053

Table 5. Testing for Sigma Convergence

Period	Variable	Coefficient	Std. Error	t-statistics	p-value	R^2
1973-1982	ϕ_1 ϕ_2	-0.1728 0.0029	0.0946 0.0012	-1.83 2.41	0.110 0.047	0.453
1983-1993	ϕ_1 ϕ_2	0.1787 -0.0013	0.0212 0.0002	8.42 -5.71	0.000 0.000	0.784
1973-1993	ϕ_1 ϕ_2	0.0358 0.0002	0.0286 0.0003	1.250 0.718	0.226 0.482	0.028

Table 6. Levin and Lin (1992, 1993) Panel unit Root Tests

Test Name	Model	Hypothesis
LL_1	$\Delta y_{it} = \rho y_{i,t-1} + e_{it}$	$H_0: \rho = 0;\ \ H_1: \rho < 0;$
LL_2	$\Delta y_{it} = \rho y_{i,t-1} + \delta_0 + e_{it}$	$H_0: \rho = \delta_0 = 0;\ \ H_1: \rho < 0;$
LL_3	$\Delta y_{it} = \rho y_{i,t-1} + \delta_0 + \delta_i t + e_{it}$	$H_0: \rho = \delta_i = 0;\ \ H_1: \rho < 0;\ \ \delta_i \in R$ for all i
LL_4	$\Delta y_{it} = \rho y_{i,t-1} + v_t + e_{it}$	$H_0: \rho = 0;\ \ H_1: \rho < 0;$
LL_5	$\Delta y_{it} = \rho y_{i,t-1} + \alpha_i + e_{it}$	$H_0: \rho = \alpha_i = 0;\ \ H_1: \rho < 0;\ \ \alpha_i \in R$ for all i
LL_6	$\Delta y_{it} = \rho y_{i,t-1} + \alpha_i + \eta_i t + e_{it}$	$H_0: \rho = \eta_i = 0;\ \ H_1: \rho < 0;\ \ \eta_i \in R$ for all i
LL_7	$\Delta y_{it} = \rho y_{i,t-1} + e_{it}$, with serial correlation	$H_0: \rho = 0;\ \ H_1: \rho < 0;$
LL_8	$\Delta y_{it} = \rho y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + u_{it}$	$H_0: \rho = 0;\ \ H_1: \rho < 0;$
LL_9	$\Delta y_{it} = \rho y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + \alpha_i + u_{it}$	$H_0: \rho = \alpha_i = 0;\ \ H_1: \rho < 0;\ \ \alpha_i \in R$ for all i
LL_10	$\Delta y_{it} = \rho y_{i,t-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta y_{i,t-L} + \alpha_i + \eta_i t + u_{it}$	$H_0: \rho = \eta_i = 0;\ \ H_1: \rho < 0;\ \ \eta_i \in R$ for all i

Note: A similar table summarizing LL(1992, 1993) panel unit roots tests can be found in Harris and Sollis (2003) page 194.

Table 7. Panel Unit Root Test Results

Test Name[1, 2]	Deterministic Components	Test statistic[3] [Significance level for rejection]		
		Period: 1973-1993	Period: 1973-1982	Period: 1983-1993
LL_1		-10.909 [0.000]	-10.805 [0.000]	-11.378 [0.000]
LL_2	δ_0	-15.197 [0.000]	-15.073 [0.000]	-15.472 [0.000]
LL_3	$\delta_0 + \delta_i t$	-15.158 [0.000]	-15.064 [0.000]	-15.454 [0.000]
LL_4	v_t	-13.927 [0.000]	-13.771 [0.000]	-13.435 [0.000]
LL_5	α_i	-12.761 [0.000]	-12.720 [0.000]	-13.283 [0.000]
LL_6	$\alpha_i + \eta_i t$	-12.025 [0.000]	-11.725 [0.000]	-12.933 [0.000]
LL_7		-538.367 [0.000]	-508.760 [0.000]	-550.944 [0.000]
LL_8		49.677 [0.000]	49.677 [0.000]	52.662 [0.000]
LL_9	α_i	2,924.608 [0.000]	2,465.928 [0.000]	2,384.374 [0.000]
LL_10	$\alpha_i + \eta_i t$	2,000.211 [0.000]	2,405.131 [0.000]	1,786.622 [0.000]
HT_1		-34.364 [0.000]	-33.535 [0.000]	-35.086 [0.000]
HT_2	α_i	-20.918 [0.000]	-20.597 [0.000]	-21.010 [0.000]
HT_3	$\alpha_i + \eta_i t$	-11.423 [0.000]	-11.091 [0.000]	-11.493 [0.000]
UB	δ_0	-7.168 [0.000]	-9.100 [0.000]	-10.498 [0.000]
IPS97_1	α_i	-10.788 [0.000]	-11.149 [0.000]	-10.819 [0.000]
IPS97_2	$\alpha_i + \eta_i t$	-9.0246 [0.00]	-9.310 [0.00]	-9.323 [0.00]
IPSLM_1	α_i	10.387 [0.000]	10.368 [0.000]	10.639 [0.000]
IPSLM_2	$\alpha_i + \eta_i t$	6.529 [0.000]	6.512 [0.000]	6.741 [0.000]
H_1	α_i	-1.571 [0.058]	-1.937 [0.026]	-1.028 [0.152]
H_2	$\alpha_i + \eta_i t$	2.670 [0.004]	0.656 [0.256]	2.925 [0.0002]

[1] Where applicable lag length is set at 1.
[2] LL stands for the Levin and Lin (1992, 1993) test statistics, HT stands for the Harris and Tzavalis (1999) test statistics, UB stands for the Breitung (2000) test statistic, IPS stands for the Im, Pesaran and Shin (1997) test statistics, and H stands for the Hadri (2000) test statistics.
[3] All tests are (asymptotically or exactly) distributed under the standard normal distribution.

Figure 1. Shift of the frontier from the *b*th to the *t*th period

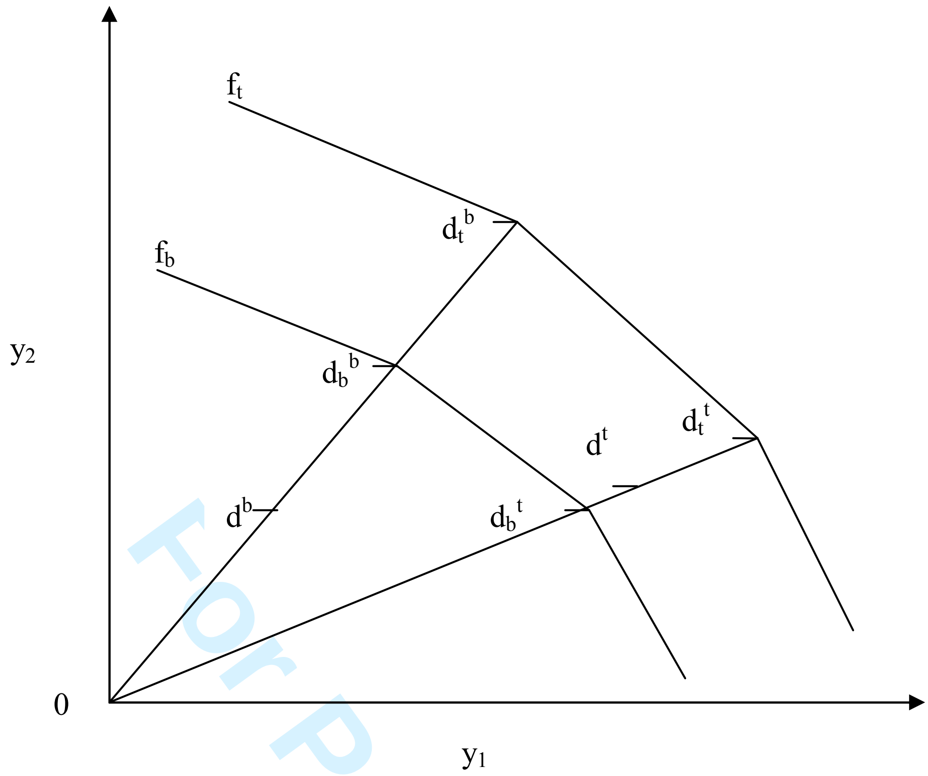

Figure 2. A cross-over among two frontiers

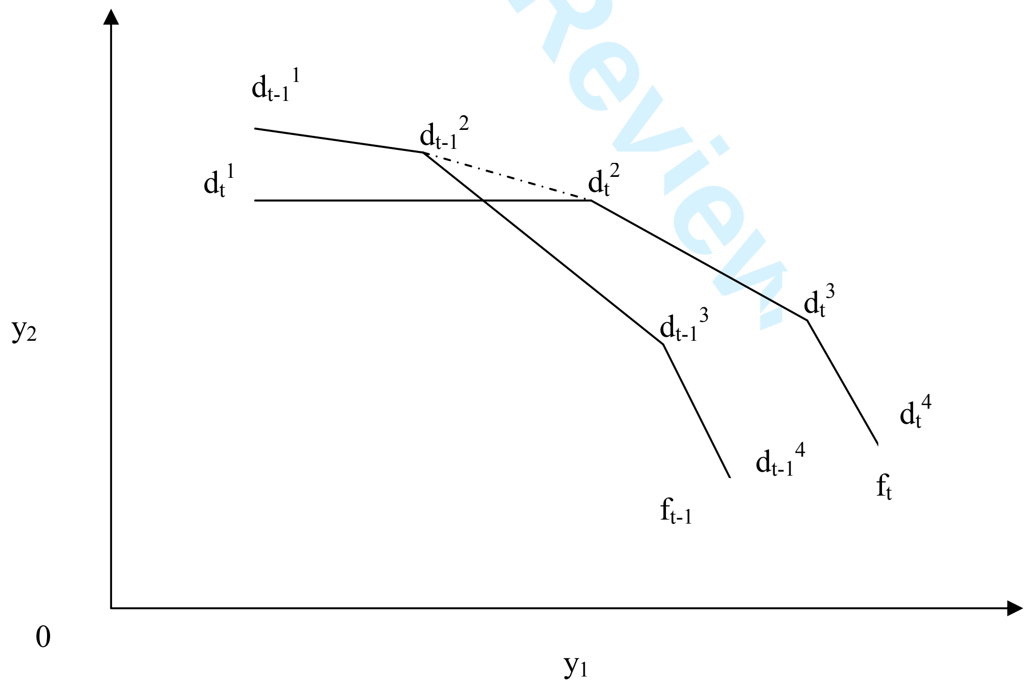

Figure 3. *TFP* Growth Rates for Nine EU countries and the US

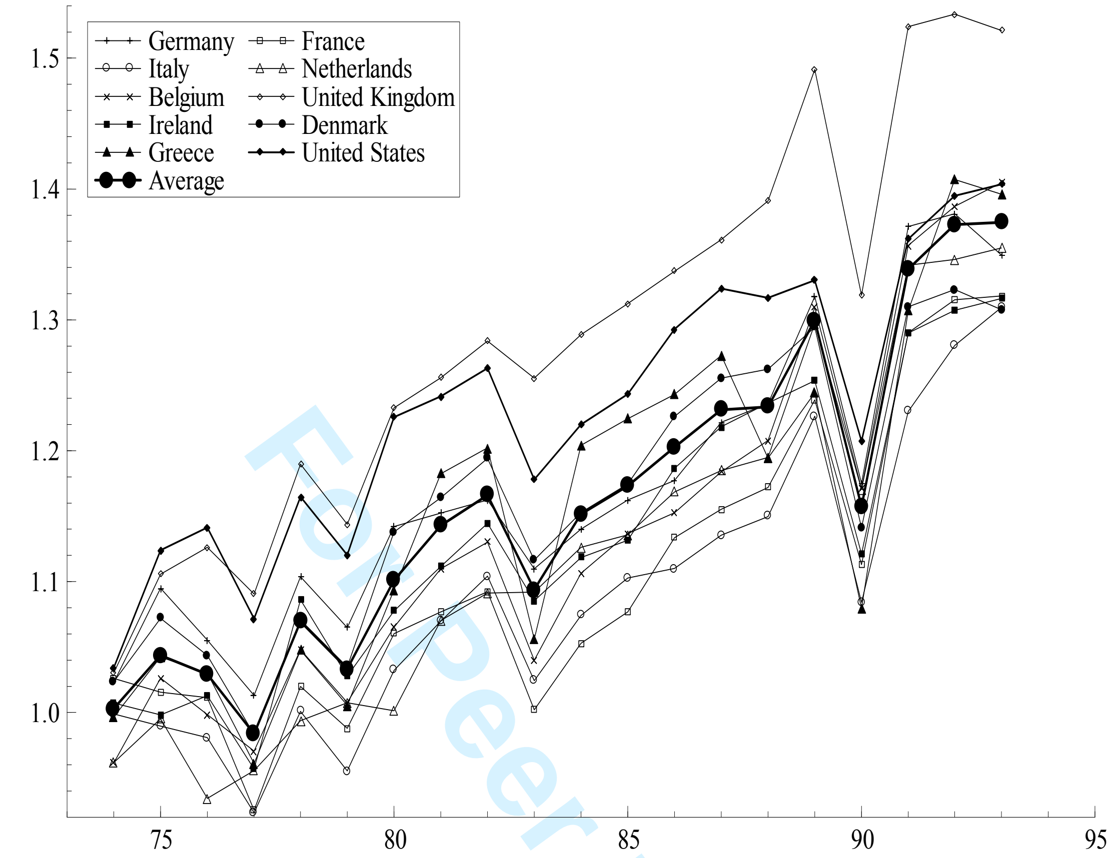

Figure 4. Standard Deviation of ln(*TFP*) for the period 1973-1993

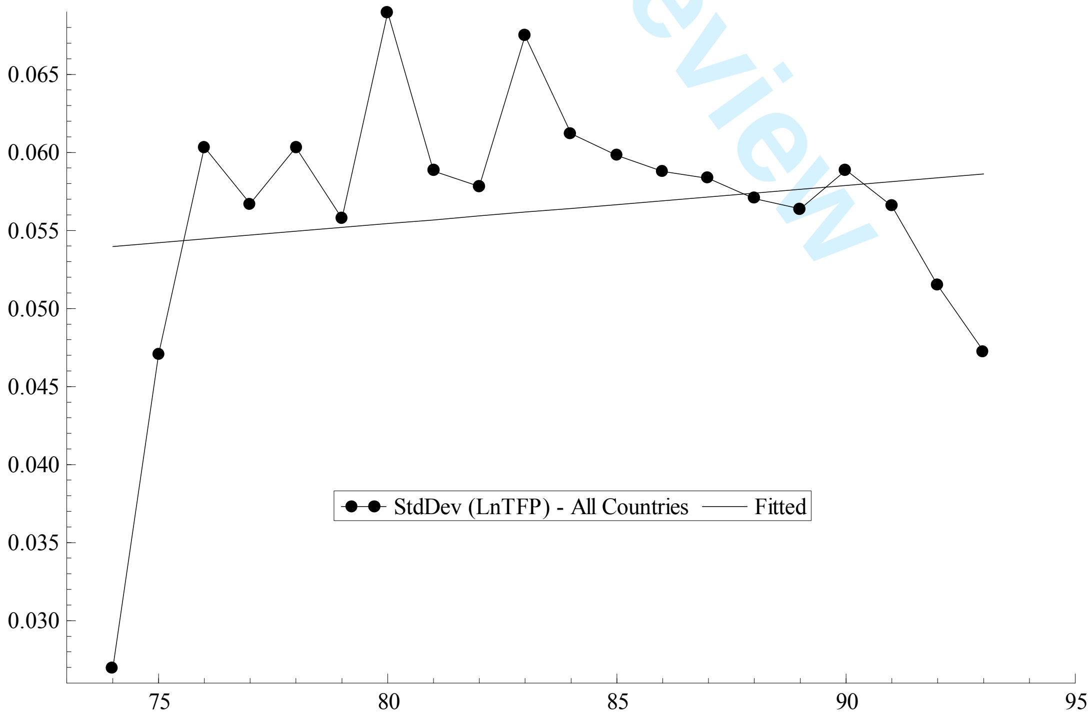

Figure 5. Standard Deviation of ln(*TFP*) for the period 1973-1982

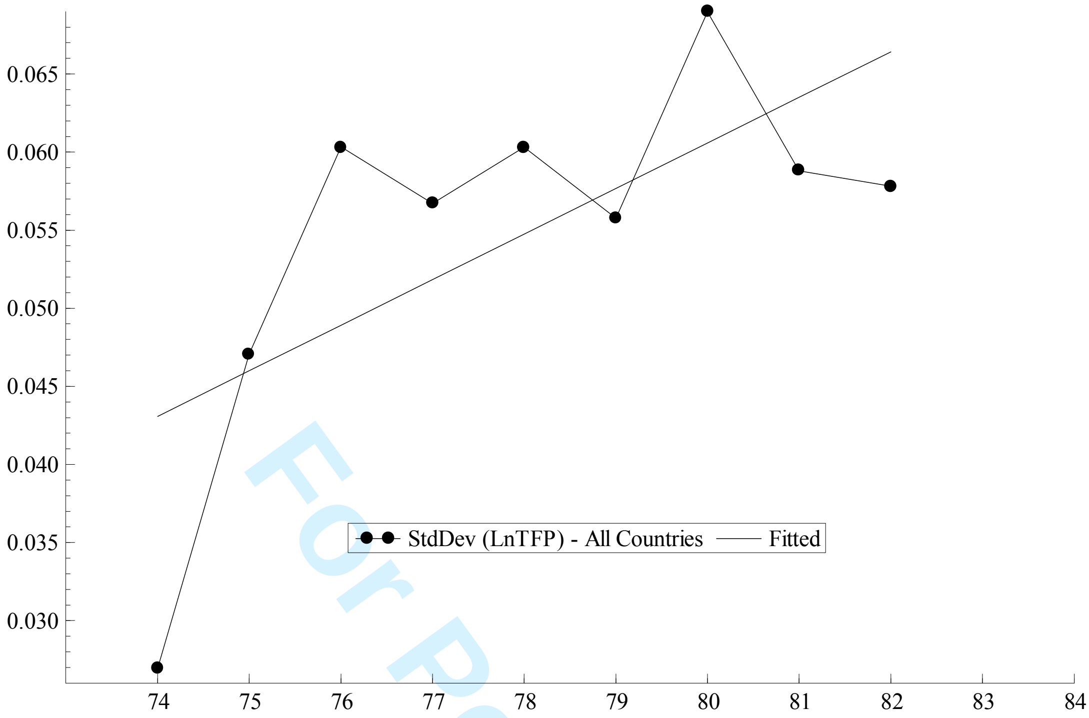

Figure 6. Standard Deviation of Ln(*TFP*) for the period 1983-1993