



**HUMAN ACCOMPLISHMENT AND GROWTH IN BRITAIN SINCE 1270:  
THE ROLE OF GREAT SCIENTISTS AND EDUCATION<sup>1</sup>**

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**Abstract:**

This paper constructs annual data on primary, secondary and tertiary education, significant inventions and great scientists in the period 1270-2011 for Britain to investigate the influence of education and science on the economic development of Britain. Institutions, culture, real book prices and other variables are used to trace the origin of innovations, great scientists and educational attainment. The regressions show that education, a highly innovative environment and knowledge spillovers were influential in shaping British economic development over the period 1270-2011.

**Keywords:** Economic growth, science, education, institutions, culture

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## 1. Introduction

Although British development over the past millennium, culminating with the British Industrial Revolution, is one of the most significant events in human economic history, there is still much debate about the role played by human capital in freeing the British economy from its Malthusian straightjacket. In his presidential address to the Economic History Association in 1980, Easterlin (1981) advocated education and science as the pillars of economic development and remarks that “at some point, we may look back and ask what produced this world – how we got where we are. Such inquiry will show, I believe, that the proximate roots of the epoch of modern economic growth lie in the growth of science and diffusion of modern education” (p 418). Similarly, Jacob (2014, p. 224) states that we should “put human capital back into the story and suddenly minds, books, lectures, school curricula become central to the story of Western Economic Development”. Furthermore, Temple and Voth (1998) show that the pace of industrialization is determined by the accumulation of human capital because it lowers the cost of adopting advanced techniques and increases their diffusion.

Several studies of the Great Divergence and endogenous growth models have stressed human capital accumulation as a potentially important source of the Great Divergence and the British Industrial Revolution (see, e.g., Weber, 1905; Easterlin, 1981; Becker *et al.*, 1990; Khan and Sokolof, 2008; Goodfriend and McDermott, 1998; Galor and Moav, 2002, 2004; Lucas, 2002; Cervellati and Sunde, 2005, 2011; Clark, 2005, 2007; Boucekine *et al.*, 2007; Baten and van Zanden, 2008; Galor 2011). Human capital also plays a critical role for innovation-driven growth in the key endogenous growth models formulated by Lucas (1988) and Romer (1990), and in models of the transition from agriculture to industry (Hansen and Prescott, 2002; Lucas, 2002; Tamura, 2002). Following Romer (1990) and most of the models referred to above, human capital encompasses formal schooling, scientific knowledge and vocational training.

Even though Easterlin (1981), Temple and Voth (1998) and Jacob (2014) stress human capital as a crucial element for industrialization some educational historians have de-emphasized education as being important for the British growth experience (see, for discussion of the earlier literature, Stone, 1964; Sanderson, 1991). More recently Mitch (2005) finds no link between education and growth. Furthermore, Allen (2003, p. 405), notes that “recent research has downplayed the importance of technological progress and literacy in explaining the British industrial revolution”. Jacob (2014, p. 6) argues that one “reason for diverting attention from knowledge derives from what little we know about formal education, particularly in Britain. Part of the reason for this myopia

about formal and informal education may derive from the appalling state of British educational records prior to about 1850”.

This paper seeks to uncover the role played by human capital in British economic growth over the period from 1270 to 2011. Human capital is measured as educational attainment at the primary, secondary and tertiary levels, as well as knowledge capital created by great scientists or significant inventions. Thus, the human capital variable includes knowledge created through formal education and also through improvements in technology and scientific knowledge created by educated as well as uneducated innovators. The data on tertiary education have been compiled over the past few years through extensive search in libraries and university web pages, examination of about 500 Parliamentary Papers, and numerous email correspondences with the 23 individual universities that were in existence in Britain before 1920 and merged with official statistics that are available first after 1920. Most of the data on tertiary education are only available from annual university calendars that list the names of students enrolled, matriculated or graduated in the particular year, and the aggregate numbers could not simply be added up since students have often been awarded more than one degree; e.g. M.B. and B.S, honorary degrees and *ad eundem* degrees.

The data on primary and secondary schooling have been collected from several historical documents and books. Enrollment data are available from official sources from 1850 at the primary level and from 1865 at the secondary level. Prior to these dates the enrollment data are based on the numbers of elementary and non-classical (primary) and classical (secondary) schools. The primary and secondary school data come from various lists of mainly endowed schools. The Digest of Reports from the Commission of Inquiry into Charities (1841, various volumes), the Schools Inquiry Commission (1868a), and the Special Reports of the Assistant Commissioners (1868b, 1869, various volumes) contain data on the foundation years of mainly endowed schools that were still in existence at the time of the inquiries, the earliest being before 1200. These were supplemented with data on schools from other sources, particularly Orme’s (2006) list of schools in England, 1066-1530, Leach’s (1896) list of schools at the Reformation 1546-48, Stowe’s (1908) list of English schools in the time of Queen Elizabeth I, Carlisle’s (1818) descriptions of endowed grammar schools, various volumes of the Victoria County Histories, as well as other sources listed in the Data Appendix.

This research contributes to the literature by investigating which factors shaped productivity growth in Britain in the period 1270-2011, including educational attainment at the primary, secondary and tertiary levels, fixed capital, international knowledge spillovers, the land-population ratio, and domestic knowledge created by great scientists. Furthermore, insight is given into forces that may have been responsible for the human capital expansion such as culture, the quality of institutions and real book prices; were book prices capture technological progress within the printing

industry which was not only pivotal for advances in intergenerational dissemination of knowledge but was also crucial for reducing the cost of acquiring knowledge. Novel annual data are constructed for culture and institutions. This paper is probably the first attempt to formally test for the role played by education and knowledge created by great scientists for British growth using annual data over the past millennium while, at the time, trying to identify the factors underlying the growth in human capital.

The paper is related to the research of Madsen *et al.* (2010) and Baten and Zanden (2008). Using patent statistics Madsen *et al.* (2010) show that the predictions of the Schumpeterian second-generation endogenous growth model are consistent with the British growth experience in the period 1620-2006. Baten and van Zanden (2008) show that book production over the period 1450-1913 was influential for growth in Europe and interpret the results as evidence that human capital was influential for pre-industrial growth in Europe.

The paper is structured as follows. The empirical framework and the influence of human capital on technological progress during the industrialization and preindustrial periods are discussed in the next section and Section 3 addresses data issues. OLS estimates are presented in Sections 4 and 5. Identification and factors that explain human capital at a deeper level are discussed and estimated in Section 6, and Section 7 presents model simulations. Section 8 concludes.

## 2. Empirical framework

Consider the following homogenous Cobb-Douglas production function:

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

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 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.

Eq. (1) can be written as per worker output:

$$\left(\frac{Y}{L}\right)_t = A_t^{\frac{1}{1-\alpha(1-\beta_t)}} \left(\frac{K}{Y}\right)_t^{\frac{\alpha(1-\beta_t)}{1-\alpha(1-\beta_t)}} \left(\frac{T}{L}\right)_t^{\frac{\beta_t}{1-\alpha(1-\beta_t)}}, \quad (2)$$

where labor productivity is cast in terms of the  $K$ - $Y$  ratio to filter out technology-induced capital deepening (Klenow and Rodriguez-Clare, 1997), which gives some identification advantages as discussed in the next section. The reason why productivity growth triggers capital deepening is that

technological progress increases expected earnings per unit of capital and causes Tobin's  $q$ , or the shadow value of capital in markets without traded stocks, to exceed its steady-state value. This initiates a capital deepening process that terminates when the shadow price of capital reaches its steady-state equilibrium, which may not be one in the presence of taxes, technological progress and population growth (see, for derivations, Madsen and Davis, 2006). The  $K$ - $Y$  ratio is assumed to be constant along the balanced growth path because factors that influence this ratio such as changes in the time preference and taxes, have only temporary growth effects.

Taking logs of Eq. (2) yields:

$$\ln\left(\frac{Y}{L}\right)_t = \frac{1}{1-\alpha(1-\beta_t)} \ln A_t + \frac{\alpha(1-\beta_t)}{1-\alpha(1-\beta_t)} \ln\left(\frac{K}{Y}\right)_t + \psi_t \ln\left(\frac{T}{L}\right)_t, \quad (3)$$

where  $\psi_t = \beta_t/[1 - \alpha(1 - \beta_t)]$ . Allowing  $A$  to be a function of broadly defined human capital yields the following stochastic counterpart of Eq. (3):

$$\ln y_t = \alpha_0 + \alpha_1 EA_t + \alpha_2 \ln S_t^d + \alpha_3 \ln S_t^{Eu} + \alpha_4 Op_t \cdot \ln S_t^{Im} + \alpha_5 \ln k_t + \alpha_6 \psi_t \ln \tau_t + \varepsilon_t, \quad (4)$$

where  $y = Y/L$ ,  $EA$  is educational attainment (average years of schooling of individuals of working age),  $S^d$  is domestic stock of knowledge created by domestic great scientists,  $S^{Eu}$  is the foreign stock of knowledge created by foreign great scientists in countries surrounding Britain (Belgium, Denmark, France, Germany, Ireland, Italy, the Netherlands, Norway, Portugal, Spain),  $S^{Im}$  is the foreign stock of knowledge created by foreign great scientists and transmitted internationally through imports,  $Op$  is trade openness,  $k = K/Y$ ,  $\tau = T/L$ , and  $\varepsilon$  is a stochastic error term. Here,  $\psi$  is allowed to vary over time due to variations in the share of agriculture,  $\beta$ , where  $\beta$  is estimated as the share of agriculture in total production. Capital's income share,  $\alpha$ , is fixed at 0.3 following the standard in the literature. The construction of the variables is discussed in the next section and data sources are listed in a separate Data Appendix.

Explaining productivity by educational attainment and the stock of domestic and foreign knowledge is now standard in the empirical literature on endogenous growth following the work of Coe and Helpman (1995) (see, for example Engelbrecht, 1997; Keller, 2004; Cohen and Soto, 2007; Madsen, 2010; Venturini, 2012). The next two subsections argue that the same framework, at least to some extent, can be used to explain growth over the past 742 years.

The  $K$ - $Y$  ratio is often omitted from long-run regressions under the assumption that the economy is in its steady state. Here, it is included as a potential contributor to the British Industrial Revolution following the predictions of the model of Galor and Moav (2004) in which capital deepening is initiated by high returns to capital relative to the cost of capital, and the model of

Voigtländer and Voth (2006) in which capital deepening is crucial for industrialization because of positive externalities from capital and embodied technological progress. The land-population ratio,  $\tau$ , is a main channel through which population growth influences output. Population growth gives rise to a population growth drag due to diminishing returns introduced by land as a semi-fixed factor of production. Since the land under cultivation in Britain has not varied much over the period considered here, most of the identifying variation in  $\tau$  comes from population growth and its interaction with  $\psi$ . Furthermore, the influence of population growth on output growth through this channel has weakened over time as the agricultural share in total output has diminished.

The approach used here deviates from the empirical endogenous growth literature by basing the knowledge stock primarily on the knowledge created by great scientists and significant inventions as opposed to patents or R&D because these data are not available before 1620 (patents) and 1960 (R&D). Patents have been used in the British historical studies of Oxley and Greasley (1998), Greasley and Oxley (2007), and Madsen *et al.* (2010), and will be used in the robustness tests below. Based on an endogenous growth model, Garner (2008) shows that growth in scientific knowledge is a precondition for sustained growth in the very long run. Regressing the log of stock of patent knowledge from Madsen *et al.* (2010) on the log of the stock of significant inventions based on the chronology of Ochoa and Corey (1997) over the period 1625-2009 using dynamic OLS (DOLS) and robust standard errors yields a coefficient of the stock of great inventions of 3.22 ( $t = 12.6$ ) and  $R^2 = 0.83$ , suggesting a strong positive relationship between the two variables.

### *2.1 Science, education and technological progress*

While education and R&D are the driving forces of growth in a modern growth regime in most endogenous growth models, it is, perhaps, less obvious why education and science would have played a role for growth over the past millennium. Like today, some scientific breakthroughs of the past did not have any immediate technological consequences and some inventions and innovations were made by practical and dexterous craftsmen who did not necessarily have a strong educational background. Furthermore, the connection between science and technology became gradually closer during the Industrial Revolution (Mokyr, 2005b), suggesting that technological progress was driven by science at a diminishing rate as we go back in time, which, at least to some extent, reflects that the fraction of scientists and educated people in the total population diminishes as we go back in time. This sub-section presents some evidence suggesting that science and education were important for British technological progress, at least after about 1500.

The historical evidence indicates that most inventions and breakthroughs were made by scientists and that the greatest innovators during the Industrial Revolution had an educational level

that went beyond very basic primary schooling (Mokyr, 2005a, 2005b; Jacob, 1997, 2014; Meisenzahl and Mokyr, 2012). Jacob (1988, 1997, 2014) argues that scientists, particularly after 1688, cooperated with engineers and manufacturers to solve pragmatic technical problems. Similarly, Mokyr (2002, 2009) argues that Victorian Britain did not become the center of the first machine tool industry only because of ingenious engineers but also because science provided the implicit theoretical underpinnings to what empirically minded technicians did.

The development of the steam engine is an example of the mutual relationship between science and skilled people. The advances of the steam engine from Newcomen's crude 1712 prototype to the advanced engines of the Victorian age, according to Mokyr (2002, 2009), went hand in hand with scientific experimentation. Furthermore, James Watt, who was pivotal in the development of the steam engine, was influenced by progress in science (see for examples, Jacob, 1997, 2014). Humphrey Davy, a friend of Gregory Watt, said that "those who consider James Watt only as a great practical mechanic form a very erroneous idea of his character; he was equally distinguished as a natural philosopher and a chemist, and his inventions demonstrate his profound knowledge of those sciences, and that peculiar characteristic of genius, the union of them for practical application" (Carnegie, 1905, p. 244). Furthermore, Musson and Robinson (1969/1994, p. 72) give several examples of how science and practical people worked together and they argue that science played a large role in the development of the steam engine. Musson and Robinson (1969/1994), furthermore, stress the invention of bleaching in the late 18<sup>th</sup> century as another example of a strong and fruitful collaborative relationship between scientifically-minded industrialists and natural philosophers.

Interest by the wider society in promoting scientific knowledge is evidenced by the formation from the 17<sup>th</sup> century of institutions such as philosophical societies, teaching academies, and, in the 19<sup>th</sup> century, mechanics institutes. The institutions were formed with various purposes including serving as forums for exchanging ideas, producing publications that spread new knowledge, and providing technical training. In England, the Royal Society of London was constituted in 1660 to promote all kinds of experimental philosophy. Financial contributions by members were used to defray the costs of the experiments, which were conducted at their weekly meetings. In his account of the history of the Royal Society of London, Thomson (1812) notes that the numerous scientific societies and academies that formed in Europe contributed much to the rapid progress of science from the mid-1600s. He also points out that these societies played a very important role in disseminating knowledge around the world, quickly and efficiently by publishing "periodically, all the discoveries which came to their knowledge" (p. 5).

Sullivan (1984) also demonstrates that scientific knowledge was disseminated to the agricultural sector through titles of farming technical manuals/books starting with John Fitzherbert's "The Boke of Husbandry" published in 1523, which marks a new era in the history of the role of agricultural technological literature in the development of farming techniques in England. Subjects that were considered in the technical farming manuals include agricultural chemistry, botany, grasses and weeds, drainage, improvements, weights and measures, and entomology.

The invention of the printing press meant that large quantities of books with new scientific discoveries could be produced and distributed. Since husbandmen and yeomen were approximately 21% and 65% literate, respectively, in 1591 and increasing thereafter (Sullivan, 1984), it is likely that a large fraction of farmers were able to follow the new trends in methods and technology through book reading. Furthermore, Sullivan (1984) argues that farming books are at least as good as patents as indicators of advancement in agrarian technology since they contain a lot more innovative ideas compared to patents. The number of technical agricultural book titles listed by Sullivan (1984) increased markedly from 1571, indicating that scientific knowledge was making important inroads into the production sphere. Based on Sullivan's data, Ang *et al.* (2013) show that the number agricultural book titles were significant determinants of agricultural productivity in the period 1620-1850. From this evidence it can be concluded that science already played a role for technological progress from at least the 16<sup>th</sup> century.

Turning to education Sanderson (1991, p. 28) argues that education may have been important for the rise in the scientific culture prior to and during the British Industrial Revolution and Schofield (1973) reasons that literacy helped transform traditional values into modern and more rational values. Stephens (1998, p. 57) argues that education went hand-in-hand with industrialization and that economic growth during the British Industrial Revolution could not have been sustained without educated workers in engineering, transport, commerce and financial services. Cressy (1980) and Reis (2005) forward the idea that literacy was productive because it lowered transaction costs in accounting, provision of trade credit, and legal matters (leases, deeds *etc.*). They, furthermore, suggest that education was vital in trade; skilled carpenters and bricklayers would not perform their duties without a basic knowledge of arithmetic and geometry, and literacy was required among the professional class. Finally, the quality of governance is likely to have been influenced by the educational revolution in the 16<sup>th</sup> century. The fraction of the members of parliament members with a degree from a university or Inns of Court increased from 38 to 70 percent in the period 1560-1642 (Stone, 1964); thus, presumably improving the quality of governance.

Collecting data for practical inventors among mechanics and engineers born over the period from 1660 to 1830, Meisenzahl and Mokyr (2012) show that of the inventors born before 1800, 25

percent of those whose background is known had a university degree and 37 percent had higher schooling or university degrees. Since the fraction of the population of working age with a tertiary degree was, on average, 0.03 percent in the period 1600-1800, the fraction of inventors with tertiary education does not reflect the educational attainment of the working population but that educated people were drawn into innovative activities. While self-selection was probably somewhat at play, it is doubtful that without education these entrepreneurs would have chosen the career path they did.

Another intriguing finding of Meisenzahl and Mokyr (2012) is that these practical inventors often published their work and engaged in debates over contemporary technological and social questions, leading to positive technology externalities that initiated further inventions. Thus, it can be argued that education was not only a way to increase the organizational efficiency of the society; it also boosted innovations and transformed scientific breakthroughs into practical inventions.

While the economics profession generally agrees that education enhances useful knowledge today in most countries, one may ask whether anything useful was taught at secondary and tertiary levels in the preindustrial period. The curriculum at grammar schools consisted of classical linguistics, grammar and religion during the 16<sup>th</sup> and the 17<sup>th</sup> centuries (Stone, 1964). While these subjects did not directly prepare students for jobs in industries they were often used as a stepping stone to enter universities (Stone, 1964) and it is quite possible that the acquired linguistic skills were useful for international transmission of knowledge. Science was taught at English universities in 1654 (Montmorency, 1904, p. 256). Mathematics was taught at Cambridge University and arithmetic, geometry, analytical algebra, the solution and application of equations, and optics was taught at Oxford University (Montmorency, 1904, p. 256).

## *2.2 International knowledge spillovers*

There is substantial evidence that Britain drew on foreign technology before and during the British Industrial Revolution and that Britain was exceptionally good at refining inventions, solving problems that other countries could not overcome, and making foreign inventions practical and workable. In the smelting and refining of metallic ores, for example, German skills and capital, applied by Hochstetter and others, were extremely important for the British technological advances (Musson and Robinson, 1969/1994, p. 60). Printing, the paper mill, wire-drawing machines, the Saxony spinning wheel, and the Dutch swivel loom were also inventions with important technological consequences imported into Britain from the continent (Musson and Robinson, 1969/1994). Foreign influences can also be traced to other industries such as silk, pottery, glass-making, sugar refining, tinplate manufacture, and brewing (Musson and Robinson, 1969/1994, pp. 60-61). Thus, while there is evidence that foreign inventions helped shape British industrialization, it

is not easy to pinpoint the channels through which technology was transmitted to Britain over the past eight centuries.

Based on in-depth case studies of French espionage in Britain, Harris (1998, particularly in Ch. 20), for example, advocates industrial espionage as an import channel of technological transfer to Britain from the continent and, especially, from France during the 19<sup>th</sup> century. The importance of this channel of transmission, however, is difficult to assess based on the cases presented by Harris (1998). Studying technology transfer from Britain to the US in the 19<sup>th</sup> century, Jeremy (1973), for example, shows that machines and models not accompanied by skilled mechanics were rarely successfully employed in the US. Furthermore, technological knowledge was, according to Jeremy (1973), extremely tacit in nature, again suggesting that espionage may not have been as important as advocated by Harris (1998).

Inflow of skilled workers, merchants and scientists from the continent is probably a more significant channel of knowledge transfer than espionage. There was, for example, a significant flow of skilled artisan and merchant refugees from France and Belgium to Britain following the persecutions of Walloons and Huguenots during the 16<sup>th</sup> and 17<sup>th</sup> centuries (Harris, 1998, p. 564). Mokyr (2009, p. 106) finds that many inventions, especially in chemicals, that made the Industrial Revolution possible, were imported from the European continent. Landes (1983) remarks that French industry was “crippled by the exodus of some of its best practitioners fleeing a wave of anti-Protestant bigotry and persecution” (p. 219). Musson and Robinson (1969/1994, p. 64) suggest that these people were particularly attracted by the British patent system, greater availability of capital, and greater freedom for private enterprise.

In the absence of time series data on immigration, espionage, ideas exchange, and personal contacts it is assumed that knowledge is transmitted 1) from Western Europe; and 2) through imports. The first measure is computed as the sum of great scientists from Gascoigne (1984) for Belgium, Denmark, France, Germany, Ireland, Italy, the Netherlands, Norway, Portugal, and Spain and accumulated with a depreciation rate of one percent. Common for all these countries is that they, with the exception of Italy, have coastlines along the Atlantic Ocean and are close to Britain; thus rendering exchange of ideas through immigration, journeymen, and personal contacts as well as through espionage. Furthermore, common for all these countries was that they were in the same Indo-European language group and Latin was widely spoken.

Knowledge spillovers through the channel of imports is today considered as one of the most important channels of technology transmission as imported machinery and equipment often incorporate new and more advanced technology that enhances productivity of the final goods producing sector (see, e.g., Grossman and Helpman, 1991; Madsen, 2007). In the models of

endogenous growth analyzed in Grossman and Helpman (1991) productivity advances depend on the horizontally (variety) and vertically (quality) differentiated intermediate inputs. Common for both cases is that the variety and the quality of intermediate inputs are predominantly explained by stock of knowledge; thus suggesting that the productivity advances of a country depends on its own knowledge stock and the knowledge stock embodied in imported intermediate inputs and, therefore, that technology is transmitted internationally by the import-weighted stock of knowledge.

From this line of reasoning it follows that knowledge spillovers are proportional to trade openness, knowledge stock of the exporting countries and the proportion of the exporting country's knowledge stock that is incorporated into the export article. The last criterion is essential for the feasible transmission of knowledge in a historical context. It is only export articles that enhance the quality and the variety of production that will enhance productivity in the recipient country such as investment goods, chemicals, and key products and component that form a part of the final good. These products have, at least to some extent, been traded since the start of the First Industrial Revolution; however, preindustrial British imports mostly consisted of raw materials, food and low-value added manufactures (see, e.g., Saltzman, 1931; Schumpeter, 1960). In the 14<sup>th</sup> and 15<sup>th</sup> centuries, for example, Britain's the main import article was wine predominantly made in France (Saltzman, 1931) and it is highly unlikely that the French scientific knowledge was transferred to Britain through trade in wine. Consequently, knowledge imports are assumed to be constant in the period 1270-1700 and then spliced to the value in 1700 to ensure that no knowledge through imports was transmitted to Britain through that channel in the regression analysis.

### 3. Measurement and Data Issues

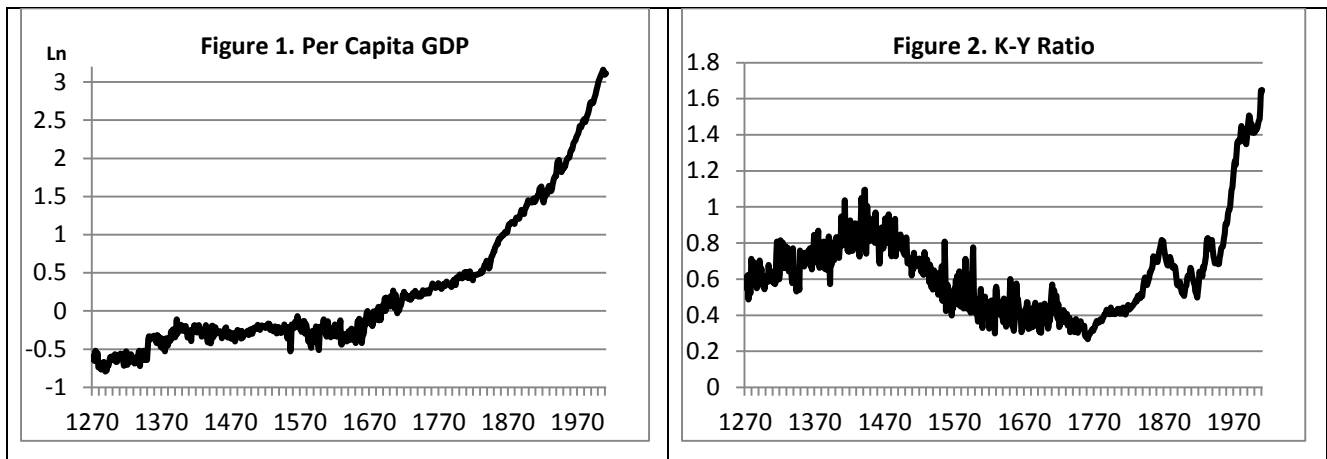
#### 3.1 Per capita income and productivity

Six measures of productivity,  $Y/L$ , are used as dependent variables in Eq. (4) in order to get a general picture of the dynamics of economic activity and industrialization and to test the robustness of the results to measurement of economic activity, since there has been a long-standing debate among economic historians about the time-profile of productivity, particularly during early industrialization. The six income measures are 1) the per capita income data of Broadberry *et al.* (2011),  $Y^B/Pop$ , where  $Y^B$  is the income data of Broadberry *et al.* (2011) and  $Pop$  is the population size; 2) Clark's (2010) per capita income data,  $Y^C/Pop$ ; 3) the agricultural share of total GDP,  $Agr^S$ ; 4) urbanization,  $Urb$ ; 5) income per hour worked,  $Y^B/H^{AW}$ , where  $H^{AW}$  is employment times annual hours worked and annual hours worked are from Allen and Weisdorf (2011); and 6) and  $Y^B/H^{CWV}$ , where  $H^{CWV}$  is employment times hours worked and hours worked is based on Vogt (2001) and Clark and van der

Werf (1998). The employment data used to construct  $H^{AW}$  and  $H^{CWV}$  are from official statistics after 1841 and backdated using population size.  $H^{CWV}$  are constructed from Clark and van der Werf (1998) (for the years 1580, 1625, 1675, 1716, and 1760), Voth (2001) (for the years 1766, 1800, 1830) and assumed constant before 1580. Official statistics are used after 1870, and the data are geometrically interpolated between the benchmark years. Finally, the per capita income data of Broadberry *et al.* (2011) and Clark (2010) are spliced to Maddison's (2003) per capita income data after 1820. The income data of Broadberry *et al.* (2011) are used as the baseline income estimate.

The income data of Broadberry *et al.* (2011) are constructed using the output approach while Clark's (2010) data are based on the income approach and show almost the same time-profile as Broadberry *et al.*'s (2011) data except that Clark's start at a higher level in 1270 and the population decline following the outbreak of the Black Death in 1348 appears to have produced an increase in Clark's income data up to 1430 and the subsequent surge in population after about 1530 resulted in a decline in income up to the end of the 17<sup>th</sup> century. The agricultural share and urbanization are used as alternative indicators of industrialization as advocated by Temple and Voth (1998) and Humphreys (2010), among others. Unfortunately, the urbanization data are of poor quality before 1800 as data are mostly only available every century and the data had to be interpolated in between, and this has to be taken into account when the results based on this variable are interpreted.

Productivity, measured as income per hours worked is a better measure of labor productivity than per capita income because it accounts for changes in annual hours worked and labor force participation rates. However, the data on annual hours are controversial and labor force participation rates are not currently available before 1841. Regarding hours worked, De Vries (1994) advances the idea that the labor supply increased substantially in North-Western Europe during the Industrial Revolution and earlier; particularly due to more working days per year and increased child labor. Based on court hearings Voth (1998, 2001) estimates that working days increased significantly over the period 1766-1830 and Allen and Weisdorf (2011) argue that working days have increased substantially since 1270 and were heavily influenced by the removal of 49 holy days in 1536 associated with the Protestant Reformation. Clark and van der Werf (1998), on the other hand, argue that there is no clear evidence of an increase in working days between the middle ages and the 19<sup>th</sup> century. Allen and Weisdorf (2011) compute the working year by estimating how many urban and rural laborer work days are required to achieve a fixed basket of basic consumption. Thus, the days worked a year is essentially a constant times the inverse of real wages, and workers are, consequently, assumed to increase the demand for leisure while holding consumption constant in response to increased real wages; an assumption that is very strong indeed.



Notes. See separate Data Appendix for data construction. Per capita GDP data are based on Broadberry *et al.* (2011).

The per capita income data of Broadberry *et al.* (2011) are displayed in Figure 1. Income increased slightly up to around 1387, fluctuated around a relatively constant level over the approximate period 1387-1600 when Britain entered the post-Malthusian growth regime with positive but not large growth rates that lasted to around 1830, and transformed into the modern growth regime from around 1830. Thus, British industrialization was associated with a gradual increase in income that had already started in the early 1600s. A noticeable feature of the figure is the high volatility of per capita income up to the 19<sup>th</sup> century. The 1920s depression and the Great Depression of the 1930s are dwarfed in comparison to the cyclical downturns before the 19<sup>th</sup> century. A possible trend growth scenario, as advocated by Mokyr (2005a), is that technological progress was random and unsystematic before the 17<sup>th</sup> century and the positive per capita income growth effects of technological progress were restrained by the population growth drag. As R&D became more systematic, technological progress became more persistent and, consequently, promoted higher growth (see, for a theoretical exposition, Peretto, 2013). According to Mokyr (2005a) and Peretto, (2013) the efficiency gains before entering the persistent growth regime were predominantly due to gains from trade and more efficient allocation of resources. Finally, the demographic transition that started in the late 19<sup>th</sup> century, in conjunction with the declining agricultural share, reduced the population growth drag and furthered economic growth (Galor, 2011).

### 3.2 The K-Y ratio

The fixed capital stock is measured as the sum of draft animals (oxen and horses) divided by the agricultural share of economy-wide real GDP from Broadberry *et al.* (2011) over the period 1270-1760 and spliced with economy-wide stock of capital based on the perpetual inventory method in the period 1760-2011. The *pre*-1760 data are scaled with the inverse agricultural share under the

assumption that the  $K$ - $Y$  ratio is the same for the agricultural and the non-agricultural sectors. Non-draft animals are not included in the *pre*-1760 data because animals for slaughtering are not considered to be investments in standard national accounting systems.

The  $K$ - $Y$  ratio, which is displayed in Figure 2, shows positive growth trends in the approximate periods 1270-1450 and 1750-2011 and a negative growth trend in the period 1450-1750. These movements may reflect changes in the time preference (propensity to save) and complex interaction between capital deepening and tax rates (see, for an analytical framework, Madsen and Davis, 2006). Assuming that movements in the  $K$ - $Y$  ratio predominantly mirror changes in the time-preference, the data suggest low returns to capital in the 15<sup>th</sup> century and, particularly, in the *post*-1960 period.

### 3.3 Educational attainment

Education is measured as the sum of primary, secondary and tertiary educational attainment and is estimated from school enrollment rates and age distributions that, implicitly, take into account age dependent mortality rates, as shown explicitly below. The data on primary and secondary school enrollment rates are compiled from various sources as detailed in the separate Data Appendix. Enrollment data are available from official sources from 1850 at the primary level and from 1865 at the secondary level. Prior to these dates enrollment is computed as the accumulated number of elementary and non-classical (primary) and classical (secondary) schools multiplied by an increasing trend in the number of pupils per school over the period from 1160 to 1850/65 as detailed below. The number of students per school is kept constant on an increasing trend before 1850/65 because there is little accurate information on the number of pupils per school over time and the information available show that the number of students per school varies wildly from extremely small numbers – often from six to several hundred – between schools and over time. A further problem is that the data most often available only includes the students studying for free and, thus, excludes the fee paying students who often were in the majority (where they are shown), though their numbers also vary wildly from none upwards.

The main source of data on the number of secondary schools is the Schools Inquiry Commission (1868a) Volume I (denoted as SIC), which lists endowed grammar and other secondary schools.<sup>2</sup> Endowed schools were able to survive swings in student numbers. Tomson (1971), for

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<sup>2</sup> According to Orme (2006), the endowment ‘movement’ began in about the 1440s with founders either establishing a new school or endowing an existing one. Endowments usually took the form of rent on a piece of land or returns from cash invested to provide for the salary of a school master. Often provision was also made for a school building and a house for the master and the founder would usually make some stipulations such as the number of children to be taught free, (often restricted to a certain number of poor children from the local area), and what was to be taught, e.g. Latin (grammar), English, reading, writing, casting accounts, etc., depending on the type of school. Hence, once a school was endowed, except in a few periods of great political upheaval or where an endowment was

example, finds that for the 15 counties examined in his study in the period 1700 to 1799, there were 334 endowed grammar schools but only 16 known closures, 9 of which were temporary, and 12 were sinecures. The commissioners define the schools in their list as Classical – those that taught Latin and Greek in their regular course of study; Semi-Classical – those that included Latin in their regular course of study but excluded Greek; and Non-Classical – those that excluded Latin and Greek, or taught only the rudiments of Latin. Schools that, at the time of the enquiry, were only for primary instruction were classified as Elementary, although most of these started out at least purporting to be grammar schools.

Schools which were categorized as non-classical or elementary by the Commissioners were recorded as primary schools in the database for this paper. To these were added other elementary school foundations, mainly from the lists available in the Digest of Reports from the Commission of Inquiry into Charities (1841, various volumes) (denoted as CIC) and from the Schools Inquiry Commission, Special Reports of the Assistant Commissioners (1868b, 1869, various volumes) (denoted RAC). These were supplemented with elementary schools from other sources, particularly those listed in various volumes of the Victoria County Histories, where they differed from those in the SIC, CIC and RAC.

The commissions of inquiries mentioned above provide extensive lists of schools and their foundation dates, however, with a few exceptions, they only include schools that still existed at the times of the inquiries and are almost exclusively schools that were endowed. In other words, they lack information about schools that existed prior to the inquiries but which did not survive into the 19<sup>th</sup> century. In an attempt to include as many early schools that had *not* survived as possible, various other sources such as Orme's (2006) list of schools in England, 1066-1530, Leach's (1896) list of schools at the Reformation 1546-48, Stowe's (1908) list of English schools in the time of Queen Elizabeth I, Carlisle's (1818) descriptions of endowed grammar schools, various volumes of the Victoria County Histories, as well as other sources listed in the Data Appendix, were used to identify as many start and end dates for these schools as possible. These schools have only been included in the database when they were shown to have existed and functioned as schools for a continuous period of time, and when their end dates are, at least approximately, known. Cross-checking was continuously undertaken to ensure data reliability.

While there is quite a lot of information about endowed primary and secondary schools going back in history, there is very little data available for great many private-venture schools including classical grammar, non-classical schools with courses of education aimed at business and navigation

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illegally misappropriated, it tended to continue because endowments were a permanent source of income that could only be used for the specific purposes as set out by the endower (Orme, 2006).

as such, as well elementary schools, parish schools, dissenter's schools and dame schools etc. Although no doubt numerous, these schools were often short lived and left very few, if any, records. They have been included in the database when definite information is known about them, but as this is only the case for a very few, in practical terms, these schools are not represented in the database give.

The number of student implied by splicing primary and secondary educational attainment in 1850 and 1865, respectively, is 109.7 students per primary school and 54.0 students per secondary school. It is assumed that these numbers are the half of 109.7 and 54.0 in 1160 and the numbers are linearly interpolated between 1160-1850 and 1160-1865. The implied number of pupils in primary education is quite consistent with the average number of pupils per school of 100.3 in a number of primary schools in the period 1369-1540 listed by Orme (1989, pp. 129-142). Similarly, Stowe (1908, pp. 188-189) shows that the number of students in 31 grammar schools scattered around England is ranging between 3 and 360 with a mean of 73.8 in the second half of the 16<sup>th</sup> century. As robustness check literacy is used as a proxy for primary educational attainment in Section 5.

The data on educational attainment precludes reading and writing skills obtained from Sunday Schools, parents and private tutors; however, whether these mediums of learning were of any significance has been questioned. For Sunday Schools Mitch (1993) suggests that their contribution to working class literacy in the 19<sup>th</sup> century England was marginal and fails to detect any increase in literacy in periods of strong advances in the number of Sunday Schools; a suggestion that is supported by Schofield (1973) who argues that Sunday Schools were more concerned with moral and religious training than giving the children basic literacy skills. More forcefully, using data from auto bibliographies the regressions of Humphries (2010) show that Sunday school experience did not have any significant impact on occupational outcomes.

Regarding teaching skills acquired at home, Cressy (1980, p. 42) states that there are few reports of mothers and fathers actually doing the teaching in pre-industrial Britain; partly because they were illiterate themselves. Close to 90% of the women in the 17<sup>th</sup> century England could not even write their own names, so few of them could be satisfactory teachers. Even if males were much more literate than females during the 16<sup>th</sup> and the 17<sup>th</sup> centuries, it was not regarded as their parental role to instruct their children (Cressy, 1980, pp. 43-50). However, it appears that home education was rather more important for the intellectual elite. According to Hans (1951) during the 18<sup>th</sup> century approximately 28% of the intellectual elite received their education at home – either from their fathers or private tutors. Of the 680 scientists born between 1600 and 1785 in Britain and Ireland, identified by Hans (1951), almost half of those born in the 17<sup>th</sup> century received their secondary education at home, while that number had fallen to 27% in the 18<sup>th</sup> century. Unfortunately, it is

probably impossible to collect a comprehensive dataset on this teaching medium. The best we can hope for is that the time-profile of home teaching has followed the time-profile of school education.

Data on tertiary education before 1920 and after 1996 are collected from numerous sources and we were able to compile data back to or close to the foundation years for almost all universities. The *post*-1996 data are estimated as the sum of enrollments for the 65 universities that were granted the Royal Charter prior to 1992. Aggregated official enrollment data in the *post*-1996 period are not used because the explosion in tertiary student enrollments in institutions that were not granted the Royal Charter, such as open universities, gives a misleading picture of the growth in tertiary education enrollment rates in this period. The *pre*-1920 data are available for all universities in Britain during almost all years from their foundation dates. The data were interpolated to bridge gaps in the data and transformed to enrollment data in the instances in which only data on graduates and matriculation are available. The number of students from dissenting academies are not included in the estimates because the data are not very complete and Mercer (2001, p. 36) suggests that fewer than 1000 lay students were educated in dissenting academies in the period 1750-1850.

Following the derivations in Madsen (2014) the following formulas are used to construct educational attainment at the primary, secondary and tertiary levels for age cohort  $i$  in the labor force completing grade  $j$ :

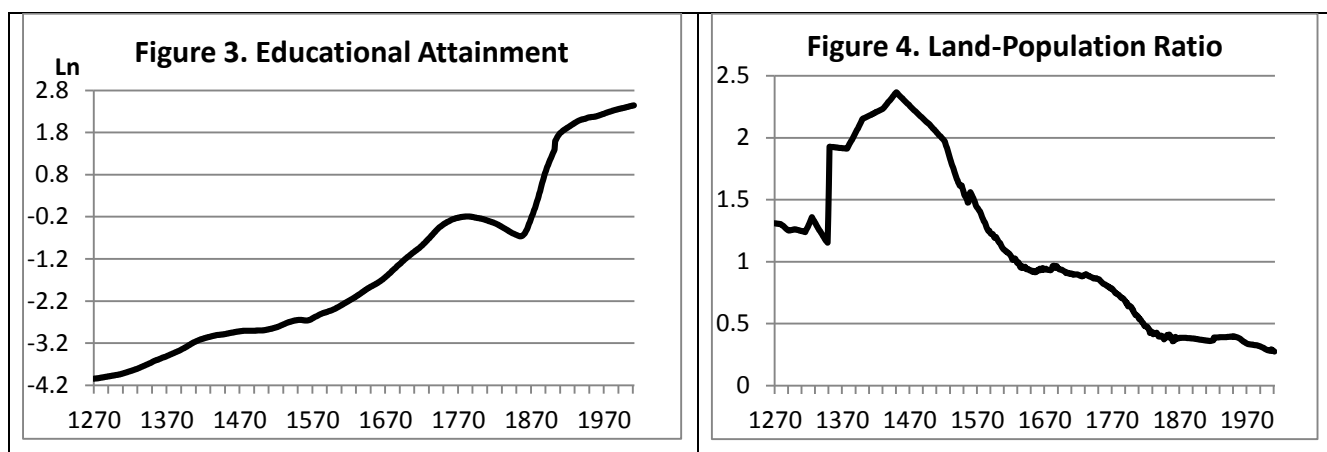
$$EA_t^P = \frac{\sum_{i=0}^{49} [Pop_{15+i} \sum_{j=4}^9 GER_{t-i-j}^P]}{\sum_{i=0}^{49} Pop_{15+i}}, \quad (5)$$

$$EA_t^S = \frac{\sum_{i=0}^{46} [Pop_{15+i} \sum_{j=1}^4 GER_{t-i-j}^S]}{\sum_{i=0}^{49} Pop_{15+i}}, \quad (6)$$

$$EA_t^T = \frac{\sum_{i=0}^{41} [Pop_{19+i} \sum_{j=0}^4 GER_{t-i-j}^T]}{\sum_{i=0}^{49} Pop_{15+i}}, \quad (7)$$

where  $pop_{15+i}$  is the size of the population aged  $15+i$ , and, as stated above,  $GER^P$ ,  $GER^S$  and  $GER^T$  are gross enrollment rates at the primary, secondary and tertiary levels. GER's are estimated as student enrollment in a given year divided by the population of the ages at which they are enrolled at a certain level. The term  $Pop_{n,15+i} \sum_{j=4}^9 GER_{t-i-j}^P$  in the numerator of Eq. (5), for example, is the total primary educational attainment among the  $15+i$  age cohort at time  $t$  and  $\sum_{j=4}^9 GER_{t-i-j}^P$  is primary school educational attainment. For 64 year olds in 1570, for example, the primary educational attainment is the sum of GERs over the period 1512-1518. The school ages are set to 6-11 for primary schooling, 12-14 for secondary schooling up to around 1902 (Gordon and Lawton, 2003). Although the schooling age intervals were probably lower than that prior to 1850 the

education attainment data are quite insensitive to the choice of age group intervals. The school reforms at the end of the 19<sup>th</sup> century and the beginning of the 20<sup>th</sup> century changed the years of schooling at the primary, secondary and the tertiary levels from the 6-4-5 model to the 7-5-5 model (Madsen, 2014). This is incorporated into the estimates of educational attainment with breaking point in 1902 as detailed in the separate Data Appendix.



**Notes.** Educational attainment is the average number of years of education of the working age population. The land-population ratio is measured as per capita hectares of crop and pastoral land use. See separate Data Appendix for data sources.

The log of educational attainment, which is displayed in Figure 3, increased steadily, up to around 1400 and rose only slightly in the next century. The increase in education in the period 1270-1400 is consistent with the marked increase in the number of documents recording property transactions and the growing use of accounting records that increased the dependence on the written word (Britnell, Ch. 13). According to Britnell, such documents became more formalized and diverse during the period after 1150. He notes that between 1250 and 1350 in Holkham, there are records of a significant number of transactions of peasants and towns people, suggesting that even people from socially lower ranks were given incentives to learn to read and write. Furthermore, there was a substantial increase in manorial record keeping from the 13<sup>th</sup> century, recording such things as cash receipts, expenses, and inventories (Britnell, 2004, p. 273). The archival revolution increased the demand for clerks with a sound understanding of legal instruments, administrative records and Latin; thus explaining the expansion in the number of grammar schools (Britnell, 2004, p. 275).

The stagnation in the educational attainment over the period 1400-1500 reflects that religious conservatives saw little merits in education and, during that period, considered with contempt the early Protestant endeavor to spread the vernacular Bible (Cressy, 1980, p. 2). The educational advances in the period 1500-1750 were the result of a high confidence in education, and political, religious and human propaganda was running in favor of schooling (Cressy, 1980, p. 168, Green,

1990, p. 28) and Protestant writing in the 16<sup>th</sup> and 17<sup>th</sup> centuries commonly urged literacy as a means to advance religion and an essential component in living a proper Christian life (Stone, 1969; Huston, 1983). Furthermore, the acceleration in educational activity in this period was stimulated by the invention of the movable type printing process and the decreasing costs of reading material (Green, 1990, p. 28). That the demand for elementary education had a strong momentum already in the second half of the 16<sup>th</sup> century is evidenced by the popularity of the ABC for children. In 1582 Roger Warde, for example, was proceeded against for infringing the patent held by John Daye and confessed that he had printed 10,000 copies of the ABC (Watson, 1908, p. 164). Another case of illegal printing of 10,000 copies of the ABC book took place in 1585 (Watson, 1908, p. 164).

By international standards the literacy rates were relatively high in Britain around 1760 and created a workforce that was able to operate the machines, read and create manuals and understand and implement the ideas created by scientists and engineers in the production process (Easterlin, 1981; Reis, 2005; Boucekine *et al.*, 2007). However, although new schools were built they failed to keep pace with the rapidly increasing population in the period 1750-1820 and educational attainment at the primary and secondary levels, consequently, suffered (Stone, 1969, p. 12; Sanderson, 1991). The First Industrial Revolution increased opportunities for child labor which halted access to education for many children (Sanderson, 1972, p. 89, and 1991, p. 13; Mitch, 1993; Humphries, 2010). The declining educational attainment in the period 1750-1820 is also consistent with the finding by Nicholas and Nicholas (1992) of deskilling of the English workforce during the early phase of British industrialization up to 1840 as industry substituted unskilled female and child laborers for skilled workers and relied on power-driven machinery that could be operated by unskilled labor (Sanderson, 1991, p. 14; Mitch, 1993).

The marked increase in educational attainment in the period 1845-1900 was driven by various factors. First, there was increasing demand for educated labor during the Second Industrial Revolution (Galor and Moav, 2004; Galor, 2011) as reflected in a literacy wage premium of 13 percent in 1869-73 (Mitch, 1982, p. 57). Furthermore, the increasing power of the capitalists relative to the landed class during the 19<sup>th</sup> century gave the capitalists a higher voice in the quest for a better educated labor force (Stone, 1969; Galor, 2005). The landed class was in favor of keeping their labor force illiterate, as an illiterate labor force was easier to control, more submissive and ensured sufficient labor supply to the agriculture (Stone, 1969).

Second, starting from around 1830 there was an increasing concern among policymakers that working class illiteracy acted as an impetus for high crime rates and workhouse populations. A better educated working class was seen as a means for reducing crime and workhouse populations and, therefore, reducing the increasing costs of prison systems and the Poor Law that would outweigh the

additional cost of education (Sanderson, 1991, p. 20). As a consequence, spending on elementary education increased no less than 45-fold over the period 1833-1870 and formal training of teachers was gradually introduced from the 1830s (Sanderson, 1991, pp. 21-22). Further funding of the educational system was ensured by the Acts of 1867 and 1870, partly to ensure enhanced military efficiency (Sanderson, 1991, p. 20).

Third, the national unease with the limitation of British scientific culture became evident with the 1867 Paris Exhibition and the rise of Prussian and French manufacturing helped initiate the civic universities movement of the 1870s and 1880s and led to an improvement in technical education (Sanderson, 1991, p. 35). This initiated the establishment of several universities that were viewed as powerhouses to stave off Britain's loss of competitiveness in the light of the slowing growth rates in the last third of the 19<sup>th</sup> century (Sanderson, 1975, p. 11). Furthermore, the rise of new electrical and chemical industries called for a new, more highly educated labor force in science (Sanderson, 1975, p. 11).

### *3.4 Land-population ratio*

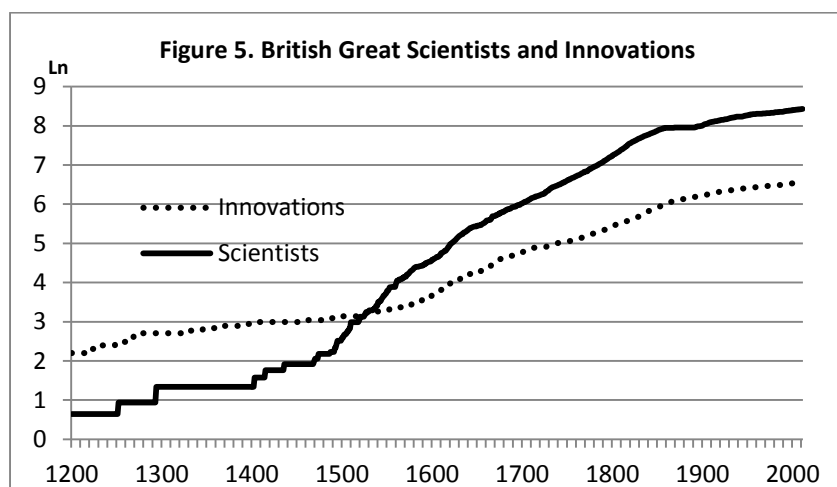
The ratio between land use and the total population is displayed in Figure 4. Land use is based on the History Database of the Global Environment in which historical statistics for crop and pastoral land and historical population are combined with satellite information and a specific allocation algorithm (see Klein Goldewijk *et al.*, 2011). Most of the variations in the land-population ratio come from variations in population growth; however, not all. Land use decreased by 30 per cent in the period 1300-1443 and the land-population ratio almost doubled in the period 1348-1350. The land use doubled over the period 1450-1850 and mitigated some of the adverse productivity effects of the increasing population on the land-population ratio. Regressing the log of land on the log of population in the period 1270-2011 yields a coefficient of population of 0.26, indicating some response in land use to population pressure; even in Britain in which the population was denser than in most other countries.

### *3.5 Domestic knowledge*

Domestic knowledge stock is measured as accumulated significant inventions (Ochoa and Corey, 1997). The score of one is given for each significant innovation and the knowledge stock is assumed to depreciate by one percent annually. The knowledge stock, which is displayed in Figure 5, shows a marked advance in the period 1270-1330 and, particularly, during the 17<sup>th</sup>, 18<sup>th</sup> and 19<sup>th</sup> centuries. Remarkably, the increase in the 17<sup>th</sup> century is not reflected in a corresponding increase in the number of university graduates, suggesting that an increasing number of university students is not a

sufficient condition for scientific discoveries although most scientists had university degrees. Hans (1951), for example, identified 680 scientists born between 1600 and 1785 in Britain and Ireland, and found that 63 percent of them had a university education, while less than a quarter had no formal secondary education, though approximately two thirds of these had apprenticeship training.

The regressions in Section 6 suggest that it was improving institutions, more secular values and cheaper books that were crucial for the growth in knowledge in the 17<sup>th</sup>, 18<sup>th</sup> and 19<sup>th</sup> centuries, indicating that they may have been some of the important driving forces behind the Scientific Revolution during the 17<sup>th</sup> century. According to Debus (1978), during the 16<sup>th</sup> and 17<sup>th</sup> centuries, research was supported by inclusive institutions and there was a decisive change in the focus from an Aristotelian natural philosophy to chemistry and biological sciences such as botany, anatomy, and medicine. Debus (1978) argues that the preparedness to question previously held truths and the search for new answers resulted in an epoch of major scientific advancements. Similarly, Bernal (1937) argues that religion, superstition, and fear were replaced by reason and knowledge during the English Renaissance. The advances in science were marked by the foundation of the Royal Society in 1660.



**Notes.** Inventions are from (No Wilson!) Ochoa and Corey (1997) and scientists are from Gascoigne (1984); accumulated with a depreciation rate of one percent.

### 3.6 International knowledge spillovers

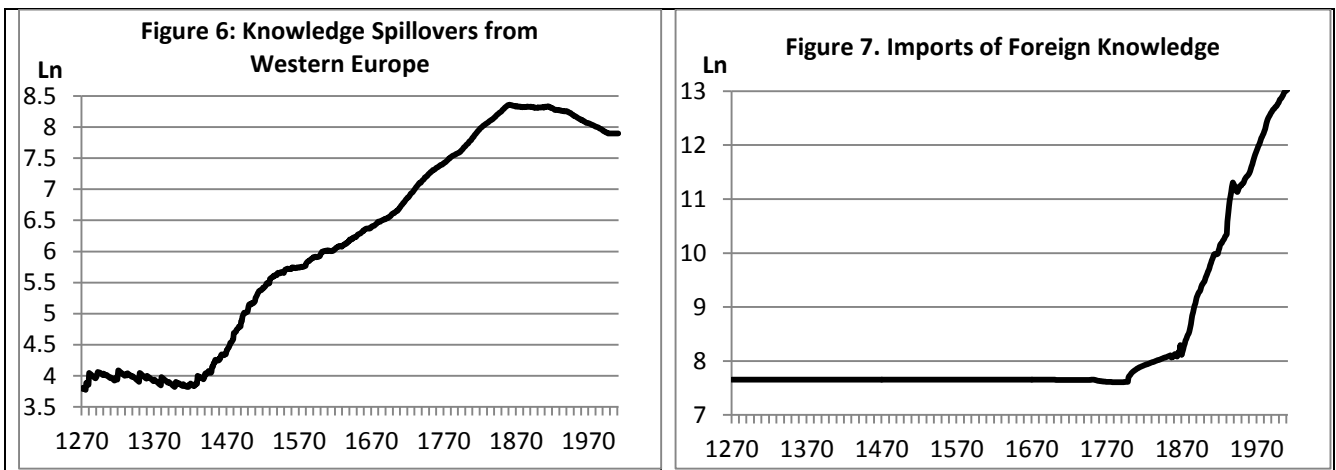
Knowledge spillovers from continental Europe is, as aforementioned, the sum of great scientists from Gascoigne (1984) for Belgium, Denmark, France, Germany, Ireland, Italy, the Netherlands, Norway, Portugal, and Spain and accumulated with a depreciation rate of one percent. The data for great scientists are classified on time and country using the 15918 biographies of great scientists listed in Gascoigne (1984). Knowledge spillovers through imports in the period 1700 to 1870 are measured as a weighted average of the stock of knowledge created by great scientists before

1870 and as a weighted average of patent knowledge stock after 1870 from Madsen (2007). No knowledge spillovers are assumed from this channel before 1700. The following weighting schemes are used:

$$S_{UK,t}^{im} = \sum_{K=1}^{16} \frac{M_t^{UK,K}}{M_t^{UK}} S_{Kt}^d, \quad 1700-1869$$

$$S_{UK,t}^{im} = \sum_{J=1}^{18} \left( \frac{M_t^{UK,J}}{Y_{Jt}} \right) S_{Jt}^d, \quad 1870-2011$$

where  $M_t^{UK,K}$  is imports of goods from country  $K$  to Britain,  $M_{UK}$  is total imports of goods to Britain,  $M_t^{UK,J}$  is UK imports of high technological products from country  $J$ ,  $Y_J$  is the nominal GDP of country  $j$ ,  $S_{Kt}^d$  and  $S_{Jt}^d$  are the patent knowledge stock in countries  $K$  and  $J$ . The  $J$ -group consists of the 18 OECD core OECD members (Canada, the US, Japan, Australia, New Zealand, Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland and the UK), while the 16 countries in the  $K$ -group consist of India, the US, Denmark, Canada, Belgium, France, Germany, Poland, Russia, Portugal, Italy, West Indies, Turkey, Argentina, Australia and New Zealand. Bilateral imports are used as weights in the *pre*-1870 estimates because of the unavailability of nominal GDP and bilateral exchange rates over the period 1700-1870. Great scientists from Gascoigne (1984) are used to construct the knowledge stock of each individual trade partner.



**Notes.** The data are based on great scientists from Gascoigne (1984).

Figures 6 and 7 show distinct time-profiles for the two knowledge spillover channels. Knowledge spillovers from Western Europe was fairly flat up to 1400, increased steeply between 1400 and 1500, increase at a slower but still at a brisk pace up to their peak in 1850 and declines thereafter as the depreciation of existing knowledge stock overrides the addition of new scientists

(Figure 6). Knowledge spillovers through imports show a modest increase from 1700 up to approximately 1850 and a marked increase thereafter (Figure 7). The modest increase from 1700 up until 1850 reflects that Britain imported heavily from countries with little growth in scientific knowledge. It was not until the middle of the 19<sup>th</sup> century that Britain expanded its imports from countries with strong growth in scientists such as the US and Western Europe. The distinct path between knowledge spillover from Western Europe (Figure 6) and through imports (Figure 7) after 1870 only reflects, to a small degree, the distinct country weights in the two indexes and is more an outcome of the different innovation variables underlying the indexes. The patent knowledge stock increased substantially in the post-1870 period while the knowledge stock based on Gascoigne's (1984) classification of great scientists decreased after 1870 because the depreciation surpassed the accumulation of new great scientists.

#### **4. OLS regressions**

The results of regressing Eq. (4) covering the period 1270-2009 are presented in Table 1. The regressions are based on dynamic OLS of Stock and Watson (1993) and two leads and lags of the regressors in first differences are included in the models to allow for dynamic adjustment around the long run equilibrium (the first-difference terms are not presented to preserve space). Note that all coefficients are expected to be positive in all regressions except for the regression in which agricultural share is the dependent variable (column 2). The Dickey-Fuller tests strongly reject the null hypothesis of no cointegration, indicating a long-run relationship between the dependent and the independent variables and that the independent variables adequately explain the dynamic path of the dependent variables.

The coefficients of educational attainment are highly significant and of the expected sign in all regressions except in the urbanization regression. The latter result can to a large extent be explained by the substantial increase in educational attainment coupled with the almost flat urbanization rate over the period 1890-1970, which have forced the significance of education down. As shown below, the coefficient of education becomes significant when the post-1900 period is omitted from the urbanization regression. Furthermore, as aforementioned, the urbanization data fail to capture short and medium-term movements in industrialization before 1800 because the data are often interpolated between centuries. The significance of educational attainment in the non-urban regressions suggests that it has been influential for the productivity growth profile since 1270. The declining educational attainment together with a more than a doubling of the population size in the approximate period 1750-1840 explains the poor growth performance during the First Industrial

Revolution. Furthermore, the marked increase in educational attainment during the second half of the 19<sup>th</sup> century was a significant contributor to the high growth in Britain during the Second Industrial Revolution.

**Table 1.** DOLS regressions, 1270-2009 (Eq. (4)).

	1	2	3	4	5	6
Dep. Var.	$Ln(Y^B/Pop)$	$Ln(Agr^S)$	$Ln(Urb)$	$Ln(Y^C/Pop)$	$Ln(Y^B/H^{AW})$	$Ln(Y^B/H^{CWV})$
$EA_t$	0.09(25.7)	-0.15(24.8)	0.00(0.04)	0.08(23.4)	0.07(15.8)	0.10(15.2)
$lnS_t^d$	0.38(19.1)	-0.21(8.47)	0.61(36.9)	0.29(14.9)	0.67(18.6)	0.33(17.4)
$lnS_t^{Eu}$	0.07(5.46)	-0.02(1.65)	0.26(25.3)	0.03(2.12)	0.18(7.46)	0.06(5.62)
$Op_t \cdot lnS_t^{Im}$	0.06(6.89)	-0.06(4.91)	0.02(2.03)	0.06(6.01)	0.02(1.43)	0.03(2.75)
$lnk_t$	0.43(20.5)	-0.27(8.72)	0.46(18.7)	0.72(34.7)	0.64(18.2)	0.24(8.82)
$\psi_t ln\tau_t$	0.25(12.6)	-0.04(1.82)	0.46(27.3)	0.37(16.0)	1.17(28.2)	0.40(20.7)
DF	-6.91	-6.66	-3.88	-5.42	-9.02	-5.12

**Notes.** The numbers in parentheses are absolute  $t$ -statistics based on serial correlation and heteroscedasticity robust (Newey-West) standard errors.  $Y^B$  = real income based on Broadberry *et al.* (2011),  $Y^C$  = real income based on Clark (2010),  $H^{AW}$  = employment times hours worked based on Allen and Weisdorf (2011),  $H^{CWV}$  = annual hours worked based on Clark and van der Werf (1998) (the years 1580, 1625, 1675, 1716, 1760, and 1730-1870) and Voth (2001) (the years 1766, 1800, and 1830),  $Agr^S$  = agricultural share of GDP,  $Urb$  = urbanization,  $S^{Eu}$  = foreign knowledge stock measured as the sum of knowledge stock in Belgium, Denmark, France, Germany, Ireland, Italy, the Netherlands, Norway, Portugal, and Spain based on Ochoa and Corey (1997) (O&C), and  $S^d$  = domestic knowledge stock based on O&C (1997). DF = Dickey-Fuller test for unit roots with critical value of 3.53 at the 1% level (constant term but no lags of the dependent variable is included). Estimation period: 1270-2009. The models are based on DOLS in which two leads and lags of the regressors are included in the regressions.

The coefficients of domestic stock of knowledge,  $S^d$ , are highly significant in all regressions, indicating that the creation of domestic knowledge was pivotal for technological advances and, consequently, productivity growth. Since the domestic knowledge stock advanced substantially in the period 1500-1900, the British scientific revolution was influential for the British growth experience in the same period. The results are consistent with the discussion of Jacob (1997, 2014) and Mokyr (2005a) who give several examples of how theories developed by great minds were subsequently used by practical people to develop new technologies and to find new ways of doing things. Almost all the coefficients of foreign knowledge spillovers are significant and of the expected signs, indicating the strong ability of the British to take advantage of the technology developed overseas. The two spillover variables appear to complement each other quite well and their statistical and economic significance of each variable is, by and large, unaffected by the exclusion of the other (the results are not shown).

The coefficients of the  $K$ - $Y$  ratio are also highly significant and the magnitudes of the coefficients are close to the predictions of the model in Section 2 (i.e.  $\alpha(1 - \beta_t)/(1 - \alpha(1 - \beta_t))$ ). Thus, saving-induced capital accumulation was an important source of growth during the early industrialization period, 1750-1864, and the *post*-WWII period up to the first oil price shock in 1973/74 and, conversely, depressed growth rates in the long period 1450-1750. Finally, the land-

population ratio is of the expected sign and is significant in all regressions except in the regression where Clark's income data are used, suggesting that population growth is a drag on productivity due to diminishing returns introduced by land as a semi-fixed factor of production. In most of the cases the coefficient of  $\psi_t \ln \tau_t$  is below the model predictions of one in the income regressions; perhaps reflecting an errors-in-variables attenuation bias.

**Table 2.** DOLS regressions, 1600-1900 (Eq. (4)).

	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
<b>Dep. Var.</b>	$\ln(Y^B/Pop)$	$\ln(Agr^S)$	$\ln(Urb)$	$\ln(Y^C/Pop)$	$\ln(Y^B/H^{AW})$	$\ln(Y^B/H^{CWV})$
$EA_t$	0.13(6.32)	-0.29(13.5)	0.10(7.18)	0.17(11.1)	0.09(2.73)	0.11(6.17)
$\ln S_t^d$	0.34(4.23)	-0.09(10.8)	0.37(8.69)	0.06(1.34)	0.60(4.93)	0.31(4.30)
$\ln S_t^{Eu}$	0.15(2.16)	0.46(5.12)	0.33(8.10)	-0.03(0.52)	0.06(0.56)	0.13(1.93)
$Op_t \cdot \ln S_t^{Im}$	0.06(5.38)	0.00(0.18)	-0.03(2.80)	0.07(4.18)	0.02(0.76)	0.04(2.82)
$\ln k_t$	0.27(3.83)	-0.65(7.00)	0.24(5.32)	0.40(5.72)	0.06(0.48)	0.08(1.17)
$\psi_t \ln \tau_t$	0.21(2.17)	-0.39(2.54)	0.18(2.40)	-0.24(2.34)	0.43(2.26)	0.45(3.91)
DF	-5.16	-4.60	-2.88	-4.23	-6.43	-4.60

Notes. See notes to Table 1. Estimation period: 1600-1900.

The estimation period is narrowed down to 1600-1900 in the regressions in Table 2 and is likely to give a better picture of the forces driving the British success during the crucial period of industrialization. The null hypothesis of no cointegration is strongly rejected in all cases except for the urbanization regression, which further underscores that the urbanization data before 1800 are flawed. The coefficients of the included regressor are mostly significant and of the expected sign; thus not only reinforcing the results in Table 1 but also showing that the model given by Eq. (4) has validity in the industrialization period. The absolute values of the coefficients of educational attainment in Table 2 are significantly higher than those in Table 1, indicating that the social returns to education were much higher during the years of industrialization than before and after. The high productivity effects of education during industrialization imply that the low growth rates during the First Industrial Revolution were heavily influenced by the declining educational attainment during the same period.

## 5 Extensions and robustness checks

This section tests the robustness of the baseline results to measurement of domestic knowledge stock, land area, education, international transmission channels, allowance for vocational training, decomposition of education into extensive and intensive margins, and using literacy as a proxy for primary education.

### 5.1 Alternative measures of knowledge

The domestic knowledge stock has thus far been based on the classification of great inventions by Ochoa and Corey (1997). The stock of knowledge computed from the classification of great inventions of Asimov (1982), Helleman and Bunch (1991), and great scientists of Gascoigne (1984) is presented in the regressions in columns 1-3 in Table 3. The coefficients of the domestic knowledge stock variables are all statistically more significant than those of the baseline regression (Table 1 column 1), suggesting that scientific knowledge is a robust and significant determinant of productivity. Almost all the other coefficients remain significant and are of magnitudes close to that of the baseline regression.

**Table 3.** Robustness tests, DOLS 1270-2009 (Eq. (4)).

	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
	$S^d$ based on As.	$S^d$ based on Gasco.	$S^d$ based on H&B	Inns of Courts incl. in EA	Apprentices added
$EA_t$	0.09(24.3)	0.10(21.2)	0.09(22.0)	0.09(25.7)	0.08(25.3)
$\ln S_t^d$	0.22(15.2)	0.14(7.07)	0.13(9.32)	0.38(19.1)	0.46(19.9)
$\ln S_t^{Eu}$	0.18(15.3)	0.05(1.63)	0.12(7.80)	0.07(5.46)	0.05(3.36)
$Op_t \cdot \ln S_t^{Im}$	0.07(7.34)	0.10(8.65)	0.08(8.02)	0.06(6.88)	0.05(5.80)
$\ln k_t$	0.48(19.3)	0.49(16.4)	0.35(11.5)	0.43(20.8)	0.38(14.5)
$\psi_t \ln \tau_t$	0.28(10.9)	0.08(3.50)	0.45(7.73)	0.25(12.6)	0.33(14.5)
$App_t$					-0.39(6.10)
DF	-6.67	-6.34	-6.97	-6.90	-6.92

**Notes.** See notes to Table 1. The dependent variable is the per capita income of Broadberry *et al.* (2011) and the domestic knowledge stock is based on Ochoa and Corey (1997) in the regressions in columns 4 and 5. Col. 1: domestic stock of knowledge based on Asimov (1982). Col. 2: domestic stock of knowledge based on Gascoigne (1984). Col. 3: domestic stock of knowledge based on Helleman and Bunch (1991).  $App$  = the fraction of population of working age that has undertaken an apprenticeship. Col. 4: Inns of Courts are included in the computations of educational attainment up to 1750. Col. 5. The fraction of the working age population that has completed an apprenticeship is included as an additional regressor.

### 5.2 Including enrollment in Inns of Court

Tertiary education has thus far been based on students enrolled in universities only. However, a large fraction of law students gained their law qualifications in Inns of Court between the 14<sup>th</sup> and the 17<sup>th</sup> centuries. Inns of Court offered professional and vocational training for prospective lawyers and a general education for the gentry at large (Stone, 1964). A complication is that the main functions of Inns of Courts have altered substantially over their 700 years of their existence in that, for a long time, they have not provided all the education and training needed by prospective barristers, but were reduced to predominantly providing supplementary education from the beginning of the 17<sup>th</sup> century (Jewell, 1998; Palfreyman, 2011).

Inns of Court educational attainment is included in the estimates of educational attainment in column 4 in Table 3, where the student enrollment in Inns are computed as the sum of students in the four major Inns of Court (Gray's Inn, Lincoln's Inn, the Inner and Middle Temple). The regression

results in column 4 are almost identical to the results in the baseline regression in Table 1, which is, perhaps, not surprising given that the number of students enrolled in Inns of Court was only a small fraction of students enrolled in tertiary education during the 14<sup>th</sup> and the 17<sup>th</sup> centuries.

### 5.3 Vocational training

Vocational training has been advanced as being an essential impetus to the early British industrialization by Humphries (2003, 2010, Ch. 8) among other economic historians. Epstein (2004) suggests that journeymen were the principal source of technology diffusion in the preindustrial period because technological progress was predominantly tacit and embodied in its practitioners. By the 18<sup>th</sup> century up to a half of all skilled workers in some trades were ‘structural’ or continuous migrants (Epstein, 2004). Humphries (2010) argues that apprenticeships were important for the industrialization for the same reasons as other forms of education (p. 305), which, presumably, would mean that they enhanced the efficiency of production, division of labor and innovative activity. Furthermore, Humphries (2010) suggests that apprenticeships lowered the transactions cost of trade and commerce as they created industrial and geographical networks (p. 292) and smoothed the transition from agriculture to urban sectors (p. 305). The number in the labor force with vocational training was sufficiently large to be potentially important for productivity. Humphries (2003, 2010, p. 258), for example, estimates the number of apprentices to be 2.3-7.8 percent of the population during the 18<sup>th</sup> century.

The educational attainment for apprentices, *App*, is included in the regression in column 5 in Table 3, where *App* is estimated in the same way as educational attainment and it is assumed that the apprenticeship is undertaken in the ages of 14-20. This time interval gives an average of 17 which is close to the average age of apprentices in the late 16<sup>th</sup> century London of 17.7 years (Wallis, 2008). In other words, *App* measures the percentage of the working age population that has completed an apprenticeship. Since complete time-series data on number of apprentices in Britain do currently not exist (Humphries, 2003), the number of apprentices over time as a percentage of the 14-20 year age cohort population in Britain is approximated by the number of apprentices within clothwork, goldsmith, draper and mercer professions in Livery Companies (trade guilds) of the City of London and then scaled up by the ratio of the British and the London population.

Contrary to expectations, the coefficient of *App* is negative and statistically significant. This counterintuitive result may reflect that the sample may be unrepresentative of the entire country and all skilled professions. It is quite possible that the fraction of apprentices in London relative to Britain as well as the fraction of clockwork, goldsmith, draper, and mercer professions in the total number of apprentices varied over time. However, educational historians agree that the number of

apprenticeships declined during industrialization (Humphries, 2010, p. 259); a feature that is echoed in the data used here. Consequently, per capita income and *App* moved in opposite directions during the period in which the British economy was growing the most barring the Golden Period, suggesting that apprentices may not have contributed much, if at all, to the productivity advance during the British industrialization.

It is also quite possible that the results, to some extent, reflect that some apprentice professions did not advance technology or efficiency and that that these professions have dominated the dataset used here. It is unlikely that goldsmiths, drapers, and mercer apprentices would have enhanced technological progress much and the productivity effects from these professions may well have overridden the productivity enhancing effects of potential innovations of clockwork apprentices. Furthermore, the innovation effects of apprentices have already been accounted for by great scientists of significant innovations in the regressions. No less than 17 percent of 680 scientists born between 1600 and 1785 in Britain and Ireland identified by Hans (1951) had apprenticeship training. Thus, based on the data available for apprentices, the overlap with great scientists/significant inventions, and the ambiguity of the productivity effects of various apprenticeship professions render it very hard to give a sound quantitative evidence of the role played by apprentices during the British Industrial Revolution.

#### *5.4 Different dimensions of education*

Education may have different productivity growth effects in the intensive and the extensive margins in that secondary and tertiary education may have productivity effects that are different from that of primary education. For that consideration the ratio of secondary (tertiary) educational attainment and total educational attainment,  $EA^S/EA$  ( $EA^T/EA$ ) are added to the regression in column 1 in Table 4, noting that  $EA$  is still measured as educational attainment at all levels. The coefficients of ( $EA^S/EA$ ) and ( $EA^T/EA$ ) are both highly significant, suggesting that the social returns to education are higher at the secondary and, particularly, at the tertiary level relative to the average educational attainment. Thus, the productivity effects of one additional year of schooling are increasing in the years of education or, simply, there are increasing returns to education in the intensive margin.

Literacy is added as regressor in the regression in column 2 in Table 4 and educational attainment,  $EA$ , is computed as secondary and tertiary education in this regression to avoid double counting basic education. The literacy data, which are only available from 1500, are backdated using the primary educational attainment. The coefficient of literacy is highly significant and the coefficient of secondary and tertiary educational attainment remains highly significant; thus reinforcing the results in the previous section that education has been a robust and significant

determinant of British economic development over the past eight centuries and during the British Industrial Revolution. Furthermore, the coefficient of secondary plus tertiary education of 0.13 is higher than that in the baseline regression of 0.09, giving further evidence of increasing returns in the intensive margin of education.

**Table 4.** Robustness tests, DOLS (Eq. (4)).

	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
	<b>Int. and ext. education</b>	<b>Literacy added (1270-2009)</b>	<b>Spillover from France added</b>	<b>Patents used for dom. Knowledge</b>	<b>20% pupils per school in 1160</b>
$EA_t$	0.07(15.4)	0.13(10.0)	0.09(25.1)	0.10(15.2)	0.09(25.7)
$\ln S_t^d$	0.82(13.9)	0.07(2.21)	0.36(6.26)		0.38(19.2)
$\ln S_t^{Eu}$	0.23(8.41)	-0.03(2.27)	0.07(4.22)	0.45(10.7)	0.07(5.45)
$Op_t \cdot \ln S_t^{Im}$	0.06(6.78)	0.03(3.90)	0.07(7.63)	0.03(3.06)	0.06(6.89)
$\ln k_t$	0.25(8.15)	0.36(15.6)	0.42(17.5)	0.50(9.49)	0.42(20.3)
$\psi_t \ln \tau_t$	0.78(10.9)	0.29(15.2)	0.25(12.9)	0.59(5.18)	0.25(12.7)
$EA_t^S/EA_t$	1.15(6.73)				
$EA_t^T/EA_t$	1.67(8.17)				
$Lit_t$		0.02(19.9)			
$\ln S_t^{Fra}$			0.02(0.36)		
$\ln S_t^{Pat}$				0.06(3.10)	
$DF$	-6.83	-6.89	-6.87	-5.15	-9.60
Est. per.	1270-2009	1270-2009	1270-2009	1620-2009	1270-2009

**Notes.** See notes to Table 1. The dependent variable is per capita income of Broadberry *et al.* (2011).  $Lit$  = literacy rate.  $S^{Fra}$  = knowledge stock in France,  $S^{Pat}$  = patent stock on the perpetual inventory method and a 15% depreciation rate and patents are measured as patent applications and of residents. Col. 1: The share of secondary and tertiary education in total educational attainment is added to the regression. Col. 2: Literacy is added to the regression and educational attainment is *only* at the secondary and the tertiary levels (primary educational attainment excluded from  $EA$ ). Col. 3:  $S^{Fra}$  (knowledge stock of France) is included as an additional regressor. Col. 4: Domestic knowledge stock is based on patent stock. Col. 4: The number of pupils per school is assumed to be 20% of the numbers in 1850 (primary schools) and 1865 (secondary school) in 1160 and linearly interpolated between 1160 and 1850/65.

One problem associated with the inclusion of the literacy rate in the regression is that the significance of domestic knowledge stock is reduced and the coefficient of knowledge spillovers from the European continent is rendered negative, suggesting that literacy captures effects from these two variables. In this context it may be noted that measured literacy rates for Britain are not always good measures of basic educational skills; partly because they suffer from sampling problems and are heavily interpolated (Schofield, 1973). More importantly, most of the literacy rates are coded as the scaled number of people being able to sign their name at marriages (Schofield, 1973). However, since reading skills were taught during first three years of the primary schooling following by writing literacy based on signatures is likely to underestimate the number of pupils actually being able to read and, importantly for estimation purposes, will overestimate the effects of changes in primary schooling in the intensive margin and underestimate the effects of changes to primary education in the extensive margin.

### 5.5 Knowledge spillovers from France

Foreign knowledge spillovers have thus far been based on knowledge spillovers from continental Europe and through imports. Here, complementary knowledge spillovers from France are considered. As discussed above France has often been emphasized as a country from which technology was transmitted to Britain through industrial espionage (Harris, 1998), the flow of skilled artisans and merchant refugees (Harris, 1998, p. 564), and the exodus of scientists and entrepreneurs following anti-Protestant bigotry and persecution (Landes, 1983, p. 219).

The coefficient of France's knowledge stock,  $S^{Fra}$ , which is included as an additional regressor in column 3 in Table 4, is insignificant. However, this does not mean that knowledge spillovers from France were unimportant since France already has a large weight in  $S^{Eu}$ . What the insignificance of  $S^{Fra}$  suggests is that the impact of each great French scientist was no more influential for British productivity than great scientists of other countries contained in  $S^{Eu}$ .

### 5.6 Other robustness tests

Domestic stock of knowledge is based on patent applications instead of significant innovations in the regression in column 4 in Table 4. Patents have been used as proxies for innovations to explain productivity advances in British history by Madsen *et al.* (2010) and productivity advances in the OECD since 1870 by Madsen (2008) and they do seem to capture productivity advances quite well; however, they are not perfect proxies for innovations and inventions. A weakness of the English patent system throughout the British Industrial Revolution was that patents were used sparingly because they were costly to file and of uncertain value (Mokyr, 2009, pp. 403-410). Furthermore, the English patent laws in the 17<sup>th</sup> and 18<sup>th</sup> centuries did not always request novelty and originality, most patent descriptions were generic and did not approximate the modern blueprint, and innovations were seldom carefully examined by assessors (Epstein, 2004). The regression period is limited to 1620-2009 due to the availability of patents. The coefficients of all variables, including patent stock,  $\underline{S}^d$ , are highly significant, reinforcing the finding in Table 2 that broadly defined human capital played a key role for productivity advances after the British economy entered its post-Malthusian growth regime with steady technological progress that was only partially kept down by population growth.

Finally, the number of pupils per school is in 1160 set to 20% of the numbers in 1850 (primary schools) and 1865 (secondary school) and the percentage is linearly interpolated between 1160 and these periods in the regression in the last column in Table 4. The regression results are quite similar to those of the baseline regression (column (1) in Table 1), suggesting that the results are not significantly influenced by this consideration. A further implication of this result is that the results are not likely to be significantly affected by stochastic trends and random year-to-year

fluctuations in the student-school ratio; particularly because educational attainment is computed as a weighted average of school enrollments of the working age population.

## **6 Instrumental variable regressions**

Domestic knowledge stock, educational attainment and the land-population ratio are instrumented in this section to partly deal with endogeneity and, more importantly, to get a better understanding of the more fundamental forces that are driving these variables. The  $K$ - $Y$  ratio is not instrumented because it is not possible to find good instruments for this variable that are available on an annual basis over the last millennium. Furthermore, the  $K$ - $Y$  ratio is not likely to be influenced much by feedback effects from per capita income because technological progress affects capital and income equally in standard economic growth models and, therefore, leaves the  $K$ - $Y$  ratio independent of technological advances in steady state. The instruments used here should *not all* be considered strictly exogenous but rather as a step further in the causal chain, and which enable one to gain insight into forces that have driven human capital during British industrialization. Furthermore, the exclusion restrictions that the instruments affect growth only through the variables they are instrumenting are not likely to hold entirely for all instruments. Overall, this section should be considered as a cautious attempt to account for forces that are likely to have been influential for the growth in scientific knowledge and education.

Education is endogenous to the extent that it is driven by demand for education and, thus, can be considered as part of economic development; or, more generally, education is a normal good and, therefore, will tend to increase in line with income. Sanderson (1991, p. 45), for example, hypothesizes that the expansion of middle-class education both in grammar and in public schools after 1830 was a response to demand for education from parents, which in turn may have been driven by parents' income. Furthermore, the increasing importance of military and state capacity building after 1500 increased the demand for literate personnel (Houston, 1988, p. 100). Officers had to understand written orders, sign for their pay, write reports and requisitions, and literate troops could read orders, read firearm manuals, and write letters home. Finally, governments needed diplomats, tax collectors, clerks, and judges. However, education was not always driven by demand and economic development. Sanderson (1991, p. 45), for example, states that the education expansion during the 19<sup>th</sup> century was often not driven by the growth in new fields of employment. Knowledge stock may be endogenous in that it may be influenced by increasing demand for knowledge as the economy advances or simply that research becomes more affordable as the society becomes richer. Finally, the

$T-L$  ratio is endogenous as the population before the demographic transition may have been influenced by income through the preventive check mechanisms advocated by Malthus.

### 6.1 Gross enrollment rates and significant inventions

GERs at each educational level and significant inventions are instrumented through the following first-round regressions:

$$GER_t^x = \beta_0 + \beta_1 \ln Mar_t^{Age} + \beta_2 \ln Oow_t^{Fert} + \beta_3 \ln Mar_t^{Rate} + \beta_4 \ln Exec_t + \beta_5 \ln \left( \frac{P_t^B}{P_t} \right) + \varepsilon_{1,t}, \quad (8)$$

$$\ln S_t^d = \gamma_0 + \gamma_1 \ln Mar_t^{Age} + \gamma_2 \ln Oow_t^{Fert} + \gamma_3 \ln Mar_t^{Rate} + \gamma_4 \ln Exec_t + \gamma_5 \ln \left( \frac{P_t^B}{P_t} \right) + \varepsilon_{2,t}, \quad (9)$$

where  $GER^x$  is gross enrollment rates at the primary ( $x = p$ ), secondary ( $x = s$ ), and tertiary ( $x = t$ ) levels,  $Mar^{Age}$  is the average age at the first marriage,  $Oow^{Fert}$  is out-of-wedlock fertility,  $Mar^{Rate}$  is the marriage rate,  $Exec$  is constraints on the executive,  $P^B$  is book prices, and  $P$  is consumer prices. As in the OLS estimates the stock of knowledge,  $S^d$ , in Eq. (9) is measured as the stock of significant inventions by Ochoa and Corey (1997). Domestic knowledge is additionally measured as the stock of patents,  $S^{Pat}$ , to get an indication of whether micro inventions/innovations (patents) were determined by the same factors as macro inventions (great inventions) and the extent to which they influence output when instrumented.

Here  $Exec$  is a proxy for the quality of institutions, the real price of books is a proxy for the cost of schooling and dissemination of knowledge, and  $Mar^{Age}$ ,  $Oow^{Fert}$  and  $Mar^{Rate}$  are, predominantly, proxies for culture. Constraints on executive are widely used indicators of the quality of institutions, while there are no established indicators of culture in the economics literature except for the more recent World Value Surveys. While marriage rates and marriage ages are, primarily, proxies for culture they also influence education through the cost-benefits aspects of education. Low marriage rates and high marriage ages have often been important for the growth in mass education (Stone, 1969), presumably because marriage has often been associated with the establishment of family and investment in real estate; thus savings are channeled away from investment in education into catering for children and investment in real estate. Furthermore, females' expected returns from schooling are declining functions of the probability of marriage. The average marriage age is endogenous to the extent that the preventive check (fertility) mechanism of Malthus operated through marriage age. This mechanism, however, is muted to the extent that population growth was primarily determined by mortality. A large body of the demographic literature shows that mortality

was much more influential for population growth than fertility (see, e.g., McKeown and Brown, 1955; Omran, 2005).

The quality of institutions is often considered to be fundamental for economic development and growth (see, e.g., North and Weingast, 1989; Acemoglu *et al.*, 2005; Acemoglu and Robinson, 2013). Britain is the perfect testing ground for the institutional hypothesis since it is often highlighted by North, Weingast, Acemoglu and Robinson as a sterling example of how institutional progression, culminating with the Glorious Revolution in 1688, not only paved the way for the British Industrial Revolution but also spread across the world through British settlements. The quality of institutions is potentially affecting education and knowledge production because it increases the expected reward from investing in education and science (Acemoglu and Robinson, 2013). Improved institutions also influenced the schooling decision by increasing the demand for writing skills as evidenced by the marked increase in the usage of charters after 1050 (Britnell, 2004, Chs. 13 and 23). The charters, recorded details of property transactions and listed the names of the witnesses (Britnell, 2004, p. 267). That they became increasingly widespread in Britain after 1050 is a testimony of record-keeping institutions that were required by formal property rights.

The real price of books is used as instruments for GERs since books were very expensive back in time and they had to be purchased by pupils regardless of whether enrollment was free (Stone, 1969). The real price of books is essentially determined by technological progress in printing and paper manufacturing. The invention of the printing press by Gutenberg in 1440 and the subsequent large number of innovations in printing manufacturing reduced the real price of books substantially (Stone, 1969). The printing press spread across Europe, including Britain, with great speed during the 16<sup>th</sup> century and lowered the real price of books substantially (Stone, 1964). Since most of the printing press innovations were made in Germany (Eisenstein, 2005) the reduced real price of books was an exogenous event from the British perspective. Furthermore, the exclusion restriction is easily satisfied since it is unlikely that real book prices influence income through channels other than education and science. Thus, real book prices should be excellent instruments for the schooling decision. The real price of books is also a potentially good instrument for creation of knowledge, as academic learning almost entirely builds on previous knowledge and knowledge created in other countries – transmission of knowledge, at least until recently, is easiest through books and journals.

The same instruments are used for GERs and  $S^d$  because cultural and institutional variables are fundamental explanatory variables for education as well as for the creation of great inventions and scientists. Institutions may set the reward structure of education and, hence, influence the expected returns to education (Dias and Tebaldi, 2012), while culture influences how much

education is valued, for example whether science and education are valued in their own right, or whether it is dogmas and traditional values that are most highly valued. Cultural values influence the utility derived from education and the higher is the utility attached to education, the larger is the share of the budget the household is willing to expend on education.

Culture is a key determinant of the values, preferences and beliefs of individuals and societies and is advocated to have been an important factor behind the Industrial Revolution by Weber (1905), Landes (1998), and Doepke and Zilibotti (2008). Landes (1998) concludes that, “if we learn anything from the history of economic development it is that culture makes all the difference ... what counts is work, thrift, honesty, patience, tenacity” (pp. 516, 523). For Mokyr (2005a) the Industrial Enlightenment is a milestone in human history as people became more tolerant to new ways of solving problems. People’s attitudes towards knowledge are critical to the progress of human civilization and a positive attitude towards knowledge is shaped by secularism. The key here is that the European Enlightenment was associated with increasing religious and political tolerance, human rights and freedom and natural law and justice, allowing potentially outrageous and eccentric ideas of innovators to be tolerated without violent responses (Mokyr, 2005a).

According to Karl Marx and Max Weber Britain became increasingly secular after the 15<sup>th</sup> and the 16<sup>th</sup> centuries and this was ultimately responsible for the British Industrial Revolution (MacFarlane, 1978a, 1978b, 1992). Similarly, Riesman (1961, p. 13) assumes that modern individualism emerged out of a collectivist society and its emergence was directly related to the Reformation, the Renaissance and breaking up of feudalism. According to Weber one of the central causes of the emergence of capitalism was the disappearance of extended family structures which broke the link between the social and the economic spheres; thus freeing the market and the individual (MacFarlane, 1992). The significance of this transition was that it allowed the development of political states and an economic sphere, distinct from the ties of kinship.

Landes (1998) recognizes that culture does not stand alone in explaining growth in science and education. To the question of why the Chinese have ‘long been so unproductive at home and yet so enterprising away’ (p. 517) he remarks that, “the same values thwarted by bad government at home can find opportunity elsewhere” (p. 517), suggesting that the interaction between each of the cultural variables and institutions could enter as additional regressors into Eqs. (8) and (9). Interaction terms were included in preliminary regressions, however, did not give clear-cut results in the first-round regressions, partly reflecting a large number of interaction terms, and they were, consequently, excluded from the regressions.

Although culture and institutions are not strictly exogenous they are probably further down the causality chain than the knowledge created by great scientists, and instruments can never be the

first link in a causal chain. Take the example of legal origin, which is probably the most popular instrument used in economic growth regressions for different variables (which, by implication, renders the exclusion restrictions invalid). Clearly, this is not a strictly exogenous instrument since the legal institutions were formed by other factors in the causal chain. The same applies to culture and the quality of institutions. There are no persuasive instruments used for institutions in the literature and some suggest that the quality of institutions is an outcome of the struggle between various groups with different interests (Acemoglu *et al.*, 2005; Acemoglu and Robinson, 2012).

For culture very little empirical modeling has tried to determine its origin. Landes (1998) attributes the roots of British individualism much to the Magna Carta of 1215 which gave some political and civil freedom, first to the nobles after which these benefits were very gradually extended to the common folk. Compared to the continent, “Englishmen were free and fortunate” Landes (1998, p. 220). Landes (1998) sees England as one of the first nations in the world, founded well before the Industrial Revolution and the Italian Renaissance. Lesthaeghe and Surkyn (1988) argue that the dynamics of culture are determined by the cultural elitist class – often by the intellectuals who do not have large commercial interests.

Finally, pertaining to the question of exclusion restrictions for culture and institutions; it is likely that they have influenced productivity advances through broadly defined human capital, which is consistent with the predictions of endogenous growth theory that assumes that growth in steady state is entirely driven by technological advances due to R&D and education (Aghion and Howitt, 1998). However, the exclusion restrictions may not entirely hold outside steady state as culture and institutions may influence growth through Smithian growth and the  $K$ - $Y$  ratio.

Before discussing measurement of culture and institutions, the choice of instruments for GERs and stock of knowledge is first substantiated.

### 6.1.1 Education

Common for the literature on the origins of education is that culture and institutions are repeatedly stressed as potentially important for the rise in education. Examining the origins of culture Stone (1964), Katz (1976), Easterlin (1981), and Boli *et al.* (1985) suggest that culture and institutions have been important underlying forces behind the rise in education.<sup>3</sup> Furthermore, Dias and Tebaldi (2012) derive an endogenous growth model in which institutions affect growth by increasing the

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<sup>3</sup> Based on a present value model Bouckkine *et al.* (2007) show that education during industrialization was driven up by a combination of lower cost of schooling and increased returns to schooling through 1) higher wages in the modern sector that increased the expected returns from education; 2) an increasing life expectancy that increased the number of years over which the excess returns were discounted; and 3) higher population density that reduced the cost of schooling facilitated by more schools. Life expectancy and urbanization were included as instruments for GERs in an earlier draft of the paper but were dropped because of potential endogeneity problems.

returns to education and their empirical estimates give support for their model. Boli *et al.* (1985) advance the idea that mass education arose primarily as a means of transforming individuals into members of the new institutional framework that emerged in Europe after the Middle Ages as the societies became more rational and secular. They, furthermore, argue that “mass education arises as a purposive project to construct the modern polity, reconstructing individuals in accordance with collective religious, political, and economic goods and purposes” (p. 158). Easterlin (1981) reasons that education arose primarily from political conditions and ideological influences and that Protestantism, humanism, and central government efforts at national integration were influential for the rise of education in Germany, England, France, and the United States. Katz (1976) suggests that the four major factors affecting educational development were industrialization, urbanization, state intervention and family structure. Stone (1964) argues that social stratification, job opportunities, religion, demographic and family patterns, and institutions were the main forces behind the increase in education. Surveying the literature on the origins of education, Green (1990, Ch. 2) highlights Protestantism and the Reformation as important forces behind the increase in education.

Central for the IV approach taken for education is that it is not educational attainment *per se* that is instrumented; instead, the GERs are regressed on their instruments and the predicted values from these regressions are used to generate educational attainment through Eqs. (5)-(7). The reasoning behind this identification strategy is that external forces influence schooling at the time at which children and youths decide to enroll in the educational system; once the students finish their studies and join the labor force their level of educational attainment is more or less set and only a very few people further their education formally after the age of 23. For example, schooling of the oldest working age cohort was decided up to 58 years earlier, and the identification strategy should reflect that.

The cost-benefit aspects of the educational decision in Britain in the past must also have featured in the educational decision since the costs were often high, therefore, rendering GERs sensitive to the financial situation of the lesser gentry and trading classes (Stone, 1964; Houston, 1985, 1988). The costs of attending university, for example, were about £20 a year in 1600 and about £30 a year in 1660 and £30 in 1750 (Stone, 1964, p 71, Houston, 1985, p. 121). This has to be compared to, for example, daily wage of 2s 6d for skilled workers in the Carpenter’s Company in London in 1665 (Lane, 1996, p. 90), which means that a skilled carpenter had to work 240 days a year to pay the university tuition fee for one student! In Scotland in the 17<sup>th</sup> century a male day laborer had to pay more than a quarter of his salary to keep his child in grammar school (Houston, 1985, p. 121). Although some schooling was supported by charitable endowments, fees were often required at the primary and secondary levels and parents in most cases had to pay for candles,

heating, books and other teaching materials (Cressy, 1980, p. 28, Houston, 1985, Ch. 4). Furthermore, 'free' schooling in Scotland and, presumably also the rest of Britain, was only available for a tiny minority during the 17<sup>th</sup> century (Houston, 1985, p. 119). Consequently, the cost of education is crucial for the schooling decision, suggesting that the cost of schooling should weigh heavily in the GER regressions. However, instruments for the cost of schooling are limited to the real prices of books since real wages, which are probably the heaviest cost components, are endogenous. Furthermore, establishment of schools, which is a requirement for education to go ahead in the first place, is probably determined by norms, culture and institutions.

### *6.1.2 Science*

Fundamental for Eq. (9) is that the stock of scientific knowledge is determined by culture, institutions and book prices and not, as in some endogenous and unified growth models, by the sheer size of the population. The social, cultural and political conditions of a society deeply influence or shape the questions and claims generated by science. As long argued by Mokyr, Britain's success rests, to a large degree, on its ability to take advantage of its endowment of human and physical resources through the combination of the Baconian program of useful knowledge and the recognition that better institutions created better incentives (see, for example, Mokyr, 2009, p. 122). Although recognizing the importance of good institutions, Mokyr (2009, p. 377) stresses that the prosperity owed much to a culture in which the crucial economic actors, such as merchants, craftsmen, bankers, farmers, and professional, were bound by moral codes or concerns about their reputations.

A scientific culture is often stressed by sociologists as a precondition for an innovative environment. Merton (1973), as a leading sociologist, argues that although mental ability plays an important role in discovery and invention, cultural factors are much more important than individual personalities. There are always many people with high intelligence in a large population at any given time that are potential innovators and inventors for cultures that promote science and innovations. In support of this feature of innovation Merton (1973) reasons that it is no coincidence that similar discoveries are often made by scientists working independently of each other. Important independent discoveries in the 17<sup>th</sup> century included the formulation of calculus by Newton and Leibniz, the Newton-Raphson method, invented independently by Newton and Raphson, and Boyle's law, invented independently by Boyle and Mariotte. Addressing the rise of science in early-modern England Merton (1938) stresses the social behaviors promoted by the Puritans and argued in his collected writing, published in 1973, that science requires certain values and sentiments that allow the individualism that fosters interest in transcendent and secular improvements; a value system that

was found in the Puritan asceticism, which provided the right context in which science could develop.

## *6.2 Measuring culture*

As aforementioned culture is measured as marriage age, marriage rate and out-of-wedlock fertility because they are measurable reflections of the tolerance towards science, new ideas and individual thinking. The most important dimension of culture is traditional (collectivist) versus secular-rational (individualist) values (Schwartz, 1999). Individualism, at one end of the scale, emphasizes personal freedom, self-fulfillment, self-chosen goals, and achievement, and it forms a culture that is open to change (Schwartz, 1999; Lesthaeghe and Surkyn, 2004). Collectivism, at the other end of the scale, is an authoritative system, such as a society that is ruled by religious authorities or clan leaders, and emphasizes group interests, conservatism (conformity, security and preservation of tradition) and religion, discourages behavior that makes the individual stand out and encourages marriage and rejects out-of-wedlock births (Schwartz, 1999; Lesthaeghe and Surkyn, 2004).

Common for all three proxies for culture is that they all reflect societal values of the importance attached to marriage institutions. Analyzing the marriage institution and economic development in the world, Todd (1987) puts forth the hypothesis that traditional family values are associated with low power of women and illiteracy. This hypothesis is validated by the research of Alesina and Giuliano (2013) who show that individuals with strong family ties have more traditional beliefs about the role of women in society, are more resistant to innovation and changes in society, and show a lower level of trust. Similarly, Lesthaeghe and Syrkun (1988) find a strong correlation between emphasis on individual freedom and higher order needs and the fraction of people that consider the marriage institution as outdated.

Using Hofstede's measure of individualism, Stack (2012) finds individualism to be strongly and positively correlated with out-of-wedlock fertility ( $p < 0.001$ ). Furthermore, Lesthaeghe and Surkyn (2004) find out-of-wedlock fertility is associated with freedom of choice, increasing autonomy in ethical, moral and political spheres and values associated with "higher order needs" (self-actualization, expressive values and recognition). Marriage ages are low in traditional collectivist societies in which habits are driven by traditional institutions, religion, traditional family values, respect for parental preferences, and trust in cultural institutions (Lesthaeghe and Surkyn, 2004).

Data on marriage age, out-of-wedlock fertility and marriage rates are first available from the 16<sup>th</sup> century. Thus, they are backdated from 1610 (marriage age), 1543 (out-of-wedlock fertility), and 1539 (marriage rate) using number of churches per capita since the church during history has been

influential for the value system as discussed below.<sup>4</sup> The mapping between the per capita number of churches is found by regressing each cultural proxy on churches per capita and a constant in the overlapping period up to 2011. Underlying this approximation is the assumption that culture is closely related to religiosity, which is in turn proportional to the number of churches per capita. The latter assumption is plausible since religiosity is found to be highly correlated with the frequency at which people go to church (Lesthaeghe, 1983; Cukur *et al.*, 2004). Several studies find religiosity to be positively associated with value systems that have high preferences for preservation of social order, protection of the individual against uncertainty, moral and relational values and low preferences for personal competency and egoistic values such as pleasure, freedom, openness-to-change and being independent (Schwartz and Huisman, 1995; Cukur *et al.*, 2004; Heine, 2007). Religiosity impacts on the scientific and innovative culture through the individualist-collectivist distinction that is used by sociologists to distinguish cultures (Cukur *et al.*, 2004; Heine, 2007).

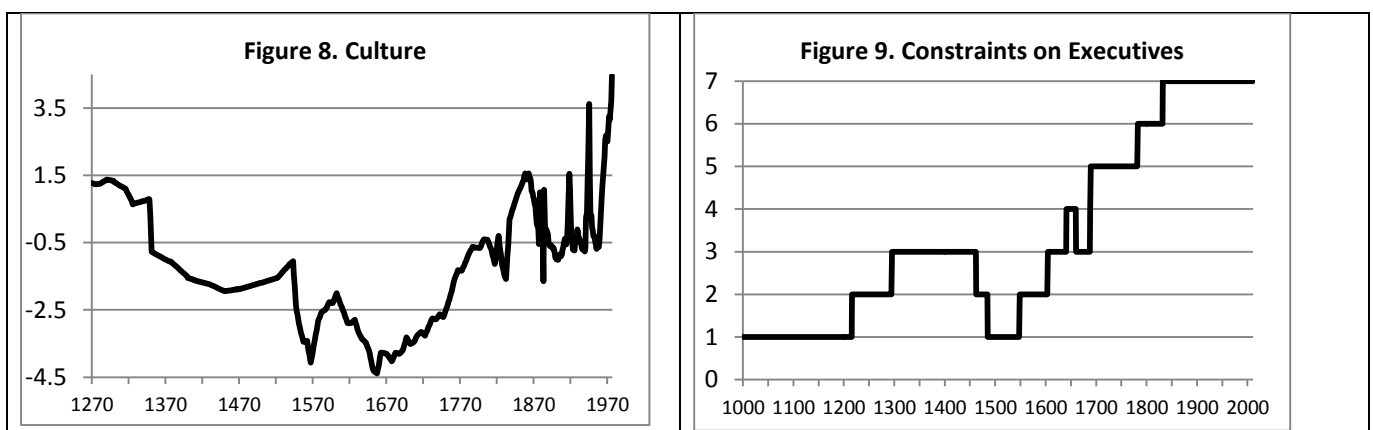
Although religiosity measures important aspects of culture, it must be acknowledged that scientists were also interested in science during the industrial and preindustrial Britain for theological reasons “because the workings of the natural law was thought to reveal the existence of rational design in the universe and hence the Creator God” (Sanderson, 1991, p. 28). Sanderson, p. 28 illustrates this point by noting that the importance of religion in teaching and science is signified by the title of the most influential textbook used in the academies, John Ray’s *Wisdom of God Manifest in the Work of Creation* (1696). Furthermore, Cambridge and Oxford Universities were an integral part of the Anglican Establishment and undergraduates at Oxford University from 1581, for example, could not matriculate before subscribing to the Thirty-nine Articles, and attendance at college chapel was compulsory (Sanderson, 1975, p. 9). Thus, the church as an institution in some way encouraged science; however, the degree of religiosity in the population, as reflected in churchgoing, is likely to have been an integral part of the value system. In any event, churches per capita is only used in the data before 1610 (marriage age), 1543 (out-of-wedlock fertility), and 1539 (marriage rate) so it is limited how much this variable will influence the estimates and regressions are carried out in the period 1600-1900 as additional robustness checks for the influence of culture on education and science.

Figure 8 displays the first principal component of the logs of out-of-wedlock fertility, the inverse marriage rate and age at the first marriage as a cultural indicator. An increase in the cultural index corresponds to an increase in individualism. The index is relatively flat up to the onset of the

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<sup>4</sup> Even if data for marriage rates and marriage ages were available back to 1218 they may have been distorted significantly as measures of culture by the Black Death. Voigtländer and Voth (2013), for example, show that the land abundance following the plague induced a transformation to land-intensive livestock production, increased female employment in pastoral production and resulted in later marriage ages that persisted since the resulting lower fertility rates kept land-labor ratios relatively high.

Black Death epidemic in 1348 when it starts a descending trend that is first reversed in 1650; a trend that fits well into the taxonomy made by religion historians (see for an overview by Byrne, 2006). In the aftermath of the plague in 1348 people turned to God for salvation or, simply, they believed that the plague was a result of God punishing them for their sins (Byrne, 2006). Priests and preachers agreed that God was the ultimate source of the plague and that disease was the expression of God's wrath provoked by humanity's sinfulness (Byrne, 2006). The increasing religiosity after the Black Death has also been detected for Venice and Genoa. Kedar (1976) identified a significant shift towards the number of Genoese rulers that bore the name of a saint over the period from 1188 to 1396; particularly during the 14<sup>th</sup> century. While only one of the 10 most frequently used names was that of a saint, the number increased to ten in 1396 (p. 100). The same trend was observed for names of ships (Kedar, 1976, pp. 102-105). Similarly, Bresc and Bresc (1979) estimates that the fraction of ships carrying names of a saint in England gradually increased from 46.9 percent in 1200-1300 to 97.4 percent 1400-1460; following the trend in the European continent. This trend is consistent with the path in Figure 8, reinforcing the finding of increasing religiosity in the late medieval period. Finally, Thomas (1971) finds that belief in witchcraft, magic healing, astrology, and prophecies increased in response to the inability to eradicate the plague in the two centuries following the outbreak of the plague.



**Notes:** Culture is measured as the first principal component of out-of-wedlock fertility, inverse marriage rate and the average age at first marriage. An increase in the cultural index is associated with a more secular-rational society. Source: see separate Data Appendix.

The cultural variable reached its nadir in the 16<sup>th</sup> and 17<sup>th</sup> centuries, which is consistent with the peaks in the number of witchcraft trials and executions in Scotland in 1661 (Goodare *et al.*, 2003) and the number of witchcraft indictments and executions in selected parishes in England (Macfarlane, 1971, p. 61, Table 4) – a conclusion also reached by Thomas (1971, p. 533). The Witchcraft Act was finally repealed in 1736; long after it has already been difficult to mount and sustain a successful prosecution in the courts (Thomas, 1971, p. 570). The influence of magic in

England followed the same path as witchcraft and gradually declined from the last decades of the 17<sup>th</sup> century (Thomas, 1971, Ch. 17). Note, in this connection, that witch-hunts were closely associated with deep religious beliefs and that the church was heavily involved in witch-hunts and beliefs in witches were encouraged by contemporaneous religious teaching, emphasizing the power of the Devil and the helplessness of those against whom he levied his assaults (Thomas, Chs. 16 and 17).

A sharp increasing trend in individualism, which can be traced after 1650, is associated with the sharp reduction in witchcraft indictments and executions as noted above and a general enlightenment in the British community. The Enlightenment was a large cultural shift that was dedicated to experimental science, questioned the traditional way of doing things, and downplayed religious practices (Jacob, 2014). There is evidence that a common Unitarianism belief was thriving among British entrepreneurs and manufacturers during the 18<sup>th</sup> century consisting of “a strange hybrid of Christianity, ancient heresy, and rationalism” (Jacob, 2014, p. 47). The Protestant ethic with interest in science of the mechanical and mathematical sorts was, for example, present in the Watt family already in 1690s (Jacob, 2014, pp. 43-44). The increasing individualism, however, came to a halt in the mid-19<sup>th</sup> century and the cultural index fluctuated substantially up to the 1960s after which there has been a marked increase in individualism. The spikes in the cultural indicator during WWI and WWII are due to increasing marriage ages and decreasing marriage rates as most males in the prime marriage age went to war.

### *6.3 Measuring institutions*

Annual data for institutional quality is constructed over the period 1200-2011 and the construction of the index is detailed in the separate Data Appendix. The quality of institutions is approximated by constraints on executives. Following the Polity IV, constraints on executives are measured as institutional constraints on the decision-making powers of the chief executive and it is operationalized by a seven-point scale, where the minimum value of 1 implies “executive authority” and the maximum value of 7 signifies “executive parity or subordination”. Constraints on executives are kept at a constant level of 7 after 1832 up to 2011 following Polity IV. The indicator deviates slightly from Polity IV in that the score 7 is not given in the period 1800-1931 because the Reform Act in 1832 sets the foundation for the executive to be elected by Parliament, which is one of the requirements for a country to reach level 7 according to the Polity IV manual. Changes in the index over the period 1200- 1832 reflect changing power relationship between the Crown and the Parliament.

The institutional quality score is displayed in Figure 9. The index is likely to be a good indicator of the quality of institutions as it has a correlation coefficient of 0.97 with the index on constraints on executives of Acemoglu *et al.* (2002), which, using various sources, has been constructed for the benchmark years 1200, 1300, 1400, 1500, 1600, 1700, 1750, and 1800. The first major event used is the signing of the Magna Charta in 1215, which was an attempt to limit the King's power by law and to assure certain freedoms (Maitland, 1963, p. 67). However, the law was not enforced until Edward I reconfirmed the Magna Charta and issued the Great Charter in 1297 (Maitland, 1963, pp. 75 and 179) in which the Parliament also gained the right to participate in legislation and, especially, to approve the King's direct taxation (Lyon, 1960, p. 420). These achievements held until the end of the Lancaster Dynasty in 1461, when the Parliament lost its influence on legislation (Lyon, 1960, p. 605).

According to North and Weingast (1989), there were two milestones in British history that permanently contributed to its great leap forward, namely the Civil War of 1642-1649, when Parliamentary forces defeated Charles I, and the Glorious Revolution in the period 1688-1689, which gave Parliament supremacy over the King, created for the first time security of property rights immune from political interference and, thus, created the incentives to innovate (North and Weingast, 1989). Furthermore, the judiciary became independent of the Crown; thus limiting the Crown's ability to alter rules without the Parliament's consent. These events introduced major checks on royal power and mark the beginning of the third phase of British parliamentary history that has lasted until the present day. The Glorious Revolution is often stressed as a major force behind the British Industrial Revolution (see, for example, North and Weingast, 1989; Acemoglu *et al.*, 2002, 2005).

In their influential paper North and Weingast (1989) make a strong economic case for the argument that changes in political representation following the Glorious Revolution 1688-1689 set the English economy on a unique growth path leading to the Industrial Revolution. They argue that the parliament rendered government behavior more predictable by making it impossible for the Crown to change the rules of economic activity *ad libitum*, which in turn lead to a financial revolution that entailed a reduction in the required returns on private and government debt, because of an increase in the perceived commitment by the government to honor its debts.

However, the thesis that the Glorious Revolution was a milestone in the British economic development has recently been challenged. Temin and Voth (2013) show that government debt crowded out private credit provision because private borrowers were credit constrained by lenders. In fact the ceiling on banks' lending rates was reduced in 1714 and private bank lending and the length of loans to maturity were reduced (Temin and Voth, 2013, p. 182). Furthermore, analyzing the gap

between interest rates on government debt in England, the Continental monarchies and the urban-based republics, Epstein (2000) fails to find support for the neo-institutionalist hypothesis that interest rates are linked to property right institutions. He finds that the lowest interest rates were enjoyed by the urban-based republics in Continental Europe, signifying a greater supply of capital and financial specialization and that the reduction in the British interest rates, rather than being a result of British institutional reforms, were driven by a convergence towards the Continent's interest rates.

According to Epstein (2000), what the Glorious Revolution did was to increase the efficiency of the state and the capacity to raise taxes and Britain went from being a marginal player in Europe to a world leader after 1700. Coffman *et al.* (2013) argue that British institutions in many cases became weaker after the Glorious Revolution as rent-seeking monopolies were allowed to grow in some sectors of the economy that were earlier constrained under the more autocratic leadership. Furthermore, English governments became more extractive and rent-seeking in order to finance wars after William III became the king in 1689. Finally, Hoppit (2011) argues that parliamentary supremacy did not better secure property rights and demonstrates that property was heavily taxed and frequently expropriated. In summary, the institutional improvement following the Glorious Revolution is highly controversial and the indicator for constraints on executive constructed here may well exaggerate the positive effects. To cater for the possibility of the absence of institutional improvement in 1688, *Exec* is encoded with and without jumps in 1688 in the first-round regressions.

#### 6.4 Instruments for the land-population ratio

The land-population ratio,  $T-L$ , is instrumented as follows:

$$\ln (T/L)_t = \beta_0 + \beta_1 \ln S_t^{Agr} + \beta_2 Temp_t + \varepsilon_{3,t}, \quad (10)$$

where  $S^{Agr}$  is the stock of agricultural knowledge and  $Temp$  is temperature anomaly. The regression period is limited to 1620-1900 because  $S^{Agr}$ , is only available over this period and, more importantly, because the forces driving mortality, particularly, and fertility and, therefore,  $L$ , changed substantially following the demographic transition starting in the late 19<sup>th</sup> century.  $S^{Agr}$  is based on agricultural patents constructed using the perpetual inventory method with a 15% depreciation rate (see, for details, Ang *et al.*, 2013).

The philosophy behind Eq. (10) is that population growth is the main force driving the  $T-L$  ratio and that the population before 1900 depended predominantly of the availability of food to support subsistence level. The only way to increase food consumption was through agricultural

technological progress that increased land productivity, imports of food or prolonged favorable weather conditions. Imports of food became a significant part of overall food consumption in Britain in the 19<sup>th</sup> century; however, a strong feedback effect from the  $T-L$  ratio to food imports renders food imports invalid as instruments. Periods of adverse weather conditions could jeopardize food supply over prolonged periods and this is captured by temperature anomalies,  $Temp$ . The stock of agricultural patents is shown by Ang *et al.* (2013) to be a significant driver of agricultural productivity and it is reasonable to assume that agricultural patents are independent of the  $T-L$  ratio. The downside of these instruments is that the exclusion restriction is likely to be violated as temperature anomalies and agricultural innovations will impact directly on per capita income, implying that the coefficient of the  $T-L$  ratio in the structural regressions will be biased towards zero.

### 6.5 First-round regressions

The first-round regressions of GERs, domestic knowledge stock and the  $T-L$  ratio are displayed in Table 5. Consider the first nine columns in which GERs are regressed on their determinants over the periods 1218-2009 and 1550-1900, noting that the estimation periods start earlier than in the structural regressions to allow for the time-lag between school enrollment and working age education. The tests of exclusion restrictions are highly significant, suggesting that the instruments are sufficiently influential for the outcome variables to act as potentially good instruments. Common for all the regressions is that the real price of books is highly significant and of the right sign. Therefore, reduced book prices have been important for the schooling decision and the invention of the Gutenberg press was revolutionary because it made education more affordable, increased the variety and the availability of books, and increased the utilization of books as an effective learning tool. It is noteworthy that the book price elasticity of education is significantly higher for primary than secondary and, particularly, tertiary education; a result that makes sense from the perspective that books probably took up a substantially higher proportion of total schooling expenses at lower than at higher levels of education.

The quality of institutions has a positive effect on  $GER^p$  and mixed effects on  $GER^s$  and  $GER^t$ , showing that good institutions aided the establishment of primary schools; however, they are not likely to have been influential for school enrollment at secondary schools and universities. Interestingly, the results are slightly better for  $Exec$  for universities when there is no jump encoded in  $Exec$  in 1688, suggesting that the Glorious Revolution may not have been as crucial for education as often argued by the advocates of the institutional hypothesis. The coefficient of out-of-wedlock fertility, is consistently a highly significant determinant of GER's, noting that this is probably the best of the three indicators for culture because it satisfies the exclusion restriction better than

marriage rates and marriage ages and because it is been found to be an important proxy for culture in the sociological literature. The coefficients of marriage age are also mostly significantly positive and the coefficients of the marriage rate are significant and negative in five of the cases as expected and statistically insignificant in the rest of the cases. Thus, overall culture has been potentially important for the time-profile of education in Britain. Finally, the size and the statistical significance of the coefficients are quite similar in the two sample periods, 1212-2009 and 1550-1900, giving further credibility to the choice of instruments in the GER regressions.

**Table 5.** First round regressions (Eqs. (8)-(10)).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Dep var	GER <sup>p</sup>	GER <sup>s</sup>	GER <sup>t</sup>	GER <sup>p</sup>	GER <sup>s</sup>	GER <sup>t</sup>	GER <sup>p</sup>	GER <sup>s</sup>	GER <sup>t</sup>	Ln S <sup>d</sup>	Ln S <sup>d</sup>	Ln S <sup>d</sup>	Ln S <sup>Pat</sup>	Ln T/L
Jump 1688	Y	Y	Y	Y	Y	Y	N	N	N	Y	N	Y	Y	-
Ln Mar <sub>t</sub> <sup>Rate</sup>	1.56 (0.42)	-16.0 (7.30)	-2.86 (6.10)	12.8 (1.55)	0.38 (1.46)	-0.13 (1.47)	-16.5 (6.31)	-13.2 (8.26)	-1.43 (6.13)	-2.04 (15.7)	-1.59 (12.1)	-0.32 (1.89)	-1.54 (2.23)	
Ln Oow <sub>t</sub> <sup>Fert</sup>	10.9 (7.00)	19.2 (14.9)	2.66 (10.5)	17.0 (4.55)	0.70 (7.96)	0.25 (6.77)	16.1 (8.89)	18.5 (15.3)	2.92 (11.8)	0.25 (5.76)	0.46 (11.6)	0.55 (8.78)	2.86 (9.47)	
Ln Mar <sub>t</sub> <sup>Age</sup>	1.56 (0.42)	-4.14 (4.09)	0.87 (3.94)	338 (4.51)	0.08 (0.06)	1.86 (3.31)	67.5 (1.73)	-99.2 (3.74)	29.9 (5.36)	-0.26 (10.3)	-1.59 (12.1)	0.16 (5.80)	0.86 (6.73)	
Ln (P <sup>B</sup> /P) <sub>t</sub>	-36.1 (20.1)	-27.1 (16.5)	-1.83 (9.62)	-21.6 (2.69)	-0.51 (3.68)	-0.27 (5.29)	-34.0 (16.0)	-27.6 (14.9)	-1.36 (5.91)	-0.51 (10.3)	-0.16 (3.45)	0.05 (0.58)	-1.59 (3.88)	
Ln Exec <sub>t</sub>	21.1 (9.97)	-3.08 (2.78)	-0.15 (0.83)	33.0 (5.71)	0.61 (4.92)	0.04 (0.95)	20.8 (6.08)	-3.67 (2.00)	1.96 (5.61)	0.93 (10.2)	3.49 (14.7)	1.30 (8.25)	3.95 (5.91)	
Temp <sub>t</sub>														0.09 (6.96)
Ln S <sub>t</sub> <sup>Agr</sup>														-0.17 (27.2)
χ <sup>2</sup> (k)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00 0
Est. Per.	1212- 2009	1212- 2009	1212- 2009	1550- 1900	1550- 1900	1550- 1900	1212- 2009	1212- 2009	1212- 2009	1270- 2009	1270- 2009	1620- 1900	1620- 1900	1620- 1900

**Notes.** The figures in parentheses are absolute *t*-statistics. Constant terms are included in the regressions but not shown. S<sup>d</sup> is based on Ochoa and Corey (1997). χ<sup>2</sup>(k) = *p*-values for Chi-squared tests for excluded restrictions, where *k* is the number of restrictions. Jump 1688 in the third row indicates whether a jump is encoded in *Exec* after 1688.

Turning to the stock of significant inventions and patents (columns 10-13) the coefficients are almost all highly significant and of the right signs and tests of exclusion restrictions are, again, highly significant. The coefficients of real price of books are significant and negative in all cases except one, suggesting that book prices were not only influential for education but also for scientific knowledge formation. This result is consistent with the results of Plopeanu *et al.* (2012) who find that books started to affect the accumulation of “ideas”, proxied by patents, in the first phase of the British Industrial Revolution

The coefficients of the constraints on the executive are all positive and significant and the cultural variables are almost all statistically highly significant and of the expected signs. It is noteworthy that the magnitude and significance coefficients are not that sensitive to estimation period and whether knowledge stock is measured by great inventions or patents; hence giving further credibility to the choice of instruments. Importantly, approximately the same factors explain patent

stock and the stock of great inventions, indicating that macro and micro inventions were determined by joint forces. In other words, a good innovative environment encouraged micro as well as macro inventions. From the first-stage regressions it can be concluded that the rise in British human capital from the 16<sup>th</sup> century has been associated with improved institutions and, particularly, secularization and declining real book prices; results that confirm the discussion in broad sections of the literature, which suggests that institutions and culture were crucial for the British industrialization.

The  $T-L$  regression is presented in the last column in Table 5 and shows that agricultural patent stock and temperature anomaly are significant determinants of the  $T-L$  ratio, have the expected sign, and the test for exclusion restrictions is sufficiently significant for agricultural patent stock and temperature to act as good instruments. This result shows that population was essentially driven by food supply, which in turn was driven by technological progress in the agricultural sector, while deterred by temperature anomalies that caused adverse weather conditions and shortened the season for agricultural production.

#### *6.6 Estimates of the structural model*

The results of regressing Eq. (4) using instruments are presented in Table 6. The dependent variable is per capita income of Broadberry *et al.* (2011) and  $S^d$  is based on the chronology of Ochoa and Corey (1997). Five sets of regressions are carried out: 1) full sample period (1270-2009); 2) restricted sample period (1620-1900); 3) using patent stock for domestic stock of knowledge,  $S^{Pat}$ ; 4) treating the  $T-L$  ratio as exogenous; and 5) allowing for no jump in  $Exec$  after the Glorious Revolution. The baseline regression from the first column in Table 2 is reported in the first column in Table 6 for comparison.

**Table 6.** IV structural regression results (Eq. (4)).

	1	2	3	4	5	6	7	8	9
	Baseline OLS	IV 1270- 2009	IV 1620- 1900	IV Patents	IV <i>T-L</i> not IV	IV Exec 1688	IV Rel. Houses	IV Cat. Started	IV Cat. Prog.
$EA_t$	0.09 (25.7)	0.10 (7.91)	0.17 (6.95)	0.18 (7.68)	0.12 (16.8)	0.11 (14.1)	0.13 (9.84)	0.12 (10.9)	0.13 (12.1)
$\ln S_t^d$	0.38 (19.1)	0.04 (3.03)	0.17 (2.82)		0.06 (4.16)	0.07 (5.56)	0.03 (4.11)	0.02 (2.45)	0.02 (3.47)
$\ln S_t^{Pat}$				0.05 (4.64)					
$\ln S_t^{EU}$	0.07 (5.46)	0.25 (20.1)	0.31 (6.01)	0.37 (11.6)	0.27 (22.1)	0.19 (14.7)	0.21 (12.8)	0.22 (15.0)	0.20 (14.1)
$Op_t \cdot \ln S_t^{Im}$	0.06 (6.89)	0.12 (8.79)	0.05 (4.06)	0.05 (3.81)	0.13 (9.81)	0.12 (6.97)	0.12 (8.48)	0.13 (8.41)	0.12 (8.00)
$\ln k_t$	0.43 (20.5)	0.53 (10.9)	-0.04 (0.75)	-0.04 (1.02)	0.45 (11.9)	0.49 (10.5)	0.48 (8.02)	0.40 (6.58)	0.38 (6.77)
$\psi_t \ln \tau_t$	0.25 (12.6)	0.18 (3.11)	0.03 (0.39)	0.13 (2.03)	0.23 (6.68)	-0.05 (0.83)	0.28 (4.11)	0.24 (3.45)	0.20 (3.10)
Period	1270- 2009	1270- 2009	1620- 1900	1620- 1900	1270- 2009	1270- 2011	1270- 2009	1270- 2009	1270- 2009

**Notes.** See notes to Table 1. The *t*-statistics are based on robust standard errors. Instruments are used for educational attainment, domestic knowledge stock, and the *T-L* ratio in the regressions in columns 2-4 and educational attainment, domestic knowledge stock are instrumented in the regression in column 5. The dependent variable is the log of per capita income based on Broadberry *et al.* (2011). Col. (1) The baseline regression refers to the regression in the first column in Table 2. Col. (6) *Exec* is computed with no jump after the Glorious Revolution in 1688. Col (7) Out-of-wedlock fertility, marriage rate and marriage age are backdated using the ratio of religious houses and population. Col (8) Out-of-wedlock fertility, marriage rate and marriage age are backdated using the ratio of accumulated number of cathedrals plus abbey building starts and population. Col (9) Out-of-wedlock fertility, marriage rate and marriage age are backdated using the ratio of accumulated number of cathedrals plus abbey buildings in progress and population.

Educational attainment and the domestic stock of knowledge,  $S^d$ , are again significant and positive in all regressions, indicating that human capital has been pivotal for technological advances and, consequently, productivity growth in Britain over the periods 1270-2009 and 1620-1900. Since the domestic knowledge stock advanced substantially faster in Britain than elsewhere in the world in the period 1620-1900 (Ochoa and Corey, 1997), the British scientific revolution was influential for the unique British growth experience, particularly during the growth spurt in the 17<sup>th</sup> century. The coefficient of domestic knowledge stock remains significant when domestic knowledge stock is based on patents,  $S^{Pat}$ . These results are consistent with the discussion of Jacob (1997, 2014) and Mokyr (2005a) who give several examples of how theories developed by great minds were subsequently used by practical people to develop new technologies and to find new ways of doing things.

Foreign knowledge stocks remain highly significant determinants of per capita income in all regressions, indicating that knowledge spillovers from the European continent as well as through the channel of imports remain significant determinants of the British growth experience. While the

coefficients of per capita land area adjusted for the agricultural share are mostly significant, they have lost some of their significance compared to the OLS regressions; perhaps because the instruments have not captured essential variations in the  $T-L$  ratio. Finally, the  $K-Y$  ratio is highly significant in the regression covering the entire period (column 2) but insignificant in the restricted sample regressions, 1620-1900.

Thus far the cultural instruments have been backdated using per capita number of churches from the Churches Conservation Trust. However, these data do not count churches that no longer exist today and which are not heritage listed. To cater for the possibility that these data are not representative for the number of churches or the degree of religiosity at any given year the cultural instruments are backdated using per capita 1) number of religious houses; 2) building of new cathedrals and abbeys starts; and 3) building campaigns of cathedrals and abbeys. The structural regressions based on these data are presented in the last three columns in Table 6. Compared to the baseline IV regression in column (2) in Table 6 the coefficients of educational attainment are statistically and economically more significant while the coefficients of domestic knowledge stock and knowledge spillovers from Europe are economically, but not statistically, less significant in these regressions. Overall, however, the results in the regressions in the last three columns are close of those in the baseline IV regression, suggesting that the results in this paper have not been affected significantly by the data used to backdate out-of-wedlock fertility, marriage rates and marriage ages.

## 7. Simulations

Thus far the regression analysis has focused predominantly on statistical significance of the variables included in the model. To get a better picture of the contribution of each of regressor in Eq. (4) to per capita output growth, Table 7 decomposes the sources of growth by simulating the baseline regression (column 1 in Table 2) using the actual movements of the data. The following three growth epochs in British growth history are considered: the preindustrial growth regime, 1271-1600, industrialization, 1601-1900, and the modern growth regime, 1901-2011. The growth rates in Table 7 are annualized geometric growth rates.

Considering the preindustrial period 1271-1600 the productivity growth rate was slightly negative at minus 0.08 percent; pulled down by a declining  $K-Y$  ratio, while education, domestic knowledge stock and knowledge spillovers from the European continent contributed positively to growth. The average annual growth rate was 0.57 percent during the crucial period of industrialization, 1601-1900. Domestic knowledge, education, international knowledge spillovers

and the  $K$ - $Y$  ratio all contributed positively to growth while population dragged growth down by 0.15 percentage points annually.

**Table 7.** Decomposing sources of growth in productivity, domestic knowledge stock and education.

<b>Decomposing productivity growth</b>							
	$EA_t$	$\ln S_t^d$	$\ln k_t$	$\ln S_t^{Eu}$	$Op_t \cdot \ln S_t^{Im}$	$\psi_t \ln \tau_t$	Actual $y_t$
1271-1600	0.04	0.07	-0.06	0.05	0.00	-0.01	-0.08
1601-1900	0.11	0.05	0.01	0.06	0.43	-0.15	0.57
1901-2011	0.61	0.02	0.25	-0.03	0.67	-0.11	1.51
<b>Decomposing growth in knowledge stock, <math>S^d</math> (O&amp;C)</b>							
	<b>Culture</b>	<b>Institutions</b>	<b>Book Prices</b>	<b>Actual <math>S^d</math></b>			
1271-1600	-0.17	0.20	0.16	1.11			
1601-1900	0.08	0.39	0.27	0.84			
1901-2011	0.66	0.00	0.26	0.31			
<b>Decomposing change in educational attainment, <math>EA</math></b>							
	<b>Culture</b>	<b>Institutions</b>	<b>Book Price</b>	<b>Actual <math>EA</math></b>			
1271-1600	-0.46	0.21	0.14	0.01			
1601-1900	0.44	0.45	0.84	1.21			
1901-2011	4.98	0.00	7.58	7.05			

**Notes:** The growth rates or changes are annualized geometric growth rates. The numbers in the lower panel are multiplied by 100. The simulations in the top panel are based on the baseline regression in Table 1 column 1 and the stock of knowledge and the educational attainment simulations are based on columns 1, 2, 3 and 7 in Table 5. Culture is measured as the joint effect of age at first marriage, marriage rate and out-of-wedlock fertility.

During the modern growth regime, 1901-2011, the average annual growth rate is 1.51 percent, and most of the growth during this period is explained by education, capital deepening, knowledge spillovers through the channel of imports and domestic stock of knowledge, while population and knowledge transmission from Western Europe,  $S^{Eu}$ , contributed slightly negatively to growth as the depreciation of the existing knowledge stock exceeded new innovations.

The number of great scientists and significant inventions has not grown much over the last century and has even declined in some European countries and, consequently, muted the contribution of great scientists to growth as reflected in the contribution of  $S^d$  and  $S^{Eu}$  to growth during the 20<sup>th</sup> century. However, the number of great scientists and significant inventions are unlikely to have been representative for the growth in R&D that has taken over as an important engine of growth after the Second Industrial Revolution (Aghion and Howitt, 2009; Madsen, 2010). Innovations were not an outcome of systematic R&D effort by firms before the 20<sup>th</sup> century where significant innovations were put into practical use by practical people such as trades people and engineers. R&D undertaken by firms gained momentum during the 20<sup>th</sup> century and it is likely that educational attainment in the simulations has captured some of the effects of innovations on growth in the last century.

The importance of knowledge stock and education in shaping growth begs the question of the relative importance of institutions, real book prices and culture in explaining these variables. The simulations in the middle panel in Table 7 show the contribution of institutions, real book prices and culture to growth in the domestic knowledge stock, where culture is measured as the joint effects of age at the first marriage, marriage rate and out-of-wedlock fertility. Falling book prices and improved quality of institutions contributed to the increase in knowledge stock while the movement towards a more collectivist and inward looking culture dragged the growth in science stock down by 0.17% annually in the period 1271-1600. Strong improvements in the quality of institutions and a significant reduction in prices of books fueled the increasing science knowledge stock during industrialization, 1601-1900, while the contribution of secularization was relatively modest (0.08%). Finally, increasing secularization was the major impetus behind the increasing knowledge stock in the period 1901-2011.

The contribution of institutions, real book prices and culture to the *change* in educational attainment, reported in the lower panel in Table 7, is more complex because the contributing variables influence educational attainment through GERs. Thus, the effect of a contributing variable on GERs is first computed and then the educational outcome effect is simulated using Eqs. (5)-(7). Like knowledge stock, improved institutions and reduced real book prices contributed to the early rise in education, 1270-1600, while culture was a large drag on educational progress. Reduced book prices followed by secularization and improved institutions were the main forces behind the improved education during the industrialization period, 1601-1900, while declining real book prices and secularization was the main factor behind the increasing education in the 20<sup>th</sup> century.

## **8. Concluding remarks**

A tremendous amount of scholarly work has tried to shed light on the approximate causes of the British Industrial Revolution and why Britain was the first country in the world that succeeded in transforming a regime with minuscule and patchy productivity growth rates into a regime with persistently positive growth rates. However, due to the lack of data, research into the quantitative aspects of British industrialization has remained underdeveloped. This paper is the first step towards illuminating the influence of human capital on income growth in Britain over the past millennium by testing the productivity-effects of educational attainment at the primary, secondary and tertiary levels, knowledge created by great scientists, international knowledge spillovers, and capital deepening, while allowing for the population growth drag.

The regressions showed that education, knowledge created by great scientists and international knowledge spillovers were the ultimate drivers of growth in Britain throughout the pre-industrial and the industrial eras. At a more fundamental level, the knowledge created by great scientists and school enrollment rates were explained by the quality of institutions, real book prices and culture, where culture was proxied by marriage rates, marriage ages and out-of-wedlock fertility.

Model simulations showed that education and domestic and international knowledge were positive contributors to growth in the pre-industrial period 1271-1600; however, these contributions were counterbalanced by population growth and a declining  $K-Y$  ratio. Although the net growth-effects of great scientists was relatively modest during this period, its path hides two strong almost counterbalancing effects; improved institutions but increasing collectivist thinking. There were large improvements in the quality of institutions during the period 1270-1600 and these were important contributing factors to the increase in scientific knowledge; however, increasing conservatism and traditional beliefs discouraged innovative behavior and independent thinking.

The main contributors to growth during the industrialization period 1600-1900 were domestic knowledge created by great scientists, international knowledge transmission and education, while population growth dragged productivity growth down by 0.15 percent annually. The increase in education and domestic knowledge stock was in turn driven by marked improvements in the quality of institutions, a very creative environment stimulated by increasingly secular thinking, and reduced book prices that reduced the cost of schooling and, importantly, increased the efficiency of dissemination of knowledge substantially.

Was the British Industrial Revolution inevitable? Probably yes. The rise in the British educational system more than a millennium ago started what was to become the most successful industrial revolution in human history. However, Britain was not the only country in Europe endowed with universities and other educational institutions before 1600. What distinguished Britain from other European countries during its industrialization was its culture, the quality of its institutions and, probably, some luck. The institutional quality improved substantially faster in Britain than in other countries in the world in the period 1600-1800 (Acemoglu *et al.*, 2002) and the force of the Reformation and the Renaissance were, according to Weber (1905) and Pirenne (1963), powerful factors behind Britain's success. The most significant development in the 16<sup>th</sup> and the 17<sup>th</sup> centuries was not a specific discovery, but rather a process for discovery; the so-called scientific method (Brotton, 2006). The scientific culture created by the Enlightenment subsequently ensured the results created by scientists were put into use in terms of inventions and engineering projects as advocated by Jacob (1997, 2014), Khan and Sokolof (2008), and Mokyr (2005, 2009).

## Data Appendix

**Real per capita GDP. 1270-1820.** Clark, G. (2010) "The Macroeconomic Aggregates for England, 1209-2008," *Research in Economic History* 27, 51-140. Broadberry, S., Campbell, B., Klein, A., Overton, M. and Van Leeuwen, B. (2011) *British Economic Growth, 1270-1870: An Output-Based Approach*, University of Kent, School of Economics Discussion Papers, KDPE1203. **1820-2011.** Maddison, A., 2003, *The World Economy: Historical Statistics*, Paris: OECD Publishing. 2000-2011. OECD, *National Accounts*.

**Marriage Age. 1610-1845:** Average of women and men. Wrigley, E.A., Davies, J.E. Oeppen, J.E. and Schofield, R.S. (2005), *English Population History from Family Reconstitution, 1580-1837*, Cambridge Studies in Population, Economy and Society in Past Time, Cambridge: Cambridge University Press, p. 134, Table 5.3. **1846-2011:** Office for National Statistics 2013, '2. Age and Previous Marital Status at Marriage', Tables 5 and 6, accessed 21 February 2014, <<http://www.ons.gov.uk/ons/datasets-and-tables/index.html?pageSize=50&sortBy=none&sortDirection=none&newquery=marriage+age&content-type=Reference+table&content-type=Dataset>>.

**Out-of-wedlock fertility. 1543-1837:** Laslett, P., Oosterveen, K. and Smith, R.M. (1980), *Bastardy and its Comparative History: studies in the history of illegitimacy and martial nonconformism in Britain, France, Germany, Sweden, North America, Jamaica and Japan*, London: Edward Arnold. The data are available in 5-year intervals and are linearly interpolated between. **1855-1975:** Flora, P., Alber, J., Eichenberg, R., Kohl, J., Kraus, F., Pfenning, W. and Seebohm, K. (1983). *State, Economy and Society in Western Europe 1815-1975 - A Data Handbook in two Volumes*, Vol. 1, The Growth of Mass Democracies and Welfare States, Frankfurt: Campus Verlag. **1975-2011:** Eurostat: viewed 4 November 2013, <<http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tps00018>>.

**Inns of Court.** 1388: J.H. Baker (1986), "The Inns of Court in 1388" in "The Legal Profession and the Common Law, Historical Essays", Hambledon Press, London, pp 1-6. **1408:** derived from a 12 year average based on a figure of 96 enrolled from as early as 1408 to 1419 from <https://archive.org/stream/recordshonorabl05englgoog#page/n3/mode/2up>, viewed on 12 December 2013. **1422-1650:** Prest, W.R (1972), *The Inns of Court under Elizabeth I and the Early Stuarts, 1590-1640*, London: Longman, pp 242-245. Data for the 4 major Inns was also obtained as follows:

- **Gray's Inn:** 1521-1674: Foster, J (1889), *The Register of Admissions to Gray's Inn, 1521-1889*, together with the Register of marriages in Gray's Inn Chapel, 1695-1754, London: Hansard Publishing Union Ltd, p viii.
- **Lincoln's Inn:** 1408-1506: Lincoln's Inn (1896), *The records of the honourable society of Lincoln's Inn: Admissions from A.D. 1420 to A.D. 1799*, vol. 1, London: H.S. Cartwright.
- **Inner Temple:** 1547-1920: Inner Temple Archives (2014), Inner Temple Library, viewed 27 January 2014, <<http://www.innertemplearchives.org.uk/search.asp#stats>>.
- **Middle Temple:** 1586, 1605, 1608-1609, 1614-1615: Harvey, R.O. (ed.) (2011), *History of the Middle Temple*, Oxford: Hart Publishing, p 85-88.

**1600-1799:** all data based on Lemmings, D. (1990), *Gentlemen and Barristers, the Inns of Court and the English Bar, 1680-1730*, Oxford: Clarendon Press, p 10. 1780-1888: Dunman, D (1983) *The*

English and Colonial Bars in the Nineteenth Century, London: Croom Helm, p 25, Table 1.10 and p 28, Table 1.12. 1800-1850: Harvey, R. O. (ed.) (2011) *History of the Middle Temple*, Oxford: Hart Publishing, p 292. 1842-1984: Abel, R.L. (1988), *The Legal Profession in England and Wales*, Oxford: Basil Blackwell Ltd, pp 328-334.

**Apprentices.** The number of apprentices over time as a percentage of the 14-20 year age cohort population is approximated by the number of pupils doing apprentices within clothwork, goldsmith, draper and mercer professions in Livery Companies (trade guilds) of the City of London in percentage of the population in London. **1289-1900:** Centre for Metropolitan History, Institute of Historical Research (2014), University of London, London, viewed 20 January 2014, <[www.londonroll.org](http://www.londonroll.org)>.

**London Population.** Bairoch, R., Batou, J. and Chevre, P. (1988), 'La Population des villes européennes : banque de données et analyse sommaire des résultats, 800-1850'. Chandler, T (1987), 'Four thousand Years of Urban Growth : An Historical Census'. Biguzzi: <http://worldcitypop.com/index.asp>, accessed on 15 November 2012.

**Literacy Rates. 1500, 1550, 1600, 1650, 1700, 1750:** Cressy David (2006), *Literacy and the Social Order, Reading and Writing in Tudor and Stuart England*, Cambridge University Press, male and female literacy rates data is extrapolated from Figure 8.1. The average literacy rate is then computed and used to splice actual total literacy using 1749 as base year. **1750-1850:** Schofield, R. S. (1973), *Dimensions of Illiteracy in England 1750-1850*, *Explorations in Economic History*, 10: pp 437-454. **1850-1970.** Banks, A.S. (1971). *Cross Polity Time Series Data*. The MIT Press: Cambridge, Massachusetts and London, England. **1970-2011.** Extrapolated using the number in 1970 (no data are available after this date because approximately full literacy is assumed).

**Agricultural patents. 1620-1900.** Ang, J. B., Banerjee, R. and Madsen, J. B. (2013) *Innovation, Technological Change and the British Agricultural Revolution*. *Southern Economic Journal*, 80(1), 162-186.

**Consumer prices. 1264-1954:** CPI of London, Wages, Prices & Living Standards: The World Historical Perspective, viewed on 12.4.2013. <<http://www.economics.ox.ac.uk/Members/robert.allen/WagesPrices.htm>>. **1955-2011:** OECD.Stat.

**Investment and capital stock. 1270-1760.** Capital stock is measured as the sum of working animals (oxen and horses) from Broadberry *et al.* (2011) (Figure 2) and divided by the agricultural share in total income. The data are geometrically interpolated between 1496 and 1500. **1761-2011.** The perpetual inventory method is used with a depreciation rate of 8%. The stock of capital is initially set to the Solow model steady state value of  $I_0/(\delta + g)$ , where  $I_0$  is investment at the initial year (1761),  $\delta$  is the depreciation rate and  $g$  is the growth in investment during the period from 1761 to 2011. **1761-1960.** Maddison, A. (1995) *Explaining the Economic Performance of Nations. Essays in Time and Space*, Aldershot: Edward Elgar. **1960-2011.** OECD, *National Accounts, Vol. 2*. An annual 3.5% war damage is corrected for in the estimates during the period 1943-45.

**Share of agriculture in total income. 1270-1870.** Broadberry *et al.* (2011). **1870-2006.** Madsen, J. B., Ang, J. B. and Banerjee, R. (2010) "Four Centuries of British Economic Growth: The Roles of Technology and Population," *Journal of Economic Growth* 15(4), 263-290. **2006-2011.** OECD, *National Accounts, Vol. 2*. Paris.

**Great scientists. 1100-2011.** Hellemans, A. and Bunch, B. (1991) *The Timetables of Science- a Chronology of the Most Important People and Events in the History of Science*, New York: Simon & Schuster Inc. Asimov, I. (1982) *Asimov's Biographical Encyclopedia of Science and Technology*, Garden City, NY: Doubleday & Company, Inc. Gascoigne, R. M. (1984) *A Historical Catalogue of Scientists and Scientific Books: From the Earliest Times to the Close of the Nineteenth Century*, New York: Garland Publishing. Ochoa, G. and Corey, M. (1997) *The Wilson Chronology of Science and Technology*, New York: Wilson. The data are updated by extrapolating the data over the last 20 years before the last year at which the data are available.

**Knowledge spillovers through the channel of imports. Bilateral import weights. 1270-1701.** Assumed to be the constant and equal to the import weights in 1701. For Australia, New Zealand and the West Indies imports are assumed to be zero before 1701. 1701-1808. Schumpeter, E. B., 1960. *English Overseas Trade Statistics 1697-1808*, Oxford: Clarendon press. 1809-1870. Mitchell, B. R. (1988), *British Historical Statistics*, Cambridge: Cambridge University Press. 1870-2011: Spliced with the data in Madsen (2007) and updated. The following 16 countries/country groups are covered in the data: India, the US, Denmark, Canada, Belgium, France, Germany, Poland, Russia, Portugal, Italy, West Indies, Turkey, Argentina, Australia and New Zealand. Knowledge stock. Estimated as the accumulated number of great scientists listed in Gascoigne (1984) *op cit.*, starting from year 1000 AD.

**Trade openness.** Trade openness is measured as the ratio of the sum of total exports and imports to nominal GDP. Re-exports (from 1697 onwards) were excluded to avoid double counting, as they were already included in the value of imports. Exports were therefore confined to exports of *domestic* goods. Next, it was interpolated to fill in any missing gaps in the collected data. To remove the effects of inflation when interpolating, imports and exports were first divided by nominal GDP before being interpolated.

**Imports and exports: 1086** (exports only): Britnell, RH & Campbell, BMS (eds) 1995, *A commercialising economy: England 1086 to c. 1300*, Manchester University Press, Manchester, England, pp. 37-38. **1306:** Miller, E & Hatcher, J 2014, *Medieval England: Towns, Commerce and Crafts, 1086-1348*, Routledge, Oxford, England, pg 213, Table 4.1. **1354:** Craik, GL 1844, *The history of British commerce, from the earliest times. Reprinted from the Pictorial history of England; with corrections, additions, and a continuation of the present day*, vol. 1, C Knight & Co, London, England, pg 144. **1559 and 1560:** Stone, L 1949, 'Elizabethan Overseas Trade', *Economic History Review*, New Series, vol. 2, no. 1, pp. 30-58, especially pg 36, fn 2. As London accounted for more than 80% of British trade (Stone, pp. 36 and 38), it is assumed that London accounted for 90% of British trade for the purposes of this paper, hence Stone's figures were divided by 0.9 to arrive at an estimate of national trade. **1613, 1622, 1663 and 1669:** Craik, GL 1844, *The history of British commerce, from the earliest times. Reprinted from the Pictorial history of England; with corrections, additions, and a continuation of the present day*, vol. 2, C Knight & Co, London, England, pp. 33 and 77. 1087-1305, 1307-1353, 1355-1558, 1561-1612, 1614-1621, 1623-1662, 1664-1696, 1705, 1712 and 1813: Interpolated. **1697-1944:** Total imports and exports data are found in the years 1697-1771 for England and Wales, for Great Britain in the years 1772-1795 and for UK in the years 1796-1944. The later series is spliced upward to get the whole series from 1697-1944. The source is from Mitchell (1988), pages 448-454. For **1945-2011:** National Statistics Online (NSO) database for UK: <<http://www.statistics.gov.uk/default.asp>>.

**Nominal GDP.** Real GDP multiplied by consumer prices before 1270 and then spliced with nominal income in 1270. **CPI: 1086-1200:** Britnell, RH & Campbell, BMS (eds) 1995, *A commercialising economy: England 1086 to c. 1300*, Manchester University Press, Manchester, England, pg 50, Table

3.5. **1200-1270.** Clark, G 2010, ‘The Macroeconomic Aggregates for England, 1209-2008’ in Field, AJ, Clark, G and Sundstrom, WA (eds) *Research in Economic History*, vol. 27, Emerald Group Publishing Ltd, Bingley, United Kingdom, pg 81, Table 13. 1087-1199, 1201-1209, 1211-1219, 1221-1229, 1231-1239, 1241-1249, 1251-1259, 1261-1269 Interpolated. **1270-1870.** Broadberry *et al.* (2011) *op cit.* **1871-1947:** Mitchell (1988) *op.cit.* **1948-2013:** Office for National Statistics 2014, Office for National Statistics, Newport viewed 16 July 2014, <<http://www.ons.gov.uk/ons/rel/naa2/second-estimate-of-gdp/q4-2013/tsd-second-estimate-of-gdp--q4-2013.html>>.

**Marriage rate. 1539-1980.** Mitchell (1988) *op cit* Table 17 pp. 70-74. **1980-2011.** Mitchell, B.R. (2007) *International Historical Statistic*, Palgrave Macmillan, New York, and Eurostat.

**Book prices. 1270-1390.** Data are not available so the real price of book is assumed constant before 1390. **1390-1690.** Paper prices, Clark (2010) *op cit.* **1690-1860.** Book prices, Clark (2010) *op cit.* The data are available every ten year in the period and are interpolated between the 10-year intervals. **1860-1938.** Real book prices in Germany (1880-1913, 1924-1938) and Switzerland (1866-1880, 1913-1924). Ritzmann-Blickenstorfer, H. (1996), *Historische Statistik der Schweiz*, Zürich: Chronos Verlag, and Hoffman, W. G. (1965) “Das wachstum der deutschen wirtshaft seit der mitte des 19. Jahrhunderts” in *Enzyklopädie der rechts und staatswissenschaft*, New York: Springer-Verlag. **1938-2011.** Real book prices are assumed constant after 1938.

**Urbanization rate. 1200-1850:** Covers the United Kingdom and is estimated as urban population greater than 1000 from Bairoch, R., Batou, J. and Chevre, P. (1988), *La Population des villes européennes : banque de données et analyse sommaire des résultats, 800-1850*, Genève : Droz and Chandler, T. (1987), *Four Thousand Years of Urban Growth : An Historical Census*, St. David's University Press. 1850-1980. **1850-1979:** urban population great than 20,000 from Cross-National Time-Series Data Archive (CNTSDA) (2012), <<http://www.databanksinternational.com/32.html>> after 1850, and divided by total population from Maddison (2003). CNTSDA (2012) data for cities of population greater than 20,000 is used because the 1,000 and greater category is not available from 1850. In between the real data points, data have been exponentially interpolated. **1980-2011.** World Development Indicators Urban Population read on 12.4.2013 from <http://data.worldbank.org/indicator/SP.URB.TOTL>

**Population. 1270-1820:** Broadberry *et al.* (2011) *op cit.* **1820-2000:** Maddison (2003) *op cit.* **2000-2011:** IMF, *International Financial Statistics*.

**Domesticated land area. 1270-2011.** Pastural plus arable land area from Klein Goldewijk, K., Beusen, A., van Drecht, G. & de Vos, M. (2011). The HYDE 3.1 spatially explicit database of human induced land use change over the past 12,000 years. *Global Ecology and Biogeography*, 20(1) 73-86. The data are available on <http://themasites.pbl.nl/tridion/en/themasites/hyde/download/index-2.html>, viewed on 2.2.2014.

**Temperature anomalies.** Guiot, J., C. Corona, and ESCARSEL members (2010): Growing Season Temperatures in Europe and Climate Forcings over the Past 1400 Years, PLoS ONE 5(4): e9972. doi:10.1371/journal.pone.0009972.

**Churches.** These data are used in the baseline regressions. The count of one is recorded at the foundation year. The Churches Conservation Trust for England. Viewed on 3.4.2013 <<http://www.visitchurches.org.uk/Ourchurches/Completelistofchurches/>>. The site lists the

foundation year. In the cases where the foundation period is given as a century, beginning of a century or the end of a century the foundation year is spread out evenly within the period given and the count and the score of one divided by the number of years within the period is given.

**Number of religious houses.** David Knowles and R. Neville Hadcock (1971), *Medieval Religious Houses*, England and Wales, Longman, London. Appendix II p. 494. The data points are in the years 1066, 1100, 1154, 1216, 1350, 1422, 1500, 1534, and 1540 and the data are geometrically interpolated. The data in the top of the interval are used.

**Cathedrals and abbeys, new building started.** Morris, Richard, 1979, *Cathedrals and Abbeys of England and Wales: The building Church 600-1540*. London: J.M. Dent and Sons Ltd., p 179. The data are available in 10-year intervals and are spread out evenly in the years covered by each decade.

**Cathedrals and abbeys, building campaigns in progress.** Morris, Richard, 1979, *Cathedrals and Abbeys of England and Wales: The building Church 600-1540*. London: J.M. Dent and Sons Ltd., p 179. The data are available in 10-year intervals and are spread out evenly in the years covered by each decade.

**Annual hours worked. 1270-1870.** Two measures are used. **First measure:** 1580, 1625, 1675, and 1716 (mid-years of time intervals for England) Clark, G. and Werf, Y. Van Der, 1998, “Work in Progress? The Industrious Revolution,” *The Journal of Economic History*, 58(03), pages 830-843, 1766, 1800, and 1830, Voth, H.-J., 2001, “The Longest Years: New Estimates of Labor Input in England, 1760-1830,” *The Journal of Economic History*, 61(4), 1065-1082. **1870-2011.** see Madsen, J. B., (2014) “Human Capital and the World Technology Frontier.” *Review of Economics and Statistics* (forthcoming). **Second measure.** Allen, R. C. and Weisdorf, J. L., 2011, “Was there an ‘Industrious Revolution’ Before the Industrial Revolution? An Empirical Exercise for England, c. 1300-1830,” *Economic History Review*, 64(3), 715-729.

**Employment. 1270-1841:** Population spliced with employment in 1841. **1841-1870:** 1841, 1851, and 1861 from Mitchell (1988) *op cit.* and geometrically interpolated in-between. **1870-2011,** see Madsen (2014) *op cit.*

**Population age distribution. 1160-1541.** The population age distributions are backdated to 1160 by assuming they are constant before 1541. **1541-1836:** age distributions from Wrigley, E. A., Davies, R. S., Oeppen, J. E., and Schofield R. S. (1997), *English Population History from Family Reconstitution 1580-1837*, Cambridge: Cambridge University Press. The data is available at 5-year intervals from 1541 as follows:

- i. The original data is in the age groups 0-4, 5-14, 15-24, 25-44, 45-64, 65-84.
- ii. Sweden is used as a proxy country and 1-year interval age distributions are backdated by assuming they are constant from 1751.
- iii. The age distributions in (i) are recalculated to 0-4, 5-14, 15-24, 25-44, 45-64, 65+.
- iv. Actual populations for each age-interval are then calculated using annual population data from McEvedy, C. and Jones, R. (1978), *Atlas of World Population History*, Harmondsworth, Middlesex: Penguin Books., interpolated. The age distributions within each age group are computed using proxy country 1-year interval age distributions as follows: Using 1-year age-interval data from the template country, the first step involves breaking down the total population within each of the given  $N$ -year intervals as follows. If  $N = 5$ , for example, the proportion of the age group  $A_i$ , is calculated as:  $A_i = P_i / \sum_{i=1}^N P_i$  where  $i$  takes values of 1-5 for a

5 year interval and  $P_i$  represents the population for age  $i$  within the interval; the  $P_i$  data from the template country (Sweden) are obtained from the University of California, Berkeley and Max Planck Institute for Demographic Research (2014), ‘The Human Mortality Database’, viewed on 15 March 2012, <[http:// www.mortality.org](http://www.mortality.org)>.

- v. Using age group populations from (iii) above, and computed age distributions from (iv), the next step is to decompose the total population into 1-year age intervals.
- vi. The 1-year interval populations are then used to compute the final age distributions from 1541-1836.
- vii. All intervening years within the 5-year intervals are linearly interpolated.

**1837-1840:** age distributions are linearly interpolated. **1841-1921:** age distributions are backdated using Mitchell (1988) *op cit.* for the census years 1841, 1851, 1861, 1871, 1881, 1891, 1901 and 1911 and linearly interpolate between the census years. **1922-2011:** Human Mortality Database (<http://www.mortality.org/>), viewed on 3.7.2013.

**Constraints on executive.** The index constraints on executives is based on the concept which is used by Polity IV and the background information for the construction of the index is based on three constitutional history books from Lyon, Keir and Maitland (Marshall, M.G., Jagers, K. and Gurr, T.R. (2010) ‘Polity IV Project: Political Regime Characteristics and Transitions, 1800-2010, Dataset Users’ Manual’, Center for Systemic Peace: Vienna, VA, USA, viewed on 30.3.2013. <<http://www.systemicpeace.org/inscr/p4manualv2010.pdf>>, p 63-67, Keir, D. L. (1969) *The constitutional history of modern Britain since 1485*, London: Adam & Charles Black. Lyon, B.D.L. (1960) *A constitutional and legal history of medieval England*, New York: Harper & Brothers. Maitland, F.W. (1963) *The constitutional history of England*, Cambridge: Cambridge university Press).

Operationalization

- 7-point scale
  - (1) “unlimited executive authority”
  - (2) “intermediate category”
  - (3) “slight to moderate limitations”
  - (4) “intermediate category”
  - (5) “substantial limitations”
  - (6) “intermediate category”
  - (7) “executive parity or subordination”

(1), (3), (5) and (7) are described by *checklist of attributes* (see Policy IV Manual) to be able to allocate a specific year to one of the main category.

(2), (4) and (6) are intermediate categories to indicate transition between the four main categories.

Difference to Polity IV: (2), (4) and (6) are used for more than ten years at a time when it seemed to be appropriate.

## Educational attainment

**Number of Schools.** The following sources were used to create a database of the number of primary and secondary schools.

Commission of Inquiry into Charities, (1841), *A Digest of the Reports made by the Commissioners of Inquiry into Charities*, London: Her Majesty’s Stationery Office, for the following counties (as they existed at that time); Bedfordshire, Berkshire, Buckinghamshire, Cambridgeshire, Cheshire, Cornwall, Derbyshire, Devon, Dorset, Durham, Essex, Gloucestershire, Herefordshire, Hertfordshire, Kent, Lancashire, Leicestershire, Lincolnshire, Middlesex, Norfolk,

- Northamptonshire, Oxfordshire, Rutland, Salop (Shropshire), Somerset, Southampton, Staffordshire, Suffolk, Surrey, Sussex.
- Schools Inquiry Commission (1868a) *Report of the Commissioners*, Vol. I, London: Her Majesty's Stationery Office, Appendices IV, V & VI.
- Schools Inquiry Commission, (1868b) *Special Reports of Assitant Commissioners and Digests of Information Received*, London: Her Majesty's Stationery Office, Vol. X London Division; Vol. XI South Eastern Division; Vol. XII South Midland Division; Vol. XIV South-Western Division.
- Schools Inquiry Commission, (1869) *Special Reports of Assitant Commissioners and Digests of Information Received*, London: Her Majesty's Stationery Office, Vol. XIII Eastern Division; Vol. XV West Midland Division; Vol. XVI North Midland Division; Vol. XVII North-Western Division; Vol. XVIII Yorkshire; Vol. XIX Northern Division.
- The Victoria History of the Counties of England, various chapters and volumes as follows:
- Schools, Arthur Francis Leach, VCH Bedfordshire, ii 149-85, 1908.
- Schools, Arthur Francis Leach, VCH, Berkshire, ii 245-84, 1906.
- Schools, Arthur Francis Leach, VCH, Buckinghamshire, ii 145-221, 1908.
- Schools, Ethel Mary Hampson, VCH Cambridgeshire, ii, 319-56, 1948.
- Schools, Arthur Francis Leach, VCH Derbyshire, ii 207-81, 1907.
- Schools, Arthur Francis Leach, VCH Durham, i 365-413, 1905.
- Schools, Charlotte Fell-Smith, VCH Essex, ii 50 1-64, 1907.
- Schools, Arthur Francis Leach, VCH Gloucestershire, ii 313-448, 1907.
- Schools, Arthur Francis Leach VCH Hampshire, ii 251-408, 1903.
- Schools, Arthur Francis Leach, VCH Hertfordshire, ii 47-102, 1908.
- Schools, Charles Guy Parsloe, VCH Huntingdonshire, ii 107-19, 1932.
- Schools, Arthur Francis Leach & Henry John Chaytor, VCH Lancashire, ii 561-624, 1908.
- Charity Schools, Richard A. McKinley, VCH Leicestershire iii 243-7, 1969
- Schools, Arthur Francis Leach, VCH Lincolnshire, ii 421-93, 1906.
- Schools, Arthur Francis Leach, VCH Northamptonshire, ii 201-88, 1906.
- Schools, Arthur Francis Leach & F. Fletcher, VCH Nottinghamshire, ii 179-264, 1910.
- Schools, Mary Doreen Lobel, VCH Oxfordshire, i 457-90, 1939
- Schools, F. Fletcher, VCH Rutland, i 259-300, 1908.
- Schools, Arthur Francis Leach and Thomas Scott Holmes, VCH Somerset, ii 435-66, 1911.
- Schools, Arthur Francis Leach & E. P. Steele Hutton, VCH Suffolk, ii 30 1-55, 1907.
- Schools, Arthur Francis Leach, VCH Surrey, ii 155-242, 1904.
- Schools, Arthur Francis Leach, VCH Sussex, ii 397-440, 1907.
- Schools, Arthur Francis Leach, VCH Warwickshire, ii 297-373, 1908.
- Schools, Arthur Francis Leach, VCH Worcestershire, iv 473-540, 1924
- Schools, Arthur Francis Leach, VCH Yorkshire, i 415-500, 1907.
- Carlisle, Nicholas (1818) *A Concise Description of the Endowed Grammar Schools in England and Wales*, Volumes I & II. London: Baldwin, Cradock & Joy.
- Hans, Nicholas (1951) *New Trends in Education in the Eighteenth Century*, London: Routledge & Kegan Paul Ltd.
- Lawson, John (1959), *Primary Education in East Yorkshire 1560-1902*, York: East Yorkshire Local History Society.
- Lawson, John (1962), *The Endowed Grammar Schools of East Yorkshire*, York: East Yorkshire Local History Society.
- Leach, Arthur F. (1896) *English Schools at the Reformation 1546-8*, Westminster: Archibald Constable & Co.
- Orme, Nicholas (2006) *Medieval Schools: From Roman Britain to Renaissance England*, New Haven & London: Yale University Press.

- Robson, Derek (1966) *Some Aspects of Education in Cheshire in the Eighteenth Century*, Manchester, The Chetham Society.
- Simon, Brian (1954) *Leicester Schools 1625-40*, *British Journal of Educational Studies*, Vol iii 42-58, 1954.
- Stow, John (1603) 'Of Schooles and other Houses of Learning', *A Survey of London, by John Stow: Reprinted from the text of 1603* (1908), pp. 71-76. URL: [http://www.british-history.ac.uk/report.aspx?compid=60022&strquery=cambridge schools](http://www.british-history.ac.uk/report.aspx?compid=60022&strquery=cambridge%20schools) Date accessed: 06 May 2014.
- Stowe, A. Monroe (1908) *English Grammar Schools in the Reign of Queen Elizabeth*, New York: Teachers College, Columbia University
- Tate, William Edward (1963), *A.F. Leach as a Historian of Yorkshire with an Index of the Yorkshire Schools (730 - 1770) Referred to in His Works*, York: St Anthony's Press.

### **Non Grammar and Primary School Enrollment**

- 1160-1902 Gross enrolment rates (GERs) are computed for a 6-year schooling duration covering ages 6-11 years while those from 1903-2009 are based on 7 years for the 6-12 year old age group.
- 1160-1811 enrolment is proxied by the accumulated number of non-grammar schools computed using number of schools data from Eyre, G. E. and Spottiswore, W, (1868), *Schools Inquiry Commission, 1868, Report of The Commissioners, Vol. I*. The series is then spliced to the level of actual enrolment using 1812 as base year.
- 1812 GER figure is obtained from Flora, P., Alber, J., Eichenberg, R., Kohl, J., Kraus, F., Pfenning, W. and Seebohm, K, (1983), *State, Economy and Society in Western Europe 1815-1975 - A Data Handbook in two Volumes, Vol. 1, The Growth of Mass Democracies and Welfare States*. Frankfurt: Campus Verlag. The GERs are based on literacy changes for brides.
- Primary school enrolment for 1830, 1840 is obtained from Lindert, P.H, (2004), *Growing Public: Social Spending and Economic Growth since the 18th Century, Volume 2: Further Evidence*. Cambridge University Press. 1850-1851, 1853-1858 Mitchell, B.R, (2007), *International Historical Statistics, 3 volumes*. New York: Palgrave Macmillan. 1859-1914, 1920-1936, 1946-2009 enrolments are all from the Central Statistical Office (CSO), *Annual Abstract of Statistics*, Her Majesty's Stationary Office: London, various issues.
- 1859-1891 consists of total for Great Britain; 1893-1901 is Great Britain sum of primary day and evening schools; 1902-1905 is total for Great Britain; 1906-1914 is sum of England and Wales primary enrolment for ages 5 and under 12 as well as ages 12 and over, and Scotland primary; 1920-1931 is the sum of England and Wales elementary enrolment, Northern Ireland primary, Scotland primary day schools, Scotland higher grade schools and Scotland continuation classes; 1932-1936 consists of England and Wales total primary, Northern Ireland primary and Scotland primary day schools; 1946-1969 is the sum of England and Wales primary, Northern Ireland primary and Scotland primary; 1970-2009 is reported as total for all United Kingdom.

### **Grammar and Secondary School Enrolment**

- GERs for 1480-1902 are computed for a 3 year schooling period covering ages 12-14, while those for 1902-2009 are computed for a 5 year period for ages 13-17.
- 1480-1865 enrolment is proxied by the cumulative number of schools, computed from the number of grammar schools data from Eyre and Spottiswore (1868) *op cit*.

- 1865 and 1905 number of schools as well as the number of pupils per school data for 1905 is obtained from Bolton, P., (2012), Education: Historical Statistics. Standard Note SN/SG/4252, House of Commons Library. The number of pupils per school in 1865 is then computed by adjusting the actual number of pupils per school in 1905 using the proportion of the number of schools in 1865 to 1905. Because only grammar schools existed then, the result is then further adjusted by a factor 0.6 to correct for the fact that grammar school only covers 3 years, while secondary schooling data that is used from 1905 is of a 5-year duration. 1866 – 1904 enrolment is growth interpolated.
- 1480-1865 cumulative schools series is then spliced to the level of grammar school enrolment using 1865 as base year.
- 1905-2009 secondary school enrolment data are obtained from the CSO *op cit*. 1905-1924 data is composed of England and Wales and Scotland; 1925-1936, 1946-1969, England and Wales, Scotland and Northern Ireland; 1970-2009 is total for the United Kingdom.
- 1937-1945 GERs are linearly interpolated.

### Tertiary Enrolment

- 1377-1919 enrolment data was obtained from University calendars, annual reports and president's reports and summed up for the following universities and start years: Oxford (1377), Cambridge (1501), Edinburgh (1589), Durham (1833), St Andrews (1413), Glasgow (1844), Sheffield (1889), Bristol (1909), Belfast (1849), Bangor (1889), London (1838), Aberystwyth (1894), Cardiff (1893), Manchester (1851), Birmingham (1900), Liverpool (1903), Leeds (1903), University College London (1835), King's College (1836), London School of Economics (1896), Wales (1896) and London Medical Schools (1880). See below for data detailed on individual universities.
- Where only graduate figures are available, the individual university enrolment is estimated by summing up the graduate numbers 5 years forward. For cases where only matriculations are available, the enrolment is estimated by summing backwards over 5 years. The average of both series was taken except in cases where graduate-estimated enrolments tended to be implausible and only the matriculation-based ones were used. The graduate and matriculation-based estimated enrolments are then spliced to the level of actual enrolment where applicable.
- Enrolments from all the above universities and colleges are summed up to obtain the total tertiary enrolment. The calculated series up to 1919 was a highly plausible match with official data and no splicing or any other adjustment was required.
- From 1920 to 1994 all data are from the CSO *op cit* and are reported as follows: 1922-1936, 1939, 1942-1953 consists of Great Britain full time and part time university enrolment; 1954-1970, includes Northern Ireland; 1971-1994 is the total for United Kingdom.
- 1996-2010, data are obtained from the UK Higher Education Statistical Agency <[http://www.hesa.ac.uk/index.php?option=com\\_datatables&Itemid=121&task=show\\_category&catdex=3](http://www.hesa.ac.uk/index.php?option=com_datatables&Itemid=121&task=show_category&catdex=3)>, viewed 25 June 2012. The data include all full time and part-time enrolment for undergraduate and postgraduate programs. To maintain consistency with the pre-1994 series, the data was filtered to include institutions that were granted the Royal Charter prior to 1992. Hence the following Institutions were included: Birkbeck College, Brunel University, City University, Cranfield University, Goldsmiths College; Institute of Education, University of London, King's College London, London Business School, London School of Economics and Political Science, London School of Hygiene and Tropical Medicine, Loughborough University, Queen Mary and Westfield College, Royal College of Art, Royal Holloway and Bedford New College, Royal Veterinary College, School of Oriental and African Studies, School of Pharmacy, University of London, Aston University, University of Bath, University of Birmingham, University of Bradford, University of Bristol, University of Cambridge,

University of East Anglia, University of Essex, University of Exeter, University of Hull, University of Keele, University of Kent at Canterbury, University of Lancaster, University of Leeds, University of Leicester, University of Liverpool, University of Newcastle-upon-Tyne, University of Nottingham, University of Oxford, University of Reading, University of Salford, University of Sheffield, University of Southampton, University of Surrey, University of Sussex, University of Warwick, University of York, University of Manchester, University College London, University of Durham, University of Wales, Aberystwyth, University of Wales, Cardiff, University of Wales, Swansea, University of Wales, Bangor, Heriot-Watt University, University of Aberdeen, University of Dundee, University of Edinburgh, University of Glasgow, University of St Andrews, University of Stirling, University of Strathclyde, and the Queen's University of Belfast.

- 1812-1882 GERs are backdated using the 20-year average growth rate from 1883-1902. GERs for 1884-1885, 1887, 1892, 1895-1921, 1937-1938, 1940-1941, and 1995 are linearly interpolated.

### **3. Student enrollment data for individual universities before 1920.**

**University of Oxford - 1377:** Leader, DR, Nugent, C. and Brooke, L. (1994) *A History of the University of Cambridge, Vol 1, the university to 1546*, Cambridge University Press, Cambridge, United Kingdom, p 35; **1400 and 1450:** Anderson, R.D. (2006) *British Universities past and present*, Hambledon Continuum, London, United Kingdom, p 8; **1449 – 1456 :** Evans, T.A.R. (1992) ‘The number, origins and careers of scholars’ in JI Catto and R Evans (eds), vol 2, *The History of the University of Oxford – Late Medieval Period*, Clarendon Press, Oxford, United Kingdom; **1518-1570:** Ball, W.W.R. (1889) *A History of the study of mathematics at Cambridge University*, University Press, Cambridge, United Kingdom, p 249; **1580, 1777, 1803, 1853:** Mansbridge, A. (1923) *The Older Universities of England: Oxford & Cambridge, based upon a course of lectures delivered on the Lowell foundation, Boston, USA, March 1922*, Houghton Mifflin Co., London, United Kingdom, p xx; **1500-1909:** Stone, L (1974) ‘The Size and Composition of the Oxford Student Body, 1580-1909’, p 94, Table 3 in L Stone (ed.) (1974), *The University in Society – Oxford and Cambridge from the 14<sup>th</sup> and to the early 19<sup>th</sup> century*, vol. 1, Princeton University Press, Princeton, New Jersey, USA; **1571-1900:** University of Oxford (1900) *The Historical Record of the University of Oxford, being a supplement to the Oxford University Calendar, with an alphabetical record of University honours and distinctions. Completed to the end of Trinity term 1900*, Clarendon Press, Oxford, United Kingdom, p 908-10; **1746-1770:** Gunther, R.W.T. (1937) *Early Science in Oxford, Vol XI, Oxford Colleges and their men of science*, Oxford University Press, Oxford, United Kingdom, p 359-98; **1809-1919:** University of Oxford, *The Oxford University Calendars*, University of Oxford, Oxford, United Kingdom; **1831-1833:** Universities of Oxford and Cambridge, *Oxford and Cambridge Universities. An account of the number of matriculations and degrees conferred in the Universities of Cambridge and Oxford, for three years; with the amount of stamp duty paid thereon*, House of Commons Paper 290, Session 1834 (1834), p 2; **1845 – 1849:** Universities of Oxford, Cambridge and Dublin, *Returns of Number of students entered annually in the books of each College or hall within the Universities of Oxford, Cambridge and Dublin, during the last five years*, House of Commons Paper 7, Session 1850 (1850).

**University of Cambridge - 1377, 1450, and middle ages:** Leader, D.R., Nugent, C. and Brooke, L. (1994) *A History of the University of Cambridge, Vol 1, the university to 1546*, Cambridge University Press, Cambridge, United Kingdom, pg 32-3, 35-6;

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