Center for
European,
Governance and
Economic Development Research

Discussion Papers

**Number 213 – September 2014**

# LONGEVITY AND TECHNOLOGICAL CHANGE

Agnieszka Gehringer, Klaus Prettner

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

**ISSN:** 1439-2305

# Longevity and technological change

Agnieszka Gehringer[a] and Klaus Prettner[b]

a) University of Göttingen
Department of Economics
Platz der Göttinger Sieben 3
37073 Göttingen, Germany
email: agnieszka.gehringer@wiwi.uni-goettingen.de

b) Vienna University of Technology
Institute of Mathematical Methods in Economics
Argentinierstraße 8/4/105-3
1040 Vienna, Austria
email: klaus.prettner@econ.tuwien.ac.at

**Abstract**

We analyze the impact of increasing longevity on technological progress within an R&D-based endogenous growth framework and test the model's implications on OECD data from 1960 to 2011. The central hypothesis derived in the theoretical part is that — by raising the incentives of households to invest in physical capital and in R&D — decreasing mortality positively impacts upon technological progress and thereby also on productivity growth. The empirical results clearly confirm the theoretical prediction which implies that the ongoing demographic changes in industrialized economies are not necessarily detrimental to economic prosperity, at least as far as technological progress and productivity growth are concerned.

**JEL classification:** J11; O11; O40; O41
**Keywords:** Demographic Change; Longevity; Productivity; Technological Progress; Economic Prosperity

# 1 Introduction

In the last few decades, industrialized countries have had to face substantial demographic changes. In the OECD, the life expectancy at birth has increased from 67 years in 1960 to 80 years in 2011, while the total fertility rate (TFR) has declined over the same time frame from 3.2 children per woman to 1.8 children per woman (World Bank, 2014). In addition, the projections of the World Health Organization (WHO, 2012) suggest that in Europe the proportion of the population aged 65 and above will almost double over the coming decades, increasing from 14% in 2010 to 27% in 2050. These demographic developments have attracted considerable attention not only among the scientific community, but also in the public debate: while The Economist (2004) predicts that "Europe's rapid ageing will inflict economic pain", Peterson (1999) even states that aging is a "threat more grave and certain than those posed by chemical weapons, nuclear proliferation, or ethnic strife". Even less alarmist economists and commentators broadly share some substantial concerns: the ongoing increase in the ratio of retirees to working-age population is expected to undermine the fiscal sustainability of social security systems and pension schemes (see for example Gertler, 1999; Gruescu, 2007; Bloom et al., 2010); savings and investment rates decline when the members of larger, older cohorts retire and start to run down the assets they accumulated in the past (cf. Mankiw and Weil, 1989); and population aging might undermine the innovative capacity of a society because older individuals are seen to be less inclined to use new technologies than young ones (cf. Canton et al., 2002; Borghans and ter Well, 2002, with the latter summarizing the relevant literature).

We aim to contribute to this debate by explicitly analyzing the extent to which increasing longevity impacts upon technological progress and productivity growth. Our contribution therefore relates most closely to the R&D-based growth literature that studies the determinants of technological progress and productivity growth as equilibrium market outcomes resulting from the interaction of utility-maximizing individuals and profit-maximizing firms.[1] To analyze our research question from a theoretical perspective, we follow Kuhn and Prettner (2012), Prettner and Trimborn (2012), and Prettner (2013) in proposing a framework of R&D-based endogenous economic growth according to Romer (1990) with a demographic structure of overlapping generations in the spirit of Blanchard (1985). Our main theoretical finding suggests that increasing longevity positively affects technological progress and therefore productivity growth. Intuitively, a decrease in the rate of mortality implies that households expect to live longer and therefore they discount the

---

[1] See, for example, Romer (1990), Grossman and Helpman (1991), Aghion and Howitt (1992), Jones (1995), Kortum (1997), Peretto (1998), Segerström (1998), Young (1998), Howitt (1999), Funke and Strulik (2000), Strulik (2005), Bucci (2008), Strulik et al. (2013), and many others. Note that in frameworks with diminishing returns to capital, the effects of population aging on per capita output growth can only be transient (see Solow, 1956; Cass, 1965; Diamond, 1965; Koopmans, 1965; Gruescu, 2007). For studies that analyze the effects of demographic change outside the R&D-based growth literature, see, for example, de la Croix and Licandro (1999, 2013), Reinhart (1999), Boucekkine et al. (2002, 2003), Kalemli-Ozcan (2002, 2003), Zhang and Zhang (2005), and Heijdra and Mierau (2010, 2011, 2012). For two recent interesting contributions regarding the theoretical effects of aging in a framework with directed technical change see Heer and Irmen (2009) and Irmen (2013).

future less heavily. As a consequence, aggregate savings rise, exerting downward pressure on the long-term market interest rate. The effect that population aging is accompanied by an increase in savings and by a declining interest rate is an established finding in the literature. Krueger and Ludwig (2007) show in an Overlapping Generations model that, in industrialized countries, the demographic transition toward a longer living population exercises a downward pressure on the rates of return on capital. Analogously, Bloom et al. (2003) demonstrate that greater life expectancy leads to higher savings rates at every age. Since the expected profits of R&D investments are discounted with the market interest rate, the profitability of R&D rises. This implies that more resources are devoted to R&D activities with a positive impact upon technological progress and productivity growth.

We empirically test and confirm the central theoretical prediction by relying on a panel dataset for 22 OECD countries observed over the period from 1960 to 2011. Our estimates suggest that a 10% decrease in the death rate leads to approximately a 1% increase in the TFP index and a 1.7-2% increase in labor productivity. To the extent that the death rate was decreasing at an average rate of 1.3% in our OECD sample, increasing longevity contributed to an annual improvement in TFP by 0.13 percentage points and in labor productivity by 0.2-0.3 percentage points. These results are remarkably robust to the application of different estimation techniques, the introduction of additional control variables, and different ways of expressing the dependent variable, with only small variations in the magnitude of the estimated effect among the different specifications.

Our findings contribute to the ongoing debate on whether an expansion of the individual lifetime horizon has a positive or a negative effect on economic growth. On the one hand, Acemoglu and Johnson (2007, 2014) provide empirical evidence indicating that improvements in life expectancy reduced economic growth as measured in terms of GDP per capita and GDP per working age population. This contrasts with the findings of Weil (2007) and Lorentzen et al. (2008), who find that countries with better health conditions and thus greater longevity exhibit faster economic growth. In attempts to clarify this issue, Aghion et al. (2011) and Bloom et al. (2014) provide conceptual and methodological explanations for the results of Acemoglu and Johnson (2007). In particular, they argue that the negative relationship between improved health and economic growth in the period 1960-2000 might be due to the omission of the initial health condition from the estimation. Consequently, the observed significant negative coefficient of life expectancy might not emerge because improvements in the health conditions of the population have a detrimental effect on economic growth, but because countries with better initial health conditions experienced slower gains in terms of population health over the following decades. Acemoglu and Johnson (2014) in turn suggest that the results reported by Bloom et al. (2014) are driven by the fact that the inclusion of initial health prevents them from applying a suitable panel data framework. Cervellati and Sunde (2011) provide reconciliation based on the presence of non-monotonic effects in the estimations of Acemoglu and Johnson (2007). In a Malthusian setting (prior to the demographic transition), increasing life expectancy indeed raises population growth and thereby reduces per capita income growth.

However, in the modern growth regime (after the demographic transition), increasing life expectancy leads to a reduction in fertility and thereby contributes to a slowdown in population growth and a rise in economic growth. By splitting the sample of Acemoglu and Johnson (2007) into pre-transitional and post-transitional countries, Cervellati and Sunde (2011) show that the link between life expectancy and economic growth is likely to be negative in the former, and positive in the latter.

Since we focus on OECD countries, both issues, the convergence of health and the non-linearities due to different stages in the demographic transition, are much less of a concern. This allows us to apply panel data estimation techniques without including initial health and without splitting the sample to take into account the differential effects of longevity in a pre-transitional and in a post-transitional environment. Furthermore, whereas the aforementioned studies focus on the impact of increasing life expectancy on economic growth, we aim to complement the discussion by focusing on the relationship between longevity and an important determinant of long-run economic growth, namely, technological progress. Doing so allows us to abstract from complicated interactions with other mechanisms by which demography affects economic growth directly, like physical and human capital accumulation, Malthusian dynamics, and changes in dependency ratios. This, of course, also has the drawback that we are unable to conclude that any particular effect of longevity on technological progress will necessarily feed through to economic growth as such. For example, it could very well be the case that the negative effect of rising longevity on the fiscal balance of social security systems and the accompanying increases in social security contributions and/or taxes even overcompensate for the positive effect of increasing longevity on productivity growth.

The paper is structured as follows. Section 2 presents the theoretical framework of R&D-based economic growth with overlapping generations. Section 3 is dedicated to our empirical analysis by means of (dynamic) panel methods. Finally, Section 4 concludes.

## 2 Longevity and technological change: theory

### 2.1 Basic assumptions

Consider a modern knowledge-based economy with three sectors in the vein of Romer (1990): final goods production, intermediate goods production, and R&D. Two production factors, capital and labor, are used in these sectors; the former is converted into machines in the intermediate goods sector and the latter can be subdivided into "workers" in the final goods sector and "scientists" in the R&D sector. Scientists develop the blueprints for machines in the R&D sector, capital and blueprints are used to produce machines in the intermediate goods sector, and workers and machines are used to produce consumption goods in the final goods sector.

In contrast to the representative agent assumption on which the Romer (1990) framework relies, we assume the following demographic structure (see Blanchard, 1985; Heijdra and van der Ploeg, 2002; Prettner, 2013): At each point in time ($t$), different cohorts that are distinguishable by their date of birth ($t_0$) are alive. A cohort consists of a measure $L(t_0, t)$ of individuals each of whom inelastically supplies one unit of labor to the labor market. For the sake of analytical tractability, we assume that individuals face a constant risk of death, which we denote by $\mu$ and which determines an individual's longevity. Due to the law of large numbers, $\mu$ also refers to the fraction of individuals who are dying at each instant. We follow Romer (1990) and assume that the population size stays constant. This implies that the death rate is equal to the birth rate, which is tantamount to the period fertility rate in such a setting. Consequently, changing longevity affects the *period* fertility rate but leaves the *cohort* fertility rate and hence households' fertility *decisions* unaffected (see Kuhn and Prettner, 2012, for formal proof).

## 2.2 Consumption side

Suppressing time subscripts, an individual's discounted stream of lifetime utility can be written as

$$u = \int_{t_0}^{\infty} e^{-(\rho+\mu)(\tau-t_0)} \log(c) d\tau, \tag{1}$$

where $c$ denotes individual consumption of the final good and $\rho > 0$ is the subjective time discount rate, which is augmented by the mortality rate $\mu > 0$ because, as compared with the infinitely-lived representative agent setting, somebody who is facing a positive risk of death is less inclined to postpone consumption to the future. Following Yaari (1965), individuals save by investing in actuarial notes of a fair life insurance company. Consequently, the evolution of individual wealth is given by

$$\dot{k} = (r + \mu - \delta)k + \hat{w} - c, \tag{2}$$

where $k$ denotes the individual capital stock, $r$ refers to the rental rate of capital, $\delta > 0$ is the depreciation rate, and $\hat{w}$ refers to non-interest income consisting of wage payments and dividends. Utility maximization implies that the optimal consumption path of an individual belonging to a certain cohort is characterized by the individual Euler equation

$$\frac{\dot{c}}{c} \quad = \quad r - \delta - \rho, \tag{3}$$

stating that consumption growth is positive if and only if the interest rate $(r - \delta)$ exceeds the time discount rate ($\rho$). The interpretation is straightforward: individuals only save if the financial sector (as represented by the life insurance company) is able to offer an interest rate that over-compensates their impatience. Since saving means consuming less today and more in the future, an increase in savings is associated with an increase in consumption growth.

### 2.3 Aggregation

Individuals are heterogeneous with respect to age. Older individuals have had more time to build up positive assets in the past and they are therefore richer and can afford more consumption. To obtain the law of motion for *aggregate* capital and the *economy-wide* ("aggregate") Euler equation, we apply the following rules to integrate over all the cohorts alive at time $t$ (cf. Blanchard, 1985; Heijdra and van der Ploeg, 2002):

$$K(t) \equiv \int_{-\infty}^{t} k(t_0,t)L(t_0,t)dt_0, \tag{4}$$

$$C(t) \equiv \int_{-\infty}^{t} c(t_0,t)L(t_0,t)dt_0, \tag{5}$$

where we denote aggregate variables by uppercase letters. After applying our demographic assumptions, we can rewrite these rules as

$$C(t) \equiv \mu L \int_{-\infty}^{t} c(t_0,t)e^{\mu(t_0-t)}dt_0, \tag{6}$$

$$K(t) \equiv \mu L \int_{-\infty}^{t} k(t_0,t)e^{\mu(t_0-t)}dt_0 \tag{7}$$

because, in the case of a constant population size ($L$), each cohort is of size $\mu L e^{\mu(t_0-t)}$ at time $t > t_0$. Consequently, $\int_{-\infty}^{t} \mu L e^{\mu(t_0-t)}dt_0 = L$ holds for the total population and, due to our assumption of an inelastic unitary labor supply, for the size of the workforce as well. After carrying out the calculations described in Appendix A, we arrive at the following expressions for the evolution of *aggregate* capital and *aggregate* consumption

$$\dot{K} = (r-\delta)K(t) - C(t) + \hat{W}(t), \tag{8}$$

$$\frac{\dot{C}(t)}{C(t)} = r - \rho - \delta - \mu(\rho+\mu)\frac{K(t)}{C(t)}, \tag{9}$$

where $(\rho+\mu)K(t)/C(t) = [C(t) - c(t,t)L]/C(t) > 0$ (cf. Heijdra and van der Ploeg, 2002; Prettner, 2013). Consequently, *aggregate* consumption growth is always lower than *individual* consumption growth. The reason is that at each instant, a fraction $\mu$ of older and therefore wealthier individuals die and they are replaced by poorer newborns. Since the latter can afford less consumption than the former, the generational turnover slows down aggregate consumption growth as compared with the individual consumption growth.

### 2.4 Production side

Following Romer (1990), the final goods sector produces the consumption aggregate with workers and machines as inputs according to the production function

$$Y = L_Y^{1-\alpha} \int_{0}^{A} x_i^{\alpha} di, \tag{10}$$

where $Y$ is output of the consumption aggregate, $L_Y$ are workers in final goods production, $A$ is the technological frontier, $x_i$ is the amount of machine $i$ used in the final goods production, and $\alpha \in (0,1)$ is the elasticity of final output with respect to machines. Profit maximization implies that the production factors are paid their marginal (value) products such that

$$w_Y = (1-\alpha)\frac{Y}{L_Y}, \qquad\qquad p_i = \alpha L_Y^{1-\alpha} x_i^{\alpha-1}, \tag{11}$$

where $w_Y$ refers to the wage rate paid in the final goods sector and $p_i$ to the prices paid for machines. Note that we refer to the final good as the numéraire.

The intermediate goods sector is monopolistically competitive such that each firm produces one of the blueprint-specific machines (cf. Dixit and Stiglitz, 1977). To be able to do so, it has to purchase one blueprint from the R&D sector as fixed input and employ capital as a variable production factor. Without loss of generality, we assume that one unit of capital can be transformed into one machine, that is, we have $k_i = x_i$. Free entry into the intermediate goods sector ensures that operating profits are equal to fixed costs in equilibrium such that the overall profits are zero. Operating profits are given by

$$\pi_i = p_i k_i - r k_i = \alpha L_Y^{1-\alpha} k_i^{\alpha} - r k_i \tag{12}$$

and the profit maximization of firms yields the prices of machines as

$$p_i \;=\; \frac{r}{\alpha}, \tag{13}$$

where $1/\alpha$ is the markup (cf. Dixit and Stiglitz, 1977). Note that this holds for all firms, so we can drop the index $i$ in the subsequent analysis.

The R&D sector employs scientists to discover new blueprints according to

$$\dot{A} = \lambda A L_A, \tag{14}$$

where $L_A$ denotes the employment of scientists and $\lambda$ refers to their productivity. There is perfect competition in the research sector such that firms maximize $\pi_A = p_A \lambda A L_A - w_A L_A$, with $\pi_A$ being the profit of a firm in the R&D sector and $p_A$ representing the price of a blueprint. The first-order condition of the profit maximization problem pins down the wages in the research sector to

$$w_A = p_A \lambda A. \tag{15}$$

### 2.5 Market clearing

In an interior equilibrium, the wages of final goods producers and the wages of scientists have to equalize because of perfect labor mobility. Inserting Equation (11) into Equation

(15) yields the following equilibrium condition

$$p_A \lambda A = (1-\alpha)\frac{Y}{L_Y}. \tag{16}$$

Firms in the R&D sector charge prices for blueprints that correspond to the present value of the operating profits in the intermediate goods sector. The reason is that there is always a potential entrant who is willing to pay that price due to free entry (cf. Romer, 1990). Consequently, the prices for blueprints are $p_A = \int_0^\infty e^{-[R(\tau)-R(t_0)]}\pi \, d\tau$, where the discount rate is the market interest rate, that is, $R(t_0) = \int_0^{t_0}[r(s)-\delta]\, ds$. Via the Leibniz rule and the fact that the prices for blueprints do not change along a balanced growth path (BGP), we obtain

$$p_A = \frac{\pi}{r-\delta}. \tag{17}$$

Using Equation (12), operating profits can be written as $\pi = (1-\alpha)\alpha Y/A$ such that Equation (17) becomes $p_A = [(1-\alpha)\alpha Y]/[(r-\delta)A]$. Equation (16) and labor market clearing ($L = L_A + L_Y$) imply that the amounts of labor employed in the final goods sector and in the R&D sector are, respectively,

$$L_Y = \frac{r-\delta}{\alpha\lambda}, \qquad L_A = L - \frac{r-\delta}{\alpha\lambda}. \tag{18}$$

Inserting $L_A$ from Equation (18) into Equation (14) and dividing by $A$ yields the growth rate of technology:

$$g = \lambda L - \frac{r-\delta}{\alpha}, \tag{19}$$

where the right-hand side still depends on the endogenous interest rate. From the definition of a BGP, we know that $\dot{A}/A = \dot{C}/C = \dot{K}/K = g$. Furthermore, along the BGP, the aggregate Euler equation implies the following relationship between the interest rate on the one hand and economic growth, the rate of depreciation, individual impatience, and the demographic characteristics of the economy on the other:

$$r \;=\; g + \rho + \delta + \mu(\rho+\mu)\frac{K}{C}. \tag{20}$$

This relationship can be used to substitute for the interest rate in Equation (19). In contrast to a representative agent setting, however, we still have to account for an endogenous expression, namely $K/C$. In so doing, we rewrite the law of motion of aggregate capital based upon the economy's resource constraint such that $\dot{K} = Y - C - \delta K$. Dividing by $K$ and using the relation $Y/K = r/\alpha^2$ derived in Appendix A provides the following additional equation that holds along the BGP and that can be used to pin down the relationship of aggregate physical capital to aggregate consumption $\xi := K/C$

$$g \;=\; \frac{r}{\alpha^2} - \frac{C}{K} - \delta. \tag{21}$$

We now have the three equations (19), (20), and (21) to solve for the three unknowns $g$, $r$, and $\xi$. The solutions are given by, respectively,

$$\begin{aligned}
g &= \frac{\delta - \alpha^2\delta - \alpha\rho - \sqrt{4\alpha^3\mu(\mu+\rho) + [(\alpha-1)(\alpha\delta+\delta+\alpha\lambda L) - \alpha\rho]^2} + \alpha^2\lambda L + \alpha\lambda L}{2\alpha(1+\alpha)}, \\
r &= \frac{(\alpha+1)^2\delta + \sqrt{4\alpha^3\mu(\mu+\rho) + [(\alpha-1)(\alpha\delta+\delta+\alpha\lambda L) - \alpha\rho]^2} + \alpha[(\alpha+1)\lambda L + \rho]}{2(1+\alpha)}, \\
\xi &= \frac{\delta - \alpha^2\delta + \alpha\rho + \sqrt{4\alpha^3\mu(\mu+\rho) + [(\alpha-1)(\alpha\delta+\delta+\alpha\lambda L) - \alpha\rho]^2} - \alpha^2\lambda L + \alpha\lambda L}{2\alpha^2}.
\end{aligned}$$

We can now state the central theoretical result that we aim to test empirically in Section 3.

**Proposition 1.** *Increasing longevity positively affects technological progress and productivity growth.*

*Proof.* The derivative of the growth rate ($g$) with respect to mortality ($\mu$) is given by

$$\frac{\partial g}{\partial \mu} = -\frac{\alpha^2(2\mu+\rho)}{(1+\alpha)\sqrt{4\alpha^3\mu(\mu+\rho) + [(\alpha-1)(\alpha\delta+\delta+\alpha\lambda L) - \alpha\rho]^2}}. \tag{22}$$

Since $\alpha$, $\mu$, $\rho$, $\delta$, $\lambda$, and $L$ are positive and the second term under the square root in the denominator is non-negative, we can conclude that $\partial g/\partial\mu$ is negative. The fact that a rise in longevity is tantamount to a decrease in mortality $\mu$ establishes the proof. □

The intuition for this finding is that a decrease in mortality slows down the turnover of generations. This leads to higher aggregate savings, which in turn reduce the interest rate. Due to the fact that the future profits of R&D investments are discounted with the interest rate, an increase in longevity implies a rise in the profitability of R&D investments, which spurs technological progress and productivity growth.

# 3 Longevity and technological change: empirical analysis

## 3.1 Data and variables

Our theoretical model provides a central testable hypothesis on how increasing longevity influences technological progress. In this section, we want to test this theoretical prediction empirically. Our dataset includes 22 OECD countries, for which data on the main dependent variable (productivity) are available (see Appendix C for the detailed list of countries). By focusing on these industrialized economies, we are able to overcome four central obstacles: i) the problem of strong heterogeneity in the sample, which can be a serious issue for growth regressions (Maddala and Wu, 2002; Hineline, 2008);[2] ii) the problem that demographic change has completely different implications for growth in a Malthusian regime of stagnation as opposed to a modern growth regime (see Cervellati and

---

[2] We also address the concerns regarding cross-country heterogeneity by controlling for country-specific fixed effects (Lindh and Malmberg, 1999).

Sunde, 2011); iii) the issue pointed out by Bloom et al. (2014) that unaccounted health convergence in a heterogeneous sample could be responsible for the finding of spurious effects; and iv) that less developed countries do not contribute sufficiently to an advancement of the world technology frontier to warrant their inclusion in the sample (see Jones, 2002; Keller, 2002; Ha and Howitt, 2007). We chose the longest time span possible, which resulted in 52 annual observations between 1960 and 2011.

As the dependent variable, we use the levels of the total factor productivity (TFP) index as proxied by the Solow residual. The index is provided by the European Commission's Directorate General for Economic and Financial Affairs (DG ECFIN) in its AMECO database for macroeconomic analysis.[3] Alternatively, in our robustness check, we replace the TFP variable with a measure of labor productivity as represented by the real GDP per employee [calculated as the ratio $rgdpe/emp$, with both series obtained from the Penn World Tables (PWT), version 8.0 (Feenstra et al., 2013)].

Our most important explanatory variable is the death rate taken from the World Development Indicators database (World Bank, 2014). This variable reflects the parameter $\mu$ of our theoretical model most precisely and its inverse is a reasonable approximation of longevity. Further explanatory variables include factors that have been argued to constitute important determinants of productivity: trade openness [$openk$ from the PWT, version 7.1 (Heston et al., 2012)], investment as a share of per capita GDP [$ki$ from the PWT, version 7.1 (Heston et al., 2012)], and human capital. The last variable is newly included in the PWT, version 8.0 (Feenstra et al., 2013)] and is expressed in terms of an index of years of schooling — based on Barro and Lee (2013) — and returns to education — based on Psacharopoulos (1994). In some additional specifications, we control for the contribution to productivity of the two main production inputs, labor, and capital. Labor is measured either in terms of total employment or as the average annual hours worked by persons engaged [$emp$ and $avh$, respectively, from the PWT, version 8.0 (Feenstra et al., 2013)], while the capital stock is expressed at constant 2005 prices [$rkna$ from the PWT, version 8.0 (Feenstra et al., 2013)].

To capture the long-run influence in the underlying relationships better, we use data on TFP, the death rate, and human capital in five-year intervals, starting in 1960 in our baseline estimations. To the rest of the variables, we apply a transformation into five-year non-overlapping averages, again starting in 1960, to overcome the concerns with regard to cyclical influences and to average out the noisy observations that are typical of annual data. This notwithstanding, in our robustness check, we apply alternative five-year transformations of our original data to rule out the possibility that a particular data transformation procedure could have influenced our results.

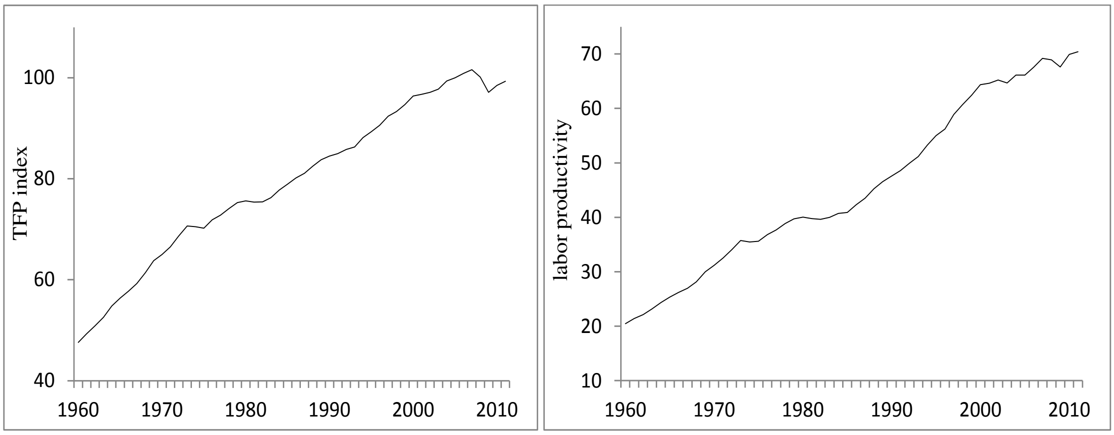
Figure 1 illustrates the development of the average TFP index and of average labor productivity for our OECD sample. A clear growth pattern is visible, with some fluctuations, in particular as a consequence of the recent economic turmoil. In one of the

---

[3] The full database is available at: `http://ec.europa.eu/economy_finance/db_indicators/ameco/index_en.htm`.

specifications, we assess whether the investigated relationship has been substantially affected by the crisis after 2007. The development of TFP and labor productivity is by and large similar for all the countries in our sample (see Figure 2 in Appendix B for more details).

Figure 1: Development of productivity in the OECD countries



Note: The mean TFP and labor productivity are calculated on the basis of 22 OECD countries (see Appendix C for the full list of countries). TFP is an index with the base year 2005. Labor productivity is defined as the real GDP per person employed in thousands of 2005 US dollars.

Source: AMECO macroeconomic database (TFP index) and PWT (labor productivity).

### 3.2 Empirical specification

Following our theoretical model, we test whether increasing longevity, as represented by a decrease in the mortality rate $\mu$, has positively affected technological progress in our sample of OECD countries. To test the underlying hypothesis, we use a dynamic specification that fully accounts for the countries' unobserved heterogeneity. Our motivation to adopt the dynamic panel data framework is twofold. From an econometric point of view, we account for the strong persistence of the productivity variable, which requires a necessary AR(1) check. From a conceptual point of view, the specification including the lagged values of productivity permits us to account for the path-dependent nature of productivity development.

To this end, we specify our empirical model in dynamic form as follows:

$$\mathrm{lnTFP}_{i,t} \quad = \quad \beta_1 + \beta_2 \mathrm{lnTFP}_{i,t-1} + \beta_3 \mathrm{ln}\mu_{i,t} + \beta_4' \mathbf{Z}_{i,t} + \theta_i + \tau_t + \epsilon_{i,t} \tag{23}$$

where $TFP_{i,t}$ is the natural logarithm of the TFP index in country $i$ at time $t$, $TFP_{i,t-1}$ is its lagged value, $\mu_{i,t}$ refers to the death rate, $\mathbf{Z}_{i,t}$ is the vector of control variables, $\beta_4'$ is a row vector of the corresponding coefficients to be estimated, $\theta_i$ and $\tau_t$ control for country-specific and time-specific fixed effects, respectively, and, finally, $\epsilon_{i,t}$ is the idiosyncratic error term. Despite the fact that our dynamic model theoretically eliminates the omitted variable bias, we still control for important country-specific characteristics that display some variability over time and that potentially influence the productivity dynamics. First, we control for the degree of international openness to trade to take into account the possibility that competition from abroad might raise the efforts of firms in the home country to increase their productivity (Bernard et al., 2006). More generally, international trade could affect the overall efficiency of an economy by enhancing specialization and by enabling access to new markets with new and advanced technologies (Grossman and Helpman, 1991). Second, we include human capital to capture the fact that better educated scientists are typically more productive (Strulik et al., 2013) or, more broadly, that a better educated workforce contributes to the development of more efficient production techniques. Third, as a robustness check, we control for the contribution to productivity coming from the two main production factors, capital and labor.[4]

### 3.3 Econometric method

The inclusion of the lagged dependent variable on the right-hand side of the specification in Equation (23) potentially generates endogeneity.[5] As a valid solution, Generalized Method of Moments estimation (GMM; see Arellano and Bond, 1991; Blundell and Bond, 1998, for the pioneering contributions on the difference and system GMM methodologies, respectively) has been suggested. This method, however, is only asymptotically efficient for samples with a small time dimension (small $T$) and a large cross-section dimension (large $N$). Consequently, it is not suited to our sample consisting of 22 countries observed over 52 years. A method proposed to deal with dynamic panel data in cases in which the GMM framework cannot be applied efficiently is the corrected least square dummy variable (LSDVC) estimator proposed by Kiviet (1995), Judson and Owen (1999), and Bun and Kiviet (2003), which was extended by Bruno (2005b) to allow for application in the case of an unbalanced panel such as the one used in the present study.[6]

To provide a better illustration of our method, suppose that we have an AR(1) autoregressive panel data model with observations that can be collected over time and across

---

[4] In our first specification, we include neither these factors nor the human capital variable. The reason is that these variables — except human capital — enter the production function directly and, thus, their influence is in principle accounted for in the estimation of the TFP indicator. This notwithstanding, it is plausible to expect that capital and labor would directly influence efficiency. The influence here is a priori unclear, depending on the quality of the stock of existing capital and the abilities of the labor force. There is a second reason for the exclusion of these three variables from the first specification, namely the potential collinearity between them and the openness variable, so first we want to assess the impact of openness on productivity separately from the other possible factors.

[5] This renders the estimation results from the standard methods, in particular, fixed-effects estimation, biased (Nickell, 1981). We also show the results from the static fixed-effects estimations and from the pooled OLS estimations to assess the direction and the extent of the bias by not accounting for the underlying autoregressive process.

[6] The LSDVC estimator has been shown to outperform other consistent estimators, such as GMM, by Anderson and Hsiao (1982) and Arellano and Bond (1991) in Monte Carlo simulations based on small samples (see Bun and Kiviet, 2003).

individuals. Such a model can be written as

$$\mathrm{y} = \alpha\mathbf{X} + \zeta\mathbf{D} + \omega, \tag{24}$$

where y is the vector of individual, time-specific observations of the dependent variable, **X** is the matrix of explanatory variables, including the lagged dependent variable, $\alpha$ refers to the corresponding vector of coefficients, **D** is the matrix of individual dummies, $\zeta$ represents the corresponding vector of individual effects, and $\omega$ is the idiosyncratic error term. The (uncorrected) LSDV estimator is then given by

$$\eta_{LSDV} = (\mathbf{X'AX})^{-1}\mathbf{X'A}y, \tag{25}$$

where **A** is the transformation matrix wiping out the individual effects. This estimator is not consistent when the lagged dependent variable enters the specification. Bun and Kiviet (2003) derive the analytical form of the bias as

$$E(\eta_{LSDV} - \eta) = c_1(T)^{-1} + c_2(N^{-1}T^{-1}) + c_3(N^{-1}T^{-2}) + O(N^{-2}T^{-2}) \tag{26}$$

with the analytical expressions for $c_1(T)^{-1}$, $c_2(N^{-1}T^{-1})$, and $c_3(N^{-1}T^{-2})$ described by Bun and Kiviet (2003), p. 147. Based on this estimation bias, Bun and Kiviet (2003) and Bruno (2005a) consider its three possible nested approximations, extended to the first ($B_1$), the first two ($B_2$), and the first three ($B_3$) terms of Equation (26).[7] Given that $B_3$ is the most comprehensive and accurate approximation (Bun and Kiviet, 2003; Bruno, 2005b), we correct for it, such that the LSDVC estimator that we use is given by

$$LSDVC = LSDV - B_3. \tag{27}$$

The correction procedure implies that, as a first approximation, the estimation has to be performed with a consistent estimator. There are three possible variants, namely the Anderson and Hsiao (1982), the Arellano and Bond (1991) and the Blundell and Bond (1998) estimators, which are, however, asymptotically equivalent. In our estimation procedure, we opt for correction with the Blundell and Bond (1998) initial estimator. As a final improvement to the standard estimation procedure, we bootstrap our standard errors. In so doing, we overcome the issue that the estimated standard errors are poor approximations in small samples, with unreliable t-statistics.

### 3.4 Results

The results for the main model as described above are reported in Table 1. Three different methods are implemented, pooled OLS (columns 1-4), the standard static fixed-effects estimator (columns 5-8) and, finally, the corrected least squares dummy variable estimator (columns 9-12). The comparison between the methods allows us to perform a better

---

[7] Precisely, $B_1 = c_1(T)^{-1}$, $B_2 = B_1 + c_2(N^{-1}T^{-1})$, and $B_3 = B_2 + c_3(N^{-1}T^{-2})$.

assessment of the direction and the extent of the bias i) by not controlling for unobserved time-invariant country characteristics and ii) by excluding the dynamic effects. Overall, the significance of the coefficient of the lagged dependent variable in columns 9-12 provides strong support for a dynamic specification.

In the first columns referring to each method, we start with a parsimonious specification, considering only the death rate and trade openness (in addition to the lagged dependent variable in the case of the LSDVC method). These two factors are significant across almost all the methods, specifications, and robustness checks. In the subsequent columns, we add other explanatory variables one by one. This permits us to detect how the basic results are affected by enlarging the set of covariates. The results clearly show that there is some variation in the magnitude but not in the direction of the estimated coefficients due to the inclusion of further variables.

Generally, according to the results reported, there is a significantly negative effect of the death rate on TFP, which confirms our theoretical findings. As the death rate declined steadily over the years considered in our sample, it contributed to the observed rise in TFP. More precisely, according to the dynamic specification, a 10% decrease in the death rate brought about an increase of around 1% in TFP. The effect estimated according to the static specification is slightly higher (around 1.3%), but it is known to be upwardly biased due to the exclusion of the dynamic effect.

In addition to the death rate, trade openness positively influenced TFP across all the specifications, which supports the view that openness to international markets raises competition, which induces firms to increase their productivity. This result is in line with the previous literature explicitly investigating the impact of trade openness on TFP (see Miller and Upadhyay, 2000; Gehringer, 2013, the latter of which contains recent evidence from a sample of developed countries). Regarding other explanatory variables, human capital did not have any significant impact on TFP, which is consistent with the previous literature (cf. Miller and Upadhyay, 2000). In a comprehensive investigation, Pritchett (2001) provides three reasons for no (or even a negative) association between increases in human capital and growth in productivity. First, a greater demand for a better educated workforce could have come in part from "socially wasteful or counterproductive activities" (Pritchett, 2001, p. 368). Second, by expanding the supply of educated labor and the stagnating demand for it, the rate of return on education could fall. The third explanation, which is probably less valid in the context of OECD countries, states that the quality of schooling could be low such that there is no positive contribution of education on skills upgrading and productivity. For employment and capital, the results are mixed. The coefficient estimates of employment are positive but insignificant under the LSDVC method, whereas they are almost always negatively significant under the static methods. The LSDVC results for capital suggest a negative impact on productivity, which is consistent with Gehringer (2014), who finds a negative impact of the current rate of investment on the manufacturing growth rate of TFP. The main explanation for this finding is the capital-saving nature of recent waves of technological progress as characterized by the substitution of both capital and unskilled labor with skilled workers (cf. Antonelli and Fassio, 2014).

Based on additional estimations, we want to corroborate the results from the baseline model. To this end, we first replace our dependent variable TFP with a labor productivity measure, expressed in terms of output per employee. The results are reported in Table 2 and confirm that the established relationship between the death rate and productivity is valid not only for total factor productivity but also, more specifically, for labor productivity. It is also worth noting that the magnitude of the effect is slightly stronger for labor productivity than for TFP. The explanation is that a lower death rate implies a better health condition of workers, which raises their productivity directly, while it has no impact on the productivity of physical capital. For the other explanatory variables we could broadly confirm the results obtained previously, with the exception of the two production factors, capital and labor. Here the signs of the coefficient estimates are reversed, with a positive sign estimated for capital and a negative sign for labor. The intuition behind this outcome is straightforward: technological contexts characterized by greater employment of physical capital are generally more skill-intensive and at the same time more productive in terms of output per worker. The contrary is the case for the employment of labor.

Table 1: Baseline results

| | POLS<br>(1) | POLS<br>(2) | POLS<br>(3) | POLS<br>(4) | FE<br>(5) | FE<br>(6) | FE<br>(7) | FE<br>(8) | LSDVC<br>(9) | LSDVC<br>(10) | LSDVC<br>(11) | LSDVC<br>(12) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *lagged* TFP | | | | | | | | | 0.741 | 0.739 | 0.722 | 0.874 |
| | | | | | | | | | (0.049)*** | (0.050)*** | (0.052)*** | (0.063)*** |
| $\mu$ | -0.129 | -0.128 | -0.131 | -0.183 | -0.115 | -0.114 | -0.176 | -0.213 | -0.106 | -0.108 | -0.118 | -0.101 |
| | (0.056)** | (0.057)** | (0.057)** | (0.047)*** | (0.068)* | (0.070) | (0.069)** | (0.055)*** | (0.037)*** | (0.038)*** | (0.035)*** | (0.036)*** |
| $TO$ | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| | (0.000) | (0.000) | (0.000)* | (0.000)** | (0.000)** | (0.000)** | (0.000)* | (0.000)* | (0.000)*** | (0.000)*** | (0.000)*** | (0.000)*** |
| $HC$ | | 0.000 | -0.000 | -0.000 | | -0.000 | 0.001 | 0.001 | | 0.001 | 0.001 | 0.002 |
| | | (0.001) | (0.001) | (0.001) | | (0.002) | (0.002) | (0.001) | | (0.001) | (0.001) | (0.001)* |
| $L$ | | | 0.019 | -0.246 | | | -0.219 | -0.236 | | | -0.316 | 0.036 |
| | | | (0.011)* | (0.027)*** | | | (0.059)*** | (0.048)*** | | | (0.038) | (0.036) |
| $K$ | | | | 0.259 | | | | 0.293 | | | | -0.128 |
| | | | | (0.023)*** | | | | (0.028)*** | | | | (0.034)*** |
| $N$ | 225 | 225 | 225 | 225 | 225 | 225 | 225 | 225 | 204 | 204 | 204 | 204 |
| country fe | no | no | no | no | yes | yes | yes | yes | yes | yes | yes | yes |
| time fe | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| $R^2$ | 0.825 | 0.823 | 0.845 | 0.856 | 0.811 | 0.811 | 0.215 | 0.800 | 0.945 | 0.941 | 0.776 | 0.575 |

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, FE and LSDVC refer to pooled OLS, fixed effects, and corrected least squares dummy variable estimations. The bootstrapped standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell-Bond estimator.

Table 2: Estimation results with labor productivity as the dependent variable

| | POLS<br>(1) | POLS<br>(2) | POLS<br>(3) | POLS<br>(4) | FE<br>(5) | FE<br>(6) | FE<br>(7) | FE<br>(8) | LSDVC<br>(9) | LSDVC<br>(10) | LSDVC<br>(11) | LSDVC<br>(12) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *lagged LP* | | | | | | | | | 0.827 | 0.829 | 0.828 | 0.646 |
| | | | | | | | | | (0.034)*** | (0.034)*** | (0.034)*** | (0.038)*** |
| $\mu$ | -0.394 | -0.362 | -0.360 | -0.158 | -0.462 | -0.457 | -0.494 | -0.161 | -0.254 | -0.254 | -0.291 | -0.293 |
| | (0.105)*** | (0.106)*** | (0.106)*** | (0.056)*** | (0.112)*** | (0.124)** | (0.121)*** | (0.064)** | (0.066)*** | (0.067)*** | (0.072)*** | (0.058)*** |
| $TO$ | 0.003 | 0.003 | 0.003 | 0.002 | 0.003 | 0.003 | 0.003 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 |
| | (0.001)*** | (0.001)*** | (0.001)*** | (0.001)*** | (0.001)** | (0.001)** | (0.001)** | (0.001)** | (0.001) | (0.001) | (0.001) | (0.001) |
| $HC$ | | 0.003 | 0.002 | 0.001 | | 0.001 | 0.002 | -0.001 | | 0.000 | 0.001 | 0.000 |
| | | (0.003) | (0.003) | (0.001) | | (0.003) | (0.003) | (0.002) | | (0.002) | (0.001) | (0.002) |
| $L$ | | | 0.020 | 0.671 | | | -0.080 | -0.628 | | | -0.084 | -0.230 |
| | | | (0.036) | (0.033)*** | | | (0.099) | (0.056)*** | | | (0.041)** | (0.063)*** |
| $K$ | | | | 0.675 | | | | 0.683 | | | | 0.162 |
| | | | | (0.026)*** | | | | (0.028)*** | | | | (0.050)*** |
| $N$ | 262 | 262 | 262 | 262 | 262 | 262 | 262 | 262 | 238 | 238 | 238 | 238 |
| country fe | no | no | no | no | yes | yes | yes | yes | yes | yes | yes | yes |
| time fe | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| $R^2$ | 0.621 | 0.633 | 0.639 | 0.896 | 0.611 | 0.616 | 0.545 | 0.866 | 0.962 | 0.962 | 0.873 | 0.904 |

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, FE and LSDVC refer to pooled OLS, fixed effects, and corrected least squares dummy variable estimations. The bootstrapped standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell-Bond estimator.

The second set of robustness checks refers to the possible influence of the recent financial and economic crisis. As the data description showed, the development of productivity was affected by the crisis. This could potentially have repercussions for the underlying relationships that we estimated. We therefore exclude the last observation from our sample (corresponding to the years 2008-2011) and report the results in Table 3. The direction of the influence of the death rate remains the same as in the baseline estimations. The magnitude of the influence, however, is slightly higher, by approximately 0.03 percentage points, suggesting that the years of the crisis were associated with sluggish productivity growth, despite the increasing longevity.

Finally, we assess the sensitivity of our results in response to a modification of the averaging procedure with respect to our TFP measure. To obtain the results displayed in Table 4, we used five-year non-overlapping averages instead of the TFP series in five-year intervals. Qualitatively, in terms of the sign and the significance of the coefficient estimates, the results are robust to this different measurement of productivity. However, the coefficient estimates are slightly closer to zero in the case of the alternative specification.

Table 3: Estimation results excluding the crisis

| | POLS (1) | POLS (2) | POLS (3) | POLS (4) | FE (5) | FE (6) | FE (7) | FE (8) | LSDVC (9) | LSDVC (10) | LSDVC (11) | LSDVC (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *lagged* TFP | | | | | | | | | 0.740 | 0.740 | 0.728 | 0.888 |
| | | | | | | | | | (0.038)*** | (0.039)*** | (0.041)*** | (0.058)*** |
| $\mu$ | -0.147 | -0.149 | -0.152 | -0.211 | -0.144 | -0.141 | -0.189 | -0.237 | -0.138 | -0.142 | -0.146 | -0.127 |
| | (0.062)** | (0.063)** | (0.063)** | (0.051)*** | (0.078)* | (0.078)* | (0.060)*** | (0.079)** | (0.055)** | (0.055)** | (0.056)*** | (0.058)** |
| $TO$ | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| | (0.000) | (0.000) | (0.001) | (0.000)* | (0.001)* | (0.001)* | (0.001) | (0.000)* | (0.000)** | (0.000)** | (0.000)** | (0.000)** |
| $HC$ | | -0.000 | -0.001 | 0.000 | | -0.001 | 0.000 | 0.001 | | 0.002 | 0.002 | 0.002 |
| | | (0.001) | (0.001) | (0.001) | | (0.002) | (0.002) | (0.001) | | (0.001) | (0.001) | (0.001) |
| $L$ | | | 0.021 | 0.263 | | | -0.191 | -0.280 | | | -0.037 | 0.044 |
| | | | (0.013) | (0.028)*** | | | (0.065)*** | (0.050)*** | | | (0.047) | (0.051) |
| $K$ | | | | 0.278 | | | | 0.334 | | | | -0.137 |
| | | | | (0.025)*** | | | | (0.030)*** | | | | (0.043)*** |
| $N$ | 203 | 203 | 203 | 203 | 203 | 203 | 203 | 203 | 182 | 182 | 182 | 182 |
| country fe | no | no | no | no | yes | yes | yes | yes | yes | yes | yes | yes |
| time fe | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| $R^2$ | 0.812 | 0.811 | 0.832 | 0.841 | 0.802 | 0.799 | 0.249 | 0.777 | 0.942 | 0.934 | 0.842 | 0.808 |

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, FE and LSDVC refer to pooled OLS, fixed effects, and corrected least squares dummy variable estimations. The bootstrapped standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell-Bond estimator.

Table 4: Robustness check on data averaging method

| | POLS | POLS | POLS | POLS | FE | FE | FE | FE | LSDVC | LSDVC | LSDVC | LSDVC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| *lagged* TFP | | | | | | | | | 0.791 | 0.787 | 0.767 | 0.954 |
| | | | | | | | | | (0.052)*** | (0.052)*** | (0.052)*** | (0.051)*** |
| $\mu$ | -0.132 | -0.130 | -0.131 | -0.174 | -0.109 | -0.111 | -0.173 | -0.202 | -0.078 | -0.081 | -0.093 | -0.061 |
| | (0.051)** | (0.052)** | (0.051)** | (0.044)*** | (0.060)* | (0.061)* | (0.060)*** | (0.051)*** | (0.034)** | (0.035)** | (0.035)*** | (0.036)** |
| $TO$ | 0.001 | 0.001 | 0.001 | 0.001 | 0.002 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| | (0.000)** | (0.000)** | (0.000)*** | (0.000)*** | (0.000)*** | (0.000)*** | (0.000)*** | (0.000)*** | (0.000)*** | (0.000)*** | (0.000)*** | (0.000)*** |
| $HC$ | | 0.000 | 0.000 | -0.000 | | 0.000 | 0.002 | 0.002 | | 0.001 | 0.001 | 0.002 |
| | | (0.001) | (0.001) | (0.001) | | (0.002) | (0.001) | (0.002) | | (0.001) | (0.001) | (0.001) |
| $L$ | | | 0.019 | -0.197 | | | -0.223 | -0.297 | | | -0.057 | 0.049 |
| | | | (0.011)* | (0.025)*** | | | (0.052)*** | (0.045)*** | | | (0.037) | (0.038) |
| $K$ | | | | 0.211 | | | | 0.223 | | | | -0.150 |
| | | | | (0.023)*** | | | | (0.027)*** | | | | (0.024)*** |
| $N$ | 227 | 227 | 227 | 227 | 227 | 227 | 227 | 227 | 206 | 206 | 206 | 206 |
| country fe | no | no | no | no | yes | yes | yes | yes | yes | yes | yes | yes |
| time fe | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| $R^2$ | 0.808 | 0.808 | 0.833 | 0.846 | 0.786 | 0.987 | 0.171 | 0.600 | 0.966 | 0.961 | 0.758 | 0.516 |

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, FE and LSDVC refer to pooled OLS, fixed effects, and corrected least squares dummy variable estimations. The bootstrapped standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell-Bond estimator.

# 4 Conclusions

The theoretical predictions of an endogenous growth model with overlapping generations suggest a positive relationship between longevity and technological change, which in turn determines productivity. This is due to the fact that — under the expectation of a longer lifetime horizon — investments in physical capital and in R&D, the pay-offs of which accrue in the future, are more lucrative. Consequently, agents substitute savings and technology investments for consumption, which in turn raises the R&D intensity, technological progress, and productivity. The implications of the model are confirmed empirically based on estimations of dynamic panel data models using a sample of 22 OECD countries observed over 52 years. The positive effect of increasing longevity could be found for both TFP and labor productivity and the results are remarkably robust to different estimation techniques, the use of additional control variables, and different methods of measuring productivity.

Overall, this outcome suggests that some aspects of aging exert a positive effect on technological progress and hence on economic growth. However, there are of course many more channels — not explicitly investigated in this paper — through which demographic changes impact upon economic well-being (e.g. changing dependency ratios, changing patterns of human capital accumulation, and influences on fiscal balances of social security systems, which in turn can clearly have repercussions for governmental investments and/or governmental taxation, etc.). A promising avenue for future research would thus be to assess the quantitative importance of the different channels through which demographic changes influence economic prosperity and to use the results to estimate the overall impact of demographic change on economic growth as such.

# Acknowledgments

We would like to thank Cristiano Antonelli, Giuseppe Bertola, Alexia Prskawetz, and Russell Thomson for valuable comments.

# A Derivations

**The individual Euler equation with overlapping generations:** The current-value Hamiltonian is

$$H = \log(c) + \lambda\left[(r+\mu-\delta)k + \hat{w} - c\right].$$

The corresponding first-order conditions (FOCs) are:

$$\frac{\partial H}{\partial c} = \frac{1}{c} - \lambda \overset{!}{=} 0 \Leftrightarrow \frac{1}{c} = \lambda \tag{A.1}$$

$$\frac{\partial H}{\partial k} = (r+\mu-\delta)\lambda \overset{!}{=} (\rho+\mu)\lambda - \dot{\lambda} \Leftrightarrow \dot{\lambda} = (\rho+\delta-r)\lambda. \tag{A.2}$$

Taking the time derivative of Equation (A.1) and plugging it into Equation (A.2) yields

$$\frac{\dot{c}}{c} \;=\; r-\rho-\delta,$$

which is the individual Euler equation.

**Aggregate capital and aggregate consumption:** Following Heijdra and van der Ploeg (2002) and differentiating Equations (6) and (7) with respect to time yields

$$\begin{aligned}
\dot{C}(t) &= \mu L\left[\int_{-\infty}^{t}\dot{c}(t_0,t)e^{\mu(t_0-t)}dt_0-\mu\int_{-\infty}^{t}c(t_0,t)e^{\mu(t_0-t)}dt_0\right]+\mu Lc(t,t)-0\\
&= \mu Lc(t,t)-\mu C(t)+\mu L\int_{-\infty}^{t}\dot{c}(t_0,t)e^{-\mu(t-t_0)}dt_0 \qquad \text{(A.3)}\\
\dot{K}(t) &= \mu L\left[\int_{-\infty}^{t}\dot{k}(t_0,t)e^{\mu(t_0-t)}dt_0-\mu\int_{-\infty}^{t}k(t_0,t)e^{\mu(t_0-t)}dt_0\right]+\mu Lk(t,t)-0\\
&= \mu Lk(t,t)-\mu K(t)+\mu L\int_{-\infty}^{t}\dot{k}(t_0,t)e^{-\mu(t-t_0)}dt_0. \qquad \text{(A.4)}
\end{aligned}$$

From Equation (2) it follows that

$$\begin{aligned}
\dot{K}(t) &= -\mu K(t)+\mu L\int_{-\infty}^{t}\left[(r+\mu-\delta)k(t_0,t)+\hat{w}(t)-c(t_0,t)\right]e^{-\mu(t-t_0)}dt_0\\
&= -\mu K(t)+(r+\mu-\delta)\mu L\int_{-\infty}^{t}k(t_0,t)e^{-\mu(t-t_0)}dt_0\\
&\quad -\mu L\int_{-\infty}^{t}c(t_0,t)e^{-\mu(t-t_0)}dt_0+L\left(\frac{\mu\hat{w}e^{-\mu(t-t_0)}}{\mu}\right)_{-\infty}^{t}\\
&= -\mu K(t)+(r+\mu-\delta)K(t)-C(t)+\hat{W}(t)\\
&= (r-\delta)K(t)-C(t)+\hat{W}(t),
\end{aligned}$$

which is the law of motion for aggregate capital. Reformulating an agent's optimization problem subject to its lifetime budget restriction, stating that the present value of lifetime consumption expenditures has to be equal to the present value of lifetime non-interest income plus initial assets, yields the optimization problem

$$\begin{aligned}
\max_{c(t_0,\tau)}\quad U &= \int_{t}^{\infty}e^{(\rho+\mu)(t-\tau)}\log[c(t_0,\tau)]d\tau\\
s.t.\qquad & k(t_0,t)+\int_{t}^{\infty}\hat{w}(\tau)e^{-R^A(t,\tau)}d\tau=\int_{t}^{\infty}c(t_0,\tau)e^{-R^A(t,\tau)}d\tau, \qquad \text{(A.5)}
\end{aligned}$$

where $R^A(t,\tau)=\int_t^\tau(r(s)+\mu-\delta)ds$. The FOC to this optimization problem is

$$\frac{1}{c(t_0,\tau)}e^{(\rho+\mu)(t-\tau)}=\lambda(t)e^{-R^A(t,\tau)}.$$

In period ($\tau=t$) we have

$$c(t_0,t)=\frac{1}{\lambda(t)}.$$

Therefore we can write

$$\begin{aligned}
\frac{1}{c(t_0,\tau)}e^{(\rho+\mu)(t-\tau)} &= \frac{1}{c(t_0,t)}e^{-R^A(t,\tau)} \\
c(t_0,t)e^{(\rho+\mu)(t-\tau)} &= c(t_0,\tau)e^{-R^A(t,\tau)}.
\end{aligned}$$

Integrating and using Equation (A.5) yields

$$\begin{aligned}
\int_t^\infty c(t_0,t)e^{(\rho+\mu)(t-\tau)}d\tau &= \int_t^\infty c(t_0,\tau)e^{-R^A(t,\tau)}d\tau \\
\frac{c(t_0,t)}{\rho+\mu}\left[-e^{(\rho+\mu)(t-\tau)}\right]_t^\infty &= k(t_0,t)+\underbrace{\int_t^\infty \hat{w}(\tau)e^{-R^A(t,\tau)}d\tau}_{h(t)} \\
\Rightarrow c(t_0,t) &= (\rho+\mu)\left[k(t_0,t)+h(t)\right], \qquad \text{(A.6)}
\end{aligned}$$

where $h$ refers to human wealth, that is, non-interest wealth, of individuals. Human wealth does not depend on the date of birth because productivity and lump-sum transfers are age independent. The above calculations show that optimal consumption in the planning period is proportional to total wealth with a marginal propensity to consume of $\rho+\mu$. Aggregate consumption evolves according to

$$\begin{aligned}
C(t) &\equiv \mu N\int_{-\infty}^t c(t_0,t)e^{\mu(t_0-t)}dt_0 \\
&= \mu N\int_{-\infty}^t e^{\mu(t_0-t)}(\rho+\mu)\left[k(t_0,t)+h(t)\right]dt_0 \\
&= (\rho+\mu)\left[K(t)+H(t)\right]. \qquad \text{(A.7)}
\end{aligned}$$

Note that $k(t,t)=0$ because there are no bequests such that newborns do not own capital. Therefore

$$c(t,t) = (\rho+\mu)h(t) \qquad \text{(A.8)}$$

holds for each newborn individual. Putting Equations (3), (A.3), (A.7), and (A.8) together yields

$$
\begin{aligned}
\dot{C}(t) &= \mu(\rho+\mu)H(t) - \mu(\rho+\mu)\left[K(t)+H(t)\right] + \\
&\quad \mu N \int_{-\infty}^{t} (r-\rho-\delta)c(t_0,t)e^{-\mu(t-t_0)}dt_0 \\
&= \mu(\rho+\mu)H(t) - \mu(\rho+\mu)\left[K(t)+H(t)\right] + (r-\rho-\delta)C(t) \\
\Rightarrow \frac{\dot{C}(t)}{C(t)} &= r-\rho-\delta + \frac{\mu(\rho+\mu)H(t) - \mu(\rho+\mu)\left[K(t)+H(t)\right]}{C(t)} \\
&= r-\rho-\delta-\mu(\rho+\mu)\frac{K(t)}{C(t)} \\
&= r-\rho-\delta-\mu\underbrace{\frac{C(t)-c(t,t)L}{C(t)}}_{\in(0,1)}.
\end{aligned}
$$

The last two lines contain equivalent expressions for the aggregate Euler equation that differs from the individual Euler equation by the term $-\mu\left[C(t)-c(t,t)L\right]/C(t)$ that is due to the generational turnover induced by birth and death.

**Operating profits of intermediate goods producers:** Profits of intermediate goods producers can be obtained via Equation (12) as

$$
\pi = \frac{r}{\alpha}x - rx = (1-\alpha)\alpha\frac{Y}{A}.
$$

**Labor input in both sectors:** We determine the fraction of workers employed in the final goods sector and in the R&D sector by making use of Equation (16)

$$
\begin{aligned}
p^A\lambda A^{\phi} &= (1-\alpha)\frac{Y}{L_Y} \\
\Leftrightarrow L_Y &= \frac{(r-\delta)A^{1-\phi}}{\alpha\lambda} \\
\Rightarrow L_A &= L - \frac{(r-\delta)A^{1-\phi}}{\alpha\lambda},
\end{aligned}
$$

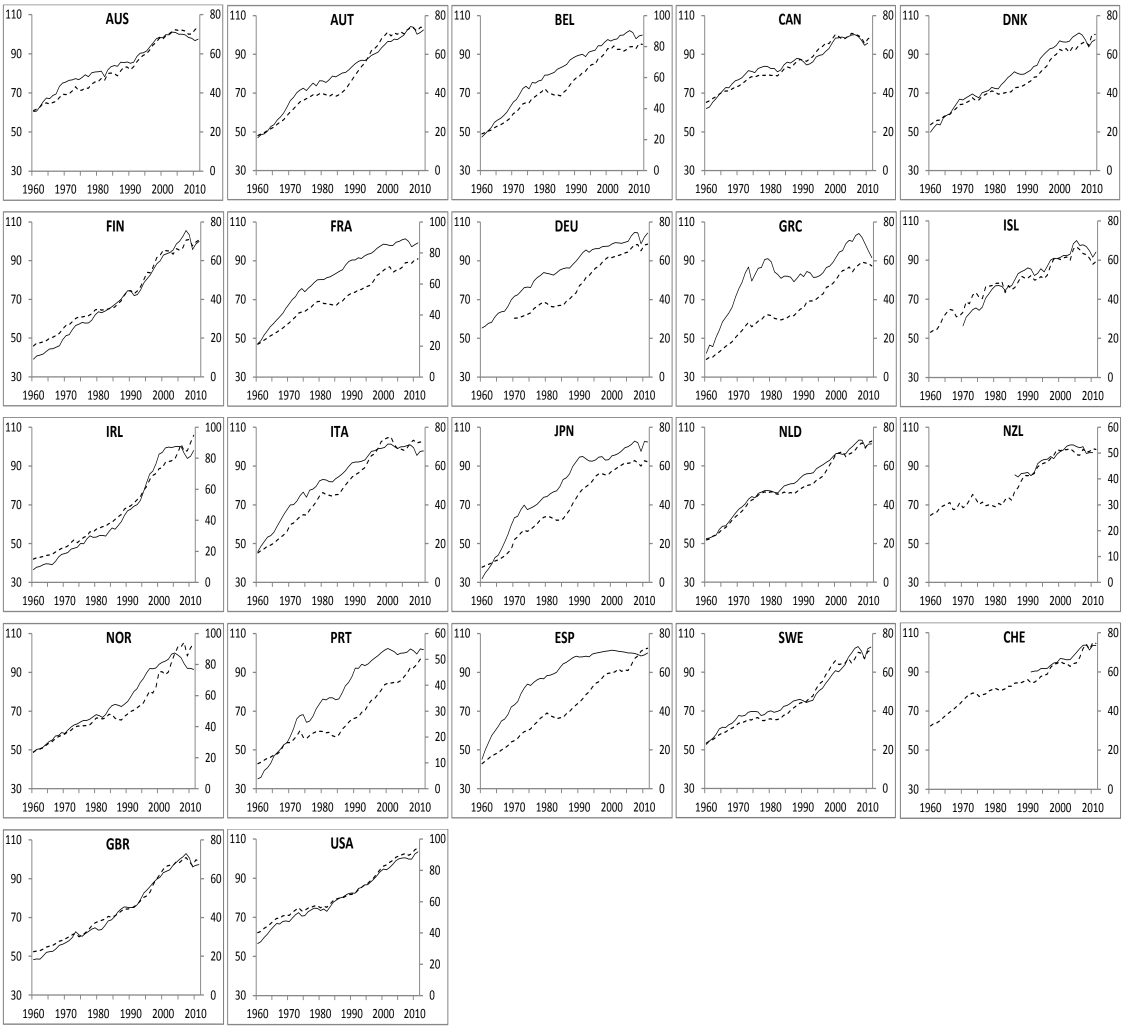
where the last line follows from labor market clearing, that is, $L = L_A + L_Y$.

**Rewriting production per capital unit:** Production per capital unit can be written as a function of the interest rate and the elasticity of final output with respect to machines of type $i$ as

$$
r = \alpha p = \alpha^2\frac{Y}{K} \Rightarrow \frac{Y}{K} = \frac{r}{\alpha^2}. \tag{A.9}
$$

# B Country-specific TFP and labor productivity development

Figure 2: Country-specific TFP and labor productivity development



Note: TFP is an index (2005=100) and is represented on the left axis. Labor productivity is defined as real GDP per person employed, in thousand of 2005 US dollars. It is represented on the right axis. The sample is composed by 22 OECD countries: AUS - Australia; AUT - Austria; BEL - Belgium; CAN - Canada; CHE - Switzerland; DEU - Germany; DNK - Denmark; ESP - Spain; FIN - Finland; FRA - France; GBR - United Kingdom; GRC - Greece; IRL - Ireland; ISL - Island; ITA - Italy; JPN - Japan; NLD - Netherlands; NOR - Norway; NZL- New Zealand; PRT - Portugal; SWE - Sweden; USA - United States.

Source: Ameco macroeconomic database.

# C Data

The list of countries included in our sample is the following: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States. Data on TFP start in 1970 for Iceland, in 1986 for New Zealand, and in 1991 for Switzerland. Table 5 contains a description of the variables, their abbreviations, and the data sources.

Table 5: Variables and their sources

| Variable | Definition | Source |
|---|---|---|
| TFP | Total factor productivity index, 2005=100, computed as a residual from a standard Cobb-Douglas production function | Ameco |
| $LP$ | Labor productivity, given by the GDP at constant 2005 and PPP adjusted prices (*rgdpe*) over total employment (*emp*) | PWT, 8.0 |
| $\mu$ | crude death rate | WDI |
| $TO$ | trade openness at constant 2005 prices, obtained as the share of the sum of imports and exports over GDP (*openk*) | PWT, 7.1 |
| $HC$ | human capital index, based on years of schooling and returns to education | PWT, 8.0 |
| $L$ | employment in terms of number of persons engaged (*emp*) | PWT, 8.0 |
| $K$ | capital stock at constant 2005 prices in mil. US dollars (*rkna*) | PWT, 8.0 |

# D Descriptive statistics:

Tables 6 and 7 provide some useful information regarding the descriptive statistics and pair-wise correlations between the variables. Among the most important variables of interest, average TFP was equal to 80.1, ranging from a minimum of 31.9 (Japan in 1960) to a maximum of 105.6 (Finland in 2007). Correspondingly, the average level of labor productivity was equal to around 46,000 of constant (2005) PPP adjusted US-Dollars, with a minimum of 3,900 US-Dollars (Korea in 1962) to a maximum of 95,000 US-Dollars (Ireland in 2011). The average death rate in our sample was equal to 9.1 per thousand midyear population. This means that in a population of 1 million, a death rate of 9.1 would imply 9100 deaths per year. The minimum value of the death rate was observed in Korea in 2006 and amounted to 5.0, whereas the maximum death rate of 14.4 was registered again in Korea in 1960. From the correlation matrix it emerges that the death rate is negatively (although weakly) correlated with all the other explanatory variables, with the exception of trade openness.

Table 6: Descriptive statistics

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| TFP | 1075 | 80.1 | 16.8 | 31.9 | 105.6 |
| $LP$ | 1238 | 45804.3 | 18083.8 | 3865.5 | 94716.5 |
| $\mu$ | 1248 | 9.1 | 1.8 | 5.0 | 14.4 |
| $TO$ | 1214 | 48.2 | 28.8 | 4.1 | 172.4 |
| $I$ | 1214 | 24.5 | 5.4 | 8.1 | 46.1 |
| $HC$ | 1248 | 2.7 | 0.4 | 1.5 | 3.6 |
| $L$ | 1238 | 15.2 | 24.7 | 0.1 | 147.8 |
| $K$ | 1248 | 2553257.0 | 5453996.0 | 5264.8 | 40900000.0 |

Table 7: Correlation matrix

| | TFP | $LP$ | $\mu$ | $TO$ | $I$ | $HC$ | $L$ | $K$ |
|---|---|---|---|---|---|---|---|---|
| TFP | 1 | | | | | | | |
| $LP$ | 0.723 | 1 | | | | | | |
| $\mu$ | -0.292 | -0.230 | 1 | | | | | |
| $TO$ | 0.364 | 0.520 | 0.084 | 1 | | | | |
| $I$ | -0.016 | -0.089 | -0.193 | 0.006 | 1 | | | |
| $HC$ | 0.339 | 0.637 | -0.370 | 0.264 | -0.149 | 1 | | |
| $L$ | 0.084 | 0.260 | -0.160 | -0.418 | -0.074 | 0.316 | 1 | |
| $K$ | 0.166 | 0.360 | -0.149 | -0.344 | -0.073 | 0.377 | 0.969 | 1 |

# References

Acemoglu, D. and Johnson, S. (2007). Disease and Development: The Effect of Life Expectancy on Economic Growth. *Journal of Political Economy*, Vol. 115(No. 6):925–985.

Acemoglu, D. and Johnson, S. (2014). Disease and development: a reply to Bloom, Canning, and Fink. *The Journal of Political Economy.* Forthcoming.

Aghion, P. and Howitt, P. (1992). A model of growth through creative destruction. *Econometrica*, Vol. 60(No. 2):323–351.

Aghion, P., Howitt, P., and Murtin, F. (2011). The Relationship Between Health and Growth: When Lucas Meets Nelson-Phelps. *Review of Economics and Institutions*, Vol. 2(No. 1):1–24.

Anderson, T. W. and Hsiao, C. (1982). Formulation and estimation of dynamic models using panel data. *Journal of Econometrics*, Vol 18:47–82.

Antonelli, C. and Fassio, C. (2014). The economics of the light economy: Globalization, skill biased technological change and slow growth. *Technological Forecasting and Social Change*, Vol. 87:87–107.

Arellano, M. and Bond, S. (1991). Some tests of specification for panel data: Monte carlo evidence and an application to employment equations. *Review of Economic Studies*, Vol. 58:277–297.

Barro, R. J. and Lee, J.-W. (2013). A New Data Set of Educational Attainment in the World, 1950-2010. *Journal of Development Economics*. Forthcoming.

Bernard, A. B., Jensen, J. B., and Schott, P. K. (2006). Trade costs, firms and productivity. *Journal of Monetary Economics*, Vol. 53:917–937.

Blanchard, O. J. (1985). Debt, deficits and finite horizons. *Journal of Political Economy*, Vol. 93(No. 2):223–247.

Bloom, D., Canning, D., and Fink, G. (2014). Disease and development revisited. *The Journal of Political Economy*. Forthcoming.

Bloom, D. E., Canning, D., and Fink, G. (2010). Implications of Population Ageing for Economic Growth. *Oxford Review of Economic Policy*, Vol. 26(No. 4):583–612.

Bloom, D. E., Canning, D., and Graham, B. (2003). Longevity and Life-cycle Savings. *Scandinavian Journal of Economics*, Vol. 105(No. 3):319–338.

Blundell, R. and Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data methods. *Jornal of Econometrics*, Vol. 87:115–143.

Borghans, L. and ter Well, B. (2002). Do older workers have more trouble using a computer than younger workers? *The Economics of Skills Obsolescence*, Vol. 21:139–173.

Boucekkine, R., de la Croix, D., and Lica, O. (2003). Early mortality decline at the dawn of modern growth. *Scandinavian Journal of Economics*, Vol. 105(No. 3):401–418.

Boucekkine, R., de La Croix, D., and Licandro, O. (2002). Vintage human capital, demographic trends, and endogenous growth. *Journal of Economic Theory*, Vol. 104(No. 2):340–375.

Bruno, G. S. F. (2005a). Approximating the bias of the LSDV estimator for dynamic unbalanced panel data models. *Economics Letters*, Vol. 87:361–366.

Bruno, G. S. F. (2005b). Estimation and inference in dynamic unbalanced panel-data models with a small number of individuals. *The Stata Journal*, Vol. 5(No. 4):473–500.

Bucci, A. (2008). Population growth in a model of economic growth with human capital accumulation and horizontal R&D. *Journal of Macroeconomics*, Vol. 30(No. 3):1124–1147.

Bun, M. J. G. and Kiviet, J. F. (2003). On the diminishing returns of higher order terms in asymptotic expansions of bias. *Economics Letters*, Vol 79:145–152.

Canton, E., de Groot, H., and Hahuis, R. (2002). Vested interests, population ageing and technology adoption. *European Journal of Political Economy*, Vol. 18(No. 4):631–652.

Cass, D. (1965). Optimum growth in an aggregative model of capital accumulation. *The Review of Economic Studies*, Vol. 32(No. 3):233–240.

Cervellati, M. and Sunde, U. (2011). Life expectancy and economic growth: the role of the demographic transition. *Journal of Economic Growth*, Vol. 16:99–133.

de la Croix, D. and Licandro, O. (1999). Life expectancy and endogenous growth. *Economics Letters*, Vol. 65(No. 2):255263.

de la Croix, D. and Licandro, O. (2013). The child is father of the man: Implications for the demographic transition. *The Economic Journal*, Vol 123:236–261.

Diamond, P. A. (1965). National debt in a neoclassical growth model. *American Economic Review*, Vol. 55(No. 5):1126–1150.

Dixit, A. K. and Stiglitz, J. E. (1977). Monopolistic competition and optimum product diversity. *American Economic Review*, Vol. 67(No. 3):297–308.

Feenstra, R. C., Inklaar, R., and Timmer, M. P. (2013). The Next Generation of the Penn World Table. Available for download at `www.ggdc.net/pwt`.

Funke, M. and Strulik, H. (2000). On endogenous growth with physical capital, human capital and product variety. *European Economic Review*, Vol. 44:491–515.

Gehringer, A. (2013). Financial liberalization, growth, productivity and capital accumulation: The case of European integration. *International Review of Economics & Finance*, Vol. 25:291–309.

Gehringer, A. (2014). Uneven effects of financial liberalization on productivity growth in the EU: Evidence from a dynamic panel investigation. *International Journal of Production Economics*. Forthcoming.

Gertler, M. (1999). Government debt and social security in a life-cycle economy. *Carnegie-Rochester Conference Series on Public Policy*, Vol. 50:61–110.

Grossman, G. M. and Helpman, E. (1991). Quality ladders in the theory of economic growth. *Review of Economic Studies*, Vol. 58(No. 1):43–61.

Gruescu, S. (2007). *Population Ageing and Economic Growth*. Physica-Verlag, Heidelberg.

Ha and Howitt (2007). Accounting for Trends in Productivity and R&D: A Schumpeterian Critique of Semi-Endogenous Growth Theory. *Journal of Money, Credit and Banking*, Vol. 39(No. 4):733–774.

Heer, B. and Irmen, A. (2009). Population, Pensions, and Endogenous Economic Growth. Center for Economic Policy Research (CEPR), London, Discussion Paper, No. 7172.

Heijdra, B. J. and Mierau, J. O. (2010). Growth effects of consumption and labor-income taxation in an overlapping-generations life-cycle model. *Macroeconomic Dynamics*, Vol. 14:151–175.

Heijdra, B. J. and Mierau, J. O. (2011). The Individual Life Cycle and Economic Growth: An Essay on Demographic Macroeconomics. *De Economist*, Vol. 159(No. 1):63–87.

Heijdra, B. J. and Mierau, J. O. (2012). The individual life-cycle, annuity market imperfections and economic growth. *Journal of Economic Dynamics and Control*, Vol. 36:876–890.

Heijdra, B. J. and van der Ploeg, F. (2002). *Foundations of Modern Macroeconomics.* Oxford University Press. Oxford.

Heston, A., Summers, R., and Aten, B. (2012). Penn World Table Version 7.1, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, November 2012.

Hineline, D. (2008). Parameter heterogeneity in growth regressions. *Economics Letters*, Vol. 101:126–129.

Howitt, P. (1999). Steady endogenous growth with population and R&D inputs growing. *Journal of Political Economy*, Vol. 107(No. 4):715–730.

Irmen, A. (2013). Capital- and Labor-saving Technical Change in an Aging Economy. CREA Discussion Paper Series 13-27, Center for Research in Economic Analysis, University of Luxembourg.

Jones, C. I. (1995). R&D-based models of economic growth. *Journal of Political Economy*, Vol. 103(No. 4):759–783.

Jones, C. I. (2002). Sources of U.S. Economic Growth in a World of Ideas. *American Economic Review*, Vol. 92(No. 1):220–239.

Judson, R. A. and Owen, A. L. (1999). Estimating dynamic panel data models: a guide for macroeconomists. *Economics Letters*, Vol. 65:9–15.

Kalemli-Ozcan, S. (2002). Does the Mortality Decline Promote Economic Growth? *Journal of Economic Growth*, Vol. 7:411–439.

Kalemli-Ozcan, S. (2003). A stochastic model of mortality, fertility, and human capital investment. *Journal of Development Economics*, Vol. 70:103–118.

Keller, W. (2002). Geographic Localization of International Technology Diffusion. *The American Economic Review*, Vol. 92(No. 1):120–142.

Kiviet, J. F. (1995). On bias, inconsistency, and efficiency of various estimators in dynamic panel data models. *Journal of Econometrics*, Vol. 68:53–78.

Koopmans, T. C. (1965). On the concept of optimal economic growth. In *The Econometric Approach to Development Planning*. Amsterdam: North Holland.

Kortum, S. (1997). Research, patenting and technological change. *Econometrica*, Vol. 65(No. 6):1389–1419.

Krueger, D. and Ludwig, A. (2007). On the consequences of demographic change for rates of returns on capital, and the distribution of wealth and welfare. *Journal of Monetary Economics*, Vol. 54:49–87.

Kuhn, M. and Prettner, K. (2012). Growth and welfare effects of health care in knowledge based economies. Courant Research Centre: Poverty, Equity and Growth - Discussion Paper 120.

Lindh, T. and Malmberg, B. (1999). Age structure effects and growth in the oecd, 1950-1990. *Journal of Population Economics*, Vol. 12:431–449.

Lorentzen, P., McMillan, J., and Wacziarg, R. (2008). Death and development. *Journal of Economic Growth*, Vol. 13:81–124.

Maddala, G. S. and Wu, S. (2002). Cross-country growth regressions: Problems of heterogeneity, stability and interpretation. *Applied Economics*, Vol. 32(No. 5):635–642.

Mankiw, G. N. and Weil, D. N. (1989). The Baby-Boom, the Baby-Bust and the Housing Market. *Regional Science and Urban Economics*, Vol. 19:235–258.

Miller, S. M. and Upadhyay, M. P. (2000). The effects of openness, trade orientation, and human capital on total factor productivity. *Journal of Development Economics*, Vol. 63:399–423.

Nickell, S. S. (1981). Biases in dynamic models with fixed effects. *Econometrica*, Vol. 49:1117–1126.

Peretto, P. F. (1998). Technological change and population growth. *Journal of Economic Growth*, Vol. 3(No. 4):283–311.

Peterson, P. G. (1999). Gray Dawn: The Global Aging Crisis. *Foreign Affairs*, (January/February).

Prettner, K. (2013). Population aging and endogenous economic growth. *Journal of Population Economics*, Vol. 26(No. 2):811–834.

Prettner, K. and Trimborn, T. (2012). Demographic change and R&D-based economic growth: reconciling theory and evidence. cege Discussion Paper 139.

Pritchett, L. (2001). Where has all the education gone? *The World Bank Economic Review*, Vol. 15(No. 3).

Psacharopoulos, G. (1994). Returns to Investment in Education: A Global Update. *World Development*, Vol. 22(No. 9):1325–1343.

Reinhart, V. R. (1999). Death and taxes: their implications for endogenous growth. *Economics Letters*, Vol 62(No 3):339–345.

Romer, P. (1990). Endogenous technological change. *Journal of Political Economy*, Vol. 98(No. 5):71–102.

Segerström, P. S. (1998). Endogenous growth without scale effects. *American Economic Review*, Vol. 88(No. 5):1290–1310.

Solow, R. M. (1956). A contribution to the theory of economic growth. *The Quarterly Journal of Economics*, Vol. 70(No. 1):65–94.

Strulik, H. (2005). The role of human capital and population growth in R&D-based models of economic growth. *Review of International Economics*, Vol. 13(No. 1):129–145.

Strulik, H., Prettner, K., and Prskawetz, A. (2013). The past and future of knowledge-based growth. *Journal of Economic Growth*, Vol. 18(No. 4). 411-437.

The Economist (2004). Demographic change: Old Europe. The Economist. September 30th 2004.

Weil, D. (2007). Accounting for the effect of health on economic growth. *The Quarterly Journal of Economics*, Vol. 122(No. 3):1265–1306.

WHO (2012). Strategy and action plan for healthy ageing in europe, 2012-2020. WHO, Regional Committee for Europe. Available on: `http://www.euro.who.int/__data/assets/pdf_file/0008/175544/RC62wd10Rev1-Eng.pdf`.

World Bank (2014). World Development Indicators & Global Development Finance Database. `http://data.worldbank.org/data-catalog/world-development-indicators`.

Yaari, M. E. (1965). Uncertain lifetime, life insurance and the theory of the consumer. *The Review of Economic Studies*, Vol. 32(No. 2):137–150.

Young, A. (1998). Growth without scale effects. *Journal of Political Economy*, Vol. 106(No. 5):41–63.

Zhang, J. and Zhang, J. (2005). The effect of life expectancy on fertility, saving, schooling and economic growth: Theory and evidence. *Scandinavian Journal of Economics*, Vol. 107(No. 1):45–66.