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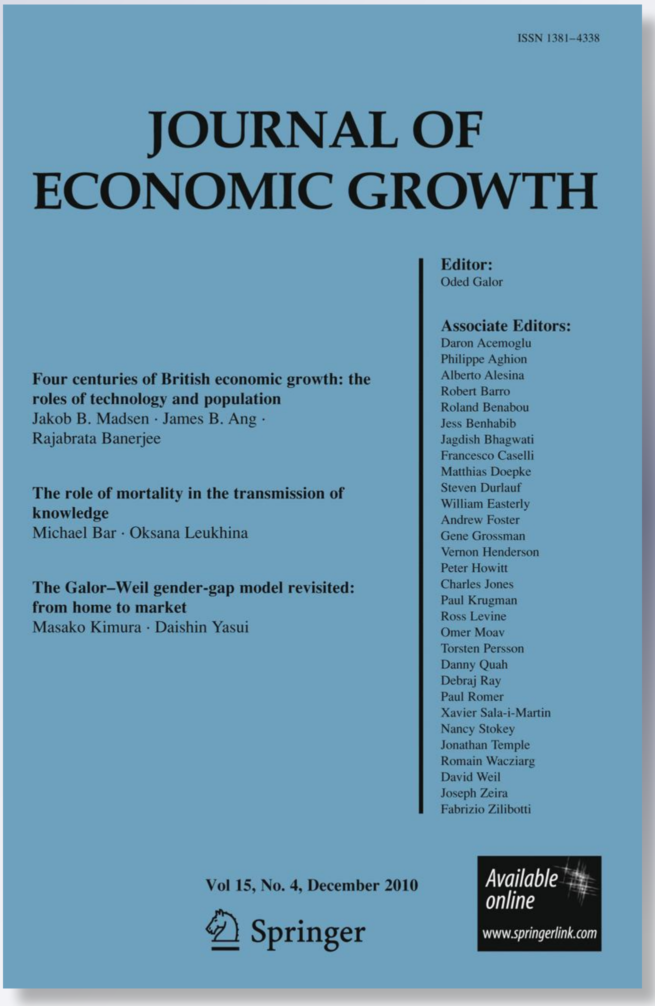
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# Four centuries of British economic growth: the roles of technology and population

**Jakob B. Madsen · James B. Ang · Rajabrata Banerjee**

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**Abstract** Using long historical data for Britain over the period 1620–2006, this paper seeks to explain the importance of innovative activity, population growth and other factors in inducing the transition from the Malthusian trap to the post-Malthusian growth regime. Furthermore, the paper tests the ability of two competing second-generation endogenous growth models to account for the British growth experience. The results suggest that innovative activity was an important force in shaping the Industrial Revolution and that the British growth experience is consistent with Schumpeterian growth theory.

**Keywords** Endogenous growth · British Industrial Revolution

**JEL Classification** O30 · O40

## 1 Introduction

Before the late eighteenth century, per capita growth rates were either zero or miniscule and average per capita incomes in different regions of the world were quite similar (Galor 2005; Maddison 2007). Galor and Weil (2000), Hansen and Prescott (2002) and Galor (2005) argue that this period of stagnation can be described as the Malthusian epoch. Instead of resulting in improved standards of living, technological progress led to increased population. However, with the onset of the Great Divergence around 1760, on the eve of the First Industrial Revolution in Britain, the British economy began the transformation from the Malthusian trap to the post-Malthusian epoch during which the rate of technological progress outpaced the population growth drag, resulting in positive per capita growth rates. Yet the transformation of the British economy is still one of the great mysteries in the history of human evolution.

Economic growth literature contains extensive coverage of Britain due mainly to its pre-eminent position in the First Industrial Revolution and the availability of well-documented

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historical facts and data. However, despite being one of the most significant events in economic history, little is known about the role played by innovation in freeing the British economy from its Malthusian straightjacket. While the literature suggests different roles played by technology during the Industrial Revolution, technological progress has also been deemphasized as being important for the British growth experience by some economic historians. Allen (2003, p. 405) notes that "recent research has downplayed the importance of technological progress and literacy in explaining the British Industrial Revolution". Furthermore, Crafts (1995) suggests that the augmented neoclassical growth model is the appropriate tool for modeling growth during the Industrial Revolution and that the most important innovations were exogenous during that period. Based on the statistical properties of productivity data, historiography and growth accounting exercises, Crafts (1995) concludes that both the *AK* model of Rebelo (1991) and the endogenous growth model of Grossman and Helpman (1990) are incapable of explaining the growth rates experienced by England during the Industrial Revolution.

However, several studies have stressed that the Industrial Revolution was associated with high levels of innovative activity (see Sullivan 1989; Mokyr 1993, 2005; Crafts 2005; Galor 2005; Clark 2007; Greasley and Oxley 2007; Khan and Sokoloff 2007; Crafts and Mills 2009; Rosen 2010). Sullivan (1989, p. 424) describes the period 1762–1851 as the 'Age of Invention' for England' during which patentable inventions increased markedly. Greasley and Oxley (1997) demonstrate that output fluctuations were very persistent during the period 1780–1851, and use this as evidence to argue that endogenous growth models are more relevant in accounting for the glorious period of Britain's industrialization than the neoclassical growth model. In a similar vein, using cointegration and causality techniques, Oxley and Greasley (1998) suggest that the Industrial Revolution was shaped mostly by technological progress.

Crafts (1995) and Oxley and Greasley (1998) focus on the validity of the first-generation endogenous growth models of Grossman and Helpman (1990) and Rebelo (1991) in explaining the Industrial Revolution. However, following Jones (1995) famous critique, the first-generation endogenous growth models are no longer acceptable to have any empirical validity. In particular, Jones (1995) notes that the number of R&D workers increased substantially during this period, while the US post-WWII growth rates have remained relatively constant. This observation is inconsistent with the predictions of the first-generation endogenous growth models that productivity growth is proportional to the number of R&D workers.

The second-generation endogenous growth models overcome this unwarranted property of the first-generation growth models by abandoning the assumption of constant returns to scale in ideas production (semi-endogenous growth models) or by assuming that the effectiveness of R&D is diluted due to the proliferation of products when an economy expands (see Schumpeterian growth models of Aghion and Howitt 1998; Howitt 1999; Peretto and Smulders 2002; Ha and Howitt 2007). Thus, given the shortcomings of first-generation endogenous growth models earlier findings based on them, the second-generation endogenous growth models may be more consistent with the British growth experience since 1620. However, it remains to be seen whether any of those modern innovation-based growth models, extended to allow for population growth drag, are capable of explaining the glorious period of Britain's industrialization.

The objectives of this paper are to examine: (1) whether the second-generation endogenous growth theories, augmented to allow for the population growth path, are useful in explaining British economic growth over the past four centuries including the two Industrial Revolutions; (2) the role played by population growth during the transitional period, particularly the reductions in the population growth rate after 1813 and then again after 1907; and (3) the effects on productivity growth of foreign knowledge, government spending, financial development, reduction in trade barriers, availability of coal, urbanization and sectoral movements. This paper is, to the best of our knowledge, the first that attempts to formally test whether there is a significant relationship between growth, innovative activity and population growth during the first and the second-phase of the industrial revolution in Britain by using a direct measure of innovative activity and by allowing for land as a factor of production.

The paper proceeds as follows: the next section shows the empirical implications of various endogenous growth theories and extends the growth framework used by Ha and Howitt (2007) and Madsen (2008) to allow for land as a fixed factor of production. Section 3 discusses the construction of variables and provides some graphical analyses. Using long historical data over the period 1620–2006, the empirical analysis is performed and subsequent results are presented and discussed in Section 4. Section 5 provides an anatomy of the British Industrial Revolution. The last section concludes.

## 2 Innovation-based growth with land as a fixed factor of production

When land is a significant factor of production, labor productivity growth is a race between population growth and technological progress. Technological progress is determined by innovative activity. This section incorporates the implications of population growth into the second-generation endogenous growth models and shows the functional relationship between innovations and growth.

Consider the following homogenous Cobb-Douglas production function:

$$Y_t = A_t K_t^{\alpha(1-\beta_t)} T_t^{\beta_t} L_t^{(1-\alpha)(1-\beta_t)} \tag{1}$$

where $Y_t$ is real output, $A_t$ is the knowledge stock, $K_t$ is the capital stock, $T_t$ is land, $L_t$ is labor, $\alpha\,(1-\beta_t)$ is the share of income going to capital and $\beta_t$ is the share of income going to land under the maintained assumption of perfect competition. The production function exhibits constant returns to scale in $K_t$, $T_t$ and $L_t$ and increasing returns to scale in $A_t$, $K_t$, $T_t$ and $L_t$ together.

Equation 1 can be written as per worker output so that:

$$\frac{Y_t}{L_t} = A_t^{\frac{1}{1-\alpha(1-\beta_t)}} \left[\frac{K_t}{Y_t}\right]^{\frac{\alpha(1-\beta_t)}{1-\alpha(1-\beta_t)}} T_t^{\psi_t} L_t^{-\psi_t}, \tag{2}$$

where $\psi_t = \beta_t/[1-\alpha(1-\beta_t)]$. Labor productivity is cast in terms of the $K$–$Y$ ratio to filter out technology-induced capital deepening (Klenow and Rodriguez-Clare 1997). The reason why productivity growth triggers capital deepening is that technological progress increases expected earnings per unit of capital and causes Tobin's $q$ to exceed its steady-state value through the channel of the equity market. This initiates a capital deepening process that terminates when Tobin's $q$ reaches its steady-state equilibrium, which may not be one in the presence of taxes, technological progress and population growth (see Madsen and Davis 2006). The $K$–$Y$ ratio can change transitionally due to changes in time-preferences and taxes.

Taking logs and differentiating Eq. 2 under the assumption that land is a fixed factor of production, yields labor productivity growth along the balanced growth path:

$$g_{y_t} = \frac{\psi_t}{\beta_t} g_{A_t} - \psi_t g_{L_t} \tag{3}$$

where $g_y$ is labor productivity growth, $g_A$ is growth in TFP and $g_L$ is growth in the labor force. The role of capital for growth is suppressed in Eq. 3 under the assumption that the economy is on its balanced growth path in which the $K$–$Y$ ratio is constant. Capital deepening cannot act as an independent growth factor since it is driven entirely by technological progress along the balanced growth path. Transitional dynamics is allowed for in the empirical estimation.

In the case where land is omitted as a factor of production ($\beta = 0$), Eq. 3 reduces to a standard neoclassical growth model in which labor productivity growth is driven entirely by technological progress, independent of population growth, along the balanced growth path. Growth is independent of population growth along the balanced growth path in these models because capital stock endogenously adjusts until the $K$–$Y$ ratio returns to its initial level following a population shock. When land is an essential factor of production, population growth reduces labor productivity. Population growth slows growth in Eq. 3 because of diminishing returns introduced by land as a fixed factor of production. The greater the importance of agricultural production in total output, the more population growth acts as a growth-drag on the economy.

The population growth drag was potentially important for labor productivity growth during the first part of the period considered in this paper. Agriculture was a dominant production sector in Britain up to the Second Industrial Revolution. In 1600 almost 75% of the English working population was employed in the agricultural sector (Allen 2001). Agriculture remained the dominant mode of production over the next two centuries. The fraction of the working population in agriculture was 35% in 1800 (Allen 2001), 28% in 1851 and 12% in 1901 (Mitchell 1988). Thus, population growth rates lowered per capita income growth rates almost on a one-to-one basis around 1600 and were still very influential for per capita growth over the next two centuries.

While population affects growth directly, innovative activity influences growth indirectly through the channel of ideas production. There are three established theories of ideas production functions and they have quite different implications for how innovative activity is transformed into technological progress and, consequently, growth. In the first-generation endogenous growth models of Romer (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992), ideas production is associated with the number of researchers. In the semi-endogenous growth models of Jones (1995), Kortum (1997) and Segerstrom (1998), R&D inputs are required to grow permanently to maintain sustained ideas production following the assumption of diminishing returns to knowledge. According to the Schumpeterian models of Aghion and Howitt (1998), Dinopoulos and Thompson (1998), Peretto (1998), Howitt (1999) and Peretto and Smulders (2002), a positive constant rate of ideas production can be maintained provided that R&D per worker remains constant. In other words, R&D has to increase over time to counteract the increasing range of products that lowers the productivity effects of R&D activity in order to ensure sustained ideas production.

It is not clear which of the second-generation endogenous growth theories can best account for the British growth experience and whether any of these theories can explain innovation-induced growth throughout the four centuries considered in this paper. Although Ha and Howitt (2007) and Madsen (2008) have found that Schumpeterian growth theory is most consistent with the experience of modern growth regimes, there is no assurance that the theory will work during the Malthusian and the post-Malthusian growth regimes, as highlighted by Howitt and Mayer-Foulkes (2005). Parente and Prescott (2005) argue that the knowledge term in the production function should be decomposed into two components: (1) the technological knowledge that is available domestically and on a worldwide scale, and (2) effective utilization of technology. The latter depends on how effectively technology is used and the extent of efficiency of operations within organizations. If innovations in the first part of the period 1620–2006 were not used effectively, positive growth rates would not have transpired. Based on historical evidence, Monteiro and Pereira (2006) argue that many growth spurts in history failed to become sustained growth regimes because insufficient human capital was provided to deal with the increasing complexity of innovations.

The following general ideas production function can be used to discriminate between different endogenous growth models (Ha and Howitt 2007; Madsen 2008):

$$g_A = \frac{\dot{A}_t}{A_t} = \lambda \left(\frac{X_t}{Q_t}\right)^{\sigma} A_t^{\phi-1}, \quad 0 < \sigma \leq 1, \quad \phi \leq 1, \tag{4}$$

$$Q_t \propto L_t^{\kappa} \text{ in steady state}$$

$$0 < \sigma \leq 1, \quad \phi \leq 1,$$

where $\sigma$ is the duplication parameter (zero if all innovations are duplications and 1 if there are no duplicating innovations), $\phi$ is returns to scale in knowledge, $\kappa$ is the coefficient of product proliferation, $\lambda$ is the research productivity parameter, $Q$ is a measure of product variety, $L$ is employment or population and $X$ is R&D inputs for semi-endogenous growth models or the productivity-adjusted R&D inputs for Schumpeterian growth models. The productivity adjustment in Schumpeterian models recognizes that there is a tendency for decreasing returns to R&D due to increasing complexity of innovations (Ha and Howitt 2007). Semi-endogenous growth theory assumes that $\phi < 1$, $\sigma > 0$ and $\kappa = 0$ while Schumpeterian models assume that $\phi = 1$, $\sigma > 0$ and $\kappa = 1$. The first-generation endogenous growth theory assumes that $\phi = 1$, $\sigma > 0$ and $\kappa = 0$.

Schumpeterian growth models maintain the assumption from the first-generation endogenous growth models of constant returns to the stock of R&D knowledge. However, they assume that the effectiveness of R&D is diluted due to the proliferation of products as the economy expands. Thus, growth can still be sustained if R&D is kept at a fixed proportion of the number of product lines, which is in turn proportional to the size of the population in the steady state. As such, to ensure sustained ideas production, R&D has to increase over time to counteract the increasing range and complexity of products that lower the productivity effects of R&D activity.

## 2.1 Empirical models of economic growth

Cointegration analysis and growth regressions are carried out to examine the factors that have been responsible for the British economic growth over the past four centuries. While the cointegration analysis is guided by the analytical framework outlined above, the growth models will be extended to allow for factors explaining growth other than population and innovations, which have been stressed by economic historians in explaining the transition of the British economy from the Malthusian regime to the post-Malthusian growth regime. First consider the cointegration analysis.

Assuming that shocks, $e_t$, are identically and normally distributed with a mean of zero, Eq. 4 forms the following model (see Ha and Howitt 2007):

$$\Delta \ln A_t = \ln \lambda + \sigma \left[ \ln X_t - \ln Q_t + \left(\frac{\phi - 1}{\sigma}\right) \ln A_t \right] + e_t. \tag{5}$$

Given that $\Delta \ln A_t$ is stationary, it follows that variables in the square brackets are cointegrated. Following the parameter restrictions discussed above, semi-endogenous growth theory requires that: (i) both $\ln X_t$ and $\ln A_t$ be non-stationary and integrated at the same order; and (ii) both variables are cointegrated with the cointegrated vector of $\left[1, \frac{\phi-1}{\sigma}\right]$, in which the second element is expected to be negative. Schumpeterian growth theory predicts: (i) $\ln(X/Q)_t$ is stationary; and (ii) $\ln X_t$ and $\ln Q_t$ are cointegrated with the cointegrated vector of $[1, -1]$.

Imposing the restrictions suggested by the two second-generation endogenous growth models implies that the terms $\upsilon_t$ and $\varsigma_t$ in the following equations are stationary:

$$\upsilon_t = \ln X_t + \left(\frac{\phi-1}{\sigma}\right)\ln A_t \quad \text{Semi-endogenous growth theory} \tag{6}$$

$$\varsigma_t = \ln X_t - \ln Q_t. \quad \text{Schumpeterian growth theory} \tag{7}$$

Taking logs of Eq. 2 and combining it with Eq. 6 yields:

$$\begin{aligned}\ln\left(\frac{Y}{L}\right)_t &= \frac{\sigma}{[1-\alpha(1-\beta_t)](1-\phi)}\ln X_t + \frac{\alpha(1-\beta_t)}{1-\alpha(1-\beta_t)}\ln\left[\frac{K}{Y}\right]_t \\ &\quad + \psi_t \ln T_t - \psi_t \ln L_t - \frac{\sigma}{[1-\alpha(1-\beta_t)](1-\phi)}\upsilon_t \end{aligned} \tag{8}$$

Using cointegration technique, Eqs. 7 and 8 can be used to test whether the two second-generation models are consistent with British historical data. Note that the output elasticity of land, $\beta_t$, is allowed to vary over time in Eq. 8, and is computed as the share of agriculture in total GDP. Annual data in the period 1620–2006 are used in the cointegration analysis.

However, cointegration tests are necessary, but not sufficient, conditions for second-generation growth models to be consistent with the growth process (Madsen 2008). A sufficient condition is that these models can explain long-run growth. Furthermore, an important part of this paper is to examine the extent to which productivity growth in Britain has been driven by innovations and other factors that have been highlighted in the economic history literature such as reductions of trade barriers, financial development, technology spillovers from other countries, sectoral movements, availability of coal, and public investment projects. Another aim is to explain the role played by innovations in the transformation of the British economy from the Malthusian trap to the post-Malthusian and modern growth regimes (see Goodfriend and McDermott 1995; Galor and Weil 2000; Hansen and Prescott 2002; Galor 2005).

Consequently, the following growth model is regressed to: (1) examine the importance on growth of innovations and other forces highlighted by economic historians, during the different growth epochs in Britain; (2) discriminate between semi-endogenous and Schumpeterian growth models; and (3) evaluate the importance of demographic transitions on growth during the different phases of the British economic growth experience:

$$\begin{aligned}\Delta\ln y_t &= b_0 + b_1\Delta\ln X_{t-1} + b_2\ln(X/Q)_{t-1} + b_3\psi_{t-1}\Delta\ln L_{t-1} + b_4\Delta\ln\tau_t + b_5\Delta\ln g_t \\ &\quad + b_6\Delta\ln FD_t + b_7\Delta\ln(I/K)_t + b_8\Delta\ln S_t^W + b_9\Delta\ln S_t^{IM} + u_t, \end{aligned} \tag{9}$$

where $y_t$ is labor productivity, $Y/L$; $\tau_t$ is trade barriers and is measured as the ratio of custom duties to imports; $g_t$ is the ratio of government expenditure to GDP; $FD_t$ is financial deepening; $I_t$ is investment; $K_t$ is capital stock; $S_t^W$ is the world stock of knowledge, $S_t^{IM}$ is international knowledge spillovers through the channel of imports, and $u_t$ is a stochastic error term. Here, $X_t$ is measured by the number of patent applications by domestic residents; $Q_t$ is measured by the labor force; $FD_t$ is measured as the ratio of money stock, $M1$, over GDP; $(I/K)_t$ is measured as the ratio of non-residential real gross investment to capital stock. The investment to capital ratio is included in the model to allow for transitional dynamics. The measurement of $S_t^W$ and $S_t^{IM}$ are discussed in the next section. The functional relationship between the innovation variables and growth is derived in Madsen (2008). Equation 9 is estimated in 5-year non-overlapping intervals to overcome cyclical influences and the erratic movements in the data on annual frequencies.

To address the issue of possible reverse causality, lagged population growth, death rates and changes in life expectancy are used as instruments for $\Delta \ln L_t$. Furthermore, the growth in $X$ and $L$ and the level of research intensity are lagged one period. It cannot be ruled out that innovative activity is driven partly by growth to the extent that activities leading to innovations are more affordable during upturns than downturns. Furthermore, Malthusian theory predicts that population growth is positively related to income growth through the channels of fertility and mortality. During the Malthusian period birth rates were potentially positively related to per capita income growth as fertility was increasing when per capita income exceeded subsistence levels and death rates were negatively related to per capita income because hygiene standards, housing quality and nutrition are positively related to income. The estimation results are similar if the growth in $X$ and $L$ and the level of research intensity are unlagged, which suggests that endogeneity is not a serious problem.

Tariff rates are included in the regressions as a proxy for trade barriers. The sum of exports and imports over GDP was also included as a proxy for openness to international trade in the initial regressions but it was found to be insignificant, which may reflect that it is a poor proxy for trade openness. Several theoretical and empirical studies suggest that trade barriers inhibit productivity (see Vamvakidis 2002; Lucas 2007; Madsen 2009). Since tariffs were reduced substantially after the Napoleonic wars they may have played an important role for British economic growth during the nineteenth century. Extraordinarily high tariff rates on imports of agricultural products before 1820 rendered British agricultural production quite profitable and Britain was a net exporter of agricultural products during the First Industrial Revolution (Deane 1969, Chap. 12). The sharp reduction in import tariffs after the Napoleonic Wars reduced the influence of agriculture in total production (Deane 1969, Chap. 12). Since manufacturing was more productive than agriculture the sectoral transitions induced by lower tariff rates would have led to more productivity gains. Furthermore, Britain imported a large volume of commodities which were used as inputs for manufacturing during industrialization. Since changes in the prices of commodities can have large output effects, as shown by Bruno and Sachs (1985), it follows that variations in import tariff rates can also have potentially important output effects.

Williamson and his collaborators have long argued that globalization was an important factor behind the Industrial Revolution in the UK and other countries (see, e.g., O'Rourke and Williamson 2005). This view supports the findings of Allen (2003). The key point is that a large world market was essential for British manufacturing expansion because of the sheer size of the global market. The hypothesis is consistent with the evidence of Clark (1987), which shows that several investment goods used around the world a century ago were manufactured in the UK. Thus, overall, we would expect the reductions in tariff rates to have had important impetuses for the British industrialization.

Government spending is included in the model to allow for positive externalities of government spending and public investment as predicted by the model of Barro (1990). Government spending on education, a good justice system that enforces property rights, a medical system that keeps the labor force healthy, and infrastructure investment are likely to be growth enhancing whereas spending on military and income transfers are not. The presence of a good legal system and enforcement of property rights have been stressed to have played key roles for the First British Industrial Revolution (Deane

1969; Galor 2005). Furthermore, government provision of health and education was considered by Court (1965, pp. 257–267) as being important for the British Industrial Revolution.

Financial development is considered as being potentially influential for British industrialization by rendering access to credit easier and by the creation of a monetary system that eased the payment of manufacturing workers and commercial transactions (Deane 1969, Chap. 11; Court 1965, pp. 59–93). The establishment of the Bank of England in 1694, and the introduction of a money market, checks and an active stock exchange in the late seventeenth century have been described as a financial revolution (Deane 1969, Chap. 11; Rousseau and Sylla 2005). Furthermore, notes issued by the Bank of England and by private banks in the seventeenth and eighteenth centuries, were essential for the development of a modern financial system (Deane 1969, Chap. 11). The ratio of broad money to GDP is used here as a proxy for financial development, which is standard in the literature on financial development and growth (see, e.g., Rousseau and Sylla 2005; Ang and McKibbin 2007; Ang 2010).

Knowledge spillovers are assumed to be transmitted to Britain through the channel of imports, $S^{IM}$, and through channels that are independent of imports, $S^{W}$. Several empirical studies have established that growth in imports of knowledge through the channel of imports play important roles for growth (see, e.g., Madsen 2007b). The importance of foreign knowledge for the British Industrial Revolution has been highlighted by several economic historians. Mokyr (1994) argues that ideas flowed from the Continent to Britain. He maintains that the ideas created on the Continent were turned into practical applications by British engineers and other skilled individuals. More generally, the reduction of traveling time during the nineteenth century increased the international transmission of technology (Clark 2007, Chap. 15). Before that technologies were predominantly transmitted internationally through journeymen and artisans (Clark 2007, Chap. 15).

The growth model is estimated using data covering the period 1620–2005. Different data periods are considered in the estimation to check: (1) the validity of the model during different periods in British history; (2) whether the coefficients are structurally stable; and (3) the extent to which second-generation endogenous growth models can explain different eras of British history and whether these models are consistent with the growth experience since the Scientific Enlightenment or only recently.

The following sample periods are considered in the analyses: 1620–1850, 1760–1850, 1620–1915, 1760–1915, 1620–2005, 1760–2005, 1620–1825, and 1825–2005. These contain the benchmark periods often highlighted in the literature. The period 1760–1850 marks the First Industrial Revolution (Sullivan 1989), 1620–1850 includes the preindustrial period and the First Industrial Revolution, 1620–1915 includes preindustrial and industrial periods (both 1st and 2nd), 1760–1915 includes both industrial revolutions, and 1760–2005 takes into account the post industrial revolution period which also includes the twentieth century. The period 1620–1825 covers the Malthusian era during which technology-induced productivity growth rates were counterbalanced by the population growth drag (Galor 2005) and the period 1825–2005 covers the post-Malthusian and modern growth regimes with innovation-driven growth and a gradual reduction in fertility rates (Galor 2005). Estimation covering the Second Industrial Revolution over the period 1850–1915 and the post-Malthusian growth regime over the period 1825–1890 cannot be undertaken with confidence since it would result in only a few degrees of freedom in the regressions where all variables in Eq. 9 are included.

## 3 Data

Testing the role played by innovations in British growth over the period 1620–2005/2006 is not an easy task because of the difficulties associated with the measurement of labor productivity, innovative activity, and the international transmission of technology. Labor productivity is difficult to measure because the measurement of output is controversial. Harley (1982) and Crafts (1985) argue that the aggregate output data compiled by Deane and Cole (1962), which are available from 1700, tend to overestimate growth during the period 1770–1815. The GDP data from Feinstein (1972) are available first from 1855 whereas data from Lindert and Williamson (1982) are available only for the years 1688, 1759 and 1801/1803. In view of these considerations, we use three different measures of labor productivity that are all spliced with per capita GDP from Maddison (2008) after 1830.

The first measure is GDP per capita using the income data for England and Wales compiled by Clark (2001), henceforth referred to as *YC*. These data are available in decadal frequencies from 1620 and are constructed as the sum of compensation to employees, taxes and rent and deflated by prices on a basket of goods that is considered representative of GDP. The second measure is per capita industrial production compiled by Crafts and Harley (1992) and is available on an annual basis from 1700, henceforth referred to as *IP*. The third measure, which is our preferred measure, is constructed as a weighted average of factor payments:

$$YA_t = \left[\left(\frac{W_t^A}{P_t}\right)^{\beta_t}\left(\frac{W_t^B}{P_t}\right)^{(1-\beta_t)}\right] + \frac{R_t T_t}{P_t L_t}, \tag{10}$$

where $W^A$ is daily wages for agricultural workers from Clark (2007), which are available on an annual basis since 1301, $W^B$ is the unweighted averages of skilled and unskilled labor wages for London and Oxford from Allen (2001), which are available annually from 1264 onwards, $R$ is land rent per acre from Clark (2001), and are available on decadal frequencies, $\beta$ is the share of agriculture in total GDP, and $P$ is the consumer price level. Factor shares are adjusted to match the decadal factor share data estimated by Clark (2001). Like the GDP estimates of Clark (2001) this measure has the advantage of covering all factor payments in the economy; however, in contrast to Clark's data the *YA* data are available in annual frequencies. Since annual data are used in the cointegration analysis in the next section and the VARs estimation of the growth equation, the annual data are clearly preferable to Clark's decadal data. The main advantage of using economy-wide data as opposed to real wages as a measure of labor productivity is that variations in land rent are accounted for. This is particularly important in medium-term frequencies where real wages may deviate from labor's marginal productivity because of rigid wages and prices (Bruno and Sachs 1985).

Although the post-1830 per capita GDP data from Maddison (2008), which are mainly based on Feinstein (1972) estimates, are probably the mostly widely used and accepted data, they do have pitfalls. Income and population data cover the Republic of Ireland up to its independence in 1922. Data covering Britain only during the period 1830–1922 are not yet available.[1] The inclusion of Ireland in this period gives rise to two potential problems. First, the Great Irish Famine in the mid nineteenth century resulted in a temporary but marked decline in the Irish population. Since the Malthusian mechanism is catered for in the model this dip in the population size should not constitute a problem; however, such a large shock may affect the dynamic adjustment and, as such, interfere with the estimates. To overcome

[1] While the United Kingdom includes the Republic of Ireland during the British rule over the period 1801–1922, we use the term Britain throughout the manuscript because the Republic of Ireland is not included in the data in most of the estimation periods.

this problem an impulse dummy was included in 1855. Second, when Ireland gained independence, the size of the population in Maddison's data shrunk by three million. Since GDP is reduced by almost the same proportion, per capita GDP is not too severely affected by the transition. However, the population growth rate shrinks artificially and, therefore, gives rise to a measurement error in population growth in 1923. Another impulse dummy variable is included in the estimation to address this problem.

The number of patent applications by domestic residents as opposed to patents granted is used as the measure of innovative activity ($X_t$) since the processing periods vary substantially over time (Griliches 1990). Patent data are available back to 1620. They are measured directly from patent counts without errors, and are the only currently available historical data on innovative activity. The main criticisms of using patents as measures of innovative activity are that the quality of patents varies over time, not all innovations are patented, the propensity to patent may change over time, and the high costs of patenting give inventors strong incentives to keep their inventions secret (see Boehm and Silberston 1967). While the law of large numbers tends to render the average quality of patents relatively constant in recent years (Griliches 1990), this law is unlikely to hold in the early part of the sample period when the number of patents was quite modest.

A major concern is whether the propensity to patent has changed over four centuries considered in this study. In probably the most detailed examination of the quality of British patents over the past four centuries, Sullivan (1989) does not find any evidence of shifts in the propensity to patent in individual industries nor changes in the industrial distribution of patents. Regarding the expense of patents, their high costs of acquisition should at least, in principle, have led to patents of higher quality and, as such, weeded out low-quality ones that are unimportant for growth. Thus, high costs of patents may improve their average quality as a measure of innovative activity. This line of reasoning is supported by the findings of Khan and Sokoloff (2007). They find that 87% of the great inventors in Britain over the period from 1750 to 1930 were patentees, indicating that most of the important innovations have been captured by patent counts.

Another concern is that major innovations such as the steam engine, the Spinning Jenny, Crompton's mule and the flying shuttle are hardly visible in the patent statistics. In this context it is important to note that it was a large series of subsequent patentable innovations that rendered mega innovations commercially viable. The Newcomen steam engine of 1769 consumed coal at the cost of GBP 3,000 per annum, whereas 500 horses with the same power cost only GBP 900 per annum (Greenwood 1999). However, several innovations over the course of the First Industrial Revolution gradually rendered the steam engine much more cost effective. The cost per unit of horse power was reduced from GBP 30 to 2.5 over less than a century (Greenwood 1999). The important lesson is that, although the Industrial Revolution produced only a handful of miracles, the subsequent array of small innovations following the grand innovations was an important factor behind the success of the British economy.

The importance of small inventions to support the major inventions is most clearly articulated by Mokyr (1990), who distinguishes between microinventions and macroinventions. Microinventions are small, incremental improvement steps on existing production techniques that increase the durability and the quality of the product and reduce the costs of production. Macroinventions, on the other hand, are known as 'strokes of genius, luck or serendipity', which are radically new important ideas. Although less frequent, they are equally important and complement microinventions. According to Mokyr (1990), microinventions are more frequent and account for most gains in productivity. These inventions are much more correlated to output and employment than macroinventions.

Griliches (1990, p. 1702) concludes that "in spite of all the difficulties, patent statistics remain a unique resource for the analysis of the process of technical change". Furthermore, Madsen (2007a) finds that the null hypothesis of constant returns to R&D cannot be rejected, which implies that there is a proportionality between R&D and patent applications. However going back as far as four centuries, one cannot deny that there are flaws in patents as indicators of innovative activity. What this essentially means is that the number of patents is potentially a noisy measure in most parts of the estimation period and, as such, may bias the parameter estimates towards zero. Thus, our estimates are likely to understate the importance of innovative activity for growth during the past four centuries of British history. Another benefit of using patents as the measure of innovative activity is that it is consistent with the hypothesis that the institutionalization of a patent system in Britain long before other countries may have helped Britain to industrialize earlier than the rest of the world.

The two knowledge spillover variables, $S^W$ and $S^{IM}$, are measured as follows. The world stock of knowledge, $S^W$, is measured as the sum of patent stock in the US, France and the Netherlands over the period from 1791 to 1870 and, thereafter, spliced with the sum of patent counts for the 21 OECD countries listed in the Data Appendix of Madsen et al. (2010).[2] Following the approach of Coe and Helpman (1995) knowledge spillovers through the channel of imports is constructed as:

$$S^{IM} = \frac{IM^M}{Y^N} \sum_{j=1}^{N} \frac{IM_j}{IM} \ln S_j, \quad j = 1, 2, \ldots, N. \tag{11}$$

where $IM^M$ is the British manufactured imports, $Y^N$ is British nominal GDP, $IM_j$ is imports of goods from country $j$ to Britain, $IM$ is total imports of goods to Britain, and $Sj$ is the patent stock in country $j$. The countries included in the estimation of $Sj$ are the sample of those used to construct $S^W$. The share of manufactured imports in total income and not the total import share as in Coe and Helpman (1995) is used to construct $S^{IM}$. This is because a high share of British imports during the seventeenth and eighteenth and most of the nineteenth century consisted of raw materials and agricultural products and hence technology is highly unlikely to be transmitted internationally through imports of commodities.

The international technology variables start from a very low base in 1791, when the data become available, and international technology spillovers first start gaining momentum in the mid nineteenth century. Coupled with the fact that British manufactured imports relative to GDP were miniscule at the beginning of the nineteenth century, technology transmission through the channel of imports could not have played much of a role around 1800. As such international knowledge transmission through channels independent of imports, was potentially more important. Although the technologies used in Britain were invented elsewhere, it is not entirely clear how foreign inventions reached Britain and the extent to which they had a significant impact on British productivity growth. The empirical application of the Mokyr (1994) hypothesis that Britain applied the ideas created on the Continent is rendered difficult by the long and time-varying lag between the creation and the application of an idea. Probably the most direct route through which technologies were transmitted was through journeymen; however, no such data are currently available.

[2] We also included the number of important scientists in the world excluding Britain in the initial regressions. However, the coefficient was insignificant in the regressions.

### 3.1 Graphical analysis

The paths of the three productivity series are displayed in Fig. 1. Clark's productivity data (*YC*) follow the trend of the data based on Eq. 10, (*YA*), which is not surprising since they are constructed based on the same method and, to a large extent, the same data. The decline in productivity in the period 1784–1800 is likely to be a result of a series of crop failures (Deane 1969, Chap. 11) and that major innovations are initially counterproductive because the initial incarnations of the new ideas are slow and wasteful (Greenwood 1999). The steam engine and Cort's puddling and rolling process were commercially unsuccessful because they were inefficient, required training and education of skilled operators, and the quality of the steam engine and the puddling and rolling process varied. Note that the argument that mega innovations are initially counter-productive seems to be inconsistent with the increasing industrial production per worker (*IP* series) during the period 1784–1800. However, since IP is measured as industrial production as a proportion of the total labor force and not in proportion to the manufacturing labor force, one cannot be certain whether industrial labor productivity increased, remained unchanged or fell during the period 1784–1800.

Looking at the long-run path, labor productivity remained pretty flat up to around 1825 and, this therefore, can be considered as the Malthusian period in which per capita output is kept down by population growth. Industrial productivity increased slowly during the eighteenth century and gained momentum in the nineteenth century. Common to all indicators of productivity is a steep increase during the later part of the First Industrial Revolution in the period 1820–1950, indicating the completion of the learning period and the appearance of supportive innovations that were required to render the mega-innovations efficient and economically viable. A similar delay in productivity gains can be traced back to after the Second Industrial Revolution, during which time the most significant innovations were the generation of electricity (the dynamo), the electric globe, telecommunication and the combustion engine. The strongest productivity gains were not during the Second Industrial Revolution 1860–1913, but thereafter.

Based on the *YA* measure, annualized productivity growth rates in 5-year intervals are displayed in Fig. 2. Productivity growth can naturally be subdivided into the Malthusian epoch with average annual growth rates of 0.07% (1620–1825), the post-Malthusian growth regime with average growth rates of 1.28% (1825–1890) and the modern growth regime with average growth rates of 1.49% (1890–2005) (Galor 2005). Although the First Industrial Revolution started around 1760, labor productivity growth rates remained miniscule up to circa 1825. This may seem paradoxical, given the high and increasing level of innovative

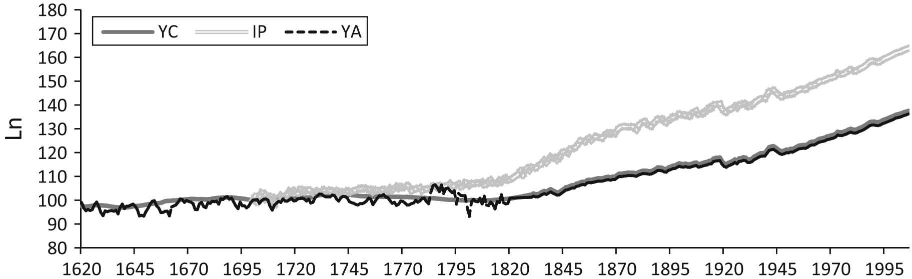


**Fig. 1** Productivity series, 1620–2005 (on log scale, 1700 = 100). *Notes*: *IP*, per capita industrial production; *YC*, Clark (2001) per capita GDP, which are both available on decadal frequencies; and *YA*, annual GDP estimates based on real wages and land rent (Eq. 10)


**Fig. 2** Annual growth rates of labor productivity, 1620–2005. *Notes*: Data in this figure are measured in 5-year differences. The growth rates, which are based on the *YA* measure, are annualized

activity. However, Britain was still trapped in the Malthusian regime in which the improved living standards derived from technological progress were translated into increasing population growth rates. Population growth rates increased gradually from zero at the beginning of the eighteenth century to 1.5% at the beginning of the nineteenth century, as shown in Sect. 5 below. With population growth rates of 1.5%, significant technological progress was required just to maintain living standards at constant levels during the first phase of the Industrial Revolution.

Figure 3 shows the time-path of the log of the number of patents. The First and Second Industrial Revolutions are easily identifiable from the surge in patenting activity after circa 1750. The increase in patenting activity was brought to an end at the peak of the Second Industrial Revolution around 1890. The surge in patenting activity during the Industrial Revolutions is still visible from the data when patents are normalized by the labor force (Fig. 4). Figure 4 shows that research intensity $(X/Q)$ increased over the first three centuries and stabilized after 1890. Apart from the period 1750–1820, the trends in per capita income growth rates and research intensity approximately coincide, as predicted by Schumpeterian growth theories. The gap between research intensity and productivity growth during this period is due to an extraordinarily high population growth rate during that period.

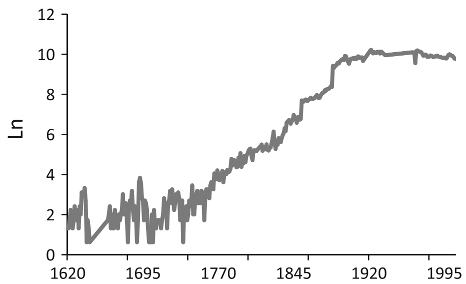


**Fig. 3** Number of patent applications by domestic residents, 1620–2005. *Notes*: The data are in 5-year averages

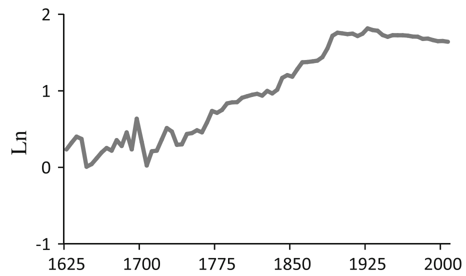


**Fig. 4** The ratio of domestic patent applications to the labor force. *Notes*: The data are in 5-year averages

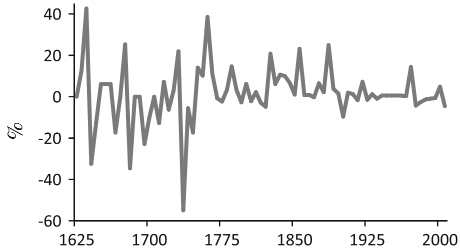


**Fig. 5** Annual growth rates of patent applications.

Finally, Fig. 5 displays the growth rates of patent applications. The data are annualized growth rates in 5-year intervals. Semi-endogenous growth theory predicts a positive relationship between per capita income growth and growth in innovative activity. Comparing Figs. 2 and 5, there is no clear-cut relationship between growth in patents and labor productivity growth, particularly after 1800. Thus, these diagrams give no clear evidence in favor of semi-endogenous growth theory.

## 4 Regression results

Integration and cointegration tests are undertaken to test the long-run relationships predicted by semi-endogenous and Schumpeterian growth theories (Eqs. 8 and 7, respectively). The growth equation (Eq. 9) is estimated in the second part of this section. Labor productivity is measured by *YA* (Eq. 10) throughout this section. The estimates in which per capita industrial production (*IP*) and Clark's per capita income data (*YC*) are used to measure labor productivity are reported in Appendix 1 of Madsen et al. (2010). However, the main results from these estimates are briefly discussed in Sect. 4.2.

### 4.1 Integration and cointegration analyses

First, integration and cointegration tests are applied to Eqs. 7 and 8. Annual data are used in all estimations in this sub-section. Unit root tests for the entire sample period are performed using the conventional Augmented Dickey–Fuller (ADF) and the Zivot and Andrews (1992) tests, where the latter accounts for the possible presence of an endogenous structural break. It tests the null of a unit root against the alternative of trend stationarity with an unknown break in the series.

The results of the unit root tests presented in Table 1 show that $\ln X_t$, $\psi_t \ln T_t$, and $\psi_t \ln L_t$ are integrated at order one, regardless of which test is applied. However, $\ln(Y/L)_t$ and $\ln(K/Y)_t$ are found to contain a unit root according to the conventional ADF tests but the Zivot–Andrews tests suggest stationarity once a structural break is allowed for. The results underscore the importance of estimating the models for different sub-sample periods. When the *YC* and *IP* series are used as alternative measures of labor productivity, both tests suggest that labor productivity contains a unit root (see Appendix 1, Madsen et al. 2010). Research intensity ($\ln(X/Q)_t$) is found to be stationary, as predicted by Schumpeterian growth theory under the maintained assumption that productivity growth is stationary. The null hypothesis of stationarity is rejected at the 1% level and the test results are insensitive to the choice of unit root tests.

Turning to the cointegration analysis, it is tested whether $\ln(Y/L)_t$, $\ln X_t$, $\ln(K/Y)_t$, $\psi_t \ln T_t$ and $\psi_t \ln L_t$ are cointegrated (semi-endogenous growth) and whether $\ln X_t$ is

**Table 1** Unit root tests (1620–2006)

| | ADF | | Zivot–Andrews | | Conclusion |
|---|---|---|---|---|---|
| | Levels | 1st differenced | Levels | 1st differenced | |
| Labor productivity | −0.43 | $-9.93^{\#}$ | $-7.40^{\#}$ | $-14.52^{\#}$ | $I(0)/I(1)$ |
| $[\ln(Y/L)_t]$ | (0.98) | (0.00) | (BP = 1800) | (BP = 1814) | |
| Patent applications | −2.79 | $-12.73^{\#}$ | −4.18 | $-13.05^{\#}$ | $I(1)$ |
| $(\ln X_t)$ | (0.21) | (0.00) | (BP = 1853) | (BP = 1706) | |
| Capital deepening | −2.11 | $-9.39^{\#}$ | $-5.77^{\#}$ | $-22.14^{\#}$ | $I(0)/I(1)$ |
| $[\ln(K/Y)_t]$ | (0.54) | (0.00) | (BP = 1762) | (BP = 1802) | |
| Land | −1.59 | $-4.42^{\#}$ | −1.57 | $-21.91^{\#}$ | $I(1)$ |
| $[\psi_t \ln T_t]$ | (0.79) | (0.00) | (BP = 1945) | (BP = 1679) | |
| Population growth drag | −0.86 | $-4.65^{\#}$ | −3.32 | $-21.265^{\#}$ | $I(1)$ |
| $[\psi_t \ln L_t]$ | (0.96) | (0.00) | (BP = 1877) | (BP = 1853) | |
| Patent applications/labor force | $-4.01^{\#}$ | $-12.79^{\#}$ | $-5.24^{+}$ | $-13.08^{\#}$ | $I(0)$ |
| $[\ln(X/Q)_t]$ | (0.00) | (0.00) | (BP = 1884) | (BP = 1706) | |

*Notes*: *p*-Values for the ADF tests are indicated in parenthesis. For the Zivot–Andrews tests in levels, the 1 and 5% critical values are −5.57 and −5.08, respectively. In first-differenced form, the values are −5.43 and −4.80, respectively. The endogenously determined break point (BP) for each series is indicated in parentheses $^{+}$ and $^{\#}$ indicate 5 and 1% significance, respectively. The labor productivity data are based on *YA*

cointegrated with $\ln Q_t$ (Schumpeterian growth). Tables 2 and 3 display the results of these cointegration tests. The results are based on the Johansen (1988) procedures. First, consider the results for semi-endogenous growth theory in Table 2. Except for one case, the results in columns (2) and (3) show that the variables in Eq. 8 are either not cointegrated or have more than one cointegrating vector. These results are inconsistent with the prediction of only one cointegrated relationship among the variables by semi-endogenous growth theory (see the derivation in Eq. 8). Moreover, although innovative activity $(\ln X_t)$ enters the equation significantly in some cases, in half of the cases the coefficients are either insignificant or significant but have the wrong sign. The coefficients of $\psi_t \ln L_t$ are either statistically insignificant or of the wrong sign when significant. Finally, the coefficients are highly sensitive to the estimation periods.

Overall the results in Table 2 provide no support for semi-endogenous growth theory. The same conclusion is reached when the Malthusian era (1620–1825) and the modern growth regimes period (1825–2005) are considered (as shown in Appendix 2, Madsen et al. 2010). The results are also consistent when the other two labor productivity measures, *YC* and *IP*, are used (see Appendix 1, Madsen et al. 2010).

On the other hand, the cointegration results in Table 3 provide strong support for Schumpeterian growth theory. The null hypothesis of no cointegration between innovative activity $(\ln X_t)$ and product variety $(\ln Q_t)$ is rejected in all cases. Furthermore, the coefficients of $\ln Q_t$ are statistically and economically significant at the 1% level in all cases and are quite stable across periods. The statistical and economic significance of the coefficients of the error-correction term provides further evidence in favor of the presence of a long-run relationship between the variables. On average, the economy takes about 6 years to adjust towards equilibrium following a shock to the steady state (the inverse of the average coefficients of the ECT terms). Finally, the coefficients of product variety are quite consistent across time

**Table 2** Johansen cointegration tests for semi-endogenous growth theory (Eq. 8)

| (1) Period | (2) No. of CEs based on trace test | (3) No. of CEs based on max-eigenvalue test | (4) Cointegrating vector $[\ln Y/L,\ \ln X,\ \ln K/Y,\ \psi_t \ln T,\ \psi_t \ln L]$ | | | | | (5) *ECT* |
|---|---|---|---|---|---|---|---|---|
| 1620–1850 | 3 | 2 | 1.00 | −0.05 | −0.12$^{+}$ | −0.08 | 0.58 | −0.30$^{\#}$ |
| | | | | [−1.24] | [−2.27] | [−0.33] | [0.78] | [−6.36] |
| 1760–1850 | 3 | 0 | 1.00 | −0.18$^{\#}$ | 0.85$^{\#}$ | −0.07 | −2.36$^{\#}$ | −0.42 |
| | | | | [−6.71] | [21.25] | [−0.60] | [−5.51] | [−1.08] |
| 1620–1913 | 4 | 4 | 1.00 | −0.22$^{\#}$ | −0.12$^{+}$ | −0.53* | −0.22 | −0.12$^{\#}$ |
| | | | | [−4.66] | [−2.11] | [−1.85] | [−0.45] | [−4.94] |
| 1760–1913 | 3 | 1 | 1.00 | 0.11 | −0.80 | −0.49 | −0.50 | −0.03$^{+}$ |
| | | | | [0.44] | [−1.43] | [−0.41] | [−0.38] | [−2.01] |
| 1620–2006 | 4 | 4 | 1.00 | −5.51$^{\#}$ | −7.76$^{\#}$ | −35.33$^{\#}$ | −40.78$^{\#}$ | −0.01 |
| | | | | [−3.29] | [−4.14] | [−3.43] | [3.79] | [−0.89] |
| 1760–2006 | 2 | 2 | 1.00 | 0.61$^{+}$ | −1.09$^{+}$ | 1.44 | −3.17$^{\#}$ | −0.01 |
| | | | | [2.24] | [−2.52] | [0.97] | [−3.32] | [−0.83] |

*Notes*: The results show the number of cointegrated equation(s) found based on the trace and maximum-eigenvalue tests using the 5% decision rule. An intercept but no trend is included in the estimation. The optimal lag length is pinned down using the SBC. Critical values are taken from Mackinnon et al. (1999). *ECT* is the error-correction term associated with the $\Delta\ln(Y/L)$ equation. Figures in parenthesis indicate $t$-statistics *, $^{+}$ and $^{\#}$ indicate 10, 5 and 1% levels of significance, respectively. $Y/L$ is measured using the *YA* series

**Table 3** Johansen cointegration tests for Schumpeterian growth theory (Eq. 7)

| Period | Hypothesis | Trace statistic | Max-eigenvalue statistic | Cointegrating vector $[\ln X_t,\ \ln Q_t]$ | *ECT* |
|---|---|---|---|---|---|
| 1620–1850 | $r = 0$ | 32.02$^{\#}$ | 25.21$^{\#}$ | 1.00, −2.92$^{\#}$ | −0.37$^{\#}$ |
| | $r \leq 1$ | 6.81 | 6.81 | [−5.89] | [−5.93] |
| 1760–1850 | $r = 0$ | 23.47$^{\#}$ | 15.26$^{+}$ | 1.00, −2.17$^{\#}$ | −0.16$^{+}$ |
| | $r \leq 1$ | 8.21 | 8.21 | [−6.46] | [−1.97] |
| 1620–1913 | $r = 0$ | 34.43$^{\#}$ | 27.49$^{\#}$ | 1.00, −2.97$^{\#}$ | −0.12$^{\#}$ |
| | $r \leq 1$ | 6.94 | 6.94 | [−12.53] | [−2.86] |
| 1760–1913 | $r = 0$ | 19.18$^{+}$ | 17.41$^{+}$ | 1.00, −3.31$^{\#}$ | −0.16$^{\#}$ |
| | $r \leq 1$ | 1.88 | 1.88 | [−28.36] | [−4.23] |
| 1620–2006 | $r = 0$ | 32.65$^{\#}$ | 31.72$^{\#}$ | 1.00, −3.25$^{\#}$ | −0.12$^{\#}$ |
| | $r \leq 1$ | 0.93 | 8.08 | [−26.63] | [−3.93] |
| 1760–2006 | $r = 0$ | 16.38$^{+}$ | 9.37 | 1.00, −2.21$^{\#}$ | −0.05$^{\#}$ |
| | $r \leq 1$ | 7.02 | 7.02 | [−7.60] | [−3.02] |

*Notes*: The null hypothesis is that there is $r$ cointegrated relationships between the variables. An intercept but no trend is included in the estimation. The optimal lag length is determined by SBC. Critical values are taken from Mackinnon et al. (1999). *ECT* is the error-correction term associated with the $\Delta\ln X$ equation. Figures in parentheses are $t$-statistics

$^{+}$ and $^{\#}$ indicate 5 and 1% levels of significance, respectively

**Table 4** Parameter estimates of Eq. 9

| Period | $\Delta\ln X_{t-1}$ | $\ln(X/Q)_{t-1}$ | $\psi_{t-1}$ $\Delta\ln L_{t-1}$ | $\Delta\ln\tau_t$ | $\Delta\ln g_t$ | $\Delta\ln FD_t$ | $\Delta\ln(I/K)_t$ | $\Delta\ln S_t^{W}$ | $\Delta\ln S_t^{IM}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1620–1850 | −0.007 | | −6.931$^{+}$ | | | | | | |
| | (0.756) | | (0.038) | | | | | | |
| | | 2.439$^{+}$ | −8.077$^{+}$ | | | | | | |
| | | (0.023) | (0.027) | | | | | | |
| | −0.024 | 2.706$^{+}$ | −9.035$^{+}$ | | | | | | |
| | (0.385) | (0.028) | (0.021) | | | | | | |
| | −0.014 | 6.684$^{+}$ | −8.910$^{+}$ | 0.746$^{\#}$ | 0.209$^{\#}$ | 0.019$^{\#}$ | −0.001 | 0.169* | −1.379 |
| | (0.517) | (0.016) | (0.019) | (0.000) | (0.009) | (0.004) | (0.999) | (0.079) | (0.183) |
| 1760–1850 | −0.177 | | −15.314 | | | | | | |
| | (0.294) | | (0.201) | | | | | | |
| | | 5.754 | −8.266 | | | | | | |
| | | (0.372) | (0.402) | | | | | | |
| | −0.185 | 5.262 | −21.176 | | | | | | |
| | (0.365) | (0.375) | (0.176) | | | | | | |
| | −0.025 | 23.077$^{+}$ | −23.761 | 0.712$^{+}$ | 0.299$^{+}$ | −0.314 | −1.175$^{+}$ | 0.131 | −3.968* |
| | (0.817) | (0.034) | (0.122) | (0.011) | (0.011) | (0.108) | (0.029) | (0.263) | (0.027) |
| 1620–1915 | 0.007 | | −5.403* | | | | | | |
| | (0.758) | | (0.094) | | | | | | |
| | | 1.573$^{\#}$ | −6.119* | | | | | | |
| | | (0.002) | (0.066) | | | | | | |
| | −0.002 | 1.622$^{\#}$ | −6.329* | | | | | | |
| | (0.921) | (0.004) | (0.067) | | | | | | |
| | 0.018 | 0.610 | −4.542* | 0.525$^{\#}$ | 0.098 | 0.012* | 0.312$^{+}$ | 0.195$^{\#}$ | 0.424$^{+}$ |
| | (0.365) | (0.521) | (0.099) | (0.000) | (0.137) | (0.060) | (0.032) | (0.002) | (0.045) |
| 1760–1915 | −0.039 | | −4.768 | | | | | | |
| | (0.648) | | (0.438) | | | | | | |
| | | 2.782$^{+}$ | −6.031 | | | | | | |
| | | (0.043) | (0.299) | | | | | | |
| | −0.018 | 2.664$^{+}$ | −6.388 | | | | | | |
| | (0.828) | (0.035) | (0.270) | | | | | | |
| | 0.029 | 0.363 | −2.730 | 0.399$^{+}$ | 0.084* | −0.501$^{+}$ | 0.293$^{+}$ | 0.240$^{+}$ | 0.331$^{+}$ |
| | (0.607) | (0.794) | (0.502) | (0.013) | (0.064) | (0.025) | (0.026) | (0.020) | (0.035) |
| 1620–2005 | 0.012 | | −3.737 | | | | | | |
| | (0.587) | | (0.207) | | | | | | |
| | | 1.512$^{\#}$ | −4.394 | | | | | | |
| | | (0.000) | (0.154) | | | | | | |
| | 0.004 | 1.531$^{+}$ | −4.702$^{+}$ | | | | | | |
| | (0.896) | (0.040) | (0.049) | | | | | | |
| | 0.007 | 1.593$^{+}$ | −3.895* | 0.046 | 0.077* | −0.001 | 0.026 | 0.198$^{\#}$ | −0.045 |
| | (0.813) | (0.023) | (0.084) | (0.305) | (0.043) | (0.976) | (0.789) | (0.004) | (0.603) |

**Table 4** continued

| Period | $\Delta\ln X_{t-1}$ | $\ln(X/Q)_{t-1}$ | $\psi_{t-1}\Delta\ln L_{t-1}$ | $\Delta\ln\tau_t$ | $\Delta\ln g_t$ | $\Delta\ln FD_t$ | $\Delta\ln(I/K)_t$ | $\Delta\ln S_t^W$ | $\Delta\ln S_t^{IM}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1760–2005 | −0.043 | | −4.617 | | | | | | |
| | (0.578) | | (0.458) | | | | | | |
| | | $2.595^+$ | −4.089 | | | | | | |
| | | (0.011) | (0.380) | | | | | | |
| | 0.001 | $2.601^\#$ | −4.081 | | | | | | |
| | (0.993) | (0.009) | (0.360) | | | | | | |
| | 0.032 | $3.797^\#$ | −2.163 | 0.032 | 0.043 | $-0.444^+$ | −0.064 | $0.255^+$ | −0.043 |
| | (0.594) | (0.000) | (0.557) | (0.377) | (0.135) | (0.049) | (0.398) | (0.013) | (0.466) |

*Notes*: The Newey–West procedure was used to obtain heteroskedasticity consistent robust estimates. An intercept was included in the estimation but the estimates are not reported. $p$-Values are reported in parentheses $^*$, $^+$ and $^\#$ denote significance levels at 10, 5 and 1%, respectively. The dependent variable is $\Delta\ln YA$

periods, suggesting that a stable functional relationship exists between product varieties and innovative activity, as predicted by Schumpeterian growth theory.

### 4.2 Estimates of labor productivity growth

The results of regressing Eq. 9 are presented in Table 4.[3] Four sets of results are presented: three sets of regressions without control variables and with different combinations of the innovative activity variables and one regression including all variables contained in Eq. 9. The coefficients of population growth are consistently negative and significant in the regressions covering the earlier centuries of the sample. Similar results are obtained when Clark's income data (*YC*) are used, as shown in Madsen et al. (2010) (see Appendix 1). The results are reasonably consistent with the finding in the literature that real wages respond negatively to population growth in Britain (Anderson and Lee 2002; Nicolini 2007; Crafts and Mills 2009). The principal difference between this study and those of Anderson and Lee (2002), Nicolini (2007) and Crafts and Mills (2009) is that they regress real wages on population and let the constant term varies over time to allow for the upward drift in labor demand, which is driven entirely by technological progress along the balanced growth path. They do not allow the coefficients of the population drag to change over time to account for the reductions in this variable as land's importance as a factor of production diminishes.

Interestingly, the population growth drag loses some of its significance when labor productivity growth is measured by per capita industrial production, *IP*, as shown in Madsen et al. (2010) (Appendix 1) or when it is based on Clark's (2005) data on growth in urban real wages (results are not shown). These results give further support to the Malthusian theory where population growth is a drag on the economy through allowing for land as a non-reproducible factor of production that introduces diminishing returns as the population grows. Since the

[3] The following five dummy variables were initially included in the regressions, however, they were subsequently omitted from the regressions since the estimates were unaffected by their inclusion. The first dummy captures the abrupt changes in per capita GDP growth during the period 1645–1660. The second dummy captures the sudden increases in per capita growth in the years 1780–1810. The third dummy captures the severe negative growth in per capita GDP in the years 1915–1930. The fourth dummy captures the Great Irish Famine during the period 1847–1851. The fifth dummy is in 1925, spanning the period 1950–1925, as the Irish Republic becomes independent from Britain in 1922.

Malthusian mechanism is not directly operative in the urban sector, where land is not an important factor of production, these results underscore the point that population growth influences growth predominantly through land, rather than through other channels that have been highlighted in the literature.

The coefficients of growth in patenting ($\Delta \ln X_t$) are all insignificant while the coefficients of research intensity ($\ln(X/Q)_t$) are highly significant in almost all cases regardless of the estimation periods and regardless of whether control variables are included. This result is also not very sensitive to the use of different labor productivity measures (see Madsen et al. 2010, Appendix 1) and an alternative estimator (see Madsen et al. 2010, Appendix 3 for VAR estimates). Moreover, the coefficients of research intensity are quite stable across the regressions, except for the period 1760–1850 in which they are sensitive to the inclusion of control variables. However, with only ten degrees of freedom in this period it is not surprising that the parameter estimates are sensitive to model specifications and that the coefficients have low significance levels.

Economic and statistical significance of the coefficients of research intensity ensure that R&D as a proportion of the labor force has permanent growth effects. The only mechanism that prevents the economy from growing on a positive perpetual path is the population growth drag. This kept labor productivity growth rates down during the Malthusian and, to some extent, the post-Malthusian growth period. The declining agricultural share during the nineteenth century along with lower fertility rates has reduced the population growth drag to a negligible magnitude and the economy entered a balanced growth path where growth was driven almost entirely by research intensity.

The coefficients of the control variables vary in significance. The coefficients of the growth in the ratio of government expenditure to GDP are in most instances significant, suggesting that public spending has been an important factor behind British growth over the past four centuries. Given its aggregate nature and the unavailability of itemized government spending data over the entire sample period, it is difficult to pinpoint the exact growth-inducing components of government spending. In all instances the results do suggest that the growth in government expenditures have played a positive role for British productivity growth over the past four centuries. The coefficients are particularly significant for the first two centuries, suggesting positive government involvement during the First Industrial Revolution. The significance of government expenditure is particularly noteworthy given that public spending blew out during wars, presumably without having significant productivity consequences.

The coefficients of tariff rates are consistently positive and statistically significant in two thirds of the cases. These results are, perhaps, not surprising given that the historical literature has been struggling to find a significant negative relationship between productivity growth and trade barriers (see, e.g., Vamvakidis 2002; Madsen 2009). Coupled with the fact that openness was also insignificant in the initial regressions, the results suggest that a large outside market has not been vital for the British take-off during the Industrial Revolutions. Thus, there is no strong evidence indicating that access to a large foreign market was vital for the success of the British Industrial Revolutions. The results are consistent with the findings of Oxley and Greasley (1998).

The coefficients of financial development also have conflicting signs and vary in significance, which may indicate that a large fraction of the credit was channeled to consumption instead of productive investment. Historical evidence for the UK indeed suggests that the landed class increased borrowing substantially during the Industrial Revolution and used the funds for consumption rather than for industrial investment (Doepke and Zilibotti 2008). Had the access to credit predominantly benefitted the industrial class we would probably have found financial development to have been positive for growth. The coefficients of the $I$–$K$

ratio are significant in some of the cases but are mostly insignificant and are of conflicting signs, indicating that transitional dynamics have not been very important for the British growth experience.

Turning to the technology spillover variables, the coefficients of $\ln S^W$ are significant and positive in almost all cases. This result is not surprising given that technology spillovers have been stressed in the literature on British economic history and recent developments in endogenous growth theories. What is surprising, however, is that the coefficients of $\ln S^{IM}$ are rarely economically and statistically significant, which may reflect a small sample bias or that the British experience is different from that of other OECD countries. In any event, the primary result is that technology spillovers do play a significant role for growth in Britain.

### 4.3 Robustness of growth model with additional control variables

Special attention has been given to coal production, urbanization and sectoral changes as important factors behind the British Industrial Revolutions. This sub-section investigates the importance of these variables for growth during the period 1700–1915 and checks whether research intensity and the population growth drag remain significant determinants for growth when these additional control variables are allowed for. The estimation period is limited to 1700–1915, as dictated by the availability of data.

Extending Eq. 9 with these additional control variables yields the following model:

$$\begin{aligned}\Delta \ln y_t = {} & a_0 + a_1 \Delta \ln X_{t-1} + a_2 \ln(X/Q)_{t-1} + a_3 \psi_{t-1} \Delta \ln L_{t-1} \\ & + a_4 \Delta \ln \tau_t + a_5 \Delta \ln g_t + a_6 \Delta \ln FD_t \\ & + a_7 \Delta \ln(I/K)_t + a_8 \Delta \ln S_t^W + a_9 \Delta \ln S_t^{IM} + a_{10} \Delta \ln UR_t \\ & + a_{11} \Delta \ln Coal_t + a_{12} \Delta \ln \theta_t^{IP} + a_{12} \Delta \ln \theta_t^{Ag} + u_{1,t},\end{aligned} \tag{12}$$

where $UR_t$ is urbanization, $Coal_t$ is coal production in British coal mines, $\theta_t^{IP}$ is the share of industrial production in total economic activity, and $\theta_t^{Ag}$ is the agricultural share in total economic activity.

Urbanization is measured as the fraction of the population living in cities over the size of 20,000. Urbanization is included in the regressions as a proxy for the division of labor. The importance of division of labor for growth has been particularly emphasized by Smith (1776). The idea is that per capita income growth is a result of either technical progress or more efficient use of the existing technology. Division of labor will potentially increase the effectiveness of the existing technology and temporarily increase growth. Urbanization is used as a proxy for the division of labor because it requires higher population densities—division of labor starts with the formation of towns. Allen (2003) argues that urbanization promoted agricultural productivity, which in turn impacted positively on productivity throughout the economy.

Pomeranz (2001) argues that the availability of coal was a key factor for Britain's take-off and the reason why it industrialized earlier than China and other Asian countries. In the absence of easily accessible energy resources, he suggests that the British Industrial Revolution would have been delayed, possibly substantially. The steam engine, which was essential for industrialization, initially consumed a huge amount of coal and, as such, was only economically viable in areas in which coal was easily available. As such, coal production is included in the regression as an additional regressor to cater for Pomeranz (2001) hypothesis.

The shares of agriculture or industry in total economic activity are often stressed as sources of economic growth (see, e.g., Hobsbawm 1962) where productivity is expected to be negatively related to the agricultural share and positively related to the industrial share. The argument is simply that productivity is automatically enhanced as labor moves from the low productivity agriculture sector to the higher productivity manufacturing sector. However, Peretto and Seater (2008) show that sectoral transitions are endogenous responses to returns from R&D and sectoral transitions, and as such, cannot be treated as an exogenous force. Other theories of sectoral transformations show that manufacturing takes over from agriculture because income elasticities are higher for manufacturing than for agricultural products (Kongsamut et al. 2001). Since income is driven by technological progress in these models we again arrive at the conclusion that sectoral changes are endogenous responses and, as such, cannot be treated as exogenous forces for productivity growth.

The results of regressing Eq. 12 are shown in Table 5. First consider the results in the first column in which all the variables are included. The coefficient of research intensity is still highly significant whereas growth in innovative activity remains statistically insignificant, again giving support only for Schumpeterian growth theory. Moreover, the population growth drag is also statistically and economically significant. The coefficients of the control variables considered in Table 5 are quite similar to those reported in Table 4. However, none of the additional control variables are statistically significant.

Excluding the innovation variables in the second column yields some remarkable results. The coefficient of urbanization becomes positive and significant while the population growth drag is rendered insignificant when the innovation variables are excluded. The population growth drag is rendered insignificant probably because it operates jointly with research intensity. Once research intensity is excluded from the regressions there is no variable which ensures that productivity is growing over time and the coefficient of the population growth drag is, consequently, rendered insignificant. The coefficient of urbanization is statistically insignificant when the innovative activity variables are included in the regressions, because they are endogenously driven by innovative activity and not vice versa.

**Table 5** Parameter estimates of full growth model (1700–1915) (Eq. 11)

| | Coefficient | $p$-Value | Coefficient | $p$-Value |
|---|---|---|---|---|
| $\Delta\ln X_{t-1}$ | 0.010 | 0.735 | | |
| $\ln(X/Q)_{t-1}$ | $11.915^{\#}$ | 0.003 | | |
| $\psi_{t-1}\Delta\ln L_{t-1}$ | $-6.700^{+}$ | 0.036 | $-4.444$ | 0.106 |
| $\Delta\ln\tau_t$ | $0.923^{\#}$ | 0.000 | $0.816^{\#}$ | 0.000 |
| $\Delta\ln g_t$ | $0.229^{\#}$ | 0.002 | $0.213^{+}$ | 0.017 |
| $\Delta\ln FD_t$ | $0.030^{\#}$ | 0.000 | $0.026^{\#}$ | 0.001 |
| $\Delta\ln(I/K)_t$ | $1.556^{+}$ | 0.019 | 0.008 | 0.991 |
| $\Delta\ln S_t^W$ | $0.196^{\#}$ | 0.009 | $0.167^{+}$ | 0.049 |
| $\Delta\ln S_t^{IM}$ | $-10.190^{\#}$ | 0.003 | $-0.781$ | 0.662 |
| $\Delta\ln UR_t$ | $-0.226$ | 0.686 | $1.470^{*}$ | 0.058 |
| $\Delta\ln Coal_t$ | 0.093 | 0.614 | $-0.057$ | 0.798 |
| $\Delta\ln\theta_t^{IP}$ | 0.192 | 0.588 | $-0.058$ | 0.864 |
| $\Delta\ln\theta_t^{Ag}$ | 0.460 | 0.253 | $0.750^{*}$ | 0.096 |

*Notes*: The Newey–West procedure was used to obtain heteroskedasticity consistent robust estimates. An intercept was included in the estimation but the results are not reported
$^{*}$, $^{+}$ and $^{\#}$ denote significance levels at 10, 5 and 1%, respectively. The dependent variable is $\Delta\ln YA$

Overall the results in this sub-section confirm the previous findings that productivity growth has been driven predominantly by the population growth drag and domestic and foreign innovative activity, even if the influence of coal production, urbanization and sectoral changes are allowed for in the estimation. Thus, these results reinforce the importance of innovation-driven growth during the British Industrial Revolution.

## 5 The anatomy of growth during the British Industrial Revolution

The empirical estimates so far give support to the hypothesis that productivity growth in Britain, until the twentieth century, was predominantly a race between technological progress and population growth. Research intensity was relatively low before the First Industrial Revolution around 1760. However, since the population growth rate was, on average, also very close to zero before the First Industrial Revolution (see Fig. 6a), innovations led to small positive per capita growth rates. The period 1760–1813 is remarkable. The marked increase in research intensity should have led to significant economic progress during that period. However, the population growth rate was extraordinarily high and increased to such an extent that per capita income growth rates became negative. It appears that during this period the economy was in a Malthusian trap and the straightjacket was only broken when the Second Industrial Revolution started in the latter half of the nineteenth century. Although the population growth rate slowed somewhat after 1813, it remained a drag on the economy during the first half of the nineteenth century as agriculture remained important during that period (see Fig. 6b).

Table 6 displays the simulations of the contribution to *changes* in per capita productivity growth rates by *changes* in research intensity and *changes* in population growth rates based on the coefficients in Table 4 (see notes to Table 6 for more details). The simulations are carried out by multiplying the average coefficient estimates in rows two and three in Table 4 by the actual values of research intensity and the population growth rate times $\psi$ to find the contribution of each of these variables to growth. The simulations will shed light on the domestic forces behind the increasing growth rates during the British industrialization.[4] The first column shows actual changes in per capita growth rates while the second and the third columns show the contributions of research intensity and population growth to changes in per capita growth rates. The simulation results show that changes in research intensity and population growth rates explain actual changes in per capita income growth rates rather well. This provides further evidence in favor of Schumpeterian growth models.

During the transition to the First Industrial Revolution over the period from 1620–1760 to 1761–1850, per capita growth rates decreased by 0.38 of a percentage point. Increasing research intensity contributed 1.6 percentage points to growth whereas the increasing population growth reduced growth rates by no less than 2.5 percentage points. This result underscores how powerful the population growth drag was in keeping per capita income low and shows that the British economy failed to produce significant growth during the First Industrial Revolution due to the population growth path despite the marked increase in innovative activity.

From the First to the Second Industrial Revolution in the periods 1760–1850 to 1851–1915, per capita growth rates increased by 1.09 percentage points. Increasing research intensity

[4] The simulations cannot be easily conducted in growth terms because the log of research intensity in the growth regressions influences the constant term, as research intensity is a level variable. In other words the inclusion of research intensity will alter the magnitude of the constant term, which renders it difficult to disentangle the growth effects of research intensity.

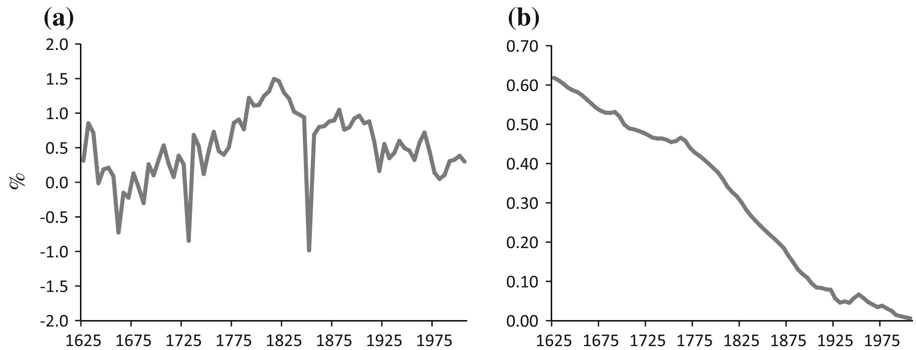


**Fig. 6** Population growth rates (**a**) and share of agriculture in total income (**b**), 1620–2005. *Notes*: The growth rates of population are annualized growth rates measured in 5-year differences. The share of agriculture in total income is measured in 5-year averages

**Table 6** Simulation results excluding foreign technology spillovers

| Period | Actual changes in $\Delta \ln y_t$ (%) | Contribution from $\ln(X/Q)_t$ (%) | Contribution from $\psi_t \Delta \ln L_t$ (%) |
|---|---|---|---|
| (1620–1760) to (1761–1850) | −0.384 | 1.567 | −2.506 |
| (1760–1850) to (1851–1915) | 1.091 | 1.802 | 1.503 |
| (1620–1760) to (1761–1915) | 0.232 | 1.401 | −1.170 |
| (1620–1915) to (1916–2005) | 1.736 | 1.436 | 0.870 |

*Notes*: The growth rates are annualized growth rates. The simulations are based on the regressions in the 2nd and 3rd rows of each section in Table 4. For example, over the period (1620–1760) to (1761–1850), actual changes in the averages of research intensity and population growth drag are 0.609 and 0.293, respectively. These changes are then multiplied with their respective average coefficients reported in the 2nd and 3rd rows of each section in Table 4 to obtain the contributions from each variable

contributed to a 1.8 percentage point increase in growth. The increasing growth rate was further strengthened by decreasing population growth rates that contributed to a 1.5 percentage point increase in the productivity growth rate. While the positive population growth rates continued to exert downward pressure on growth, this pressure was smaller during the Second than the First Industrial Revolution. Finally, comparing the modern growth regime for the period 1916–2005 with the pre-1916 period suggests that most of the 1.7 percentage point increase in the growth rate is explained by increasing research intensity (1.4 of a percentage point) while the reduction in population growth has also had a positive influence on growth (0.9 of a percentage point).

Thus far the simulations are based on the regressions in which only domestic R&D activity influences growth. The simulations in Table 7, which are based on the regressions in the last rows of each section in Table 4, allow for the influence of international technology spillovers on growth. The simulation results again highlight that changes in research intensity and the population growth rates are important in driving changes in the productivity growth rates, particularly over the period from 1620–1760 to 1761–1850. International technology spillovers played an increasingly important role during the First and the Second Industrial Revolutions. They first reduced growth rates over the period from 1620–1760 to 1761–1850. However, they were significant contributors to the increasing growth rates over the very long time-span from 1761 to 1915, during which they contributed 0.6 percentage point to growth

**Table 7** Simulation results including foreign technology spillovers

| Period | Actual changes in $\Delta \ln y_t$ (%) | Contribution from $\Delta \ln X_t$ (%) | Contribution from $\ln(X/Q)_t$ (%) | Contribution from $\psi t \Delta \ln L_t$ (%) | Contribution from $\Delta \ln S_t^W$ (%) | Contribution from $\Delta \ln S_t^{IM}$ (%) |
|---|---|---|---|---|---|---|
| (1620–1760) to (1761–1850) | −0.384 | −0.078 | 4.072 | −2.610 | −0.032 | −0.679 |
| (1760–1850) to (1851–1915) | 1.091 | −0.057 | 0.240 | 0.661 | 0.070 | 0.513 |
| (1620–1760) to (1761–1915) | 0.232 | 0.099 | 0.535 | −0.854 | −0.012 | 0.480 |
| (1620–1915) to (1916–2005) | 1.736 | −0.007 | 1.503 | 0.745 | −0.346 | −0.070 |

*Notes*: See notes to Table 6. The simulations are based on the regressions in the 4th row of each section in Table 4

rates. This period coincides with the period of increasing globalization, during which time Britain gradually lost its leadership. During this period, the increasing growth in import of technology contributed more to growth than the increase in domestic research intensity.

The finding that population growth was a major drag on British per capita income growth up to the Second Industrial Revolution raises the question of why it took so long for the British economy to be freed from its Malthusian straightjacket. Galor and Weil (2000) argue that the returns to human capital during the Second Industrial Revolution increased to such an extent that it gave parents a strong incentive to care for the education of their off-spring. The evidence of Britain shows that while there was not much demand for skilled labor during the First Industrial Revolution, there was a high demand for skills during the Second Industrial Revolution (Galor 2005).

The finding that per capita growth was predominantly driven by research intensity and population growth may appear too simplistic to capture the entire development of Britain from a Malthusian growth regime through to the modern growth regime. However, research intensity captures many factors that are often highlighted as being responsible for growth during the Industrial Revolution as well as the key aspects of unified theories of economic growth. The unified theories of economic growth of Goodfriend and McDermott (1995), Galor and Weil (2000), Hansen and Prescott (2002) and Lucas (2009) all focus on innovations and population growth as the principal drivers of per capita income growth. The results in this paper are also broadly consistent with the hypotheses that Britain took off because of institutions (North 1981), religion (Weber 1905), the high fertility rates among the special class of entrepreneurs and innovators (Galor and Moav 2006; Clark 2007), or a socioeconomic transformation whereby industrial capitalists replaced the landed class (Doepke and Zilibotti 2008).

What is remarkable here is that patents can account for the increase in total factor productivity over the past four centuries. This brings up the question whether Britain was the first country in the world to industrialize because they institutionalized their patent system in 1624 with the enactment of the Statute of Monopolies of 1623, well ahead of other countries in the world. Rosen (2010) certainly thinks that this is the case and argues that the institutionalization of the patent system in Britain in 1624 was the most important cause of the early industrialization in Britain. Since we have only one observation we cannot conclude that the introduction of a formal patent system in 1624 was responsible for the early industrialization in Britain. However, what we can conclude is that the patent system effectively captured the technological progress and in that sense given the right incentives to innovate.

## 6 Conclusion

Although innovations and population growth are the key ingredients in almost all theories of the Great Divergence, the British Industrial Revolution and unified theories of economic growth, almost no empirical work has been conducted to explain the British growth in the context of innovations and population growth. The lack of any correlation between economic growth and the level of innovative activity, as predicted by the first-generation endogenous growth theories, has probably discouraged researchers from focusing on innovation-driven growth to explain the transformation of the British economy from the Malthusian epoch to modern economic growth. Recent developments in endogenous growth models have overcome the difficulties associated with the first-generation growth models and enabled us to reconsider the role played by innovative activity during the British Industrial Revolution.

By introducing land as a factor of production in the endogenous growth models, this paper has shown that innovations and population growth have been the principal factors explaining per capita growth rates in Britain since 1620. Furthermore, it was shown that the functional relationship between growth and innovation follows that of the Schumpeterian rather than the semi-endogenous growth models. In fact, very strong support for Schumpeterian growth theory was found. The significance of this result is not only that research intensity has played a major role in British growth history but also that R&D has permanent growth effects and that the productivity growth rate remains constant and positive as long as the number of researchers is kept to a constant proportion of the number of product lines or the size of the population.

Simulations of the model show that innovative activity and population growth were economically significant determinants of per capita growth in Britain during most of the last four centuries. Population growth was a significant drag up to the mid nineteenth century because land was, until then, a significant factor of production. Despite a surge in innovative activity during the First Industrial Revolution, per capita growth rates were rendered negative by a marked increase in population size. Significant positive per capita growth rates were first experienced after the start of the Second Industrial Revolution due to an increase in domestic research intensity, international technology spillovers, and a decline in population growth along with a reduction of the importance of land as a factor of production.

The results of this paper have implications for growth modeling and the history of the British Industrial Revolution. Endogenous growth models are assumed to apply to modern economic growth only where land is not a factor of production. Furthermore, endogenous growth models are thought not to have empirical counterparts historically because innovative activity is often assumed to be of an informal character before WWII (Howitt and Mayer-Foulkes 2005). However, this study has shown that Schumpeterian growth theory can adequately account for British growth through history once the population growth drag is allowed for in the analysis.

The paper does not resolve the issue of the deep causes of Britain industrializing earlier than other nations. However, it does suggest that the literature should focus on factors that were responsible for the surge in innovative activity during the Industrial Revolution and whether the institutionalization of patents in the early seventeenth century was fundamental for the British success, as argued by Rosen (2010). As noted by Crafts and Mills (2009, p. 92), *"Future attempts by growth economists to model the transition to modern economic growth should perhaps pay more explicit attention to improvements in capabilities and in incentive structures that increased the probability of technological advance"*.

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