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POPULATION AND TECHNOLOGICAL INNOVATION: THE OPTIMAL INTERACTION ACROSS MODERN COUNTRIES

Mario Coccia

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Population and technological innovation: the optimal interaction across modern countries

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ABSTRACT: Population growth is one of the major problems facing the world today because it affects the pattern of sustainable economic growth. Theory of endogenous growth shows that total research output increases faster than proportionally with population due to increases in the size of the market, more intensive intellectual contact and greater specialization. The study here analyses the relationship between population growth and level of technological outputs (patent applications of residents), focusing on OECD countries. The study seems to show the existence of an inverted-*U* shaped curve between the growth rate of population and the patents with an optimal zone in which the average rate of growth of the population (roughly 0.3131%) is likely to be associated to a higher level of technological outputs. The policy implications of the study are that, in average, it is difficult to sustain a optimal level of technological outputs either with a low (lower than 0.2197%) or high (higher than 1.0133%) average growth rate of population (annual). In addition, the estimated relationship of technological outputs *vs.* population growth tends to be affected by decreasing returns of technological innovation to population growth.

Keywords: Population, Population Growth, Innovation, Technological Change, Demographic Change, Patents, Economic Change.

JEL Codes: O33; J10

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CONTENTS

1. INTRODUCTION

Since Thomas Robert Malthus in 1790s, several economic studies have investigated the relationship between population and economic growth (Coccia, 2007). The economic literature analyzes different perspectives of this main relationship such as: effects of population growth on per-capita income growth within a endogenous growth framework with human capital accumulation (Bucci, 2008), economic growth, population and long-run world income distribution (Chamon and Kremer, 2009), inverted-*U* curve between the growth rate of population and the growth rate of the GDP per capita (Valli and Saccone, 2011, pp. 7-9), modified Verhulst logistic model of population dynamics (Miranda and Lima, 2010; *cf.* Marchetti *et al.*, 1996), etc. Population growth is one of the major problems facing the world today, associated to resource management, environmental conservation and restoration (Austin and Brewer, 1971, p. 47). In fact, the contribution of the "Club di Roma" showed negative scenarios for worldwide economic growth due to high growth rate of population and limited natural resources (Meadows *et al*., 1972; *cf.* Campbell, 2002 for an interesting study concerning peak oil, human population dynamics and migration pressures). Although the existence of severe risks for global environment due to population growth, the system dynamics group ("Club di Roma") did not consider the main role played by technological innovation that can generate higher outputs with the same resources (also natural) and can support a sustainable and continuous economic growth over time. Models of endogenous growth show a positive association between per-capita growth and population size (Grossman and Helpman, 1991). Population growth is also a key element of semi-endogenous economic growth models (Jones, 1995; *cf.* Ehrlich and Lui, 1997). The common features of these models are decreasing returns of knowledge in the production of new knowledge and a positive population growth (Kortum, 1997). Some economic models display that research productivity increases with the income and that per-capita research productivity varies with economic and political institutions (Kremer, 1993, pp. 685-699). Kuznets (1960) claims that research productivity increases are associated to population growth since larger population generates more intensive intellectual contacts. In particular, Kuznets (1960, p. 328) states: "Population growth ... produces an absolutely larger number of geniuses, talented men, and . . . contributors to new knowledge whose native ability would be permitted to mature to effective levels when they join the labor force". In fact, many inventions and innovations are demand-induced mainly by larger population with active demographic change (*cf.* Boserup, 1981, p. 5*ff*). "Semiendogenous growth states that economic growth is correlated with the growth rate of *effort* in research and development" (Jones, 1998 as quoted by Strulik, 2005, p. 131, original emphasis). Strulik (2005) argues that economic growth depends positively on rate of human capital accumulation and positively or negatively on population growth: "In particular, long-run growth is compatible with a stable population" (p. 129). In addition, Strulik (2005, p. 131, original emphasis) relaxes the strong tie between population growth and economic growth:

> First, growth in a general two-sector R&D model is no longer semiendogenous (driven by exogenous population growth) but *fully endogenous* (driven by endogenously explained human capital accumulation). Second, growth of an economy is no longer positively tied to population growth. The correlation can be positive or negative; or, as a special intermediate case, economic growth may be independent of population growth. This result corresponds with the empirical findings of a weak, sometimes mixed, and frequently negative correlation between growth rates of population and income per capita.

Instead, LePoire (2010, p. 1303) claims that: "leadership moves from smaller states to larger states. . . because larger states have the flexibility to develop more complex organizational processes and adapt new technology".

As a matter of fact, economic literature shows that when population grows, constraints on resources may negatively affect economic growth. The typical response to such Malthusian argument is that technological innovation plays a crucial role, allowing for larger output to be generated from the same resources. Thus an interesting question arises with respect to how both population and population growth are linked with technological innovation.

The study here analyzes the interaction between population growth and technological output of countries, measured by patent applications of residents. In particular, the purpose is to wonder whether the relationship between population growth and technological output exhibits an inverted-U shaped form. This form can be similar to one utilized by Kuznets that associates income inequality and per-capita income.

The aim is to analyze the relationship and optimal zone, in which the rate of growth of population is likely to be associated with a high level of technological outputs.

Results can provide main findings to detect the complex interaction between population growth and technological change to support adequate economic growth public policies for modern countries. The paper is laid out as follows: section 2 describes the theoretical framework of the study, section 3 presents the methodology of research; section 4 shows the main results of the empirical analysis; section 5 discusses vital theoretical relationships between observed facts. Then conclusion and public policy implications are drawn in section 6.

2. THEORETICAL FRAMEWORK AND RELATED WORKS

Boserup (1965, 1981) and Lee (1988) argue that population growth, supported by existing technology, induces people to adopt new technological innovations (*cf.* also Kremer, 1993, p. 682ff). Kuznets (1960) and Simon (1977) claim that higher populations have a higher probability to create potential inventors: larger populations have proportionally more persons with new ideas. In particular, Kuznets (1960) states that:
" 'research productivity per capita increases with population since higher population allows more intensive intellectual contact and greater specialization' " (as quoted by Kremer, 1993, p. 690). Some scholars analyse the interaction between demographic and technological change, focusing on the role of technological innovations in the decline of mortality and fertility across societies (*e.g.* Boserup, 1981, p. 184ff; *cf.* Rostow, 2001). On the one hand, the decline of mortality is due to continuous advances of medical

techniques, drugs and healthcare. On the other hand, the diffusion of medical innovations for controlling fertility, such as oral contraceptive pills, it has played a critical role to decrease the population growth in advanced countries (Boserup, 1981). Models by Grossman and Helpman (1991), within the theory of endogenous growth based on the assumption of nonrivalry of technology, imply that total research output increases faster than proportionally with population due to increases in the size of the market (*see* also Kremer, 1993, p. 681 and p. 690; Young, 1993, p. 448 and p. 465, *passim*). Kremer (1993) notices that: "among technologically separate societies, those with higher population had faster growth rates of technology and population" (pp. 684-685). Diamond (1993) argues that low technological level of Tasmania region is due to its low population, whereas Kremer (1993, p. 686) points out that Belgium has lesser population than Zaire, although the former is richer than the latter not for higher inventions generated within the country, but because its human capital and institutions have the capacity to absorb the widespread technological innovation of European geo-economic area by a diffusion-orientation policy *à la* Ergas. Jones (1995) claims that growth is generated endogenously through R&D, moreover the long-run growth rate depends only on parameters that are usually exogenous, including the rate of population growth (p.759). In particular, Jones (1995) displays that if the level of resources for R&D is doubled (*e.g.* number of scientists in R&D), then the per-capita growth rate of output should double (p.760): "the economy with more researchers should growth faster" (Jones, 1995, p.778). Generally speaking, economic literature remarks a positive correlation between per-capita growth and population size (endogenous growth); research productivity may increase with income (driven by higher R&D investments); in addition, when population grows, technological change can also increase because there are larger intellectual networks and greater specialization, which raise the probability that new ideas and new innovations can be adopted (demand-induced innovations). In fact, socio-economic mechanisms that can support the diffusion of innovations are (Young, 2009, p. 1900): contagion (contact among people as for epidemics); social influence ("people adopt when enough other people in the group have adopted") and social learning ("people adopt one they see enough empirical evidence to convince them that innovation is worth adopting"). However, according to Young (1993), high population can reduce per-capita income, and if research productivity is sensitive to income (Kealey, 1996, p. 106*ff*), this may reduce total research output (as quoted by Kremer, 1993, p. 687).

Recent economic literature is also focusing on the relationship between immigration (a main determinant of demographic change) and innovation. Young (2009, p. 1899) claims that: "new ideas, products, and practices take time to diffuse, a fact that is often attributed to some form of heterogeneity among potential adopters". In fact, Hunt and Gauthier-Loiselle (2010) show the fruitful effect of immigrants on patents per capita increase and inventive activity of native in the US: "a 1 percentage point increase in immigrant college graduates' population share increases patents per capita by 9-18 percent" (p. 31*ff*). Kerr and Lincoln (2010, p. 473*ff*), instead, notice the positive correlation between increases in visas H-1B by Indian and Chinese immigrants and higher US patenting activity, suggesting the helpful effects of higher cap for immigrant visas to foster US innovation (*cf.* also Hunt, 2011, p. 421*ff*).

To sum up, the economic theory remarks that the relationship between population and technological change can provide different results, however Kremer (1993, *passim*) shows that societies with larger initial population, and without technological contacts, have faster technological change and population growth. In short, although there are controversial results, several economic studies confirm that larger populations have a higher technological change in advanced economies.

3. RESEARCH DESIGN

The study here explores the possibility of quadratic effects concerning the relationship between population growth and technological outputs. The hypothesis (*HP*) that I am going to test is:

HP: Technological outputs of countries are negatively affected both by low and high growth rate of population.

In particular, the purpose is to detect if there exists a range of population growth, which optimally supports the level of technological outputs by countries. The results can be important to understand the socio-demographic conditions that trigger, amplify or slow down the interaction between demographic and technological change within economic systems.

Econometric Model Setting

- This study analyzes the 34 countries by Organisation for Economic Co-operation and Development (OECD), which are based on governments that foster prosperity through economic growth and financial stability.
- Non-OECD members are not considered because they include economies with wide socio-economic heterogeneity. In addition, innovation of countries with low GDP per capita may not be technological and may not be patented (*e.g.* India, etc.).
- The original sample of OECD countries is cleaned by excluding countries with a population lower than 1 million (*e.g.* Luxembourg, Iceland, etc.) because they can generate misleading results.
- The study considers the data over a period of twenty years, from 1985 to 2005.
- The structural indicators of the research, by “World Development Indicators” (World Bank, 2008), are:
  - *Patent Applications of Residents per million people*: acronym *PAR.* Innovations are protected by patents, which indicate the current innovations of countries and also commercially promising inventions (*cf.* Coccia, 2010). According to Hunt and Gauthier-Loiselle (2011, p. 32): “the purpose of studying patents is to gain insight into technological progress, a driver of productivity growth, and ultimately economic growth”. In particular, the study here applies patents of residents that are applications filed through the patent cooperation treaty procedure or with a national patent office for exclusive rights for an invention – a product or process that provides a new way of doing something or offers a new

technical solution to a problem. Patents as metrics of innovation could have some limits, for instance, transaction costs and disclosure rules vary among countries. Moreover, some patented inventions may not give information on innovation and process of development of the technology (Coccia, 2010, pp. 252-253). However, patents have a fruitful influence for pathways of innovation (*cf.* Lampe and Moser, 2010) and they are the most common metrics of innovative output, mainly in advanced countries, to analyze the technological performance (*cf.* Steil *et al.*, 2002, pp. 3-22).

- *Population growth (annual %) at year t: POPGRW* (the rate of growth of midyear population from year t-1 to t, expressed as a percentage of the population).
- *Population Density (people per sq.km): POPDENS.* The study here considers the population as a group of people that are residents in a country. This population is open because can change for migration inflows and outflows.
- *Fertility Rate (%): FER*
- *GDP per capita, PPP (constant 2005 international $): GDPPC*

Remark: These variables are plausible exogenous sources of population variation.

Starting data of the sample (34 OECD member countries) have been subjected to horizontal and vertical cleaning, such as excluding some years of countries with missing values (*e.g.* in Poland, Italy, etc.) and countries with outliers. The normal distribution of variables is checked by Curtosi and Skewness coefficients, as well as by the normal Q-Q plot. As variables do not have normal distributions, a logarithmic transformation is carried out to adjust these distributions in order to apply parametric estimates, thereby the specification is based on a *log*-model. Some countries have negative population growth and it is not possible apply the logarithmic transformation, as a consequence they are not considered but this does not affect the analysis. In addition, as the direction of causality between innovative outputs and population growth (annual %) can be bidirectional (as observed by Boserup, 1981), the estimation of parameters is carried out by a two-stage last-squares method (2SLS) to remove possible problem of endogeneity. Working model equations are:

Stage I of 2SLS

In general, population growth is affected by level of economic development and cultural factors (Sheffield, 1998, pp. 55-56), population history (Ross, 1979), total population, fertility rate, etc. Econometric modelling here considers the Population Growth -annual % (POPGRW) as a function of the Gross Domestic Product per capita (GDPPC), Population density (POPDENS) and Fertility Rate (FER) of countries. The equation is:

$$LNPOPGRW_{i,t} = \beta_0 + \beta_1 LNGDPPC_{i,t} + \\ + \beta_2 \, \mathrm{LNPOPDENS}_{i,t} + \beta_3 \, \mathrm{LNFER}_{i,t} + \varepsilon_{i,t} \quad [1]$$

As the underlying data have a time series structure, models are estimated by the Prais-Winsten method, which removes the autocorrelation. In addition, the demographic variable LNPOP POP is not inserted in the

Eq.[1] because can lead to multicollinearity with LNPOPDENS and endogenous bias with respect to population.

Stage II of 2SLS

In the second stage, the dependent variable is the LNPAR (*Ln* of patent applications of residents-million people), whereas the fitted value of the equation [1] is the explicative variable.

The specification is a quadratic model:

$$LNPAR_{i,t} = \lambda_0 + \lambda_1 FIT\ LNPOPGRW_{\ i,t} + \lambda_2 FIT\ LNPOPGRW^{2}{}_{i,t} + u_{i,t} \quad [2]$$

Remark: The square of the annual growth rate of population (POPGRW) is introduced to take into account the possibility of non-linear effect, as showed by some similar economic studies concerning the relationship between population and economic growth (Valli and Saccone, 2011).

In addition, the second order polynomial function (Eq. [2]) suitable fits with scatter data. The model is estimated by Ordinary Least Square (OLS) method, using statistics software SPSS (Statistical Package for the Social Sciences).

The estimated relationship [2] is an objective function of *one* (real) variable represented by a polynomial function of an order higher than the first order. This estimated relationship (Eq. [2]) is a continuous and infinitely differentiable function, thereby it can be analyzed by differential calculus to find the optimal range of population growth (around the max value) favourable to support higher technological outputs in the long-run development of advanced countries.

4. RESULTS

Logarithmic transformations of variables show normality of distributions to apply correctly the parametric estimates.

Table 1 shows descriptive statistics of the sample based on OECD member countries.

Table 1. Descriptive statistics of OECD member countries (sample)

	Arithmetic Mean	*Std. Deviation*
Patent Applications of Residents per million people: PAR	356.09	556.40
Population growth (annual %): POPGRW	0.75	0.65
Population Total	39,752,608.72	56,935,851.85
Population Density (people per sq.km): POPDENS	139.67	135.17
Fertility Rate (%): FER	1.78	0.49
GDP per capita, PPP (constant 2005 international $): GDPPC	24,091.38	8,183.78

Table 2. Parametric estimates, results of LNPopulation growth (annual %) on predictors (The Prais-Winsten estimation method is used) - Stage I

Coefficients					Model Fit	
	Predictors	*Unstandardized Coefficients*			*Adjusted R Square (Std. Error of the Estimate)*	*Durbin-Watson*
OECD Countries		B	Std. Error	Sig.		
	LNPOPDENS	–0.115	0.030	0.0	0.402	2.176
	LNFER	3.016	0.180	0.0	(0.641)	
	LNGDPPC	0.414	0.100	0.0		
	(Constant)	–6.000	1.066	0.0		

Note: The Prais-Winsten estimation method is used. Dependent variable: LNPopulation growth (annual %)

Table 3. Parametric estimates, OLS results of LNPatents of residents (million people) on LNFitPOPGRW – Quadratic Log model - Stage II

Coefficients						Model Fit	ANOVA
	Predictors	*Unstandardized*				*Adjusted R Square (Std. Error of the Estimate)*	*Fisher test (sign.)*
		B	Std. Error	T	Sig.		
OECD Countries	Fit LNPOPGRW	–0.836	0.118	–7.065	0.0	0.093 (1.410)	26.120 (0.000)
	Fit $LNPOPGRW^2$	–0.360	0.056	–6.409	0.0		
	(Constant)	4.903	0.083	59.144	0.0		

Note: Dependent variable: LNPAR; The independent variable is FIT for LNPOPGRW from stage I

Bivariate correlations show that Patent applications of residents per million people (PAR) have a negative association (significant at the 0.01 level, 2-tailed) with population growth rate (–0.29). Partial correlation (control variable GDPPC) between PAR and POPGRW is also negative (*r*= –0.08); in this case the association between variables is not confounded by economic wealth of nations.

Instead, the correlation is positive between PAR and GDPPC (*r*=+0.74; *cf.* Coccia, 2010).

Table 2 and 3 show the estimated relationships of OECD countries by 2SLS.

In short, the parametric estimates of models are unbiased and the significance of the coefficients of equations is good.

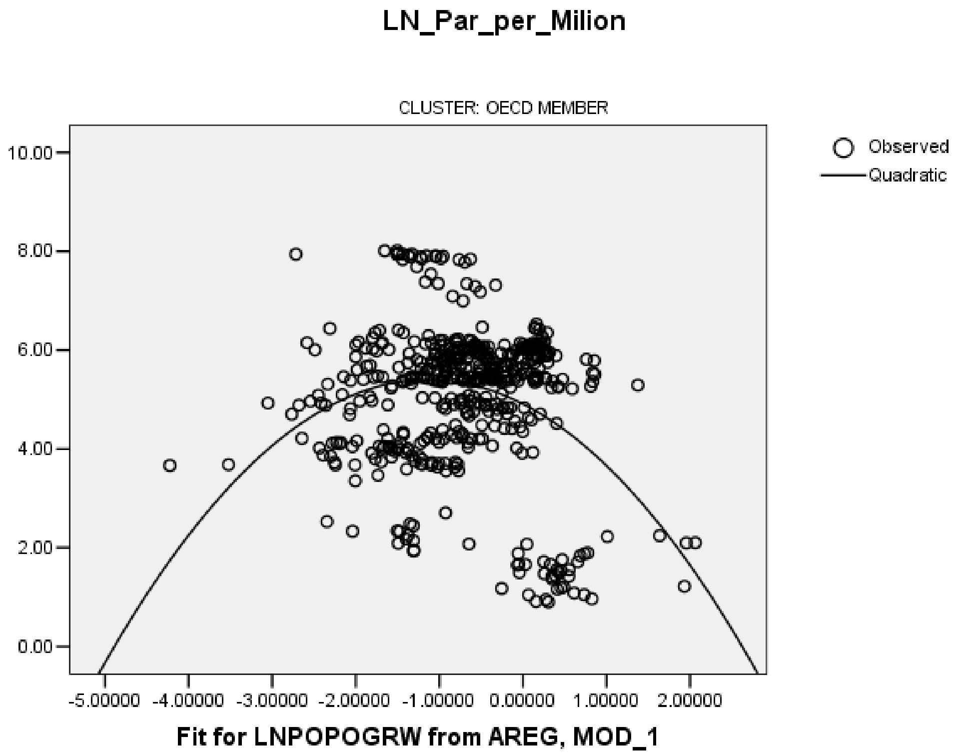


Figure 1: LNPatent applications by residents-million people (dependent variable) on Fit for LNPOPGRW based on OECD member countries

Figure 1, based on estimated relationship of table 3, shows an inverted-*U* curve.

Vital results of this empirical evidence validate the hypothesis. It seems that there exists an inverted-U curve representing the empirical relationship between population and technological growth.

In other words, estimated relationship in table 3 (represented in fig.1) suggests that countries with low and high population growth rates are characterized by lower pace of technological outputs. This estimated relationship also seems to show some decreasing returns of technological outputs to Population growth-annual % beyond a rate of the population growth (% annual) of roughly 1%.

Of course, the estimated U-shaped curve of this study differs from various versions of Kuznets' curve both for variables applied and for positions on the axes.

In order to determine the range of population growth that optimally supports technological outputs (PAR), the maximum of the estimated Eq. [2] (in table 3) is calculated:

Let:

$$LNPAR_{i,t} = \lambda_0 + \lambda_1 FIT\ LNPOPGRW_{i,t} + \lambda_2 FIT\ LNPOPGRW^2_{i,t} + u_{i,t}$$

$$LNPAR_{i,t} = 4.903 - 0.836 FIT\ LNPOPGRW_{i,t} - 0.360 FIT\ LNPOPGRW^2_{i,t} + u_{i,t}$$

if y=LNPAR and h= Fitted LN Population growth (annual %)

Necessary condition to maximize is:

$$\frac{dy}{dh} = y'(h) = -0.836 - 0.72h = 0$$

Table 4 – Comparison considering three clusters of rate of Population growth (% annual) based on OECD countries

Percentile	<25	25-75	>75
	Range of Population Growth (% Annual)		
Variables (Arithmetic Mean)	<0.2197	0.2197% to 1.0133% *	>1.0133
Patent Applications of Residents per million people: PAR	274.9	381.3	210.0
Population growth (annual %): POPGRW	–0.1	0.5	1.6
Population Total	25,211,960	32,858,655.3	46,509,004.7
Population Density (people per sq.km): POPDENS	137.0	156.7	78.5
Fertility Rate (%): FER	1.40	1.7	2.2
GDP per capita, PPP (constant 2005 international $): GDPPC	19,073.6	26,285.8	23,420.1

* Optimal range of population growth for OECD countries favourable to technological outputs.

The first derivative equal to 0 gives:

$y'(h) = 0$

$h = -1.161 \in \Re$ (the set of real numbers),

then

Exp (h)= Population growth (% annual) = 0.3131 Population growth % annual (*Max*).

If we split the distribution considering data of the 25 percentile of the distribution (0.2197% average annual rate of population growth); from 25 percentile to the 75 percentile (≥0.2197% to 1.0133%), above the 75 percentile (>1.0133% annual), results show that population growth (annual %) in the optimal intermediate zone [0.2197% to 1.0133%], which includes the optimal rate of the population growth of 0.3131 (% annual), should be favourable to technological outputs: *i.e.* PAR per million people is higher, about 381 units (see Tab.4). Low (lower than 0.2197%) and high (higher than 1.0133%) of POPGRW could hamper technological outputs. In fact, average values of PAR are lower than optimal zone (*cf.* Tab. 4).

This empirical evidence confirms the epistemological stance: the U-shaped curve between growth rate of population and technological outputs (patent applications of residents - million people). In addition, there exists a range of population growth from 0.2197% to 1.0133% -annual favourable to support technological output growth.

5. DISCUSSION AND INDUCTIVE THEORETICAL IMPLICATIONS

Results show that Population growth (annual %) seems to support technological outputs, but higher rate of population growth can also hamper the production of technological outputs due to decreasing returns of technological innovation to population growth (annual %). Figure 2 shows the inverted-U curve based on arithmetic mean of variables over time with four types of countries that pinpoint a different behaviour based on the interaction between population growth and technological outputs. Figure 3 displays a theoretical curve with these different types of countries.

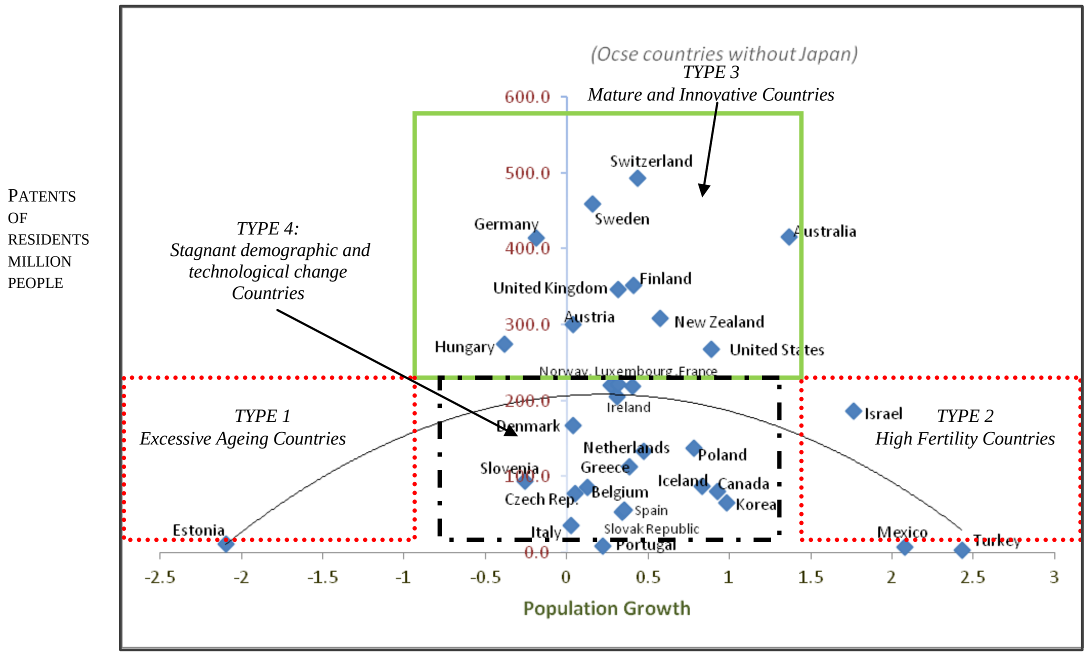


Figure 2: Inverted-U Curve between the population growth rate and the Patents (million people) –arithmetic mean over time

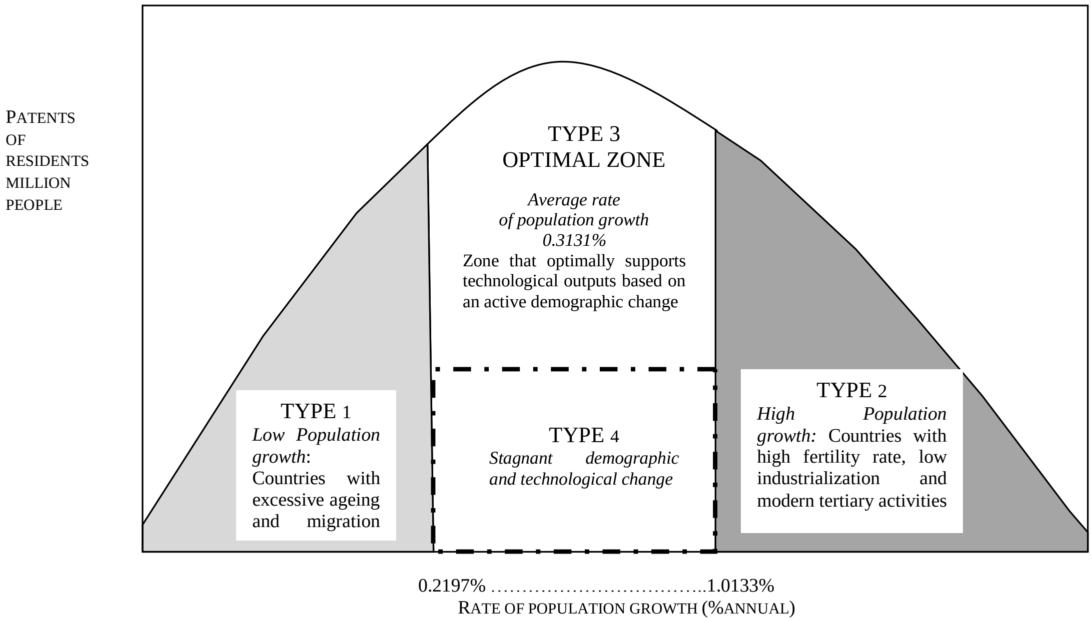


Figure 3: Types of countries according to effects of the population growth on technological outputs

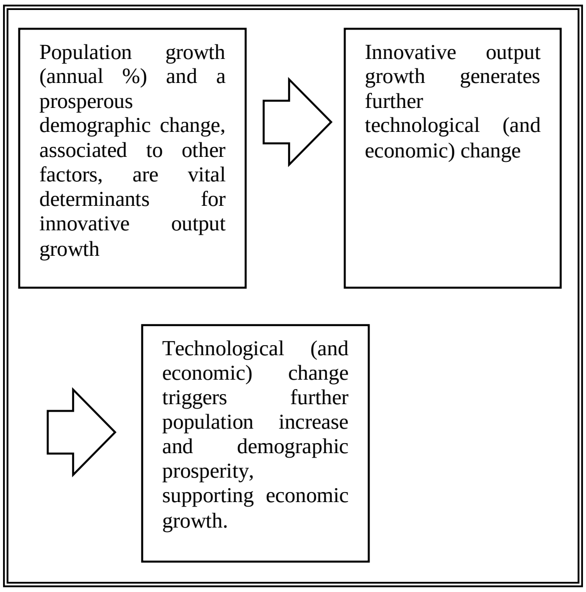
Results show that there exists an inverted-U curve, similar in shape to Kuznets's curve, between the growth rate of population and technological outputs.

The relationship between observed facts can provide two main inductive theoretical implications concerning the co-evolution of population growth and technological outputs.

On the one hand, when population grows, higher populations have a higher probability to create potential inventors since there are proportionally more persons with new ideas. In addition, the growth in output favours the development of demand-induced inventions and innovations. This is because larger intellectual networks, together with greater specialization, raise the probability that new ideas and new innovations can be introduced and adopted. This argument can be rooted in the theory of population-push (Boserup,1965; cf. Simon, 1981).

The basic linkages can be schematically represented by the following inductive schema 1 Phase:

1. *Phase*

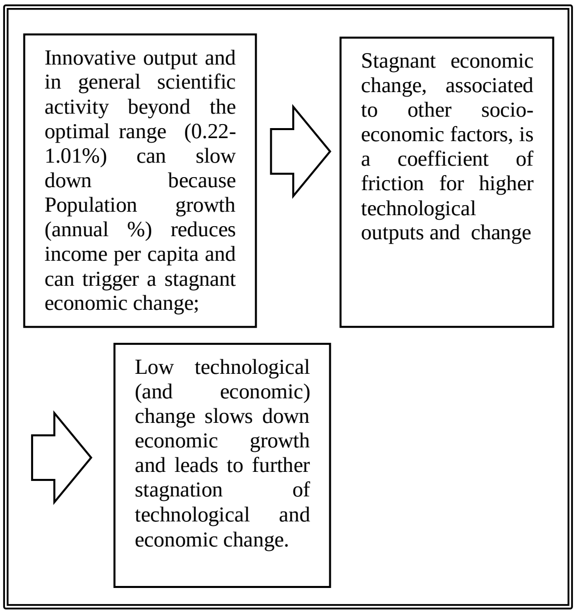


Phase 1 creates a virtuous circle for technological and demographic growth. United States of America is a main historical example (Steil et al., 2002, Chps. 2-3).

On the other hand, research productivity may increase with income but high population can reduce per-capita income, and if research productivity is sensitive to income, this can reduce total research output. In addition, the incentives to introduce new innovations may become smaller when income grows as the result of previous innovation. Hence, higher population might decrease research productivity by increasing duplication of effort.

In this case, the economic system may degenerate in functional inconsistencies. This second phase can be summarized through the inductive schema 2 Phase:

2. *Phase*



This *vicious circle* generates negative effects for technological and economic change of countries.

Remark: Theoretical models able to explain the main sources of these nonlinearities of the estimated relationship are described by Kremer (1993) for research productivity as a function of technological level (pp. 689-690) and for research productivity as a function of population (pp. 690-692).

The results are the foundation for some economic behaviour of countries according to the interaction between population growth and technological outputs (*see* figure 2-3):

1) *Excessive ageing countries (TYPE 1: left side of estimated curve)*. Countries with low population growth (lower than 0.2197% annual) have population total, GDP per capita and PAR lower than countries located in the upper central part of the estimated curve (Figs.2-3; *cf.* Tab. 4). The stagnant demographic change (due to excessive ageing and migration outflows) associated to lower industrialization, modern service sector, and a not developed national system of innovation is factor of friction for technological outputs. The ageing population of these countries leads to higher public and private economic resources on pensions and healthcare services, rather than R&D investments that can support technological outputs (Coccia, 2012). Moreover, old-age people behave differently from younger people: they tend to consume more services and prefer to invest their savings in low-risk financial assets rather than high-risk productive investments, which may support fruitful patterns of innovations. These countries can be represented by Estonia, Slovenia, etc.
2) *High fertility countries (TYPE 2: Right side of estimated curve)*. Countries with high rate of population growth (higher than 1.0133% annual), driven by a high fertility rate (1.97% annual; *cf.* Sato *et al.*, 2008) have GDP per capita and PAR lower than countries located in the upper central part of the estimated curve (Figs. 2-3; *cf.* Tab. 4). These countries have also low industrialization and modern tertiary activities such that educated people can have difficulty in finding an adequate employment; this hampers the development of human capital that can support patterns of technological innovation. Because of high unemployment rate, these countries have also high migratory outflows towards richer countries. The national system of innovation is not well developed. These countries have limited financial resources to support higher education and R&D intensity (Coccia, 2009; 2012). These conditions, associated to imperfect capital markets, can hamper real investments and R&D investment by business enterprises, main drivers of the patenting activity and, in general, of the patterns of technological innovation. These countries can be represented by Turkey, Mexico, etc.
3) *Mature and innovative countries (TYPE 3 IN THE OPTIMAL ZONE: Upper central part of the estimated curve)*. Rich mature countries with average rate of population growth equal to roughly 0.3131% annual, a high population density and GDP per capita (see table 4). These countries have a higher average number of patents in comparison to countries with high and low average rate of population growth (type 1, 2 and 4). The determinants of these higher technological performances are due to an efficient national system of innovation,

driven by high public and private investment in R&D (Coccia, 2009), a developed industrial structure, supported by immigration inflows, a modern tertiary sector, a higher democratization that lays the foundations for a good economic governance (Coccia, 2010) and financial stability of the economic system (Coccia, 2012). Current economic behaviour of these countries persists in a leadership concerning patterns of technological innovation worldwide.

4) *Stagnant demographic and technological change countries (TYPE 4: Lower central part of the estimated curve)*.These OECD countries have some difficulties to rapidly economic growth, also due to a low fertility rate and a rapid growing ageing of the population that lead to economic policies favourable to older people rather than younger people, which represent a minority in the population; these factors may lead to less dynamism in starting entrepreneurial and in innovating activities because these countries can devote limited financial resources to support higher education and R&D intensity (Coccia, 2009; 2012). Hence, the combination of institutions, cultural and socio-economic factors generates friction for higher technological performance.

5.1 General remarks on empirical analyses

The econometric model confirms, *ceteris paribus*, that an average population growth rate within the optimal zone (*e.g.* about 0.3131% annual), associated to efficient institutions and fruitful socio-cultural factors, seems to support technological outputs (patents per million people). However, the residuals of the model [Eq. 2] have a great amount of variance to be explained (Tab. 3). This strongly suggests that the estimated relationship between population growth and technological outputs is also driven by omitted factors influencing both socio-economic-demographic structure of countries and patterns of technological innovation. For instance, Spain and UK have a roughly similar average rate of population growth, but Spain has an annual average of about 57 patents per million people, whereas UK has an annual average of roughly 330 patents. I can conjecture that the different behaviour of these societies is associated to the coevolution of respective economic systems. In particular, patterns of technological innovation are also driven by a complex system of socio-economic forces, represented by: efficient national system of innovation (Coccia, 2012); fruitful University, Industry and Government Linkages (*Triple Helix*); effective and efficient institutions, higher level of democracy (Coccia, 2010); higher R&D spending by governments and business enterprises (Coccia, 2011); active industrial structure of countries (Coccia, 2012); fertilizing high-skilled immigration inflows for socio-economic system; etc. Hence, institutions, cultural factors and socio-economic attitudes can deeply differ among countries, as a consequence they can affect demographic, technological and economic trends and can generate a variety of economic and technological performances.

6. CONCLUDING REMARKS

The main findings of the study are:

- The estimated relationship shows that average population growth (annual %) is a main determinant of demographic change, which can support technological change. This demand-pull approach is based on following mechanism: more population growth leads to more demand for goods that leads to more innovation. In addition, population growth may support a larger supply of inventors and thereby innovations.
- There exists an inverted-U curve, similar in shape to Kuznets's curve, between the growth rate of population and technological outputs
- There is an optimal zone of the inverted-*U* curve in which population growth within the range [0.2197%, 1.0133% annual] is likely to be associated with higher technological outputs (*necessary but not sufficient condition)*
- Beyond the optimal range of population growth to support technological outputs, there can be decreasing returns of technological outputs to population growth (annual %).

The presence of a inverted *U*-shaped curve between the growth rate of population and the patent applications of resident (million people) seems to show that an average growth rate of population, equal to 0.3131% annual, is capable of maintaining a sustainable increase of technological outputs; in other words, a steady-state growth of the population in the range 0.2197%-1.0133% annual (intermediate zone of U-shaped curve) reduces problems associated to the extremities: excessive population growth (high fertility rate) or inadequate population growth (high ageing of population and migration outflows).

In particular, a main policy implication of the study here is that it is difficult to sustain high technological outputs either with a low (lower than 0.2197% annual) or high (higher than 1.0133% annual) growth rate of population. I believe that a fruitful political economy of growth for modern countries should also focus on a demographic change, based on a controlled and average rate of population growth within the optimal zone of inverted-*U* curve, which is a *necessary but not sufficient condition* to support technological outputs and economic growth. This *necessary condition* should be reinforced by *sufficient conditions* to support technological outputs, innovations and new firms, such as: higher rate of R&D intensity (Coccia, 2009; 2011; 2012), higher level of democracy that supports economic governance and good institutions (Coccia, 2010), efficient structure of national system of innovation and effective linkages of the *Triple Helix* mechanism (Coccia, 2012); high-skilled immigration inflows ("Brain Gain", *cf.* Boeri *et al.*, 2012; Docquier and Rapoport, 2012; Jones and Romer, 2010). Demographic prosperity of populations is also driven, *inter alia,* by immigration, which has a cross-fertilization for supporting technological outputs *(cf.* Hunt and Gauthier-Loiselle, 2010, p. 31ff; Kerr and Lincoln, 2010; Hunt, 2011). In fact, technological outputs (patents) have a higher share with a stable long-run population growth supported by: high-skilled human capital accumulation (that generates *the intellectual dividend),* capital accumulation and higher democratization (Coccia, 2010). A continuous demographic change fertilizes the socio-economic settings and has, *de facto*, fruitful effects on patterns of technological innovation and economic growth in the long run *(cf.* Coccia, 2010, pp. 260-261; Coccia, 2010a; 2010b, *passim*).

Anyhow, the relationship between Population growth and technological innovation generates intertwined links and effects. Boserup (1981, p.5ff) claims that the causality between technological and demographic change can be bidirectional, whereas Kremer (1993) states that the relationship between population and technological change as well as the effects of policies based on population growth to support the technological change can be ambiguous.

Although other socio-cultural-economic factors are important for a systematic analysis of this critical relationship between population growth and technological change across countries, partial model discussed here, focusing on two critical variables –population growth (annual %) and technological outputs (Patents) –, provides interesting results to detect basic vital interactions that support, or are damping factors, for pattern of technological innovation and economic growth. This study, of course, deserves further investigations based on more comprehensive models.

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