DISCUSSION PAPER SERIES

DP14138
(v. 4)

THE WHEELS OF CHANGE: TECHNOLOGY ADOPTION, MILLWRIGHTS, AND PERSISTENCE IN BRITAIN'S INDUSTRIALIZATION

Karine van der Beek, Joel Mokyr and Assaf Sarid

ECONOMIC HISTORY

MACROECONOMICS AND GROWTH

ISSN 0265-8003

THE WHEELS OF CHANGE: TECHNOLOGY ADOPTION, MILLWRIGHTS, AND PERSISTENCE IN BRITAIN'S INDUSTRIALIZATION

Karine van der Beek, Joel Mokyr and Assaf Sarid

Discussion Paper DP14138
First Published 20 November 2019
This Revision 17 November 2020

Centre for Economic Policy Research
33 Great Sutton Street, London EC1V 0DX, UK
Tel: +44 (0)20 7183 8801
www.cepr.org

THE WHEELS OF CHANGE: TECHNOLOGY ADOPTION, MILLWRIGHTS, AND PERSISTENCE IN BRITAIN'S INDUSTRIALIZATION

Abstract

This paper examines the effect of the early adoption of technology on the evolution of human capital and industrialization, in the context of Britain's Industrial Revolution. We demonstrate that millwrights, eighteenth century specialists in advanced carpentry and hydraulic machinery, evolved following the diffusion of watermills, and are recorded in the Domesday Book survey (1086). Our results suggest that their availability was a major factor in determining the persistence of English industrial location from the thirteenth century to the eve of the Industrial Revolution. Furthermore, in locations that adopted watermills in the Middle Ages, we show that the availability of physical infrastructure and of highly skilled wrights jointly determined the location of English industry from the end of the thirteenth century to the eve of the Industrial Revolution.

JEL Classification: O14, O15, O33, N00, N13, N53, N73, N93

Keywords: Human Capital, Industrialization, economic growth, mechanical skills, watermill, England

Karine van der Beek - kvdbeek@bgu.ac.il
Ben-Gurion University of the Negev and CEPR

Joel Mokyr - j-mokyr@northwestern.edu
Northwestern University

Assaf Sarid - asarid@econ.haifa.ac.il
University of Haifa

Acknowledgements
We thank Morgan Kelly, Cormac O'grada, Eric L. Jones and David Weil, as well as conference participants at the Nicholas Crafts@70 Conference;"Deep Rooted Factors in Comparative Development" 2017, DEGIT 2019, ESPC 2019, and seminar participants at Bar Ilan, Brown, Haifa, Hebrew University in Rehovot, and Paris School of Economics for useful comments and discussions.

The Wheels of Change: Technology Adoption, Millwrights, and the Persistence in Britain's Industrialization

Joel Mokyr, Assaf Sarid, and Karine van der Beek[+]

2nd draft

November 2020

This paper examines the effect of the early adoption of technology on the evolution of human capital and industrialization, in the context of Britain's Industrial Revolution. We demonstrate that millwrights, eighteenth century specialists in advanced carpentry and hydraulic machinery, evolved following the diffusion of watermills, and are recorded in the Domesday Book survey (1086). Our results suggest that their availability was a major factor in determining the persistence of English industrial location from the thirteenth century to the eve of the Industrial Revolution. Furthermore, in locations that adopted watermills in the Middle Ages, we show that the availability of physical infrastructure and of highly skilled wrights jointly determined the location of English industry from the end of the thirteenth century to the eve of the Industrial Revolution.

[+] Joel Mokyr, Northwestern University (j-mokyr@northwestern.edu), Assaf Sarid, University of Haifa (asarid@econ.haifa.ac.il), Karine van der Beek, Ben-Gurion University of the Negev (kvdbeek@bgu.ac.il)

We are grateful to Morgan Kelly, Cormac Ó Gráda, Eric L. Jones and David Weil, three referees and the editor of this Journal, as well as conference participants at the Nicholas Crafts @70 Conference; the "Deep Rooted Factors in Comparative Development" conference in 2017, DEGIT 2019, ESPC 2019, and seminar participants at Bar Ilan, Brown, Haifa, Hebrew University in Rehovot, and the Paris School of Economics for useful comments on an earlier version. Michael Giordano provided excellent research assistance. The authors are responsible for all remaining errors.

1. Introduction

The key role of human capital in the process of innovation and economic growth has been emphasized by economists for more than half a century now, and has since become a central component in many growth theory studies (e.g. Lucas, 1988; Galor & Weil, 1999, 2000; Acemoglu, 2003; Galor, 2011; and others).[1] When examining the role of human capital in the context of Britain's industrialization in the eighteenth century, there remains much room for skepticism, as Britain had, at best, mediocre levels of schooling and literacy on the eve of the Industrial Revolution (Mitch, 1999). Our paper follows recent studies that suggest modifications to our thinking about the role of human capital during the British Industrial Revolution: (Mokyr, 2009; Kelly, Mokyr, and Ó Gráda 2014, 2020a, 2020b). The argument, in brief, is that in the early stages technical competence mattered much more than schooling and literacy. The key factor was the supply of upper-tail human capital: the manufacturing and maintenance of relatively sophisticated devices using high-quality materials required top-quality mechanical competence. The evidence that British craftsmen were of superior quality during the Industrial Revolution has been presented elsewhere, but until recently its causes and ramifications have been little explored.

There are a number of complementary hypotheses explaining the superior quality of British artisans. One focuses on the flexibility and effectiveness of the institutions that supported apprenticeship and the supply of high-skill labor in Britain (Mokyr, 2020).[2] A second view sees certain specific features of British geography as facilitating the demand for skills and focusing devices (Mokyr, 2009, pp. 114-15). A third explanation, and one we will propose here, is the persistence and heritage of the medieval English economy, which was technically more advanced and sophisticated than is commonly believed. In this paper we combine the high-skill interpretation with the historical persistence view, and focus on a particular group of craftsmen, known as *wrights*. These were highly skilled carpenters specialized in the planning, construction, improvement and maintenance of water-powered machinery. We can think of them as the engineers of the pre-industrial era.

In line with recent studies on the role of long-run persistence in economic and social development, our hypothesis is that the formation of human capital was a persistent process. Skilled artisans produced not only sophisticated devices, they also produced more artisans. The historical process was triggered by the initial production technologies determined by geographical factors. It had unintended

[1] The empirical evidence for the existence of such a relationship remains, however, indecisive due to the use of unsatisfactory schooling measures as a proxy for human capital. More generally, there are many other issues in the postulated role of human capital in growth suggesting that education or more generally human capital are not the magic formula for rapid economic development.

[2] The agility and effectiveness of England's apprenticeship system (notwithstanding the 1562 law) was one of the underlying causes that explain Britain's advantage in terms of high-skilled mechanics (Ben Zeev et al., 2017; De la Croix et al., 2018; Kelly et al., 2020b). Here we zoom in on one particular occupation that played an important role in the creation of these skills.

long-run consequences. In the case of England, the demand for such workers with high mechanical skills originated from the adoption of water-powered mills for grain grinding in the early middle ages. Once in place, the wrights' competence in the construction, maintenance, and improvement of the machinery generated an advantage for the adoption of complementary water-power machinery in other industrial uses (e.g. fulling mills in textile, blowing mills in tin smelting, water raising mills in mines, and forging mills in iron-works), in the same locations where possible. This symbiotic relationship was most pronounced in the textile sector, in which fulling mills were widely adopted by the beginning of the fourteenth century. The industry shifted its location from the urban centers of the Eastern plains to the hilly Northern and Western rural districts in the thirteenth and fourteenth centuries (Carus-Wilson, 1941; Lucas, 2005). In the following centuries, the number of wrights continued to grow hand-in-hand with the technological changes that were taking place and the expanding use of machinery (Feldman and van der Beek, 2016). This process continued at least until late in the eighteenth century, when the steam engine began to replace the waterwheel as a source of energy. Engineers — a profession that in part grew out of the skilled millwrights of the pre-Industrial Revolution era — became the newly demanded skill and became one of the key parts of the upper tail of skill distribution and thus one of the main drivers of the Industrial Revolution (Musson & Robinson, 1960; MacLeod and Nuvolari, 2009; de Pleijt et al. 2019; Hanlon, 2020). Thus, the adoption of grinding mills was important as a source of motive energy, as a stimulus to skill accumulation that spilled over to other industries, and as a focusing device for more innovation.

To test our hypothesis of the central role that the skills and technical competence of England's millwrights played in its technological evolution, we use district-level data on England's government area districts, containing information from various sources. Mainly, we use the Apprentice Tax Registers to proxy for the numbers of wrights in every district, by employing the number of apprentices to masters in the relevant occupations before the onset of the Industrial Revolution (1710-50).[3] Our exogenous source of identification for the location of wrights in a district is based on the mentions of mills in the early Middle Ages (as registered in Domesday Book in 1086).[4] Thus, we can identify the districts in which the number of wrights grew in response to the adoption of grinding mills before the introduction of industrial mills, and thus overcome the obvious simultaneity of the numbers of wrights and mills in the eighteenth century. The obvious objection is that geographical suitability of sites for watermills (a time invariant feature) drove their location, and that the same conditions explain the prevalence of millwrights six centuries later. To isolate non-geographical

[3] Board of Stamps: *Apprenticeship Books*, Series IR 1.

[4] It is common to assume that all mills mentioned in Domesday Book were grinding mills (e.g. Langdon, 2004, p. 11), though there is no direct evidence for it. There probably were a few mills used for purposes other than grain milling. For a discussion on the topic see Bennett & Elton, 1899, pp. 107-8.

factors such as millwright skills we introduce a large number of geographical controls, yet these hardly affect the correlation between Domesday mills in 1086 and the prevalence of millwrights in the eighteenth century. Something else must have been taking place.

Our results provide empirical evidence for a strong and persistent capital-skill complementarity between the location of Domesday mills and the spatial distribution of wrights across England more than 600 years later. Controlling for a wide range of geographic, climatic, and agricultural variables, we show that one additional mill per ten thousand people in a district in 1086 is associated with an average increase of 0.13 wright apprentices per ten thousand people in 1710-1750. To address the concern that the estimators we obtain may be biased due to some omitted unobservable geographical characteristic of the sites where mills were located in the early middle ages, we also estimate the regressions instrumenting Domesday mills with a geographical IV capturing the suitability of a site to constructing grinding rather than industrial mills.

Furthermore, we provide suggestive evidence for the role of wrights in the process of early industrialization. We show that the existence of Domesday Book (hence DB) mills in a district predicts the spatial distribution of the textile and iron making industries on the eve of the British Industrial Revolution. These industries had adopted growing numbers of water-powered machines since the late thirteenth century. In contrast, the spatial distribution of other industries, which did not adopt such machinery, cannot be explained by the existence of Domesday mills. Again, in these regressions we use a considerable number of geographical controls, to reduce the concern for spurious correlation. To reinforce this finding, we conduct a horserace between the density of mills and wrights in the entire Domesday sample that indicates that the mills alone are much less important once wrights are taken into account. Moreover, to further rule out the "pure" effect of topography, we perform a mediation analysis that directly separates the geographical elements from other sources of persistence. This analysis suggests that wrights are responsible for 40%-70% of the total effect of mills on industrialization.

Finally, we also utilize the location of worsted producers. Worsted relied on combed rather than carded wool, and unlike wool rarely depended on water mills since worsted cloth did not require fulling. We show that in the first half of the eighteenth century, worsted production was not located where mills were. Worsteds were easier to adapt to the new spinning technologies developed for cotton than wool. Hence, in the second half of the eighteenth century worsted producers switched their location to locations where DB mills where. Worsteds did not much use these mills, but needed increasingly complex machinery (some of it water-powered). We conclude that the presence of wrights and their skills is what in part enticed this relocation.

2. Related literature

This paper relates to the wide-ranging empirical literature concerned with the role of human capital in economic growth. There is still controversy surrounding empirical evidence for the positive effect of schooling measures as a proxy for human capital and its subsequent effect on economic performance.[5] In the context of Britain's industrialization, there is even more room for skepticism (Mitch, 1992; Crafts, 1996; Allen, 2003; Clark, 2005). Since the seminal work of David Mitch (1999), showing that schooling and literacy in Britain were not exceptionally favorable, more studies have focused on schooling and literacy rates and reached similar conclusions as to the role of human capital e.g., Lindert (2004). Reis (2005) found that literacy rates were about 60 percent for British males and 40 percent for females around 1800, more or less on a par with Belgium, slightly better than France, but worse than the Netherlands and Germany. Like Mitch (1999), de Pleijt (2018) also argues that there was at best sluggish improvement in British literacy during the Industrial Revolution itself. As far as higher education is concerned, Khan (2018) shows that formally-trained scientists were not highly represented among the known British inventors until very late in the nineteenth century.

Others have disagreed with the finding, that human capital was not a major factor in the Industrial Revolution. Madsen and Murtin (2017), in their analysis of the determinants of British economic growth since the Middle Ages, find that education has been the most important driver of income growth during the period 1270–2010 and further, that it has been equally important before and after the first Industrial Revolution. They suggest that opposite findings as to the role of schooling may be a result of the "appalling state of British educational records prior to about 1850" (p. 230). For the follower countries, the evidence is mixed. O'Rourke and Williamson (1995) and Taylor (1999) conclude from country-level cross-sectional and panel analyses that human capital was not a crucial driver of economic catch-up in the 19th century. In contrast, Becker, Hornung, and Woessmann (2011) document that elementary education in nineteenth century Prussia predicts employment levels in metals and other industries, but not in textiles. Franck and Galor (2017) look at the causality between human capital and industrialization, exploiting the exogenous regional variations in the adoption of steam engines across France, and find a reverse effect, namely that industrialization generated wide-ranging gains in literacy rates and educational attainment. De Pleijt et al. (2019), similarly show that English industrialization, proxied by steam engines, led to a greater share of

[5] While the results of cross-country regressions, such as Glaeser et al., 2004 provided significant support to the existence of a positive association between different measures of schooling and countries' economic growth, contemporary development economists (e.g. Pritchett, 2001; Easterly, 2001) found little support for a major role for education. These results may be explained by measurement errors in education (see for example Krueger and Lindahl, 2001 and Hanushek and Woessmann, 2008).

skilled workers in the nineteenth century.

This paper focuses on artisanal mechanical skills, rather than on formal schooling, and connects to a growing literature that places artisans at center stage in explaining the Industrial Revolution (Berg, 1994, 2007; Harris, 1992; Kelly, Mokyr and Ó Gráda, 2020b). It is also related to the large (and growing) literature on the role of persistence in economic and social phenomena (Voth, 2020). This literature has pointed to a considerable number of cultural and institutional features of pre-modern societies that explain variations in later generations. For example, in recent years, the emergence and dissemination of technological change has been linked directly to the presence of Upper Tail Human Capital and the useful knowledge of an artisanal or intellectual elite (Mokyr, 2009, pp. 121-122; Kelly, Mokyr and Ó Gráda, 2014; Hanlon, 2020).[6]

Our study is concerned with the effects of the earlier adoption of technology and the impact of unintended spillover effects on the evolution of human capital and on industrialization. From there, we go a step further and identify the geographical characteristics that determined locations that industrialized in the first half of the eighteenth century. Similarly, but in another context, Bleakley and Lin (2012) used geomorphological features of final rapids (i.e., sections of a river where there is difficulty of navigating due to increase in water velocity and turbulence), to identify the path dependent development of cities that were formed in these locations, where continued transport required overland hauling or portage, and attracted much commerce. These features of final rapids allowed the authors to identify the role of path dependence in their later industrialization long after their geographical advantage was no longer relevant. In the context of Britain's Industrial Revolution, Trew (2014) calibrates a model that uses various geographical characteristics to estimate the role of geography in the growth of manufacturing employment in English parishes and shows that nineteenth century industrialization concentrated in coal abundant regions.

Driven by the technological competence of pre-Industrial Revolution millwrights, the presence of watermills is associated with later technological developments. The strong complementarity of watermills with later technologies was also exploited by Ashraf et al. (2018) who used watermills in 1819 as a proxy measure of proto-industrial physical capital, "because their ownership was institutionally restricted to the landed elites, and second, because they foreshadowed the adoption of steam engines and related skill-intensive methods of industrial production" (p. 2). Caprettini and Voth

[6] Cantoni and Yuchtman (2014) show that medieval universities played a causal role in expanding economic activity by training students in the law and contributing to the development of legal institutions, encouraging greater economic activity in medieval Germany. Squicciarini and Voigtländer (2015), examined the density of subscribers to the famous Encyclopédie in mid-18th century France, and have shown it is a strong predictor of city growth after the onset of French industrialization. Boerner and Severgnini (2019), show that the early adoption of clocks can explain variations in growth rates between European cities between 1500 and 1700.

(2018) use the location of watermills to instrument for the location of Swing Riot incidents (1830-2) in England, again based on their complementarity with later agricultural machinery (i.e. threshing machines). Our study differs by using data from a much earlier period, the eleventh century, and show how mills constructed in the Middle Ages are correlated with – and perhaps even contributed – to the emergence of early industrial processes. The study by Crafts and Wolf (2014) finds that Britain's cotton textiles factories in 1838 "preferred those locations with good availability of water power, rugged terrain, a history of textile invention, close to ports, and with good markets" (p.1184). This finding is consistent with our finding of strong persistence of the location of earlier textile mills, which before 1760 meant the woolen industry, as cotton was still in its infancy. The mechanism we suggest for this persistence, however, is different.

Unlike most studies of the location of mechanized factories that look at coal field location, we examine the location of manufacturing prior to the application of steam power. We show that coal did not matter much before the Industrial Revolution (appendix C). A possible explanation for the shift of textile manufacturing to areas close to coalfields is that collieries, too, were a source of high skill labor.[7] Another explanation offered by Sugden et al. (2018) is the lower cost of living due to cheaper coal for heating in the late seventeenth century (see also Crafts and Wolf 2014).

3. Mills and Skills

Mechanical engineering was one of the unsung heroes of the Industrial Revolution. Most scholars writing about the origins of engineering during the Industrial Revolution recognize that "millwrights can be considered the most direct ancestors of professional engineers" (MacLeod and Nuvolari, 2009, p. 229; see also Musson & Robinson, 1960; Hanlon, 2020). During the Industrial Revolution, the class of artisans trained as millwrights generated a large number of outstanding engineers and mechanics who contributed widely to technological advances in a variety of areas.[8]

The upper tail of the distribution of wrights on the eve of the Industrial Revolution included some of the finest artisans found anywhere in Europe at that time and the most distinguished of them have found their way into modern accounts of the Industrial Revolution and compilations such as the *Oxford Dictionary of National Biography.* Millwright in the medieval and early-modern era may not have been sophisticated engineers by the standards of the mid nineteenth century, but clearly they

[7] In this regard watermills and coal mines are similar in that they provided a focusing device and thus a major source of innovation and skilled engineers who played major roles in generating a host of inventions that spilled over to other sectors, not least the steam engine itself (Kelly et al., 2020a).

[8] Some of the best-known engineers of the Industrial Revolution originally apprenticed as millwrights. Two famous examples were James Brindley, the great builder of canals during the early canal era after 1750 and John Rennie, the co-inventor of the path-breaking breast-wheel water mill (with John Smeaton) and who built the first steam driven flour mills as well as Waterloo and Southwark bridges in London. for more details, see Appendix H.

were relatively well-trained craftsmen with a good if intuitive understanding of mechanics and power-transmission, the properties of timber and iron, and some informal notions about force and velocity (even if they used a different vocabulary). Through their apprentices, this knowledge was passed on from generation to generation. Moreover, medieval millwrights were flexible enough to adapt to new demands on their competence as technology changed. In the twelfth century the inanimate power provided by watermills was supplemented with the introduction of windmills. This adaptation of the mechanism to a new external source of power demonstrates a technical agility at a high level. The same is true for the replacement of horizontal with vertical waterwheels between the tenth and the thirteenth centuries in England, although on the Continent horizontal wheels persisted. The vertical wheels were far more expensive and complicated to construct, but more efficient. Their diffusion was perhaps associated with tighter seigneurial control.

The perception of the millwright as an all-around technically competent craftsman remained paramount during the Industrial Revolution. Textile engineering installations categorized their equipment as either "millwright's work" or "clockmaker's work" and these concepts "were soon enshrined in insurance policies" (Cookson, 2018, p. 68). The exact meaning of the term "millwright" was evolving, but Cookson (2018, p. 72) points out that their role as professional consultants, akin to coal viewers, remained of central importance to the textile industry.

Millwrights during the Industrial Revolution were a kind of labor aristocracy, comparable to mule operators. They should be regarded as implementers rather than the inventors who made dramatic changes in technology The Industrial Revolution changed their roles in the industrializing regions, and the profession morphed into something that today would be called mechanical engineering (MacLeod and Nuvolari, 2009). Engineers were a critical component of innovation in the Industrial Revolution and accounted for a large proportion of patents (Hanlon, 2020). More details on the transition from "millwright" to "engineer" are provided in Appendix H, which contains a more detailed historical background.

3.1 Mills, wrights, and the location of the textile industry

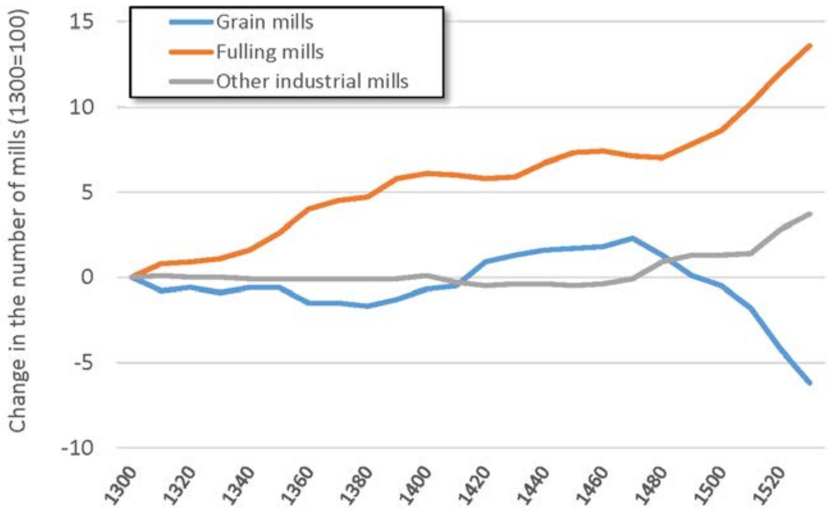
An early manifestation of the persistent effect of the location of medieval watermills for grinding was in the late thirteenth century, when the location of textile manufacturing shifted from the urban centers of the Eastern plains to the hilly Northern and Western countryside (Carus-Wilson, 1941; Pelham, 1944). Carus-Wilson famously argued that the new locations were determined by their suitability for the newly adopted water-powered fulling mills.[9] The locations identified by Carus-Wilson and

[9] Worsted manufacturing, which rarely required fulling, widely diffused to the West Riding later, by 1700-20 (Clapham, 1907, p.

Pelham persisted well into the fifteenth century and remained England's main textile manufacturing centers until the eighteenth, as can be observed in the maps provided by Darby (1973).[10] The main pulling forces of these locations were both the availability of a physical environment and topography suitable for mill construction and the presence of workmen specialized in the construction and in the inner workings of mills, elements which constituted an important advantage for setting up a cloth manufacturing center based on mechanical fulling.

As can be observed in figure 1, in the closing decades of the Middle Ages the mechanical principles of watermills were adopted to other industrial uses besides fulling. For example, forging mills in iron making, tin mills for crushing tin-ore, blowing mills for smelting, tanning mills in leather-working, tool-grinding mills, saw mills, water raising mills in mines, and others. According to Langdon's 2004 sample, the number of such industrial mills in England expanded by more than 130 percent between the years 1300-1540 (Langdon, 2004, p. 41 figure 2.8). Their share of the total number of mills increased as well, and represented almost a quarter of the mills by the end of the fifteenth century (Langdon, 2004, pp.43-44). The connection of millwrights' skills to industrial mills must have run primarily through fulling mills: the heaviest machinery used in textile manufacture at that time.

Figure 1. Growth in the number of grain mills vs. industrial mills (1300-1540)



Source: Langdon, 2004, Table 2.2, p.35.

The complementarity between the technologies of the grain grinding mills and the other industrial mills was obviously high, as the latter evolved from the former. The setup of the water control system,

71; Darby, 1973, pp. 90-91).

[10] Darby (1973) provides a map of the cloth industry circa 1500 in Figure 49, p. 224, and for 1720 in Figure77, p. 359.

depending on the type of mill, and the waterwheel were similar, and the inner-workings of the two machines were based on the same mechanical principles.[11] Whether the mills were used for grinding, fulling, or for other industrial uses, their construction was carried out by the same artisans.

These men were much like building contractors today. They negotiated with the client, designed the mill, secured the workmen and materials employed to build it and supervised the construction (Langdon, 2004, p. 252). Millwrights were a major force behind machinery improvement centuries earlier.[12] The "stocks" (hammers used to beat the cloth), the water wheels, and the transmission gear in fulling mills, had traditionally been the preserve of the millwright (Cookson, 1994, p. 19). By the 1780s, however, in some cases artisans calling themselves millwrights sold other textile machinery to the rapidly evolving textile mills (Tann, 1974, p. 82).

The drive toward mechanization in textile manufacturing in the early eighteenth century characterized the entire textile industry. An illustrative example is the construction of the silk-throwing mill by the Lombe brothers in Derby, widely seen as one of the first modern large-scale factories. The elaborated water-powered machinery that drove the equipment was set up around 1720 by the Derbyshire millwright and engineer George Sorocold (1668-1739), who had earlier carried out pioneering work in the construction of water supply works (Chrimes, 2002b, p. 643). Innovations in wool manufacturing included, above all, Kay's flying shuttle (1733), which increased the efficiency of handlooms significantly.

By the eighteenth century, millwrights were hired to build early factories (known, of course as mills). Cookson stresses that cases in which millwrights constructed the equipment from top to bottom were rather unusual and that other skilled artisans were equally likely to have been able to supply the machinery. Moreover, she argues, millwrights were much in demand in the late eighteenth century and might have been too busy to diversify into textile machinery (Cookson, 1994, p. 49). At least as far as the Yorkshire textile machinery is concerned, she doubts any *direct* linkage between millwrights and textile machinery. Where millwrights may have been more important is as technical consultants to entrepreneurs (Tann, 1974, p. 85) or as masters who trained technically competent apprentices who then went off to work in the growing textile industry, calling themselves "engineers" or "machinists."

[11] Most medieval mills worked from cams or wooden projections set into the mill axle, which 'tripped' various devices, such as vertical stamps, horizontal hammers, bellows, or saws (Langdon, 2004, p. 98). The different types of mills were for instance leat mills, wear-and-leat mills, and millpond mills,

[12] Such was the case with the fulling mill, which, according to John Luccok, a woolstapler, who wrote about England's woollen industry in 1805 (Luccok, 1805, p.167): "In the last age, the operation of the fulling mill was very laborious and tedious. A piece of cloth was then submitted to it for thirty successive hours, whereas now it is often rendered sufficiently thick in seven or eight; an instance of (economy in the use of time and labor which augurs well for the interest of the manufacture."

Moreover, millwrights helped construct the early factories:[13] For more historical details on the role of millwrights in engineering the Industrial Revolution, see Appendix H.

The technical changes in the textile industry after 1750 involved radical technological breakthroughs. They marked the spectacular rise of the mechanized cotton industry, still quite marginal as late as 1780. The skills that had accumulated over the centuries in the woolen and especially the worsted industries were found to be useful in cotton even though the technical challenges of mechanization of carding, spinning, weaving and finishing differed between the different branches of the textile industry, with cotton being most similar to worsted. It was quite different for linen because of its different physical characteristics (Cookson, 2018, p. 15). Yet over time the existing skill base in 1750, which had been largely engaged in making equipment such as looms and spinning wheels for the wool, worsted, and linen cottage industries, was sufficiently adaptable and powerful to eventually mechanize every branch of the textile industry, even if the speed of progress was uneven across both products and processes. Cotton was clearly in the lead; in wool spinning and carding technology led weaving and combing. In creating that skill base, many millwrights were key players.

4. Description of the Data

We constructed a cross-sectional dataset of England's government area districts, which contain 325 districts in its 48 counties.[14] The dataset contains historical information about occupations, geographical features, and production factors in 10,201 locations gathered from various sources. The construction of our main variables are described below. Table 1 presents summary statistics for all the variables in our dataset.

4.1 Occupational variables

To approximate the size of various skilled occupational groups as well as of industrial sectors in England during the first half of the eighteenth century (1710-50), we make use of the information include in the *Apprenticeship Stamp Tax registers*.[15] This approximation relies on the assumption that most skilled occupations in Britain required some form of apprenticeship that involved a formal contract. The entries in these registers represent *indentures* (i.e. apprenticeship contracts), whereby masters agreed to instruct their trade for a set term of years, usually seven, in exchange for a sum of

[13] Richard Arkwright relied on two well-known millwrights: Thomas Lowe of Nottingham and John Sutcliffe of Halifax, both of whom were involved in the set-up of a substantial number of early textile factories (Cookson, 2018, p. 37).
[14] We restrict our research to England. There are 326 districts, however, due to missing data in the HYDE project on population in Isles of Scilly, we are left with 325 districts.
[15] The registers are organized in 72 volumes, which are available on a microfilm format at the National Archives, Kew, in London.

money, the *premium*. They begin in 1710, following the introduction of a stamp duty payment on apprenticeship contracts (such that, indentures were void without the stamp), and contain information on the masters' trade, location, and on the premium paid.[16]

The location of masters (where the apprenticeship took place) was matched to locations as they appear in *TownsList*, the most comprehensive database of locations of cities, towns and villages in the United Kingdom.[17] Apprentices were found in 10,201 of the 36,144 English locations and in all the other places their number was set to zero. The number of apprentices in each occupation was then aggregated to the district level and divided by the average population in the district during the same period (1710-50), and are thus, in per capita (per 10,000) terms.[18]

The *Stamp Tax Registers*' main limitations are broadly discussed in Feldman & Van der Beek (2016, p. 99). The main limitation of the registers is that they do not include indentures of pauper apprentices, they do not cover all the eighteenth-century trades. Trades that did not exist in 1563 when the *Statute of Apprentices* was passed (e.g., trades, that appeared towards in the eighteenth century with the transition to the factory system) were not included, nor do the registers include information on unskilled and agricultural laborers. Hence, these categories are not used in this analysis. These limitations, however, do not affect our analysis, as we concentrate on the first half of the eighteenth century, while the significant changes in the occupational distribution of pauper apprentices occurred in the second half of the eighteenth century when some of them were bound in factories. The omission of "modern trades" and of paupers may imply that the occupational classes associated with the factory system are not well represented in our data. This does not affect the occupational category used here as a proxy for mechanical skills, apprentices to wrights. It does however affect the category we use to proxy for the extent of textile production, that is, cloth merchants / entrepreneurs. We therefore use a different occupational group, as described below.

Two of the main variables in our analysis, human capital and early industrialization are measured using this data. To measure the extent of manufacturing in the district, we used the ratio of apprentices to masters we refer to here as *drapers*. This occupational category is composed of 4,359 apprentices to masters in the categories of *drapers* and/or *clothiers*, who had a pivotal role in the organization of cloth manufacturing during the first half of the eighteenth century.[19] As can be observed in Figure

[16] The classification of trades into broader categories was based on Feldman & Van der Beek, 2016.
[17] This dataset is available at www.townslist.co.uk.
[18] Estimates on population size are taken from the HYDE project (Klein Goldewijk et al., 2010; Klein Goldewijk et al., 2011) and specified in tens of thousands throughout the paper. These data are given as a grid cell of 0.5′ × 0.5′ degrees (i.e., approximately 1 km^2).
[19] These contain mostly masters described in the Stamp Tax registers simply as draper (2,510), clothier (1,337), and woollen draper (195), and a few other variations.

2b, our measure captures the geographical distribution of the overall level of activity in cloth manufacturing in England, as it appears in the map produced by Darby (1973).[20]

The clothier was the person responsible for the production and marketing of the cloths. He was involved in all stages of manufacturing; "from the time when the wool was picked, washed, carded, and spun, until it was woven, fulled, and 'perfected' into cloth" (Lipson, 1921, p.41). He provided the necessary capital, "put-out" the raw or semi-processed materials to domestic spinners, weavers, fullers, and other cloth-workers, and brought the finished cloth to Blackwell Hall, and other town markets and fairs, to be displayed, and sold to drapers, who supplied the goods to tailors and shops (Campbell, 1747).[21]

The functions of the clothier varied with the scale of his operation. In large scale manufacturing, as in West England, there was more specialization. In this case the clothier employed a large number of spinners, weavers, etc. and would not engage in the processes himself, "but confined his attention to buying the raw material, employing people to work it up, and selling the cloth" (Heaton, 1920, p. 92). Before the first half of the eighteenth century, the Northern woollen industry was largely in the hands of small independent clothiers. They were themselves cloth makers on a small scale, usually weavers or cloth finishers, who bought the wool themselves, and carried out through most of the processes together with their family and a small number of employees.

The extensive changes that took place in the organization of textile manufacturing in the second half of the eighteenth century make this measure of the level of activity in textile manufacturing (i.e. the number of *drapers* and *clothiers*) inconsistent for this period. Thus, in the second half of the eighteenth century the average clothier and draper firm was responsible for much more output than before.

The organizational changes in textile manufacturing in Northern England during the second half of the eighteenth century were mainly a result of the remarkable expansion in the scale of woolen manufacturing in Yorkshire and Lancashire, the fast growth of worsted and cotton cloth manufacturing, and the shift to the factory system. These changes were reflected in an increase in the number of big Northern clothiers. The worsted masters were a small group who controlled considerable capital and were very different from the typical small-scale Northern clothiers in the woollen trade (Clapham, p. 517). With growth of mechanization, mill-owners in the factory system acquired capital as merchants and left no more place for clothiers (Clapham p. 163-4). Thus, in the

[20] Our measures also seem correlated with the distribution of textile workers in England during the 15th-16th centuries in Sugden et al. (2018) as it appears in Figure 3, p. 40.

[21] Blackwell Hall in London, was the main center for wool and cloth trade in England from medieval times until the 19th century.

second half of the eighteenth century the number of clothiers declined, while woolen output was much greater. We therefore use other proxies, such as, the number of *weavers* in analysis that requires comparable measures of output in the two periods.[22]

To proxy for the districts' level of human capital, we use the number of apprentices to masters we refer to as *wrights* (Figures 2a presents their distribution in 1710-50). Our definition of wrights consists mainly of apprentices to millwrights, wheelwrights, or simply, "wrights." Millwrights, who were fewer, were engaged in the heavy mechanisms of the mill, the fulling stocks, the water wheels and the transition gears. Wheelwrights, whose skills were ranked below those of millwrights, were nevertheless highly involved in the making of textile machinery, e.g. spinning wheels and other machines (Cookson, 2018, p. 30). They also appear as part of the trades connected with cotton manufacture in Lancashire, in the Population returns for 1831, (Baines, 1835, p. 424).[23]

Figure 2. The spatial distribution of apprentices (1710-50)

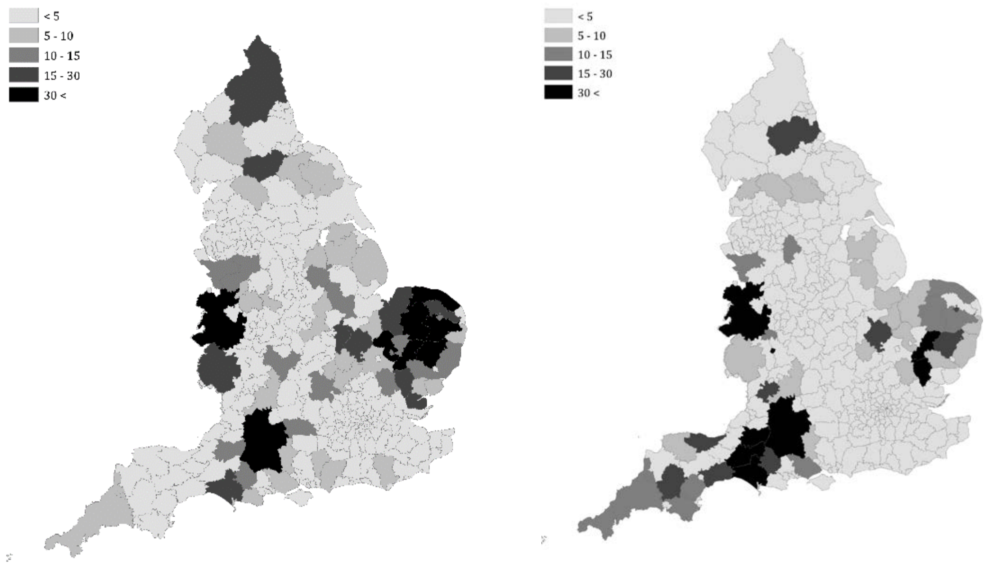


Figure 2a. Apprentices to *wrights (p/c)* Figure 2b. Apprentices to *drapers (p/c)*

Source: Stamp Tax Rgisters (see text)

In the second half of the eighteenth-century wheelwrights took out a similar number of patents as millwrights did, and for a similar category of inventions in machinery. Jedediah Strutt, for example came from a farming family and was apprenticed to a wheelwright in 1740. He and his brother-in-

[22] Most master weavers are referred to in the Stamp Tax registers, simply as weaver ((9,072 observations), however, in the cases of other types of textiles, rather than woolen cloths (i.e. linen, cotton and, mainly, worsted textiles), they are sometimes referred to as linen weaver (760 observations), cotton weaver (321 observations), or worsted weaver (2,146 observations).
[23] Wheelwrights appear under carpenters while millwrights are a category in itself.

law, William Woollat, were granted s in 1758-1759 for the Derby Rib machine, their "new invented engine or machine, on which is fixed a set of turning needles, which engine is fixed to a stocking frame for the making of turned ribbed stockings, pieces & other goods usually manufactured upon stocking frames". Another example is James Summers, a wheelwright from Gloucester, who was granted a patent in 1791 for "his new invented method for constructing a steam engine, by which maybe worked mills for grinding, rolling, cutting, turning …" as well as others (Woodcroft, 1854, p. 133, 135 and 136).

For the iron-making industry, which also made wide use of water-powered machinery in the Middle Ages, we used the number of apprentices to *smiths* (1,049 apprentices) and to *blacksmiths* (7,328 apprentices).[24] Interestingly, their spatial distribution is very similar to the one of the textile industry, presented in Figures 2a and 2b.

4.2 Domesday watermills

This study makes use of the valuable economic information enclosed in Domesday Book, a land survey from 1086 commissioned by William the Conqueror. The survey documented all the landholdings and resources in England: plough teams including arable land, woodland, meadows, farmers (different types of legal statutes), and mills (about 5600 mills in more than 3000 locations). We use this source mainly to gather evidence on the location of watermills, which were used for grain grinding at the time.

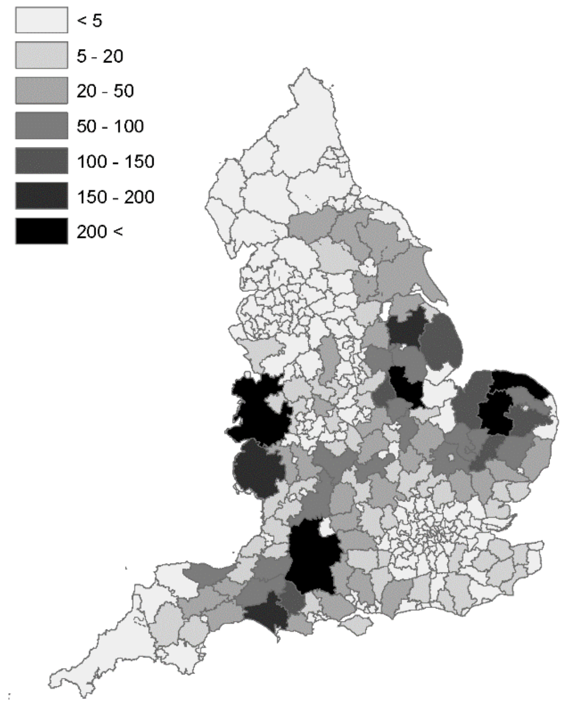
Domesday Book covers England with the exception of the cities of London, Winchester, Bristol and Tamworth and the coverage of the northwest is limited: the counties of Durham and Northumberland are omitted, and the coverage of Cumberland, Westmorland and Lancashire is partial (The omitted areas are represented by the striped areas in Figure 3). Thus, using the Domesday mills in our analysis limits us to 298 districts. The survey simply refers to water powered mills as 'mills', most of which were used for grain grinding.

A systematic analysis of the determinants of their location in 1086 shows that it was highly correlated with arable land and population density in 1086, the availability of river streams, and the potential for wheat growing (see below). Possible institutional variables, such as relative royal holdings in the district (King's "Vill Share") or the relative share of arable land held by lords, have no significant effect. The Share of ecclesiastical holdings (Ecclesiastical Vill Share) seems at first blush to have had

[24] While a smith is generally term for a metal worker, which comprises of both blacksmiths, who work iron with forge and hammer, and whitesmiths, who do the finishing and are usually specialized in the making of different iron goods. Our category of smiths contains mainly masters who are referred to as simply "smiths" (1,007).

a significant effect on the number of mills in the districts. However, controlling for the geographical characteristics of the district, none of these institutional variables are significant (see Appendix Table A2 for details). In fact, in his extensive book about the ecclesiastical role in milling, Adam Lucas finds no evidence to support the claim that the wealthy episcopal houses were proactive and entrepreneurial mill investors. It suggests that rather than having built most of their own mills in this period, most church-owned mills were acquired through grants or purchases from kings, magnates, and knights (Lucas, 2014).

Figure 3. The spatial distribution of Domesday Mills p/c (1086)



Source: Based on the information in Palmer (2010) (see text)

4.3 Geographical Characteristics

Wheat suitability: The estimates for potential wheat yield (measured in tons, per hectare, per year), for each of $5' \times 5'$ degrees (i.e., about 100 square km) cell are provided by the Global-Agro-Ecological Zones of the Food and Agriculture Organization (FAO). These measures are based on agro-climatic estimates, under low levels of inputs and rain-fed agriculture, capturing conditions that prevailed in early stages of development.[25] We calculate the average potential yield in each district as a measure

[25] GAEZ provides estimates for crop yield based on three alternative levels of inputs – high, medium, and low - and two possible sources of water supply – rain-fed and irrigation. Moreover, for each input-water source category, it provides two separate estimates for crop yield, based on agro-climatic conditions, that are arguably unaffected by human intervention, and agro-ecological constraints, that could potentially reflect human intervention.

of the district's wheat suitability. Furthermore, the FAO classes of wheat suitability are given in a scale from 1 (highly suitable) to 8. We define a district as suitable for wheat cultivation if the mean wheat suitability class in the district is lower than or equal to 5 (which is the median of this variable, its mean is 5.13).

Table 1. Summary Statistics

Variable	Mean	Std. Dev.	Min.	Max.	N
Watermills (per 10000 people)	189.225	483.818	0	4126.008	298
Wrights (per 10000 people)	37.595	91.205	0	859.265	325
Drapers (per 10000 people)	28.093	75.341	0	582.637	325
Weavers (per 10000 people	94.412	406.236	0	6455.522	325
Smiths (per 10000 people)	18.533	50.066	0	481.666	325
Blacksmiths (per 10000 people)	53.361	120.932	0	935.456	325
Area (100000 km^2)	0.409	0.560	0.003	5.078	325
Latitude	52.279	1.123	50.357	55.231	325
Ruggedness (mean)	3.355	2.133	0	11.288	379
Elevation (mean)	0.836	0.644	0.016	3.563	332
Agricultural Suitability	0.699	0.246	0.032	0.981	377
Grass Suitability (mean)	7.643	0.704	4.625	9.947	379
Total River Length (100 km)	0.798	1.099	0	10.418	325
Precipitation (mean)	0.592	0.136	0.408	1.176	325
Temperature (mean)	9.700	0.691	7.547	11.104	325
Dist. to Nearest Harbor (100 km)	0.504	0.371	0	1.629	325
Dist. from London (100 km)	0.141	0.105	0	0.406	325
Dist. to Nearest Navigable River (100 km)	0.009	0.098	0	1.54	325
Dist. to Nearest Navigable River	0.009	0.098	0	1.54	325
Population, 1710-1759 mean (100,000)	0.77	1.296	0.011	6.749	325
Population, 1750-1800 mean (100,000)	1.019	1.727	0.014	8,726	325
Worsted weavers, 1710-1750 (per 10000 people)	23.148	244.241	0	4197.68	325
Worsted weavers, 1750-1800 (per 100000 people)	36.534	335.382	0	5639.814	325
Woollen weavers, 1710-1750 (per 10000 people)	64.781	174.718	0	2257.843	325
Woollen weavers, 1750-1800 (per 100000 people)	71.108	239.986	0	2478.851	325
Textile Usage of Engines	0.295	1.89	0	28	325
Carboniferous Strata	0.342	0.475	0	1	325
Non-fulling district	0.138	0.346	0	1	325
Lords' Share of Arable Land	0.238	0.114	0	0.81	298
Ecclesiastical's Vill Share	0.14	0.161	0	1	325
King's Vill Share	0.095	0.156	0	1	298

River suitability: To provide a measure for the suitability of a river for water mill construction in the middle ages, we calculate the length of rivers with moderate levels of ruggedness in each district. Since topographic variation is highly correlated with many patterns in catchment-related hydrological responses driving the flow direction and water runoff velocity, we use the Terrain Ruggedness Index (TRI) for our purpose. TRI is a quantitative measurement of terrain heterogeneity devised by Riley et al. (1999) to express the amount of elevation difference between adjacent cells of a digital elevation grid.[26] Our TRI value calculation was based on data provided by HydroSHEDS at 15 arc-second (approximately 500 meters around the equator) resolution.[27] We sum the total length of rivers that have adequate ruggedness levels for constructing grinding mills given the technology of the time. Water flows that were too weak and slow required higher setup costs (for instance through the need of constructing leats), whereas flows that were too fast and strong would cause much faster wear and tear on the mill mechanism.[28]

Additional Confounding Factors: We control for a wide range of potentially confounding geographic and economic factors, which may have affected the location of the textile industry. Thus, the locational patterns of water mills were determined by topography and other geographical variables. By using these controls, we cleanse them as much as possible of geographical determinants, so we are left with other channels. Because the micro-climate of any particular place is influenced by a host of interacting factors, we control in our analysis for absolute latitude, mean elevation and ruggedness (also from HydroSHEDS), district area, total length of rivers, agricultural suitability (based on data from Ramankutty et al (2001)), the district's mean level of suitability for pasture cultivation, mean precipitation and temperature, as well as the district's proximity to London, to major harbors in eighteenth century England, to a historical Roman road, and to a navigable river.

5. Empirical Analysis

Our analysis is divided into two parts. Section 5.1 concentrates on examining whether there was persistence between early medieval flour mills and the distribution of wrights in the eighteenth century through capital-skill complementarity. Section 5.2 provides evidence for the role that played by wrights in the process of early industrialization.

---

[26] TRI is calculated as the difference in elevation values from a center cell and the eight cells immediately surrounding it. Then it squares each of the eight elevation difference values to make them all positive and averages the squares. The terrain ruggedness index is then derived by taking the square root of this average.

[27] Elevations are from USGC DEM (US Geological Survey, Digital Elevation Model) - a global elevation data set developed through a collaborative international effort led by staff at the US Geological Survey's Center for Earth Resources Observation and Science (EROS). Data provided by HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales).

[28] Riley et al propose the following breakdown for the values obtained for the index where: 0-80 m is considered to represent a level terrain surface; 81-116 m represents nearly level surface; 117-161 m a slightly rugged surface; 162-239 m an intermediately rugged surface; 240-497 m a moderately rugged; 498-958 m a highly rugged; and 959-4367 m an extremely rugged surface. In our analysis we used ruggedness levels between 200-300 meters, however, Appendix D shows that our results are not sensitive to these specific values, neither for the ruggedness levels, nor the share of area highly suitable for wheat cultivation.

5.1 The persistence of skills

The benchmark regression in this part of the analysis is as follows:

$$(1) \qquad w_i = \beta mills_i + X'\gamma + \varepsilon_i$$

where w_i is the ratio of apprentices to wrights per capita in district i, $Mills_i$ is the number of Domesday mills per capita, the matrix X contains our control variables (i.e. a set of geographical, institutional and economic characteristics of the district), and ε_i is the district-specific error term. Our coefficient of interest, β, describes the correlation of early eighteenth-century wrights and early medieval grinding mills. To mitigate any concern of dependence between district within the same county are not independent, in all the regressions, all observations are clustered at the county level (thus correcting for any dependency at the county level).

5.1.1 Identification Strategy

Since the watermills in the analysis were constructed (at least) 600 years before the existence of the wright apprentices on the left-hand side of the regression, there is no concern for simultaneity between the two. We also use a wide set of control variables in order to isolate the effect of mills on spatial persistence. The relationship may however still be spurious due to the possibility of omitted unobservable variables (institutional, geographical, economic and human characteristics). The size of the population does not pose a problem: Table A1 shows that the correlation between the population of 1086 and that of 1710-1750 is weakly negatively correlated. Hence, even if there were some conditions that were conducive to population growth in early middle ages, they did not affect population size six hundred years later. We also normalize both the number of Domesday mills and the number of wrights to per capita terms, based on the mean district population in the years 1710-1750.[29] Yet to exclude the possibility that the location of Domesday mills was biased by some omitted unobservable characteristic, we construct a geographical instrument that captures the suitability of a district for the construction of grain grinding watermills.

5.1.2 *Results*

Table 2 presents the results of OLS regressions between the number of Domesday mills per capita and the number of apprentices to wrights in 1710-1750 (per ten thousand).

[29] We also control for the district's population size with two controls; the mean population size in 1710-1750, as calculated from the HYDE project, and the land suitability for agriculture, as calculated from Ramankutty et al. (2001).

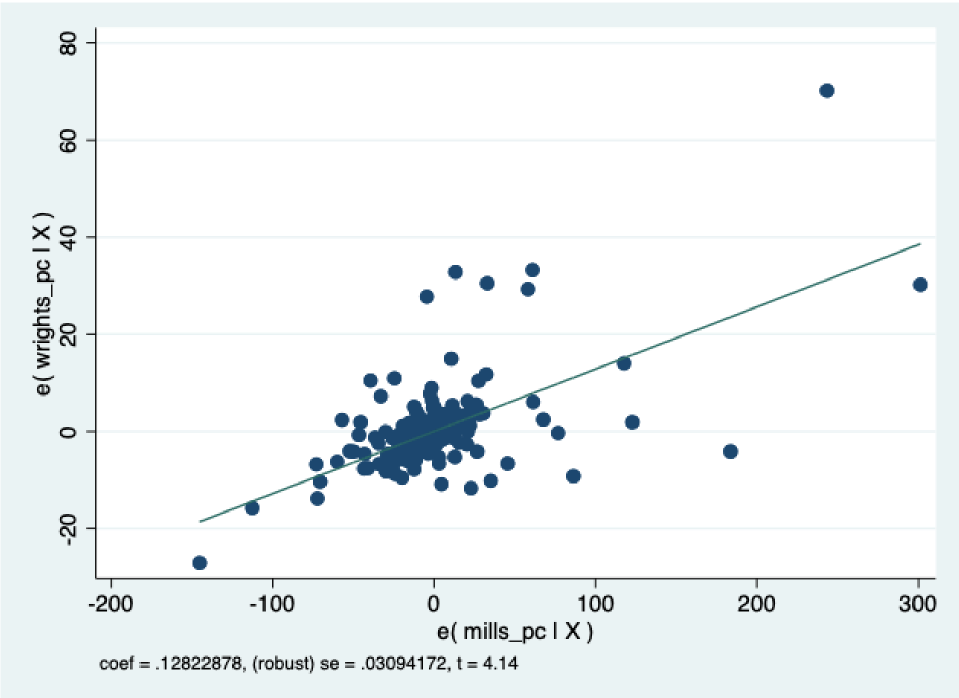
Table 2. Domesday Mills and the Number of Apprentices to Wrights: OLS

	No. of Wright Apprentices per Capita				
	(1)	(2)	(3)	(4)	(5)
Watermills (per capita)	0.15***	0.13***	0.13***	0.13***	0.12***
	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)
Area		0.00	0.00	0.00	0.00*
		(0.00)	(0.00)	(0.00)	(0.00)
Latitude		0.17	-0.21	-0.19	2.93*
		(0.49)	(0.57)	(0.90)	(1.54)
Ruggedness (mean)		-0.54	-0.07	-0.02	0.23
		(0.40)	(0.41)	(0.37)	(0.43)
Elevation (mean)		-0.00	-0.01	-0.01	-0.01
		(0.01)	(0.01)	(0.02)	(0.02)
Agricultural Suitability			-3.17	-3.76	-4.98*
			(2.25)	(2.57)	(2.78)
Wheat suitability			1.63**	1.54	1.23
			(0.77)	(0.95)	(0.95)
Grass Suitability (mean)			-0.02*	-0.01	0.01
			(0.01)	(0.01)	(0.02)
Precipitation (mean)				-0.04	0.01
				(0.05)	(0.06)
Temperature (mean)				-0.30	1.45
				(1.48)	(2.17)
Population, mean (thousand)					-0.04
					(0.03)
Dist. to Nearest Harbor					0.04**
					(0.02)
Dist. from London					-0.03***
					(0.01)
Dist to Nearest Roman Road					0.00
					(0.02)
Distance to Nearest Navigable River					0.41
					(1.29)
Adjusted-R^2	0.57	0.58	0.59	0.58	0.59
Observations	298	298	298	298	298

Notes: This table establishes the positive and economically and statistically significant association of the number of mills per capita in a district, as documented in the Domesday Book (1086), and the number of wright apprentices per capita for the period 1710-1750, controlling for the area of the district, its distance from London, major eighteenth century harbors, navigable rivers and a historical Roman road, as well as geographical controls such as the district latitude, mean elevation, ruggedness, temperature and precipitation. Specifically, the analysis suggests that an increase in the number of one mill per capita is associated with an increase of approximately 0.12 wright apprentice per capita in the district. All observations are clustered at the historical county level. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

As established in column (1), the unconditional correlation between the two is positive and economically and statistically significant at the 1% level, suggesting that one more mill per capita in a district in 1086 was associated with an increase of 0.15 wright apprentices in the same district in the early eighteenth century. Nevertheless, this could reflect no more than the simple fact that geographical suitability to waterpower determined the location of water mills in the 11th century and their location in the 18th century, and that millwright apprentices located where the mills were. We therefore control for a full array of geographic characteristics. These characteristics are: latitude of the district's centroid, district area, mean level of ruggedness and elevation. As column (2) shows, when all these factors are accounted for, the estimated relationship declines only slightly. In column (3) we add the measures of wheat suitability, suitability for pasture, river length, and agricultural suitability to control for districts' land fertility as a possible channel for more intensive economic activity (e.g. markets, trade, etc.). Even after controlling for all of these potential effects as well as other climatic characteristics (mean precipitation and temperature), the estimated relation remains stable. The resulting analysis suggests that after controlling for these geographical and topographical effects, an increase of one mill per capita in a district in 1086 is associated with an increase of 0.13 wright apprentices per capita in the eighteenth century.

Figure 4. Partial correlation between wrights and Domesday mills



Source: Specification as in table 2 column (5). See text.

Furthermore, the estimated relation may have been affected by non-topographical factors. Thus, in column (5) we control also for several potential channels through which trade may have affected the number of wrights: the proximity to London, the proximity to major harbors, the proximity to a navigable river and to a historical Roman road. We also control for the total district's population size. As the table shows, the estimated relationship remains stable after controlling for these effects and is statistically significant at the 1% level, suggesting that one additional mill per 10,000 in a district is associated with an increase of 0.13 wright apprentices. Figure 4 depicts the partial correlation between Domesday mills per capita and wright apprentices per capita as captured in column (5). It shows that our results do not rely on any outlier.

To overcome the possibility that the location of mills in 1086 was endogenous to unobserved features that affected the location of wrights in the eighteenth century, we employ an instrumental variables strategy, which captures the exogenous variation in the suitability of a district for the construction of *grinding mills* in the early middle ages, reported in Table 3. The IV consists of the length of rivers in the district that have moderate levels of ruggedness, interacted with districts that are highly suitable for wheat cultivation. In particular, in the results presented above, we assume that the adequate levels of terrain ruggedness are between 2 and 6 (which is a range of gentle to moderate degrees of undulation), and a district is considered highly suitable for wheat growing if the mean wheat suitability "category" of the district is lower than, or equal to 5 (the lower, the more suitable). We take advantage of the fact that the construction of grinding mills in the early middle ages, in contrast with later industrial mills, depended on a high potential for wheat growing and the availability of suitable hydraulic conditions. Our instrument was therefore constructed to capture the suitability of a district for the construction of grinding watermills.

In other words, the identifying logic here is that late 11^{th} century mills, which were largely used for grinding cereals would be set up in locations that had a terrain suitable for water mills on the supply side, and grew a lot of wheat on the demand side (see section 5.1.1 above). Watermills were costly in terms of the fixed cost of the construction and heavy annual maintenance and repairs costs. To cover these expenses, large amounts of wheat had to be brought to the mill to be ground into flour. Since grain was costly to transport over long distances during the early Middle Ages, and flour could not be preserved for long, grains were brought to the mill on a daily basis for grinding. Mills were therefore mostly constructed in the countryside in the vicinity of wheat fields, and not necessarily close to larger concentrations of population. In addition, as noted, their construction required reasonably adequate river streams. Whether Domesday mills had horizontal, undershot or overshot wheels was not recorded, nevertheless the vertical ones were most probably undershot wheels since overshot ones were much less common until the early sixteenth century (Reynolds, 1983, p. 124;

Munro, 2002, p. 233). In any case, the inefficient wooden medieval mills worked best in slow and steady water flows (Smil, 2017, p. 149-52). This requirement often required the constructions of weirs and dams to increase water retention and regulate its supply.[30]

Since industrial mills were not used for wheat grinding, the only way that the instrument affects the location of eighteenth-century millwright apprentices, controlling for all other geographic characteristics, is through the persistent effect of Domesday mills, so that the IV meets the exclusion restriction. Our IV approach is constructed in a way that will identify the construction of older mills, rather than more modern and industrial mills, leading us to identify the persistence of mill location over longer periods of time.

Table 3 presents the results of our IV estimation (in columns (2), (4) and (6)).[31] For ease of comparison, they are presented along with our OLS estimations. As can be seen in column (2), using our instrument increases the coefficient only slightly (comparing to the OLS estimation). This suggests that the unobservables do not seriously confound the estimation. Furthermore, the first stage F-statistic equals 19.90, assuring that the instrument is strong enough. These results hardly change when we add the same controls as in Table 2. As can be seen in columns (4) and (6), once these controls are added, an increase of one watermill (per capita) is associated with an increase of 0.15 wright apprentices (per capita) and the first stage F statistic remains strong: 16.50 and 17.61, respectively. We conclude from these results that the data are consistent with strong persistence in the location of what Gimpel (1976) has called the “Medieval machine” and that the mechanism was the high level of artisanal competence that they required. The question we now want to tackle is: did it matter for industrialization?

5.2 Capital-Skill Complementarity and Early Industrialization

The results in section 5.1 have shown that early water-powered machinery led to the emergence of a large cadre of millwrights. We now turn to the hypothesis that wrights, once in place, helped determine the location of the textile and metal industries, which, while independent of flour mills, also used water-powered machinery. The analysis presented in this section will show that the location of Domesday mills helped determine the location of the textile and iron making industries in the mid eighteenth century. We show that regions that underwent industrial progress relatively early in the

[30] The water bypass of overshot mill, powered largely by gravitational potential energy, usually consisted of a weir across a stream and a channel diverting the flow to the wheel to regulate water supply. Undershot mills could be placed directly in a stream; however, it increased the chances of flood damages and was less efficient than creating the base below the waterwheel rim into a closely suitable breast at the bottom center to increase water retention. (Smil, 2017, p. 149-52).

[31] Appendix Table G.1 presents the coefficients of the full specification. Appendix Table E.4 (panel a) presents the first stage estimation of columns (2), (4) and (6), and Appendix Table E.4 (panel b) presents the reduced form of these columns.

Industrial Revolution can be predicted by the location of Domesday mills. To do so, we estimate the following equation:

$$(2) \qquad Ind_i = \pi w_i + Z'\delta + \mu_i$$

Table 3. Domesday Mills and the Number of Apprentices to Wrights: IV

	No. of Wright Apprentices per capita					
	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)
Watermills (per capita)	0.15***	0.16***	0.13***	0.16***	0.12***	0.15***
	(0.02)	(0.04)	(0.03)	(0.04)	(0.03)	(0.04)
River Suitability		22.80		161.68		167.46
		(36.50)		(119.09)		(113.43)
Wheat suitability		11.79*		11.87		9.34
		(7.04)		(8.68)		(8.23)
Main geographic controls	No	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	Yes	Yes	Yes	Yes
Other geographic controls	No	No	No	No	Yes	Yes
First-stage F-statistic		19.90		16.50		17.61
Adjusted-R^2	0.57	0.57	0.58	0.59	0.59	0.59
Observations	298	298	298	298	298	298

Notes: This table establishes the statistically and economically positive effect of the number of Domesday mills in a district on the number of wright apprentices, controlling for the district's population, main geographic controls (area, latitude mean ruggedness, mean elevation), agricultural controls (agricultural suitability, suitability to grow pasture and wheat), climatic controls (mean precipitation and temperature), and other geographical controls (Distance from London, main eighteenth century harbors, a historical Roman road and a navigable river). To mitigate endogeneity problems, the analysis uses the number of geographical suitability for establishing grain griding mills as an IV for the number of Domesday mills. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

where Ind_i is a proxy for the extent of production of an industry *per capita* in district *i*, and w_i as before is the relative number of millwright apprentices. These industries include textiles (proxied by the number of apprentices to cloth merchants, clothiers and weavers) and iron making (proxied by the number of apprentices to smiths and blacksmiths). Z is a matrix containing our control variables, and finally μ_i is the error term. To address any concern that districts from the same county are not independent, in all the regressions, all observations are clustered at the county level, thus correcting for any dependency at the county level.

5.2.1.1 Empirical strategy

Equation (2) cannot be estimated consistently by OLS due to reverse causality. Wrights specialized in all types of machinery with similar mechanics as watermills. Their numbers in the eighteenth century may therefore have been a response to the expansion in textile production, and not just its cause. The model may also produce spurious correlations due to omitted variables (above all geographical, but also institutional, economic, and human characteristics). Thus we estimate equation (1), but instead of estimating the effect of *existing* mills on the number of wright apprentices per capita, we estimate the effect of mills in 1086 on the number of apprentices in the textile industry (drapers and clothiers, as well as weavers) and iron-making industry (smith and blacksmith apprentices). The textile (woolen and worsted) and iron industries were already slowly transforming in the eighteenth century, and the existence of millwrights facilitated that progress. We estimate equation (1) with the same IV technique, using a handful of other occupations that were not mechanized, and show that indeed they cannot be predicted by the number of Domesday mills.

Our main contention is that the availability of wrights (but not mills as such) in a district had a positive effect on the emergence of more advanced industrial techniques. The way we see the industrial history of England is that technology and skills affected each other's evolution over many centuries. Mill location was determined by initial geographical conditions that favored the specific technology of watermills, but skills were the channel through which new techniques spilled over into other industries. To lend credence on this hypothesis, we perform two different exercises: First, we run a mediation test, which analyzes how much of the direct effect of mills on the emergence of different industries was mediated through wrights. This analysis is based on a procedure proposed by Imai et al., (2010a, 2010b and 2011). We show that wrights mediated 39%-69% of the effect of the location of mills on the analyzed industries (depending on the industry). Secondly, we show that the evolution of one key textile industry, worsteds, is perfectly consistent with our view about the importance of skilled mechanics trained by and as millwrights. Worsteds had little use for water before 1750, and indeed were spread all over England. After 1750, though, they experienced a rapid mechanization, and as a result relocated to districts where mills were abundant.

5.2.2 Results

Table 4 presents the simple association between the textile industry, as proxied by the number of apprentices to drapers and clothiers per capita in a district, and the number of apprentices to wrights in the same district.[32] Column (1) presents the unconditional correlation between the two. It shows a statistically and economically significant correlation between the two, as an increase of one wright apprentice per capita is associated with an increase of 0.43 draper apprentices per capita, and the coefficient is statistically significant at the 1% level. Adding all the controls does not affect the result: as can be seen in column (5), the coefficient remains stable and highly significant at the 1% level. To overcome selection bias problems, we restrict our analysis in column (6) to the districts covered in Domesday Book (so the sample size declines by c. 9%), but the strong association is hardly affected: the coefficient declines to 0.37, and remains significant at the 1% level.

Table 4. Apprentices to Wrights and Textile Manufacturing (Drapers)

	No. of Draper Apprentices per Capita					
	All Sample					DB Sample
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	0.43***	0.35***	0.36***	0.36***	0.41***	0.37***
	(0.14)	(0.12)	(0.12)	(0.13)	(0.13)	(0.13)
Geographical controls	No	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes
Other economic controlas	No	No	No	No	Yes	Yes
Adjusted-R^2	0.27	0.35	0.35	0.35	0.41	0.44
Observations	325	325	325	325	325	298

Notes: This table establishes the positive and economically and statistically significant association of the number of wrights per capita in a district, and the number of draper apprentices per capita for the period 1710-1750, controlling for the area of the district, its distance from London, major eighteenth century harbors, navigable rivers and a historical Roman road, as well as geographical controls such as the district latitude, mean elevation, ruggedness, temperature and precipitation. Specifically, the analysis suggests that an increase in the number of one wright per capita is associated with an increase of approximately 0.41 draper apprentice per capita in the district. All observations are clustered at the historical county level. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

The results in Table 4 suggest that indeed wrights played a role in early industrialization. One concern here would be possible unobserved topographical characteristics, which might create a spurious effect as they are naturally persistent. Table 5 presents the effect of Domesday mills on industrialization in early eighteenth century, instrumenting the Domesday mills by the geographical instrument used above in Table 3.[33] As in Table 3, the suitability to construct medieval watermills, which we capture by the interaction between wheat suitability and the adequate river water flows, allows us to overcome

[32] Appendix Table G.3 replicates Table 4 displaying the coefficients of the full specification. Appendix Tables F.1 -F.3 replicate Table 4, but for weaver apprentices, smith apprentices and blacksmith apprentices.
[33] Appendix Table G.2 replicates this table displaying all coefficients of the full specification.

Table 5. Domesday Mills and the Numbers of Apprentices in Mechanized *vs*. Non-Mechanized Industries

	No. of Apprentices per capita									
	Draper	Weaver	Smith	Blacksmith	Joiner	Trader	Butcher	Attorney	Surgeon	Apothecary
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Watermills (per capita)	0.12***	0.19**	0.09**	0.12***	0.15	0.00	0.28	0.15	0.06	0.13
	(0.04)	(0.08)	(0.04)	(0.05)	(0.11)	(0.04)	(0.19)	(0.13)	(0.04)	(0.11)
Wheat suitability	4.07	71.45	4.43	4.43	4.25	40.87	-14.37	-2.82	-6.60*	-4.17
	(6.87)	(48.12)	(3.61)	(5.69)	(9.99)	(39.22)	(16.57)	(9.67)	(3.52)	(7.95)
River Suitability	131.51	792.54*	18.16	240.90**	211.48*	207.52	-35.99	364.38***	116.61**	183.07*
	(107.34)	(452.23)	(47.01)	(106.57)	(109.17)	(193.02)	(206.92)	(123.57)	(58.26)	(105.74)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	17.61	17.61	17.61	17.61	17.61	17.61	17.61	17.61	17.61	17.61
Adjusted-R^2	0.30	0.15	0.55	0.62	0.40	0.03	0.61	0.51	0.52	0.34
Observations	298	298	298	298	298	298	298	298	298	298

Notes: This table establishes that the number of wright apprentices mainly affects the number of draper, clothier, smith and blacksmith apprentices, rather than other occupation apprentices. It does so by instrumenting the number of wright apprentices per capita by the geographical IV described above, and controlling for all geographic, climatic, agricultural and economic characteristics in all previous tables. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

endogeneity problems. This is because the wrights that resided near the mills predicted by this instrument were in these districts not because of the existing textile industries there, but rather due to the suitability of the site to construct flour mills six hundred years before. In columns (1)-(4), we present the second-stage regressions showing the effect of the number of Domesday mills in a district on the number of apprentices in the textile industry (drapers and clothiers (column (1) and weavers (in column (2)), and on the iron making industry (proxied by the number of smith and blacksmith apprentices). These industries were among the first to mechanize during the Industrial Revolution, and their dependence on high-skill labor was especially prominent. Note that the effect of the number of mills in 1086 is positive and economically and statistically significant for both industries, suggesting that indeed the location of the Domesday mills had an effect on early industrialization more than six hundred years after the Domesday survey was conducted. The concern that the correlation may be spurious because textiles and iron required water for their production process is addressed by the geographical controls included.

Furthermore, river suitability and wheat suitability were orthogonal to one another as shown in Appendix Fig. E1. This implies that industries that required water could have been located also in districts that were not suitable for wheat cultivation. In this case, our IV should not predict their location. If, on the other hand, we find that our IV predicts where they resided, they must have done so because these regions provided them something else other than rivers and water.

One concern with these results is that the location of the mills could have affected all industries, either because these locations were more attractive for living in them or because other industries could use the same geographical characteristics and thus grow in areas where mills were built during the Middle Ages. If population was denser in these districts, and there were economies of scale or agglomeration in milling and manufacturing, this could produce a spurious effect. However, as Appendix Table A.1 shows, even if the mills were built in more populated areas during Middle Ages, these districts are on average *less* populated in the eighteenth century.

Most telling, the effects of millwrights can be discerned only for more dynamic industries that required high-skilled artisans and engineers. In columns (5) – (10) of Table 5 we present placebo tests that show that the Domesday mills do not have any effect on occupations that were not mechanized at this time. These occupations include similar occupations to wrights (such as the joiners), other rural occupations (such as butchers), other traders not in the textile industry (column (6)), or occupations which should reside in more heavily populated areas (attorneys, surgeons and apothecaries). We conclude from this table that the mills generated industrial clusters.

Table 6. Mediation Analysis: Apprentices to Wrights *vs*. Domesday Mills

	No. of Apprentices per Capita											
	Draper			Weaver			Smiths			Blackmiths		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Wrights (per capita)	0.37***		0.32**	1.44***		0.89***	0.31***		0.23***	0.91***		0.70***
	(0.13)		(0.13)	(0.36)		(0.28)	(0.05)		(0.08)	(0.10)		(0.17)
Watermills (per capita)		0.06**	0.02		0.29***	0.18***		0.06***	0.03**		0.16***	0.07**
		(0.03)	(0.03)		(0.07)	(0.06)		(0.01)	(0.01)		(0.03)	(0.03)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Percentage of Mediation			0.69			0.37			0.50			0.54
Adjusted-R^2	0.44	0.39	0.45	0.15	0.15	0.16	0.65	0.60	0.68	0.70	0.61	0.73
Observations	298	298	298	298	298	298	298	298	298	298	298	298

Notes: This Table shows the results of a mediation analysis, based on Imai et al., (2010a, 2010b, 2011). It shows that the direct effect of mills on drapers (69%), clothiers (51%), smiths (49%) and blacksmiths (56%), is mainly mediated via wrights. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

5.2.3 Geography and Skills compared: Horse Race and Mediation Analysis

In Table 6 we perform a horse race between mills and wrights as explanatory variable for each occupation: drapers (columns (1)-(3)), clothiers (columns (4)-(6)), smiths (columns (7)-(9)), and blacksmiths (columns (10)-(12)). In each triplet, the first column displays the results of a regression in which only wrights are used as explanatory variable. The second column of each triplet displays the results of a regression in which only mills are used as explanatory variables. Finally, the third column of each triplet represents the regression in which both are used as explanatory variables. As can be seen in the table, once both wrights and mills are explanatory variables (columns (3), (6), (9) and (12)), the coefficient of the mills drops significantly, losing 47%-67% of its size. Moreover, in the case of drapers, it also loses its significance. The coefficient of wrights on the other hand, loses much less (13%-25%). More formally, we execute a mediation analysis, which measures how much of the total effect of mills on each occupation is mediated through the wrights.[34] The results of the mediation analysis are presented at the bottom of Table 6. Interestingly, it shows that the wrights per capita mediate between 49% and 69% of the effect of mills per capita on the number of apprentices per capita in each occupation.[35]

5.2.4. The location choice of worsted manufacturing

Worsted manufacturing arrived in Yorkshire from East Anglia in the seventeenth century and remained relatively unimportant in this region until nearly 1750, when it began to grow rapidly. There are a number of differences between the manufacturing of woolens and worsteds, among them the type of wool they used, the process the wool went through before being spun, and the nature of the yarn. For our purposes, the important difference is that worsteds did not go through the process of fulling, the most heavily mechanized process in the textile industry until the second half of the eighteenth century. This implies that while the location of wool cloth manufacturing could have been determined by the "mill aspect" of the existence of medieval mills for the construction of fulling mills, the location of worsted manufacturing was not, at least not until the middle of the eighteenth century.

In the second half of the century, when spinning machinery was introduced, the differences between

[34] The mediation analysis is based on Imai et al. (2010a, 2010b, 2011). The idea behind mediation analysis is to estimate how much of the total effect mills have on each occupation is direct, and how much is indirect and mediated through wrights. The results of this analysis are obtained by predicting the value of the wrights per capita for different values of mills per capita, and then using these predictions to estimate the effect of both the mills and the predicted values of wrights on the different occupations. The analysis repeats this procedure a thousand times, sampling each time different values of mills to predict the values of wrights.

[35] A hypothetical analysis, in which the mills mediate the effect of the wrights yields much lower numbers, ranging between 15%-27% (available upon request).

the type of machinery used in the two branches increased, mainly due to the differences in the nature of the fiber. While the woolen industry adopted the spinning jenny, invented by James Hargreaves in 1764, on a large scale, the worsted branch adopted the more inventive technology of the Arkwright type of water-frames (i.e. spinning machines operated by water power and later by steam), which were widely used in large scale production factories. Thus, the strength of the worsted fiber, which imposed too much strain on the early jenny "lent itself in a way that woollen did not to the, process of spinning worked out by Arkwright" (Clapham, 1907, p. 141). The first worsted spinning mill in Yorkshire was established in 1787, and by 1820, domestic spinning of worsted yarn was almost extinct (Clapham, 1906, p. 517). At first blush, it may seem that this could simply be due to worsted spinners searching for good geographical sites suitable for water power. But the argument survives all geographical controls. Moreover, in Appendix Figure G1 we show that river suitability and wheat suitability are independent. That is, if indeed the issue was merely river suitability, worsteds could have moved also to districts that are not suitable for wheat cultivation. In this case, our IV would not have predicted where they are. The fact that we find them mainly where wheat can be cultivated (as well, of course, areas where rivers had adequate flows) implies that they moved to where mills were. Since before 1750 worsteds did not use DB mills, it must have been the presence of skilled wrights that made it profitable for them to move there.

If our hypothesis is correct, these developments would imply a much stronger dependence of the location of worsted manufacturing on the availability of skilled workmen. Given the major improvements to water-powered mills in this period, the existence of medieval grinding mills (i.e. requiring both slow streams and wheat) can no longer be regarded as a relevant determinant for the industry's location choice, unless skilled mechanical workmen were widely available in these same locations. Thus, we interpret the significant effect of the existence of medieval mills on the extent of worsted manufacturing in 1750-1800, as a dependence on human capital rather than on capital. Support for this view can also be found in Edward Baines' words in 1859: "I apprehend that the principal advantages of the West Riding over Gloucestershire, Wiltshire, and Norfolk consist, first, in the greater cheapness of coal and iron; secondly, in the larger body of men skilled in the making and working of machinery; and thirdly, in the facility of access to the great ports of Liverpool and Hull." (Baines, 1859, P.16)

The results of this analysis are presented in Table 7. As discussed earlier, since we cannot use our variable *draper* as a consistent proxy for the extent of textile production in 1710-50 and in 1750-1800, when the shift to the factory system changes the organization of the industry, we use *weavers per capita*, an occupation that remained relatively independent of the factory system at this stage, as a proxy. We therefore estimate the effect of the per capita number of Domesday mills in the district (instrumented by our geographical IV) separately on the number of woolen weavers per capita, and on the number of worsted weavers per capita.

Table 7. Domesday Mills and Apprentices to Worsted *vs*. Woolen Weavers

	No. Weaver Apprentices per Capita					
	1710-1750		1750-1800			
	(1) Woollen	(2) Worsted	(3) Woollen	(4) Worsted	(5) Worsted	(6) Worsted
Watermills (per capita)	0.12***	0.04	0.48***	0.13*	0.09**	
	(0.03)	(0.04)	(0.14)	(0.07)	(0.04)	
Wrights (per capita)						0.75**
						(0.31)
Non-fulling District					189.95	184.09
					(158.04)	(153.84)
Carboniferous Strata					2.58	-9.03
					(30.69)	(26.63)
Textile Usage of Engines					-4.09	-3.36
					(4.11)	(3.62)
River Suitability	353.36**	387.26	599.78**	543.76	538.81	357.11
	(164.18)	(279.32)	(234.70)	(412.02)	(402.00)	(328.59)
Wheat suitability	33.09*	38.89	24.32	52.73	53.64	38.66
	(19.46)	(30.95)	(23.83)	(43.45)	(45.04)	(36.10)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	17.61	17.61	17.62	17.62	19.76	16.22
Adjusted-R^2	0.27	0.07	0.23	0.10	0.11	0.13
Observations	298	298	298	298	298	325

Notes: This table establishes the positive effect of wright apprentices on the location of the worsted industry, before and after the mechanization process it experienced during the second half of the eighteenth period. In particular, it shows that during the first half of the eighteenth century, the location of the mills affects the location of the woollen industry (due to fulling), but not of worsted. After spinning machinery was adopted by the worsted industry, wright apprentices affect the location of the worsted industry, while the effect on the woollen industry is economically small. The table uses the geographical IV presented above int the paper. Furthermore, the result is robust also for controlling for the existence of carboniferous strata in the district, the number of engines used in the textile industry by 1800 and a dummy variable that indicates that the district was a textile center for yarns that were not fulled (and thus historically did not use water power). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

The results of estimating the effect of Domesday mills on the location of weavers in the years 1710-50 is presented in columns (1)-(2), and in the years 1750-1800, in columns (3)-(4). As expected, the effect on woolen manufacturing is highly significant in both periods, mainly due to the dependence on water powered fulling. However, it is also due to the industry's need for wrights and other skilled mechanics following the adoption of jennies in workshops. As for the location of worsted manufacturing, Domesday mills had no significant effect on its location in the first half of the century, when it was relatively modest and mostly manual. It becomes however significant in the second half of the century, following the expansion and mechanization of worsteds.

Column (5) of Table 7 presents the results of our IV estimation with additional controls for possible effects of the important changes that took place in the second half of the century, i.e. specialization, and increasing dependence on coal and steam engines. We therefore add a dummy variable for districts that in 1800 specialized in textiles but did not use fulling (i.e. cotton, linen and worsted), for the number of engines used in textile, and for the potential coal availability (using evidence for carboniferous strata in the district).[36] The effect of historical mills on the location of manufacturing declines but remains significant even in the presence of these additional controls. Lastly, in column (6), we replace Domesday mills with the number of wright apprentices in 1710-50 and test its effect on the location of worsted. Note that the use of the geographical IV as an instrument for wrights in this specification does not violate the exclusion restriction, because worsted did not depend on water power until the second half of the century. Consistent with our hypothesis, the results show that the availability of wrights has a positive and significant effect on the location of worsted. Thus, our results confirm that wrights clearly played a role in first phases of industrialization.

We conclude from our findings that the persistence in the location of the textile industry was determined by the agglomerating effect of both, the availability of capital and of human capital, in locations that adopted water powered machinery early in history. The suitability for grinding mills in the Middle Ages stimulated skills, and the skills in return attracted more advanced machinery and skills at a much later time. This process proceeded well into the shift to the factory system in the end of the eighteenth century.

6. Robustness

A number of concerns can be raised as to various threats to our results, given the inevitable problems

[36] The dummy variable receives the value of 1, if the district appears as specializing in linen, cotton, or worsted in 1800 in Darby (1973). The number of engines is taken from Kanefski (1979), and the data for the availability of carboniferous strata from 1:5 Million International Geological Map of Europe and Adjacent Areas (IGME 5000) project.

with the data available. This subsection establishes that our main results are robust to (i) spatial autocorrelation; (ii) the availability of coal; (iii) bias due to the effect of London; (iv) different levels of our IV components and (v) Domesday Book institutional differences.

6.1 Spatial correlation

One concern in spatial regressions, like the ones presented in this paper, is that the independence assumption is violated. According to our Moran's I statistics (Appendix B, table B.1), our results may, indeed, be affected by spatial autocorrelation and thus, our statistical significance may be an artefact of spatial autocorrelation (Moran's I statistics in our main variables are significant, receiving z-scores around 8-10). Therefore, we first correct the standard errors based on Conley (1999). Appendix Tables B.2 provides the results of these estimations, for wrights and mills, and Tables B.4, B.5, B.6 and B.7 for drapers and wrights, weavers, and wrights, smiths and wrights, and blacksmiths and wrights, respectively. Each of these tables display the results of our full specification, with all the controls, and corrects the standard errors by clustering all neighboring observations for different distances (15 km, 35 km, 60 km, 85 km, and 100 km). These tables show that our results are not affected by this correction.

Nevertheless, Kelly (2020) showed that where spatial autocorrelation is severe, the Conley correction is not enough, as the t-statistics might still be inflated. Hence, following Kelly (2020), we perform Monte Carlo simulations with 5000 repetitions, where in each we generate spatially autocorrelated white noise. The spatial autocorrelation is calculated in a radius of 55km, which provides, in 5000 simulations, a spatial autocorrelation in levels similar to the ones reported in Table B.1. In each repetition, we run two placebo tests: First, we simulate our model where the spatially autocorrelated white noise replaces our dependent variable. Figure B1 provides the full distribution of the t-statistic of the regressions where the spatially autocorrelated white noise is the dependent variable and mills per capita are the explanatory variable, including all our controls. The vertical red line represents the t-statistic we receive in our estimation. As can be seen in the figure, our t-statistic is in the 100th percentile of the distribution (99th for the t-statistics in absolute values). Repeating the same exercise for the regressions of drapers and wrights, Figure B2 presents the full distribution where the spatially auto-correlated white noise is the dependent variable and wrights per capita are the explanatory variables, with all our controls in place. Again, as can be seen in the figure, our t-statistic is in the 96th percentile (93nd in the case of the t-statistics in absolute values).

Furthermore, as Voth (2020) argues, a more important concern of spatial auto-correlation arises when spatially autocorrelated white noise can explain the dependent variable. Hence, we simulate our model with a second placebo test, but this time the spatially autocorrelated white noise substitutes our independent variable. Figure B3 shows the distribution of t-statistics for the simulations in which wrights per capita are the dependent variable and the spatially autocorrelated white noise is the explanatory variable (with all the controls). Again, our t-statistic is in the 100th percentile of the distribution (also if we look at the t-statistic in absolute values). Finally, as can be seen in Figure B4, replicating the same exercise when drapers per capita are the dependent variable and the spatially autocorrelated white noise is the explanatory variable (including all controls), yields very promising results, as our t-statistic lies in the 100th percentile (also in the case of t-statistics in absolute values).

Finally, we perform a new method suggested by Colella et al. (2020) for correcting the standard errors in case of spatial data in a 2SLS estimation. We therefore replicate our estimations correcting the standard errors based on their methodology for 15 km, 35 km, 60 km, 85 km, and 100 km. Appendix Table B.3 presents the results, and as can be seen in the table, our results are immune to this correction. We conclude from all these estimations that our results are robust to spatial autocorrelation.

6.2 Robustness to the availability of coal

Did the availability of coal affect the location of the textile (and iron making) centers prior to industrialization? Many studies have stressed the availability of coal as an explanation for the location of the Industrial Revolution.[37] Before the steam engine, coal was used exclusively for heating, both domestic and industrial (such as kilns, soap boiling, forging, and ceramics). Fuel was not used much in the textile industry except for washing and laundering the fabrics and the heating of the combs employed in the combing of wool used in worsteds, but blacksmiths and their forges needed coal. In fact, during the reign of the Tudors, coal replaced wood as the fuel of choice for processing iron, and thus its presence might have been a confounding factor. To account for the availability of coal, we use the presence of carboniferous rock strata in the district, a measure used in studies to account for the district's potential for coal. The data was taken from the 1:5 Million International Geological Map of Europe and Adjacent Areas (IGME 5000) project. The results in Appendix D show that the potential for coal does not have a significant effect on the location of mechanically-skilled workers (Table D.1), on the location of textile centers in the first half of the eighteenth century (Table D.2), or the location of the iron industry (Table D.3), when we control for other geographical and climatic characteristics of the district. In other words, a powerful factor in explaining the location of the most dynamic industries before the Industrial Revolution was the quality of the human capital embodied

[37] For a more detailed discussion of the role of coal in the Industrial Revolution and its historiography, see Kelly et al., 2020a.

in the most skilled and competent parts of England's artisans, not just the presence of natural resources. After all, the ability to extract and utilize these resources effectively depended wholly on the competence of the craftsmen and engineers engaged in it.

6.3 The Effect of London

A possible concern could be that proximity to London, as a vast commercial, demographic, and political center, could bias our results. To overcome this problem, we controlled in all our estimations for the distance from London. To show further that London does not affect our results, we replicate our main Tables 2, 5 and 6 while omitting London from the sample. These tables can be found in Appendix C. The tables show that the results remain nearly unchanged.

6.4 Robustness to Other Specifications of the Instrument Variable

In this section we examine the sensitivity of our results to changes in the construction of our instrument. Recall that our instrument is the interaction of the length of rivers with adequate levels of ruggedness (as a proxy for the flow of water) and whether a district is suitable for wheat cultivation. In particular, in the results presented above, we assume that the adequate levels of ruggedness are between 2 and 6, and a district is considered suitable for wheat cultivation if the mean wheat suitability in the district is not higher than 5. Appendix E provides evidence that the results are not sensitive to these values, and shows the balance of the instrument.

6.4.1 Balance of the Instrument

A concern may be that our instrument is correlated with (unobserved) pre-existing conditions, and thus any correlation between the instrument and mills (and thus wrights and other occupations) may merely reflect the correlation with these variables. While, by assumption, we cannot show that our instrument is (un)correlated with unobserved characteristics, Appendix Table E.1 shows that our instrument is not correlated with most of our controls. In particular, our instrument is uncorrelated with the district's latitude, mean ruggedness, mean elevation, agricultural suitability, mean temperature, mean precipitation, distance to London and the distance to the nearest harbor. It is positively correlated with the district's area and total length of rivers with moderate slopes. This makes sense, as these two variables are correlated with the length of rivers with adequate water flows, which in turn is one component of our instrument. The instrument is also negatively correlated with the suitability to grow pasture in the district and the distance to the nearest navigable river. Finally, it is also correlated with two man-made variables: total population, and the distance to a Roman road.

Again, our analysis shows that controlling for these variables does not affect the results.

6.4.2. Sensitivity to Different Levels of Ruggedness

Appendix Table E.2 presents the results of the last column in Table 3 with different levels of ruggedness. Column (1) replicates the last column of Table 3 as a benchmark. Then, in columns (2) - (9) we replace the ruggedness levels with different levels of ruggedness. As can be seen in these columns, while the effect of mills per capita on wright apprentices per capita is still significant, the first stage F-statistics become very small, suggesting that these levels are not adequate for constructing watermills. Nevertheless, as the levels of ruggedness become closer to the levels we employed in our IV, so does the first stage F-statistic. Moreover, instrumenting the mills with ruggedness levels between 2 and 5 yields very similar results to the results we presented above. Thus, our results are robust to different moderate levels of ruggedness.

6.4.3 High Levels of Ruggedness

One concern that may arise is that the instrument is constructed on relatively moderate water flows, whereas perhaps more powerful water flows could have been adequate for constructing Medieval mills as well. There is some historical reason to suspect it was not: Highly rugged terrain required overshot mills to function well, and while these machines were known in the Middle Ages, the sources show none before the thirteenth century (Reynolds, 1983, pp. 99, 172). The last column on Table E.2 and Table F.4 show similarly that very rugged terrain conditions weaken the connection between millwrights and Domesday Mills. The last column of Appendix Table E.4 replicates the last column of Table 3, only with ruggedness levels between 10 and 20. As can be seen, the first stage F-statistic is very weak (1.28), and while mills per capita are correlated with wrights per capita, the significance of this correlation is very weak.

Moreover, Appendix Table F.4 further explores the relation between mills, wrights, and high water flows. The first three columns present the results of the first stage, only with different controls. As can be seen in the table, the number of mills per capita is not statistically significant in any of these columns. Next, columns (4)-(6) present the reduced form. That is, they present how wrights per capita are correlated with the instrument (when it is built with high water flows). The coefficient of the instrument is insignificant when we control only for the two components of the instrument; it is marginally significant when we add the main geographical, agricultural, and climatic controls; and it is significant at the 5% level in the full specification. We conclude from these columns that the relation of wrights per capita and high water flows is not robust. Finally, the last three columns show the results when we estimate the relation between wrights and mills using 2SLS. The coefficient of the mills is significant when we control only for the two components of the instrument; it is insignificant when we control for the main geographic, climatic, and agricultural controls; and it is marginally significant in the full specification. Furthermore, the first stage F-statistic is very low in all three columns, suggesting that the instrument is robust when taking into account high water flows.

Lastly, during the 18th century, technological advances in waterpower enabled industries to use higher levels of water flows. We run a placebo test which replicates the reduced form of Table 5, but with our instrument using high water flows instead of terrain ruggedness levels of 2-6, as we used throughout the paper. These results are presented in Appendix Table F.5. As can be seen in the table, high water flows only correlate with drapers. We conclude from all these checks that moderate river flows affected the establishment of DB mills, the development of mechanical skilled workers, and finally, early industrialization.

6.4.4. Sensitivity to Different Levels of Wheat Suitability

Appendix Table E.3 provides further evidence that our instrument is robust to different levels of suitability for wheat growing. It shows that our instrument is valid if the mean wheat suitability "category" of a district is either lower than any value between 4.8 and 5.9, but not for higher levels of wheat suitability (recall that category 8 implies that the district has low value of the suitability index and thus is not suitable for wheat cultivation). In particular, in column (1) we replicate the last column in Table 3 as a benchmark. Then, as a placebo test, in columns (2)-(9), we replace the threshold level below which the district is considered suitable for wheat cultivation. As can be seen, if we define the district as suitable for wheat growing for too low levels of wheat suitability (see columns (8)-(9)) in which the mean wheat suitability equals at least 6), or extremely suitable for wheat cultivation (see columns (2)-(4), where wheat suitability as at most 4.5), either we find that the effect of the number of Domesday mills per capita on the number of wright apprentices per capita is not statistically significant, or the first stage F-statistic is too low (or both). Nevertheless, for any possible threshold of wheat suitability between 4.8 and 5.9, the results we receive are very similar to the ones we present in the main paper, sometimes even with a higher first stage F-statistic. Furthermore, there are 134 observations (44.97% of the DB sample), with wheat suitability between 4.8 and 5.9. Appendix Table E.3 suggests, then, that moving about 45% of the sample from the control group (that is, low wheat suitability) to the treatment group (that is, high wheat suitability) or vice versa does not change our results.

6.5 Robustness to DB Institutions

Finally, it might be that our results might be driven by some historical institutions that might have affected both the location of DB, and historical wrights, which in turn affected the location of wrights during the eighteenth century. We have shown that the share of royal holdings (King's Vill), the share of ecclesiastical holdings, and the share of arable land held by the lords did not have a significant effect on the location of DB (See Appendix Table A.2 for more details). Appendix Table F.6 shows that indeed these institutions do not affect our results. Column (1) is used as a benchmark, and it is a replication of column (6) of Table 2. Then, in columns (2)-(4), we add one by one the King's Vill share, ecclesiastical Vill share and the lords' share of arable land. Our coefficient is hardly changed, as well as the first stage F-statistic. Finally, in column (5) we add all three variables. The coefficient of DB watermills drops a little bit, from 0.15 to 0.09, and it is significant at the 5%. We conclude from this table that the DB had a very little effect on the location of wrights in the eighteenth century.

7. Conclusions

The results presented above lend credence to the hypothesis that on the eve of the first Industrial Revolution, the spatial distribution of mechanically skilled craftsmen was the outcome of a persistent process, which began in early Middle Ages, when water mills (invented in Roman times) came into wide use. As Marc Bloch (1966, p. 150) put it memorably, by the time of Charlemagne in Gaul and Domesday Book in England, "for all of those with ears to hear, [these regions] are loud with the music of the millwheel." The technical demands on building these mills played a key role in the formation of skilled craftsmen. In turn, the mechanically-skilled craftsmen trained as wrights assisted other industries that could use water power to flourish. This paper presents a test of the persistence that these skills generated.

We thus highlight one small but significant segment of England's best and brightest craftsmen, namely millwrights and engineers. The presence of geographical conditions that favored the construction of watermills engaged in grain milling created a class of highly-trained millwrights whose skills spilled over to the woolen and iron industries. The prevalence of these industries was a first step in the path of England becoming an industrial nation. It is no accident that the term "mill" became synonymous with "factory" in the early stages of the Industrial Revolution, as the role of water mills in textile manufacturing remained central for many decades in the eighteenth and early nineteenth centuries, before they were eventually superseded by steam power.

Did these locational patterns matter in any way to what happened after 1750? The importance of the woolen industry in the Industrial Revolution has been traditionally overshadowed by the spectacular growth of the cotton industry, but we should not forget that wool kept growing during the Industrial Revolution at a more than respectable rate and “the wool industry did not allow itself to be outshone” (Jenkins and Ponting, 1982, p. 296). Many of the technological breakthroughs in cotton carried over to wool and vice versa, and both industries benefitted immeasurably from the high level of competence of British craftsmen and mechanics (Kelly, Mokyr and Ó Gráda, 2020a, 2020b). Millwrights were a substantial component of this class, but so were many others: clockmakers, lens grinders, colliers, locksmiths, toymakers, ironmongers, instrument makers, and many manufacturers of up-market consumer goods -- all played a role.

Why do we see the importance of millwrights in Britain more than elsewhere in Europe? Mills and millwrights by themselves could not, of course, lead to an Industrial Revolution. Mills can be found everywhere in Europe, if perhaps not quite at the intensity we observe in Britain. In the Netherlands we observe a very high concentration of mills in some regions, both for hydraulic and industrial purposes. The Dutch published sophisticated and detailed technical descriptions of the mechanics of their mills, such as in the *Groot Volkomen Moolenboek* (1734), which is an early example of the detailed technical descriptions of handicrafts and production techniques we see later in the *Grande Encyclopédie*, and even more in the *Descriptions des Arts et Métiers* (1761–88). But as Davids (2008, Vol. 2, p. 453) points out, despite the relative openness of Dutch society, the skills of millwrights were “segmented by specialty” and their skills did not carry over to other industries. In eighteenth century France, given its heavy dependence of water and wind-power, there must have been a great number of millwrights. Yet it is striking that the 80 volumes of the *Descriptions* do not contain a separate volume on millwrighting, despite volumes on wig-making, embroiderie, pin-making, anchor-making, and the manufacture of tobacco pipes. The *Grande Encyclopédie* did contain a long and well-illustrated essay on water and wind mills, but significantly, it was classified under “agriculture and rural economy.”

Continental Enlightenment intellectuals were of course deeply interested in hydraulics, and their scientists — above all theorists such as Johann Euler, Antoine Parent, Bernard de Bélidor, Daniel Bernoulli, and Jean-Charles Borda — contributed a great deal to the formal mathematical analysis of hydraulics (Reynolds, 1983). The British Enlightenment was far more down-to-earth and pragmatic than that of the Continent, and this difference extended to the effects of its watermills on industries requiring skilled mechanics. The typical British scientist contributing to hydraulics was John Smeaton, an experimentalist, engineer, and inventor. But right below Smeaton were a large number of engineers trained as millwrights with extensive practical skills, who invented, improved, and tweaked water mills and other machinery (see Appendix H for details).

We hasten to add that there was no simple mapping from the pre-existence of a high-skilled labor force to the acceleration of technological progress during the Industrial Revolution. The Midlands and London were able to transform these skills into rapid growth. But the traditional areas of woolen manufacturing in the West Country and East Anglia ended up slowly ceding their industrial base to Yorkshire. As Jones (2010, p.8) has pointed out, the failure of the English South to industrialize may seem surprising. More than anything else, this region may have followed the rules of regional specialization, as declining transportation costs and market integration overwhelmed the traditional aptitudes in woolen manufacturing in these areas. As Jones (2010, p. 66) observes, despite its relative decline, the Gloucestershire woolen industry was quite capable of mechanization.

At the end of the day, our research helps to restore the place of human capital in Britain's technological leadership. To see this, we need to shed modern habits of looking at human capital in "modern" terms of schooling and literacy, or even in terms of the social conditioning and drilling that educational institutions in this era instilled in their students. Instead, we should look at tacit skills; technical competence passed on from master to apprentice through informal personal contact. The great historian of technology during the Industrial Revolution, John R. Harris, realized this when he noted that "so much knowledge was breathed in by the workman with the sooty atmosphere in which he lived rather than ever consciously learnt" (Harris, 1992, p. 30). The same was true for Britain's millwrights, some of whom morphed into and trained a class of mechanical engineers in the nineteenth century (MacLeod and Nuvolari, 2009). The crucial role of mechanically trained and highly competent craftsmen in the Industrial Revolution, and thus in the Great Enrichment overall, richly deserves our recognition.

References

Acemoglu, Daron. 2003. “Labor- and Capital-Augmenting Technical Change.” Journal of the European Economic Association 1(1): 1-37.

Allen, Robert C. 2003. “Progress and poverty in early modern Europe.” *Economic History Review*, 56(3), 403–443.

Allen, Robert C. 2009. “The Industrial Revolution in Miniature: The Spinning Jenny in Britain, France, and India”. *The Journal of Economic History* 69(4): 901-927.

Anonymous. 1747. *A General Description of all Trades, Digested in Alphabetical Order*. London: Printed for T. Waller.

Ashraf, Quamrul, Cinnirella, Francesco Cinnirella, Oled Galor, Boris Gershman, and Erik Hornung. 2018. “Capital-Skill Complementarity and the Emergence of Labor Emancipation”, No 12822, *CEPR Discussion Papers*.

Baines, Edward, 1835. *History of the Cotton Manufacture in Great Britain*. London: Fisher, Fisher and Jackson.

Baines Edward. 1859. “On the Woollen Manufacture of England; With Special Reference to the Leeds Clothing District”, *Journal of the Statistical Society of London*, 22(1): 1-34.

Becker, Sascha O., Erik Hornung, and Ludger Woessmann. 2011. "Education and Catch-Up in the Industrial Revolution." *American Economic Journal: Macroeconomics*, 3 (3): 92-126.

Bennett, Richard & John, Elton. 1899. *History of Corn Milling vol. II. Watermills and Windmills*. London: Simpkin, Marshall and company.

Ben Zeev, Nadav, Joel Mokyr and Karine van der Beek. 2017. “Flexible Supply of Apprenticeship in the British Industrial Revolution.” *Journal of Economic History* 77:208–250.

Bleakley, Hoyt, and Jeffery Lin. 2012. “Portage and Path Dependence”, *Quarterly Journal of Economics* 127(2): 587-644.

Bloch, Marc. 1966. “The Advent and Triumph of the Watermill.” In *Land and Work in Medieval Europe*, New York: Harper and Row, pp. 136-168.

Board of Stamps: *Apprenticeship Books*, Series IR 1; The National Archives of the UK (TNA), Kew, Surrey, England.

Boerner, Lars, and Bautista, Severgnini. 2019. “Time for Growth.” *King’s Business School, Working paper No.* 2019/4.

Byrom, Richard. 2017. *William Fairbairn: the Experimental Engineer*. Market Drayton: Railway and Canal Historical Society.

Campbell, R. 1747. *The London Tradesman*. Printed by T. Gardner at Cowley’s Head.

Cantoni, Davide and Noam, Yuchtman. 2014. “Medieval Universities, Legal Institutions, and the Commercial Revolution”, *The Quarterly Journal of Economics* 129(2): 823-887.

Caprettini, Bruno, and Hans-Joachim, Voth. 2018. “Rage Against the Machines: Labor-Saving Technology and Unrest in Industrializing England”. London, Centre for Economic Policy Research.

Carpenter, Audrey. 2011. *John Theophilus Desaguliers: A Natural Philosopher, Engineer and Freemason in Newtonian England*. London: Continuum Publishing.

Carus-Wilson, E. M., 1941. “An Industrial Revolution of the Thirteenth Century,” The *Economic History Review*, 11(1): 39-60.

Chrimes, Mike. 2002a. “Hewes, Thomas Cheek.” In Alec Skempton, ed., *Biographical Dictionary of Civil Engineers, 1500-1830*. London, Thomas Telford for the Institution of Civil Engineers, pp. 320-321.

---. 2002b. “Sorocold, George”. In: Alec Kempton et al., ed., *Biographical Dictionary of Civil Engineers*, *1500-1830*. London, Thomas Telford for the Institution of Civil Engineers, pp. 320-321.

Clapham, John H. 1906. “Industrial Organisation in the Woollen and Worsted Industries of Yorkshire”, *The Economic Journal*, 16(64): 515-522.

---. 1907. *The Woolen and Worsted Industries*. London: Methuen & Co.

Clark, Gregory. 2005. “Human Capital, Fertility, and the Industrial Revolution.” *Journal of the European Economic Association*. 3(2/3): 505-515.

Conley, Timothy G. 1999. “GMM estimation with cross sectional dependence”. *Journal of Econometrics* 92(1): 1-45.

Cookson, Gillian. 1994. “The West Yorkshire Textile Engineering Industry, 1780-1850.” Ph.D.

dissertation, University of York.

---. 2018. *The Age of Machinery: Engineering in the Industrial Revolution, 1770-1850*. London: Boydell and Brewer.

Crafts Nicholas. 1996. “The First Industrial Revolution: a Guided Tour for Growth Economists.” *AER Papers and Proceedings,* 86(2): 197–201.

Crafts, Nicholas and Nikolaus Wolf. 2014. “The location of the British cotton textiles industry in 1838: A Quantitative Analysis,” *Journal of Economic History,* 72:103- 139.

Darby H. C. ed. 1973. *A New Historical Geography of England*. London: Cambridge University Press.

Davids, Karel. 2008. *The Rise and Decline of Dutch Technological Leadership*. Leiden and Boston: Brill, 2 Vols.

Deane, Phyllis. 1957. “The Output of the British Woolen Industry in the Eighteenth Century.” *Journal of Economic History*, 17(2): 207-223.

De la Croix, David, Matthias Doepke and Joel Mokyr. 2018. “Clans, Guilds, and Markets: Apprenticeship Institutions and Growth in the Pre-Industrial Economy.” *Quarterly Journal of Economics* 133:1–70.

De Pleijt, Alexandra M. 2018. “Human Capital Formation in the Long Run: Evidence from Average Years of Schooling in England, 1300-1900,” *Cliometrica*, 12(1): 99–126.

De Pleijt, Alexandra M., Alessandro Nuvolari, and Jacob Weisdorf. 2019. “Human Capital Formation During the First Industrial Revolution: Evidence from the use of Steam Engines” *Journal of the European Economic Association* (forthcoming).

Desaguliers, John Theophile. [1734] 1763. *A Course of Experimental Philosophy*. 3rd ed. London: Printed for A. Millar.

Easterlin, Richard. 1981. “Why Isn’t the Whole World Developed?” *Journal of Economic History*, 41(1): 1–19.

Easterly, William. 2001. *The Elusive Quest for Growth*. Cambridge, MA: MIT Press.

Fairbairn, William. 1860. *Useful Information for Engineers, second series*. London: Longman, Green, Longman and Roberts.

---. 1861. *Treatise on Mills and Millwork* Part I. London: Longman, Green, Longman and Roberts.

---. 1877. The Life of Sir William Fairbairn, *bart*. London: Longmans.

Feldman, Naomi E., and Karine Van der Beek. 2016. "Skill Choice and Skill Complementarity in Eighteenth Century England." *Explorations in Economic History,* 59(1): 94-113.

Fick, S.E, and Hijmans, R.J. 2017. "Worldclim 2: New 1-km Spatial Resolution Climate Surfaces for Global Areas", *International Journal of Climatology*, available at: www.worldclim.org

Franck, Raphaël and Oded, Galor. 2017, "Technology-Skill Complementarity in Early Phases of Industrialization". NBER Working Paper Series No. 23197.

Galor Oded. 2011. *Unified Growth Theory*. Princeton University Press.

Galor, Oded, and David N. Weil. 1999. "From Malthusian Stagnation to Modern Growth," *American Economic Review*, 89: 150-154.

---. 2000. "Population, Technology and Growth: From Malthusian Stagnation to the Demographic Transition and Beyond," *American Economic Review*, 90: 806-828.

Gimpel, Jean. 1976. *The Medieval Machine: the Industrial Revolution of the Middle Ages*. Harmondsworth: Penguin Books.

Glaeser, Edward L., Rafael La Porta, Florencio Lopez-de-Silanes, and Andrei Shleifer. 2004. "Do institutions cause growth?" *Journal of Economic Growth* 9: 271–303.

Hanlon, Walker W. "The Rise of the Engineer: Inventing the Professional Inventor During the Industrial Revolution. Unpublished working paper, NYU Stern School of Business.

Hanushek, E. A., & Woessmann, L. (2008). "The role of cognitive skills in economic development". Journal of Economic Literature, 46(3), 607-668.

Harris, John. R. 1992. "Skills, Coal and British Industry in the Eighteenth Century." In J.R. Harris, *Essays in Industry and Technology in the Eighteenth Century*. Aldershot: Ashgate/Variorum.

Heaton, Herbert. 1920. *The Yorkshire Woollen and Worsted Industries, from the earliest times up to* *the Industrial Revolution*. Volume 10 of Oxford historical and literary studies. Oxford: Clarendon Press.

Heilbron, J.L. 1990. “Introductory Essay.” In *The Quantifying Spirit in the 18th Century*, ed. by Tore Frängsmyr, J.L. Heilbron, and Robin E. Rider. Berkeley: University of California Press, pp. 1–23.

Holt, Richard. 1988. *The Mills of Medieval England*. Oxford: Basil Blackwell.

Howes, Anton. 2016. “The Relevance of Skills to Innovation during the British Industrial Revolution, 1651-1851” unpublished ms., Brown University.

Hudson, Pat. 1992. *The Industrial Revolution*. Sevenoaks, Kent: Edward Arnold.

Humphries, Jane. 2003, “English Apprenticeship: A Neglected Factor in the First Industrial Revolution,” in P. A. David and M. Thomas (eds.), The Economic Future in Historical Perspective, Oxford University Press.

Imai, Kosuke, Luke Keele, and Dustin Tingley. 2010. “A general approach to causal mediation analysis.” *Psychological Methods*, 15(4): 309-334.

Imai, Kosuke, Luke Keele, Dustin Tingley, and Teppei Yamamoto. 2010. “Causal mediation analysis using R.” In *Advances in Social Science Research Using R*, ed. Vinod, H. D., pp. 129-154. New York: Springer.

---. 2011. “Unpacking the black box of causality: Learning about causal mechanisms from experimental and observational studies.” *American Political Science Review* 105: 765–789.

-

IIASA/FAO, 2012. *Global Agro-ecological Zones* (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy.

Jenkins, K.G. and Ponting, D.T. 1987. *The British Wool Textile Industry, 1770-1914*. Aldershot: Scolar Press.

Jones, Eric L. 2010. *Locating the Industrial Revolution: Inducement and Response*. Singapore: World Scientific Publishers.

Kanefsky, John W. (1979*). The Diffusion of Power Technology in British Industry, 1760-I870*. Unpublished Ph.D. thesis, University of Exeter.

Kelly, Morgan, 2020. “The Standard Errors of Persistence”, unpublished.

Kelly, Morgan, Joel Mokyr, and Cormac Ó Gráda. 2014. “Precocious Albion: A New Interpretation of the British Industrial Revolution,” *Annual Review of Economics*, 6(1): 363-389.

Kelly, Morgan, Joel Mokyr, and Cormac Ó Gráda. 2020a. “The Mechanics of the Industrial Revolution.” Unpublished.

---. 2020b. “Could Artisans have caused the Industrial Revolution?”. In Kristine Bruland et al., eds. *Reinventing the Economic History of Industrialization*. Montreal and Kingston, McGill-Queen’s University Press, pp. 25-43.

Khan, B. Zorina. 2018. “Human Capital, Knowledge and Economic Development: Evidence from the British Industrial Revolution, 1750-1930,” *Cliometrica,* 12(2): 313-341.

Klein Goldewijk, K., A. Beusen, M. de Vos and G. van Drecht. 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.

Klein Goldewijk, K., A. Beusen, and P. Janssen. 2010. “Long term dynamic modeling of global population and built-up area in a spatially explicit way, HYDE 3.1. The Holocene 20(4):565-573.

Krueger, Alan B., and Mikael Lindahl. 2001. "Education for Growth: Why and for Whom?" *Journal of Economic Literature*, 39(4): 1101-1136

Lahner, B., K., Verdin, and, A. Jarvis. 2008. “New Global Hydrography derived from Spaceborne Elevation Data.” Eos: *Transactions of the American Geophysical Union*, 89(10): 93-94. (the data is available electronically at https://hydrosheds.cr.usgs.gov/).

Langdon, John. 2004. *Mills in the Medieval Economy: England 1300-1540*, Oxford University Press.

Lindert, Peter H. 2004. *Growing Public: Social Spending and Economic Growth Since the Eighteenth Century*. Cambridge: Cambridge University Press.

Lipson, E. (1921). *The history of the woollen and worsted industries*. London: A. & C. Black, Ltd.

Lucas, Adam R. 2005. “Industrial Milling in the Ancient and Medieval Worlds: A Survey of the Evidence for an Industrial Revolution in Medieval Europe.” *Technology and Culture*, 46(1): 1-30.

---. 2006. *Wind, Water Work: Ancient and Medieval Milling Technology*. Leiden: Brill.

---. 2014. *Ecclesiastical Lordship, Seigneurial Power and the Commercialization of Milling in Medieval England*. UK: Ashgate Publishing Limited.

Lucas, Robert E. 1988. "On the Mechanics of Economic Development," *Journal of Monetary Economics*, 22: 3-42.

MacLeod, Christine and Alessandro, Nuvolari. 2009. "Glorious Times: The Emergence of Mechanical Engineering in Early Industrial Britain, c. 1700–1850." *Brussels Economic Review*, 52: 215-237.

Madsen, Jakob B. and Fabrice Murtin. 2017. "British economic growth since 1270: the role of education," *Journal of Economic Growth*, 22(3): 229-272

Meisenzahl, Ralf R. and Joel Mokyr. 2012. "The Rate and Direction of Invention in the British Industrial Revolution: Incentives and Institutions." In *The Rate and Direction of Innovation, ed. Scott Stern and Joshua Lerner*. Chicago: University of Chicago Press, pp. 443-79.

Mitch, David. 1992. *The Rise of Popular Literacy in Victorian England*. Philadelphia, PA: University of Pennsylvania Press.

---. 1999. "The Role of Human Capital in the First Industrial Revolution," in Joel, Mokyr, ed., The British Industrial Revolution: An Economic Perspective (Boulder, CO,), pp. 267- 307.

Mokyr, Joel. 2009. *The Enlightened Economy: An Economic History of Britain 1700-1850*. Yale University Press.

Munro, John H. 2002. "Industrial energy from water-mills in the European economy, 5th to 18th Centuries: the limitations of power," MPRA Paper 11027, University Library of Munich, Germany.

Musson, A., E., and E. Robinson. 1960. "The Origins of Engineering in Lancashire," *Journal of Economic History*, 20(2): 209-233.

Nicholson, John. 1830. *The Millwright's Guide: A Practical Treaty on the Construction of all kinds of Mill Work*. London: Sherwood, Gilbert and Piper.

Ó Gráda, Cormac. 2019. "The Industrial Revolution: Making Room for Wool." Private communication.

O'Rourke, Kevin H. and Jeffrey G. Williamson. 1995. "Education, Globalization and Catch-up:

Scandinavia in the Swedish Mirror.” *Scandinavian Economic History Review*, 43(3), 287-309.

Palmer, J. 2010. *Electronic Edition of Domesday Book: Translation, Databases and Scholarly Commentary, 1086*. 2nd Edition. UK Data Service. SN: 5694.

Pelham, R. A., 1944. “The Distribution of Early Fulling Mills in England and Wales,” *Geography*, 29(2): 52-56.

Pritchett, Lant. 2001. “Where Has All the Education Gone?” *World Bank Economic Review*, 15(3): 367-391.

Ramankutty, N., Jonathan A. Foley, John Norman, and Kevin McSweeney. 2002. “The Global Distribution of Cultivable Lands: Current Patterns and Sensitivity to Possible Climate Change.” *Global Ecology & Biogeography*, 11: 377– 392.

Reis, Jaime. 2005. “Economic Growth, Human Capital Formation and Consumption in Western Europe before 1800.” In Robert C. Allen, Tommy Bengtsson, and Martin Dribe, eds., *Living Standards in the Past: New Perspectives on Well-being in Asia and Europe*. Oxford: Oxford University Press, pp. 195–225.

Reynolds, Terry S. 1983. *Stronger than a Hundred Men: A History of the Vertical Water Wheel*. Baltimore MD.: Johns Hopkins University Press.

Riley, Shawn J., Stephen D. De Gloria, and Robert, Elliot. 1999. “A Terrain Ruggedness Index that Quantifies Topographical Heterogeneity.” *Intermountain Journal of Sciences*, 5(1-4): 23-27.

Robinson, Eric. 1962. “The Profession of Civil Engineer in the Eighteenth Century: A Portrait of Thomas Yeoman, F.R.S., 1704(?)–1781.” *Annals of Science*, 18(4): 195–215.

Romer, Paul M. 1990. “Endogenous Technological Change.” *Journal of Political Economy*, 98(5): S71 -S102.

Smil, Vaclav. 2017. "Preindustrial Prime Movers and Fuels”. In: *Energy and Civilization: A History*. Cambridge, Massachusetts; London, England: MIT Press. pp. 127-224

Squicciarini, Mara and Nico Voigtländer. 2015. “Human Capital and Indus- trialization: Evidence from the Age of Enlightenment.” *Quarterly Journal of Economics*, 30:1825–1883.

Sugden, Keith, Sebastian A.J. Keibek, and Leigh Shaw-Taylor. 2018. “Adam Smith Revisited: Coal and the Location of the Woolen Manufacture in England Before Mechanization, c.1500-1820,” Cambridge Working Papers, History No.33.

Tann, Jennifer. 1974. “The Textile Millwright in the Early Industrial Revolution.” *Textile History*, 5(1): 80-89.

Taylor, Alan M. 1999. “Sources of Convergence in the Late Nineteenth Century.” *European Economic Review* 43(9): 1621–1645.

Towns List. 2018. “Complete List of UK Towns”, 2018, Available at www.townslist.co.uk

Trew, Alex. 2014. “Spatial Takeoff in the First Industrial Revolution,” *Review of Economic Dynamics*, 17: 707-725.

Voth, Hans-Joachim. 2020. “Persistence: Myth and Mystery.” In Alberto Bisin and Giovanni Federico, eds., *Handbook of Historical Economics*. Forthcoming.

Winchester, Simon. 2019. *The Perfectionists: How Precision Engineers Created the Modern World*. New York: Harper-Collins.

Woodcroft, Bennet [Great Britain. Patent Office]. 1854. *Titles of Patents of Invention: Chronologically Arranged from March 2, 1617 (14 James I.) to October 1, 1852* (16 Victoriæ). London: Printed by G.E. Eyre and W. Spottiswoode.

Wrigley, E.A. (1962). “The Supply of Raw Materials in the Industrial Revolution,” *Economic History Review*, 15(1): 1-16.

Appendix A: Persistence of the distribution of population

Table A.1. Mid-18th Century Population and Domesday Population

	Mean Population 1710-1750 (thousand)				
	(1)	(2)	(3)	(4)	(5)
Population (1086)	-0.31**	-0.37**	-0.21**	-0.13**	-0.04
	(0.12)	(0.16)	(0.09)	(0.05)	(0.05)
Main geographic controls	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes
Other geographic controls	No	No	No	No	Yes
Adjusted-R^2	0.07	0.21	0.38	0.66	0.74
Observations	298	298	298	298	298

Notes: This table establishes the negative correlation between the population of England's district as documented in the Domesday Book and the population in the years 1710-1750, controlling for the area of the district, its distance from London, major eighteenth century harbors, navigable rivers and a historical Roman road, as well as geographical controls such as the district latitude, mean elevation, ruggedness, temperature and precipitation and its total length of rivers. All observations are clustered at the historical county level. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table A.2. Institutions and Domesday Mills

	No. of DB Mills per Capita (1086 population)					
	(1)	(2)	(3)	(4)	(5)	(6)
Lords share of arable land	12.83	-5.57				
	(17.99)	(9.58)				
King's Vill Share			-3.43	9.66		
			(6.33)	(7.01)		
Ecclesiastical's Vill Share					23.76*	12.48
					(11.70)	(10.45)
Geographical controls	No	Yes	No	Yes	No	Yes
Agricultural controls	No	Yes	No	Yes	No	Yes
Climatic controls	No	Yes	No	Yes	No	Yes
Other economic controls	No	Yes	No	Yes	No	Yes
Adjusted-R^2	0.00	0.20	-0.00	0.20	0.04	0.21
Observations	298	298	298	298	298	298

Notes: This table shows the how historical institutions are correlated with the number of DB mills per capita. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix B: Spatial Autocorrelation

Table B.1. Domesday Mills and Apprentices to Wrights Spatial Autocorrelation (Conley, 1999)

	No. of Wright Apprentices per Capita				
	20 km	40 km	60 km	80 km	100 km
	(1)	(2)	(3)	(4)	(5)
Watermills (per capita)	0.12***	0.12***	0.12***	0.12***	0.12***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.04)
Main geographic controls	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes	Yes
R^2	0.62	0.62	0.62	0.62	0.62
Observations	298	298	298	298	298

Notes: This table establishes the robustness of our results to spatial autocorrelation, correcting the standard errors as suggested in Conley (1999). We do so by estimating the full specification, including all the controls as in Table 2, column (6), and cluster all neighboring observations in 20 km, 40km, 60km, 80km and 100km. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table B.2. Domesday Mills and Apprentices to Wrights Spatial Autocorrelation (Colella et al., 2019)

	No. of Wright Apprentices				
	20 km	35 km	60 km	85 km	100 km
	(1)	(2)	(3)	(4)	(5)
Watermills (per capita)	0.15***	0.15***	0.15***	0.15***	0.15***
	(0.05)	(0.05)	(0.04)	(0.03)	(0.03)
Geographical controls	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	23.17	21.86	13.89	14.12	23.80
Centered-R^2	0.62	0.62	0.62	0.62	0.62
Observations	298	298	298	298	298

Notes: This table establishes a robustness check to spatial autocorrelation *a la* Colella et al. (2019). In particular, it estimates our full IV model (column 6 in Table 3), but clusters all observations in distance of 20, 35, 60, 85 and 100 km from one another. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table B.3. Apprentices to Wrights and Textile Manufacturing (Drapers)
Spatial Autocorrelation (Conley, 1999)

	No. of Draper Apprentices per Capita				
	20 km	35 km	60 km	85 km	100 km
	(1)	(2)	(3)	(4)	(5)
Wrights (per capita)	0.37***	0.37***	0.37***	0.37***	0.37***
	(0.10)	(0.09)	(0.11)	(0.10)	(0.10)
Main geographic controls	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes	Yes
R^2	0.47	0.47	0.47	0.47	0.47
Observations	298	298	298	298	298

Notes: This table establishes the robustness of our results to spatial autocorrelation, correcting the standard errors as suggested in Conley (1999). We do so by estimating the full specification, including all the controls as in Table 4, column (5), and cluster all neighboring observations in 20 km, 35 km, 60 km, 85 km and 100 km. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table B.4. Apprentices to Wrights and Apprentices to Weavers
Spatial Autocorrelation (Conley, 1999)

	No. of Weaver Apprentices per Capita				
	20 km	35 km	60 km	85 km	100 km
	(1)	(2)	(3)	(4)	(5)
Wrights (per capita)	1.44***	1.44***	1.44***	1.44***	1.44***
	(0.39)	(0.47)	(0.11)	(0.16)	(0.05)
Main geographic controls	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes	Yes
R^2	0.19	0.19	0.19	0.19	0.19
Observations	298	298	298	298	298

Notes: This table establishes the robustness of our results to spatial autocorrelation, correcting the standard errors as suggested in Conley (1999). We do so by estimating the full specification, including all the controls as in Table 4, column (5), and cluster all neighboring observations in 20km, 35 km, 60 km, 85 km and 100 km. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table B.5. Apprentices to Wrights and Apprentices to Smiths
Spatial Autocorrelation (Conley, 1999)

	No. of Smith Apprentices per Capita				
	20 km	35 km	60 km	85 km	100 km
	(1)	(2)	(3)	(4)	(5)
Wrights (per capita)	0.31***	0.31***	0.31***	0.31***	0.31***
	(0.06)	(0.07)	(0.06)	(0.07)	(0.08)
Main geographic controls	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes	Yes
R^2	0.67	0.67	0.67	0.67	0.67
Observations	298	298	298	298	298

Notes: This table establishes the robustness of our results to spatial autocorrelation, correcting the standard errors as suggested in Conley (1999). We do so by estimating the full specification, including all the controls as in Table 4, column (5), and cluster all neighboring observations in 20km, 35 km, 60 km, 85 km and 100 km. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table B.6. Apprentices to Wrights and Apprentices to Blacksmiths
Spatial Autocorrelation (Conley, 1999)

	No. of Blacksmith Apprentices per Capita				
	20 km	35 km	60 km	85 km	100 km
	(1)	(2)	(3)	(4)	(5)
Wrights (per capita)	0.91***	0.91***	0.91***	0.91***	0.91***
	(0.13)	(0.12)	(0.06)	(0.07)	(0.06)
Main geographic controls	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes	Yes
R^2	0.72	0.72	0.72	0.72	0.72
Observations	298	298	298	298	298

Notes: This table establishes the robustness of our results to spatial autocorrelation, correcting the standard errors as suggested in Conley (1999). We do so by estimating the full specification, including all the controls as in Table 4, column (5), and cluster all neighboring observations in 20 km, 35 km, 60 km, 85 km and 100 km. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

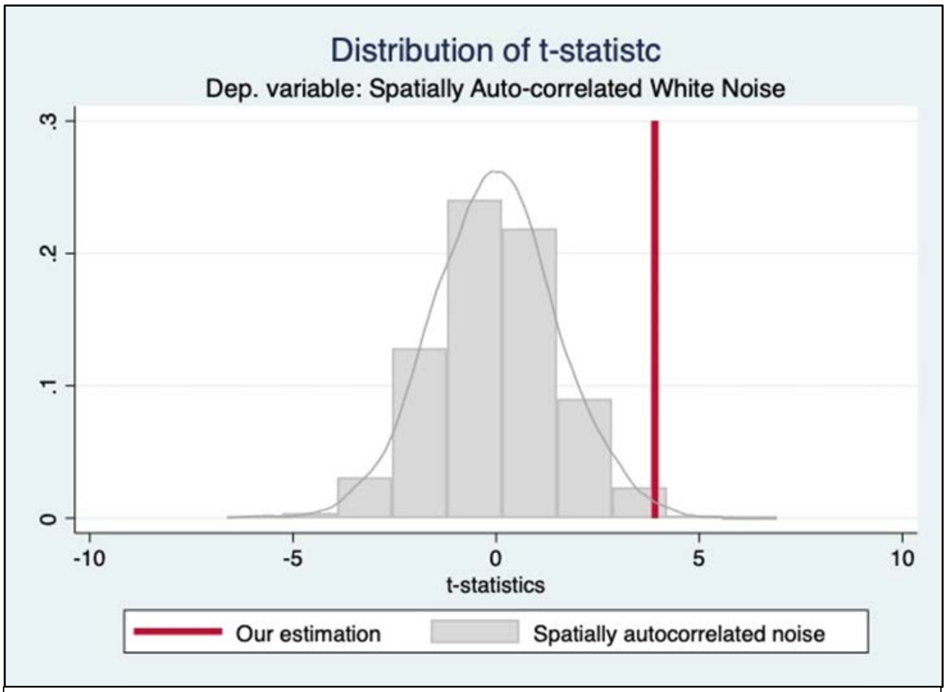


Figure B1: Spatial autocorrelated noise (left) and mills per capita (right)

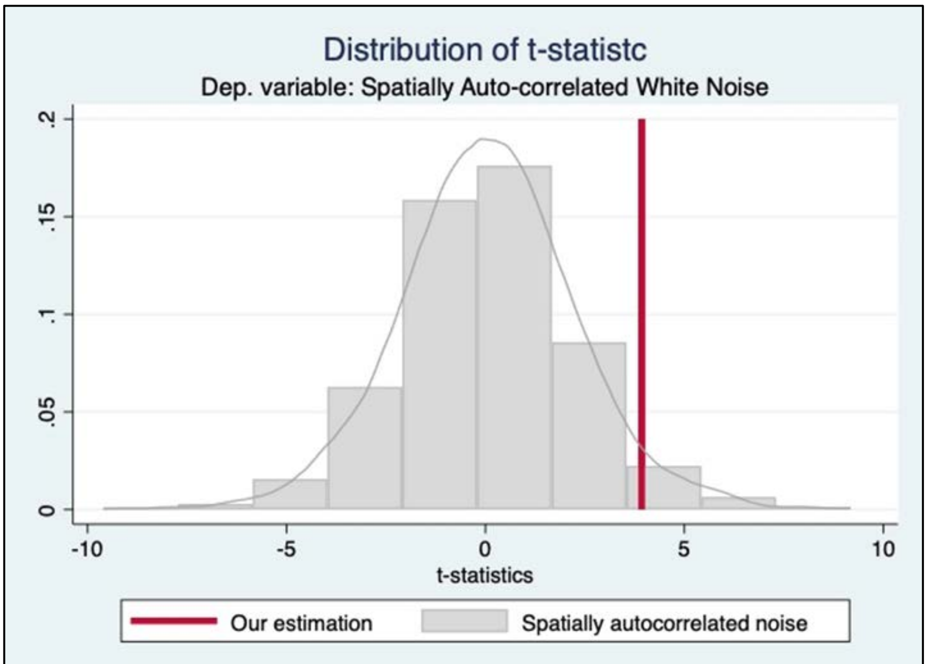


Figure B2: Spatial autocorrelated noise (left) and wrights per capita (right)

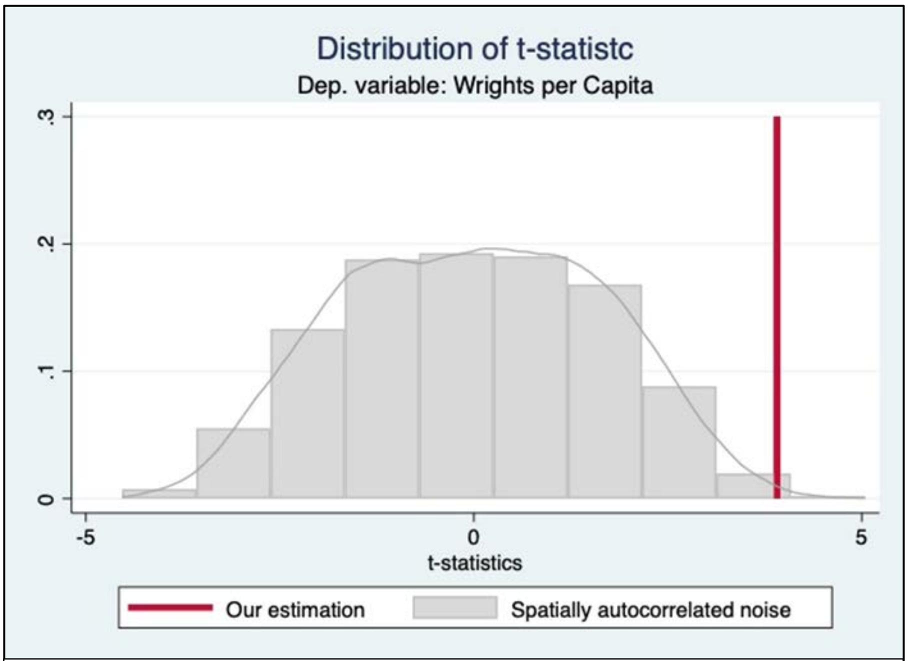


Figure B3: Wrights per capita (left) and spatially autocorrelated white noise (right)

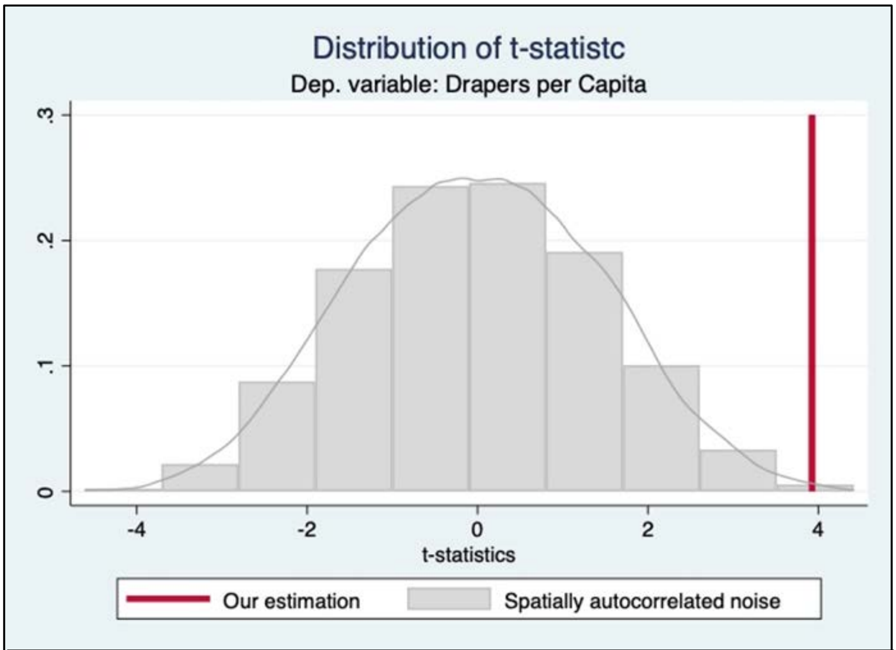


Figure B4: Drapers per capita (left) and spatially autocorrelated white noise (right)

Appendix C: Omitting the City of London

Table C.1. Domesday Mills and the Numbers of Apprentices to Wrights Omitting the City of London

	No. of Wright Apprentices per capita					
	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)
Watermills (per capita)	0.15***	0.16***	0.13***	0.15***	0.12***	0.15***
	(0.02)	(0.04)	(0.03)	(0.04)	(0.03)	(0.04)
River Suitability		24.40		160.08		165.75
		(36.33)		(118.85)		(113.40)
Wheat suitability		12.34*		11.71		8.95
		(7.03)		(8.69)		(8.18)
Main geographic controls	No	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	Yes	Yes	Yes	Yes
Other geographic controls	No	No	No	No	Yes	Yes
First-stage F-statistic		19.93		16.49		17.62
Adjusted-R^2	0.57	0.57	0.59	0.59	0.59	0.59
Observations	297	297	297	297	297	297

Notes: This table establishes a robustness check that the results do not depend on London as a commercial center of England. It establishes the statistically and economically positive effect of the number of Domesday mills in a district on the number of wright apprentices omitting London, and controlling for the district's population, main geographic controls (area, latitude mean ruggedness, mean elevation, total river length), agricultural controls (agricultural suitability, suitability to grow pasture and wheat), climatic controls (mean precipitation and temperature), and other geographical controls (Distance from London, main eighteenth century harbors, a historical Roman road and a navigable river). To mitigate endogeneity problems, the analysis uses the number of geographical suitability for establishing grain griding mills as an IV for the number of Domesday mills. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table C.2. Domesday Mills and the Numbers of Apprentices in Mechanized *vs*. Non-Mechanized Industries - Omitting the City of London

	No. of Apprentices									
	Draper	Weaber	Smith	Blacksmith	Joiner	Trader	Butcher	Attorney	Surgeon	Apothecary
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Watermills (per capita)	0.12***	0.19**	0.09**	0.13***	0.16	0.02**	0.28	0.15	0.06	0.13
	(0.04)	(0.08)	(0.04)	(0.05)	(0.11)	(0.01)	(0.19)	(0.13)	(0.04)	(0.11)
Wheat suitability	3.24	70.48	4.42	3.96	2.02	-0.05	-15.08	-4.17	-6.80*	-5.07
	(6.86)	(48.56)	(3.62)	(5.64)	(9.55)	(3.05)	(16.59)	(9.51)	(3.54)	(7.81)
River Suitability	127.96	788.40*	18.11	238.87**	201.93*	32.22*	-39.03	358.59***	115.77**	179.24*
	(106.92)	(454.43)	(47.00)	(106.35)	(107.64)	(19.57)	(206.38)	(122.89)	(58.22)	(105.39)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	17.62	17.62	17.62	17.62	17.62	17.62	17.62	17.62	17.62	17.62
Adjusted-R^2	0.30	0.15	0.55	0.62	0.41	0.15	0.61	0.51	0.52	0.35
Observations	297	297	297	297	297	297	297	297	297	297

Notes: This table shows that our results are robust to omitting the City of London. It establishes that the number of wright apprentices mainly affects the number of draper, weaver, smith and blacksmith apprentices, rather than other occupation apprentices. It does so by instrumenting the number of wright apprentices per capita by the geographical IV described above, and controlling for all geographic, climatic, agricultural and economic characteristics in all previous tables. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table C.3. Apprentices to Wrights *vs*. Domesday Mills - Omitting the City of London

	No. of Apprentices per Capita											
	Draper			Weaver			Smith			Blacksmith		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Wrights (per capita)	0.37***		0.31**	1.44***		0.88***	0.31***		0.23***	0.91***		0.70***
	(0.12)		(0.13)	(0.37)		(0.28)	(0.05)		(0.08)	(0.10)		(0.17)
Watermills (per capita)		0.06**	0.02		0.29***	0.18***		0.06***	0.03**		0.16***	0.07**
		(0.03)	(0.03)		(0.07)	(0.06)		(0.01)	(0.01)		(0.03)	(0.03)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Percentage of Mediation			0.67			0.37			0.50			0.54
Adjusted-R^2	0.45	0.39	0.45	0.14	0.15	0.16	0.65	0.60	0.68	0.70	0.62	0.73
Observations	297	297	297	297	297	297	297	297	297	297	297	297

Notes: This Table shows the results of a mediation analysis, based on Imai et al. (2010a, 2010b, 2011), this time without London. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix D: Robustness to coal

Table D.1. Domesday Mills and the Numbers of Apprentices to Wrights Robustness to the Potential availability of Coal

	No. of Wright Apprentices per capita					
	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)
Watermills (per capita)	0.15***	0.16***	0.13***	0.16***	0.13***	0.16***
	(0.02)	(0.04)	(0.03)	(0.04)	(0.03)	(0.04)
Carboniferous Strata	0.27	3.77	14.05*	17.49*	18.30**	21.20**
	(6.94)	(8.29)	(7.95)	(9.28)	(7.55)	(8.82)
River Suitability		18.15		159.00		165.70
		(42.58)		(117.41)		(111.23)
Wheat suitability		12.41*		12.70		10.14
		(6.99)		(8.87)		(8.38)
Main geographic controls	No	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	Yes	Yes	Yes	Yes
Other geographic controls	No	No	No	No	Yes	Yes
First-stage F-statistic		18.32		17.21		18.28
Adjusted-R^2	0.57	0.56	0.58	0.59	0.59	0.59
Observations	298	298	298	298	298	298

Notes: This table establishes a robustness check that the results do not depend on having a carboniferous strata in the district. It establishes the statistically and economically positive effect of the number of Domesday mills in a district on the number of wright apprentices omitting London, and controlling for the district's population, main geographic controls (area, latitude mean ruggedness, mean elevation, total river length), agricultural controls (agricultural suitability, suitability to grow pasture and wheat), climatic controls (mean precipitation and temperature), and other geographical controls (Distance from London, main eighteenth century harbors, a historical Roman road and a navigable river). To mitigate endogeneity problems, the analysis uses the number of geographical suitability for establishing grain griding mills as an IV for the number of Domesday mills. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table D.2. Apprentices to Wrights and Textile Manufacturing (Drapers)
Robustness to the Potential availability of Coal

	No. of Draper Apprentices per Capita					
	All Sample					DB Sample
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	0.43***	0.36***	0.36***	0.36***	0.41***	0.37***
	(0.14)	(0.12)	(0.12)	(0.13)	(0.13)	(0.13)
Carboniferous Strata	9.08	10.99	6.48	3.32	-5.94	-5.52
	(6.25)	(7.90)	(8.47)	(9.82)	(12.15)	(14.00)
Geographical controls	No	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes
Other economic controlas	No	No	No	No	Yes	Yes
Adjusted-R^2	0.27	0.35	0.34	0.35	0.40	0.44
Observations	325	325	325	325	325	298

Notes: This table replicates our results in Table 5, controlling for the existence of carboniferous strata in the district. This hardly affects the results, suggesting that our results are robust for the existence of carboniferous strata in the district. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table D.3. Domesday Mills and the Numbers of Apprentices in Mechanized *vs*. Non-Mechanized Industries - Robustness to the Potential availability of Coal

	No. of Apprentices									
	Draper	Weaver	Smith	Blacksmith	Joiner	Trader	Butcher	Attorney	Surgeon	Apothecary
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Watermills (per capita)	0.12***	0.19**	0.09**	0.13***	0.16	0.00	0.28	0.15	0.06	0.13
	(0.04)	(0.08)	(0.04)	(0.05)	(0.11)	(0.04)	(0.18)	(0.13)	(0.04)	(0.10)
Carboniferous Strata	7.94	1.56	14.62	9.66	42.93*	49.41	41.66	41.01*	13.97**	28.58*
	(14.72)	(40.02)	(9.95)	(13.63)	(26.00)	(43.31)	(31.02)	(21.24)	(6.11)	(15.91)
Wheat suitability	4.37	71.51	4.98	4.80	5.86	42.73	-12.81	-1.28	-6.08*	-3.10
	(6.85)	(48.48)	(3.58)	(5.51)	(9.96)	(40.37)	(16.36)	(9.56)	(3.66)	(7.78)
River Suitability	130.85	792.41*	16.95	240.10**	207.92**	203.43	-39.45	360.98***	115.45**	180.70*
	(106.92)	(451.77)	(45.43)	(105.00)	(101.22)	(187.12)	(199.25)	(116.05)	(55.62)	(101.22)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	18.28	18.28	18.28	18.28	18.28	18.28	18.28	18.28	18.28	18.28
Adjusted-R^2	0.30	0.15	0.55	0.62	0.40	0.02	0.61	0.51	0.52	0.35
Observations	298	298	298	298	298	298	298	298	298	298

Notes: This table replicates Table 4 and shows that our results are robust to controlling if the district lies on a carboniferous strata. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix E: Robustness of the IV

Table E.1. Orthogonality of the IV to All Pre-Existing Conditions

	Mill Suitability													
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Area	0.20***													
	(0.06)													
Latitude		-0.01												
		(0.01)												
Ruggedness (mean)			0.01											
			(0.01)											
Elevation (mean)				0.03										
				(0.02)										
Agricultural Suitability					0.10									
					(0.07)									
Pasture Suitability (mean)						-0.03**								
						(0.01)								
Total River Length (km)							0.11***							
							(0.03)							
Precipitation (mean)								-0.10						
								(0.08)						
Temperature (mean)									-0.04					
									(0.02)					
Dist. to Nearest Harbor										0.04				
										(0.03)				
Dist. from London											-0.14			
											(0.14)			
Dist. to Nearest Roman Road												-0.25***		
												(0.07)		
Dist. to Nearest Navigable River													-0.08***	
													(0.03)	
Population, mean (10 thousand)														-0.03***
														(0.01)
Adjusted-R^2	0.38	0.00	-0.00	0.01	0.01	0.01	0.40	0.00	0.02	0.01	0.00	0.05	-0.00	0.06
Observations	298	298	298	298	298	298	298	298	298	298	298	298	298	298

Notes: This table establishes the orthogonality of the geographical instrument to most of the pre-exisiting conditions in the districts. In particular, it shows that almost all the controls used in the paper are not correlated with the geographical instrument. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table E.2. Domesday Mills and the Numbers of Apprentices to Wrights
Robustness to Different Levels of River Ruggedness

	No. of Apprentices									
	2-6	0-1	1-3	1-4	1-5	1-6	2-3	2-4	2-5	10-20
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Watermills (per capita)	0.15***	0.29*	0.14***	0.14***	0.14***	0.14***	0.14***	0.15***	0.15***	0.21*
	(0.04)	(0.17)	(0.05)	(0.05)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.12)
Wheat suitability	9.34	3.81	7.88	8.23	8.48	8.59	7.73	8.79	9.17	6.41
	(8.23)	(7.21)	(7.33)	(7.40)	(7.56)	(7.63)	(7.62)	(7.82)	(8.11)	(6.19)
River Suitability	167.46									
	(113.43)									
River Suitability		-155.21								
		(103.65)								
River Suitability			212.47*							
			(123.53)							
River Suitability				187.36*						
				(104.09)						
River Suitability					163.86*					
					(94.31)					
River Suitability						152.55*				
						(87.49)				
River Suitability							571.06**			
							(270.92)			
River Suitability								298.05*		
								(166.37)		
River Suitability									205.44	
									(132.52)	
River Suitability										-120.90***
										(45.08)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	17.61	1.60	7.60	10.00	11.83	13.29	14.43	15.65	16.62	1.33
Adjusted-R^2	0.59	0.19	0.61	0.61	0.61	0.61	0.62	0.61	0.60	0.52
Observations	298	298	298	298	298	298	298	298	298	298

Notes: This table establishes a robustness check to different levels of river ruggedness. In particular, it shows that our IV is robust to other moderate levels of ruggedness of the rivers in the district. For weak flows of rivers, however (columns (2)-(4)), or high flows (column (10)), the first stage F-statistic is too low, suggesting that too low river flows do not predict the location of the DB mills well enough. All our usual controls are included in all specifications. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table E.3. Domesday Mills and the Numbers of Apprentices to Wrights
Robustness to Different Levels of Wheat Suitability

	No. of Wright Apprentices								
	≤ 5	≤ 3	≤ 4	≤ 4.5	≤ 4.8	≤ 5.3	≤ 5.9	≤ 6	≤ 7
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Watermills (per capita)	0.15***	-0.00	0.18**	0.16**	0.17***	0.15***	0.16***	0.22***	0.40
	(0.04)	(0.13)	(0.08)	(0.07)	(0.05)	(0.03)	(0.04)	(0.03)	(0.28)
River Suitability	167.46	241.59*	147.77	161.46	160.31	171.65	163.46	141.27	58.34
	(113.43)	(144.77)	(128.75)	(124.42)	(118.47)	(108.51)	(109.04)	(142.05)	(264.22)
Wheat suitability	9.34								
	(8.23)								
Wheat suitability		5.09							
		(13.66)							
Wheat suitability			17.07						
			(11.27)						
Wheat suitability				18.28**					
				(7.71)					
Wheat suitability					11.16				
					(9.39)				
Wheat suitability						0.39			
						(6.55)			
Wheat suitability							-6.30		
							(5.82)		
Wheat suitability								4.44	
								(6.92)	
Wheat suitability									-4.16
									(15.25)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	17.61	1.92	2.38	2.55	12.81	23.39	15.02	6.32	1.19
Adjusted-R^2	0.59	0.36	0.57	0.59	0.57	0.60	0.58	0.47	-0.59
Observations	298	298	298	298	298	298	298	298	298

Notes: This table establishes a robustness check to different levels of wheat suitability. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table E.4. Domesday Mills and the Numbers of Apprentices to Wrights
1st Stage & Reduced Form

	No. of Domesday Mills per capita		
	(1)	(2)	(3)
DB Mill Suitability	1838.59***	1709.09***	1757.44***
	(412.12)	(420.81)	(418.84)
River Suitability	316.25	-708.79	-719.36
	(198.80)	(683.85)	(670.43)
Wheat suitability	-106.60***	-106.72***	-154.91***
	(31.09)	(34.84)	(46.36)
Main geographic controls	No	Yes	Yes
Agricultural controls	No	Yes	Yes
Climatic controls	No	Yes	Yes
Other geographic controls	No	No	Yes
Adjusted-R^2	0.44	0.50	0.52
Observations	298	298	298
	No. of Wright Apprentices per Capita		
	(1)	(2)	(3)
DB Mill Suitability	292.57***	265.23***	271.98***
	(81.38)	(79.34)	(74.06)
River Suitability	73.13**	51.69	56.13
	(29.97)	(118.65)	(107.57)
Wheat suitability	-5.18	-4.70	-14.63
	(8.70)	(10.05)	(9.29)
Main geographic controls	No	Yes	Yes
Agricultural controls	No	Yes	Yes
Climatic controls	No	Yes	Yes
Other geographic controls	No	No	Yes
Adjusted-R^2	0.37	0.41	0.45
Observations	298	298	298

Notes: Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table E.5. Domesday Mills and the Numbers of Apprentices in Mechanized *vs*. Non-Mechanized Industries
1st Stage & Reduced Form

	No. of Apprentices per Capita									
	Draper	Weaver	Smith	Blacksmith	Joiner	Trader	Butcher	Attorney	Surgeon	Apothecary
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
DB Mill Suitability	216.72***	336.97	151.58**	219.30**	271.17	1.32	491.22	263.32	110.42	220.50
	(62.69)	(215.57)	(66.87)	(103.19)	(180.76)	(71.27)	(310.42)	(227.60)	(72.82)	(175.16)
Wheat suitability	-15.03	41.75	-8.93	-14.90	-19.65	40.76	-57.67	-26.03	-16.33*	-23.61
	(9.37)	(44.41)	(7.34)	(12.36)	(21.09)	(45.26)	(36.42)	(24.57)	(8.68)	(18.94)
River Suitability	42.81	654.61	-43.88	151.13	100.48	206.98	-237.06	256.60*	71.41	92.81
	(100.45)	(485.04)	(55.88)	(141.32)	(140.63)	(222.86)	(254.03)	(147.55)	(68.53)	(133.14)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.40	0.10	0.50	0.43	0.46	0.03	0.50	0.49	0.47	0.45
Observations	298	298	298	298	298	298	298	298	298	298

Notes: This table establishes the reduced form of Table 5. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix F: Additional Results

Table F.1. Apprentices to Wrights and Apprentices to Weavers

	No. of Weaver Apprentices per Capita					
	All Sample					DB Sample
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	1.68***	1.70***	1.60***	1.61***	1.47***	1.44***
	(0.45)	(0.60)	(0.54)	(0.54)	(0.40)	(0.36)
Geographical controls	No	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes
Other economic controlas	No	No	No	No	Yes	Yes
Adjusted-R^2	0.14	0.13	0.13	0.13	0.15	0.15
Observations	325	325	325	325	325	298

Notes: This table replicates Table 4, but for weaver apprentices instead of draper apprentices. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table F.2. Apprentices to Wrights and Apprentices to Smiths

	No. of Smith Apprentices per Capita					
	All Sample					DB Sample
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	0.41***	0.31***	0.31***	0.32***	0.31***	0.31***
	(0.07)	(0.05)	(0.05)	(0.05)	(0.06)	(0.05)
Geographical controls	No	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes
Other economic controlas	No	No	No	No	Yes	Yes
Adjusted-R^2	0.57	0.69	0.69	0.69	0.69	0.65
Observations	325	325	325	325	325	298

Notes: This table replicates Table 4, but for smith apprentices instead of draper apprentices. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table F.3. Apprentices to Wrights and Apprentices to Blacksmiths

	No. of Blacksmith Apprentices per Capita					
	All Sample					DB Sample
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	1.08***	0.89***	0.91***	0.91***	0.91***	0.91***
	(0.08)	(0.09)	(0.10)	(0.10)	(0.10)	(0.10)
Geographical controls	No	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes
Other economic controlas	No	No	No	No	Yes	Yes
Adjusted-R^2	0.66	0.73	0.73	0.73	0.72	0.70
Observations	325	325	325	325	325	298

Notes: This table replicates Table 4, but for blacksmith apprentices instead of draper apprentices. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table F.4. Domesday Mills, Apprentices to Wrights and High levels of Water Flows

	First Stage			Reduced Form			IV		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
High Flows Suitability	376.12	290.06	315.63	73.95	63.25	66.69*			
	(303.87)	(279.06)	(273.60)	(48.02)	(37.61)	(36.60)			
Watermills (per capita)							0.20**	0.22	0.21*
							(0.10)	(0.14)	(0.12)
River Suitability	470.91***	136.52	109.83	47.58***	-87.87**	-96.60**	-45.01	-117.64**	-120.90***
	(125.31)	(217.02)	(220.59)	(10.68)	(41.40)	(37.50)	(71.71)	(46.96)	(45.08)
Wheat suitability	22.85	19.72	-31.07	14.73	10.65	0.91	10.23	6.35	6.41
	(71.14)	(48.72)	(50.16)	(14.04)	(9.35)	(7.93)	(9.42)	(10.63)	(6.19)
Main geographic controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Agricultural controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Climatic controls	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Other geographic controls	No	No	Yes	No	No	Yes	No	No	Yes
First-stage F-statistic							1.53	1.08	1.33
Adjusted-R^2	0.38	0.41	0.44	0.22	0.34	0.38	0.53	0.51	0.52
Observations	298	298	298	298	298	298	298	298	298

Notes: This table establishes a robustness check of the instrument. In particular, it shows that high water flows are not correlated with DB mills (columns (1)-(3)), and thus such a relation perform as a poor first stage. Second, the reduced form (columns (4)-(6)) also show that high water flows are only weakly correlated with the number of wrights per capita, and the statistical significance depend on the controls included in the regression. Finally, when high water flows are used as an IV to mills per capita (columns (7)-(9)), they are a very weak instrument, which poorly predicts the number of wrights per capita. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table F.5. Domesday Mills and the Numbers of Apprentices in Mechanized *vs.* Non-Mechanized Industries and High levels of Water Flows

	No. of Apprentices per capita									
	Draper	Weaver	Smith	Blacksmith	Joiner	Trader	Butcher	Attorney	Surgeon	Apoth
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(1(
High Flows Suitability	54.82**	-21.32	34.15	43.29	-1.21	8.63	-30.82	29.43	9.88	-36.52
	(26.34)	(48.18)	(23.67)	(50.65)	(49.04)	(22.20)	(94.99)	(55.83)	(25.36)	(41.05
Wheat suitability	-3.79	49.94*	-0.22	1.02	16.90	39.52	14.86	0.78	-4.54	17.46*
	(8.94)	(25.01)	(4.60)	(12.18)	(12.37)	(40.60)	(20.47)	(10.86)	(6.27)	(9.03)
River Suitability	-90.81***	9.69	-30.50	-41.62	-89.91	-16.15	43.43	-136.37	-50.39	-35.46
	(27.03)	(46.07)	(27.24)	(43.82)	(76.50)	(26.42)	(135.52)	(88.43)	(30.49)	(75.29
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.34	0.17	0.43	0.38	0.41	0.02	0.46	0.44	0.44	0.40
Observations	298	298	298	298	298	298	298	298	298	298

Notes: This table establishes that high water flows are not associated with any profession (but drapers). the number of wrigl apprentices mainly affects the number of draper, clothier, smith and blacksmith apprentices, rather than other occupation apprentice It does so by instrumenting the number of wright apprentices per capita by the geographical IV described above, and controllir for all geographic, climatic, agricultural and economic characteristics in all previous tables. Heteroskedasticity robust standard err estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% leve all for two-sided hypothesis tests; All regressions include a constant.

Table F.6. Domesday Institutions and the Numbers of Apprentices to Wrights

	No. of Wright Apprentices per capita				
	(1)	(2)	(3)	(4)	(5)
Watermills (per capita)	0.15***	0.15***	0.16***	0.15***	0.09**
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
Wheat suitability	9.34	9.20	6.84	10.48	5.12
	(8.23)	(8.30)	(7.70)	(8.46)	(3.76)
River Suitability	167.46	167.68	174.63	168.35	19.64
	(113.43)	(113.59)	(110.57)	(113.21)	(47.36)
King's Vill Share		4.17			-7.31
		(17.61)			(14.90)
Ecclesiastical's Vill Share			52.79**		8.80
			(24.03)		(7.91)
Lords share of arable land				27.16	20.43
				(21.11)	(13.13)
Geographical controls	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes
Other Geographic controls	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	17.61	17.45	17.57	17.52	17.34
Adjusted-R^2	0.59	0.59	0.60	0.59	0.55
Observations	298	298	298	298	298

Notes: Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix G: Replication of the Results with Full Specification

Table G.1. Domesday Mills and the Numbers of Apprentices to Wrights

	No. of Wright Apprentices per capita					
	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)
Watermills (per capita)	0.15***	0.16***	0.13***	0.16***	0.12***	0.15***
	(0.02)	(0.04)	(0.03)	(0.04)	(0.03)	(0.04)
River Suitability		22.80		161.68		167.46
		(36.50)		(119.09)		(113.43)
Wheat suitability		11.79*		11.87		9.34
		(7.04)		(8.68)		(8.23)
Area			88.57*	79.33*	92.70*	76.51*
			(46.01)	(43.52)	(47.92)	(43.79)
Latitude			-10.50	-0.39	16.22	28.88**
			(7.91)	(7.26)	(12.42)	(12.33)
Ruggedness (mean)			-0.25	1.13	2.77	3.20
			(3.78)	(3.09)	(4.53)	(4.07)
Elevation (mean)			-17.93	-23.84	-18.15	-21.92
			(15.90)	(17.36)	(15.71)	(17.45)
Agricultural Suitability			-38.89	-35.27	-43.57	-44.76*
			(27.82)	(23.83)	(27.00)	(27.21)
Pasture Suitability (mean)			-16.33	-14.70	0.26	5.90
			(12.33)	(12.43)	(16.35)	(16.74)
Total River Length (km)			-35.75	-67.86*	-33.19	-64.51
			(29.26)	(39.98)	(28.34)	(39.28)
Precipitation (mean)			-57.79	-23.23	-5.68	25.83
			(55.17)	(48.52)	(60.17)	(53.08)
Temperature (mean)			-19.50	-7.38	-5.31	4.77
			(11.61)	(13.31)	(15.13)	(23.45)
Dist. to Nearest Harbor					39.65**	30.59*
					(16.08)	(17.56)
Dist. from London					-226.09***	-280.17***
					(81.50)	(78.21)
Dist. to Nearest Roman Road					-20.34	9.07
					(19.35)	(35.33)
Dist. to Nearest Navigable River					5.71	2.36
					(12.11)	(10.84)
Population, mean (10 thousand)						-3.54
						(3.45)
First-stage F-statistic		19.90		16.50		17.61
Adjusted-R^2	0.57	0.57	0.58	0.59	0.59	0.59
Observations	298	298	298	298	298	298

Notes: This table replicates Table 3, but displays explicitly all controls. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table G.2. Domesday Mills and the Numbers of Apprentices in Mechanized *vs*. Non-Mechanized Industries

	No. of Apprentices per capita									
	Draper	Weaver	Smith	Blacksmith	Joiner	Trader	Butcher	Attorney	Surgeon	Apothecary
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Watermills (per capita)	0.12***	0.12***	0.09**	0.12***	0.15	0.00	0.28	0.15	0.06	0.13
	(0.04)	(0.03)	(0.04)	(0.05)	(0.11)	(0.04)	(0.19)	(0.13)	(0.04)	(0.11)
Wheat suitability	4.07	32.85*	4.43	4.43	4.25	40.87	-14.37	-2.82	-6.60*	-4.17
	(6.87)	(19.19)	(3.61)	(5.69)	(9.99)	(39.22)	(16.57)	(9.67)	(3.52)	(7.95)
River Suitability	131.51	340.83**	18.16	240.90**	211.48*	207.52	-35.99	364.38***	116.61**	183.07*
	(107.34)	(154.97)	(47.01)	(106.57)	(109.17)	(193.02)	(206.92)	(123.57)	(58.26)	(105.74)
Area	13.41	-124.28	24.28	74.45	11.37	25.01	-102.46	-21.94	-12.40	7.03
	(52.75)	(91.24)	(27.28)	(56.36)	(79.82)	(56.10)	(123.57)	(89.39)	(44.21)	(69.37)
Latitude	-53.87***	60.04	15.87*	23.89	33.28	116.08	51.17	45.84	6.18	27.42
	(13.93)	(57.49)	(8.27)	(16.64)	(25.25)	(128.29)	(42.46)	(31.69)	(12.02)	(25.10)
Ruggedness (mean)	-1.25	14.16	0.10	-1.73	5.84	69.41	2.04	-2.10	-3.09	10.56
	(5.07)	(17.77)	(2.42)	(6.59)	(6.34)	(69.51)	(11.48)	(8.90)	(4.78)	(9.54)
Elevation (mean)	-1.15	-33.87	10.61	-3.78	5.27	-155.45	42.32	15.36	18.65	-48.04
	(18.84)	(34.24)	(12.24)	(31.15)	(34.70)	(142.41)	(52.13)	(39.04)	(18.80)	(42.19)
Agricultural Suitability	16.75	6.87	-16.04	-13.85	-35.68	377.73	-44.39	-67.25	-28.25*	-24.13
	(17.98)	(60.65)	(13.57)	(24.57)	(47.75)	(358.59)	(59.17)	(45.65)	(16.27)	(33.24)
Pasture Suitability (mean)	-44.14***	-18.59	13.61	1.34	35.50	-33.11	46.78	34.38	9.11	9.81
	(13.45)	(37.95)	(14.70)	(27.67)	(47.21)	(50.35)	(71.62)	(50.09)	(15.94)	(42.18)
Total River Length (km)	-31.01	33.60	-9.75	-43.36	-9.94	-25.37	137.39*	2.44	11.27	-2.76
	(31.93)	(38.54)	(17.67)	(35.37)	(48.92)	(35.19)	(83.14)	(53.81)	(30.67)	(40.64)
Precipitation (mean)	65.67	139.90	6.92	96.68	-58.35	594.90	-131.69	121.12	-2.73	169.66
	(91.07)	(108.18)	(33.38)	(106.32)	(130.14)	(599.73)	(135.14)	(111.71)	(42.93)	(158.05)
Temperature (mean)	2.93	47.08	2.72	7.13	13.00	124.72	9.91	31.37	14.60	-12.33
	(18.76)	(81.21)	(12.74)	(32.22)	(27.94)	(162.37)	(49.76)	(33.78)	(13.19)	(27.48)
Dist. to Nearest Harbor	-41.67***	99.84	8.55	33.04	-0.59	69.89	24.43	27.61	23.36*	9.73
	(16.08)	(73.27)	(12.14)	(21.02)	(24.59)	(62.99)	(40.24)	(30.47)	(12.35)	(22.32)
Dist. from London	497.06***	-191.73	-103.64	-200.14	-45.84	-269.59	-329.06	-245.50	-34.48	-238.71
	(128.86)	(311.79)	(70.06)	(132.05)	(222.04)	(475.73)	(373.02)	(239.22)	(86.12)	(221.66)
Dist. to Nearest Roman Road	11.10	49.10	13.47	-26.87	45.12	-173.56	-14.48	147.36	111.57***	41.27
	(45.35)	(76.11)	(31.01)	(45.74)	(77.74)	(175.31)	(155.98)	(104.06)	(38.93)	(85.49)
Dist. to Nearest Navigable River	-14.26	-17.68	-2.55	19.13	-32.57	-55.54	25.26	-38.42	-37.90**	2.01
	(17.62)	(34.09)	(8.26)	(20.32)	(22.63)	(56.82)	(34.26)	(24.92)	(17.95)	(27.52)
Population, mean (10 thousand)	4.14	5.70	1.23	0.85	2.46	77.35	-3.37	0.27	-2.92	3.77
	(2.54)	(9.71)	(1.40)	(3.61)	(4.42)	(50.72)	(5.93)	(4.92)	(2.09)	(3.71)
First-stage F-statistic	17.61	17.61	17.61	17.61	17.61	17.61	17.61	17.61	17.61	17.61
Adjusted-R^2	0.30	0.26	0.55	0.62	0.40	0.03	0.61	0.51	0.52	0.34
Observations	298	298	298	298	298	298	298	298	298	298

Notes: This table replicates Table 5, but displaying the coefficients of the full specification. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table G.3. Apprentices to Wrights and Textile Manufacturing (Drapers)

	No. of Draper Apprentices per Capita					
	All Sample					DB Sample
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	0.43***	0.35***	0.36***	0.36***	0.41***	0.37***
	(0.14)	(0.12)	(0.12)	(0.13)	(0.13)	(0.13)
Area		29.53	25.54	17.43	3.99	-8.98
		(19.06)	(40.72)	(40.63)	(50.12)	(50.92)
Latitude		-11.99**	-6.56	-9.94	-68.45***	-62.85***
		(5.75)	(4.45)	(8.27)	(16.73)	(16.43)
Ruggedness (mean)		5.04	2.27	-0.11	-4.34	-2.35
		(4.27)	(5.23)	(5.39)	(5.27)	(5.99)
Elevation (mean)		4.56	13.18	-1.79	1.20	7.32
		(9.99)	(13.43)	(17.05)	(17.63)	(19.67)
Agricultural Suitability			13.19	42.90**	45.75**	37.65*
			(15.19)	(19.85)	(21.06)	(20.26)
Wheat suitability			2.86	5.09	6.18	5.62
			(6.41)	(5.85)	(5.66)	(5.84)
Pasture Suitability (mean)			14.85	-0.55	-48.18***	-52.72***
			(11.03)	(12.30)	(14.38)	(16.45)
Total River Length (km)			1.99	6.52	6.91	23.85
			(22.72)	(22.35)	(25.64)	(23.40)
Precipitation (mean)				160.44**	83.18	66.02
				(74.73)	(70.27)	(88.66)
Temperature (mean)				6.72	0.80	15.32
				(13.96)	(19.18)	(17.75)
Population, mean (10 thousand)					4.98*	6.00*
					(2.80)	(2.97)
Dist. to Nearest Harbor					-43.28**	-39.06**
					(16.32)	(15.48)
Dist. from London					579.18***	596.90***
					(137.10)	(148.95)
Dist. to Nearest Roman Road					-21.62	-30.81
					(42.60)	(45.75)
Dist. to Nearest Navigable River					-13.13	-5.50
					(14.27)	(17.13)
Adjusted-R^2	0.27	0.35	0.35	0.35	0.41	0.44
Observations	325	325	325	325	325	298

Notes: This table replicates Table 4, but displays the coefficients of the full specification. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

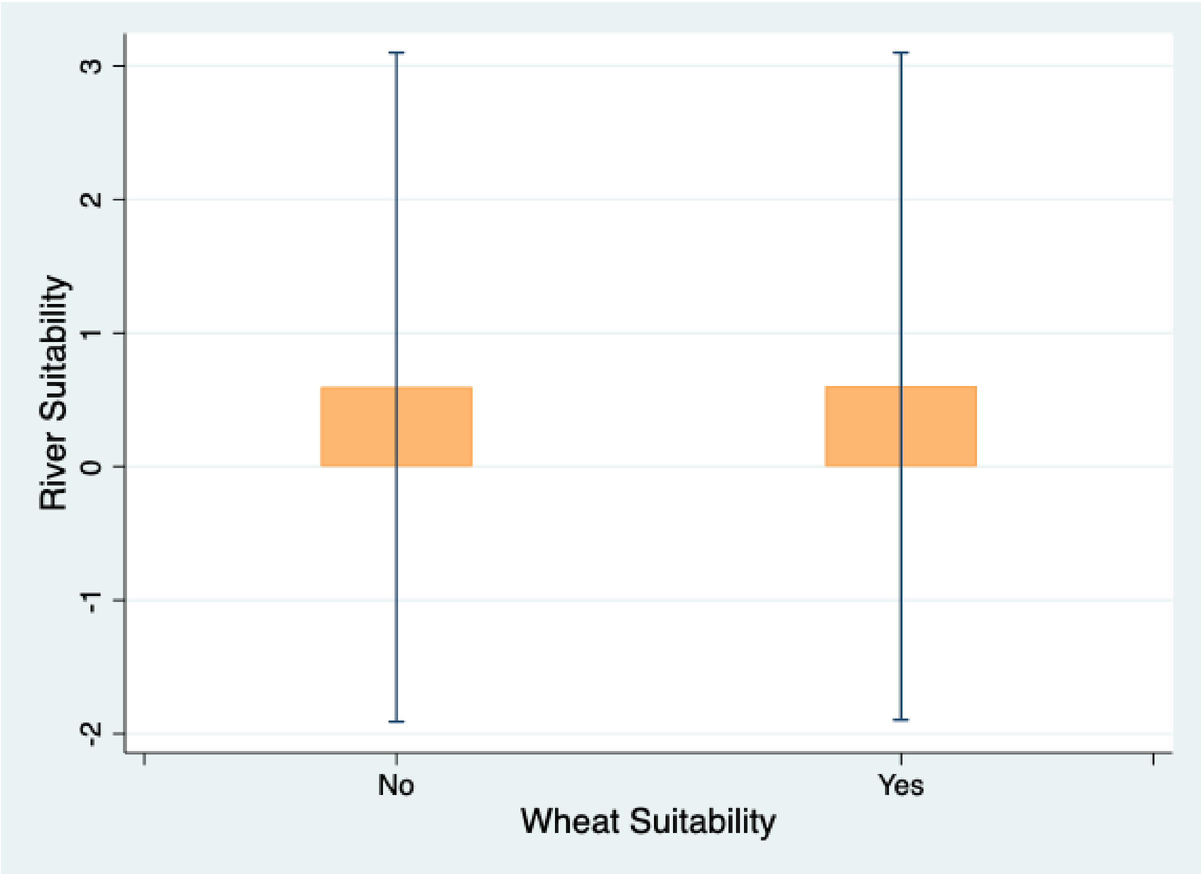


Figure G.1: The mean level of river suitability in district which are suitable for wheat cultivation and not suitable for wheat cultivation, controlling for the district's area, latitude, mean ruggedness, mean elevation, agricultural suitability, potential for pasture cultivation, total river length, distance to London, nearest navigable river and a Roman road, as well as to the district's population. The mean level of river suitability is in orange, and its confidence interval is in blue bars. The figure shows that there is no observed difference between the mean of river suitability for the two levels of wheat suitability.

Appendix H: Historical Background

Millwrights have long been recognized as a high-skill occupation, playing a crucial role in the Industrial Revolution. In a widely-cited passage, the great engineer William Fairbairn wrote in the 1850s that "the millwright of former days was to a great extent the sole representative of mechanical arts, and was looked upon as the authority of all the applications of wind and water ... as a motive power. He was the engineer of the district in which he lived, a kind of jack-of-all-trades, who could with equal facility work the lathe, the anvil, or the carpenter's bench." He was an itinerant engineer and mechanic of high reputation who could "turn, bore and forge ... was a fair arithmetician who knew something of geometry and do much of the work now done by civil engineers" (Fairbairn, 1861, pp. v-vi). Anton Howes's sample of 400 innovators in the period before and during the Industrial Revolution shows that almost a quarter of them were millwrights or similarly trained craftsmen such as "mechanics" and "engineers" (Howes, 2016, pp. 22-23).

While Fairbairn was describing the millwrights of the early nineteenth century, matters were similar five centuries earlier when the abilities of millwrights and high-end carpenters (two overlapping categories) were in high demand by millers because of the much-needed technical expertise that they brought to mill construction (Langdon, 2004, p. 203). These medieval "engineers" possessed little or no formal understanding of mechanics and relied on dexterity and the tacit knowledge they acquired as apprentices, Moreover, medieval millwrights were flexible enough to adapt to new demands on their competence as technology changed. In the twelfth century, the inanimate power provided by watermills was supplemented by the introduction of windmills. The adaptation of the mill mechanism to a new external source of power demonstrates a technical agility at a high level.[38] The same is true for the replacement of horizontal with vertical waterwheels between the tenth and the thirteenth centuries in England, although on the Continent horizontal wheels persisted. The vertical wheels were far more expensive and complicated to construct, but more efficient and perhaps associated with tighter seigneurial control.[39] Water mills were used primarily for flour milling and fulling; other industrial uses can be found but were probably not as common as the literature arguing for an Industrial Revolution in the Middle Ages suggests (Lucas, 2006, p. 262, 277). All the same, mills were commonplace in England, and Domesday Book lists about 6,000 watermills used almost exclusively for flour milling (Holt, 1988, p. 119). The high degree of expertise possessed by millwrights is consistent with the observation that many of the early medieval mills were built by Benedictine and Cistercian monks,

[38] Windmills needed to solve the problem of keeping the sails facing the wind; the fixed post that could be turned in a circle in its entirety became the dominant design to maintain that position.

[39] Tidal mills were known throughout Western Europe in the Middle Ages but their technology was not all that different from conventional watermills (Lucas, 2006, p. 86).

who embodied much of the top tier human capital and skills in the period (Bloch, 1966, p. 151; Lucas, 2006, pp. 154-66).

As Tann (1974) notes, as late as the early eighteenth-century millwrights were still working primarily with wood, but a few parts had to be made of iron (such as the iron hoop and plates that kept the vertical water wheel in place), thus requiring a breadth of expertise to work with various materials or an ability to cooperate with other artisans that went beyond simple carpentry (Holt, 1988, pp. 117-18, 123-25). A compendium of occupations published anonymously in London in 1747 maintained that even though millwrighting was a branch of carpentry, it was "very ingenious" and to understand and perform it well, a person must have "a good turn of mind for mechanics and at least some knowledge of arithmetic" (Anonymous, 1747, p. 151).

During the Industrial Revolution, the class of artisans trained as millwrights generated a large number of outstanding engineers and mechanics who contributed widely to technological advances in a variety of areas. Some of the great inventors of the period were trained as millwrights, above all Bryan Donkin, the co-inventor of food canning and a paper making machine, Andrew Meikle, the Scottish inventor of the threshing machine, and William Murdoch, Watt and Boulton's most able employee and co-inventor of gas lighting. So were the leading engineers James Brindley and John Rennie mentioned in the text.

Right below these well-known millwright-engineers was a cadre of millwrights with less name recognition, yet who played pivotal roles in the growth of the industries that made the Industrial Revolution and should be seen as "tweakers and implementers" (Meisenzahl and Mokyr, 2012). A few of those able but obscure mechanics are mentioned in Cookson's detailed work on the Yorkshire textile machinery industry, and illustrate the wide usefulness of well-trained artisans in the textile industry in the early stages of the Industrial Revolution.[40]

Yet the role of millwrights as a highly skilled source of mechanical competence has been disputed and Fairbairn's ebullient description has been contested. The early eighteenth century engineer and mathematician, John T. Desaguliers, one of the key figures in the British Industrial Enlightenment, was dismissive of the role of millwrights and complained that Britain was over-run with poorly

[40] Among them are millwrights such as John Jubb, Joseph Tempest, and Joshua Wrigley (Cookson, 2018, pp. 40, 46, 52, 73), all of whom were engaged in the woolen textile machine industry in one way or another. William Fairbairn reported in his autobiography that a certain Mr. Lowe from Nottingham (clearly a millwright), who had set up the watermill supporting a cotton mill in Ayr, Scotland, "was in demand in every part of the country where cotton mills were built" (Fairbairn, 1877, p. 121). Fairbairn himself consulted widely to cotton mills and made many suggestions that led to improvement in the machinery, such as his work with the firm of Adam and George Murray, cotton spinners in Manchester, where he proposed improvements in the transmission shafts of the machinery that led to considerable productivity gains (Fairbairn, 1877, pp. 112- 14).

educated millwrights who claimed to be engineers but set up waterworks without rigorous calculations (Carpenter, 2011, p. 282).[41] In the first half of the eighteenth century most millwrights were still seen as glorified carpenters and not particularly skillful.[42] Campbell (1747), in his famous book on the "trades" (occupations) of London, notes that "the Mill-Wright is an ingenious and laborious business in which there is a great variety ...but the wages given to Journeymen is no more than a common Carpenter" (p. 323). The authoritative biography of Fairbairn disputes his characterization and insists that as late as the mid-eighteenth century "the majority of them were artisans and much more akin to carpenters and concentrated on simple work" (Byrom, 2017, p. 88).[43]

That said, however, even though the traditional millwright's work required mostly skilled carpentry, the work required the skills of designing and installing shafting and gearing, and millwright competence was very much part of the culture of practical mathematics, high-accuracy, and low-tolerance engineering that evolved before and during the Industrial Revolution (Heilbron, 1990; Winchester, 2018).[44] The millstones in grain mills had to revolve fast enough so that the kernels of wheat poured into the center and then expelled as flour at the edges, and the waterwheel was mounted vertically and thus motion had to be transferred through ninety degrees, requiring a cog- or trundle wheel to transmit the motion to a lantern-pinion wheel on the vertical mill.[45] The skill levels of wrights clearly were heterogeneous, and not all of them may have met Desaguliers's exacting standards. That said, all mills involved a constant-moving mechanism, and because of the relatively low quality of the materials of which the mills were built, the gears and shafts were subject to high wear-and-tear and needed frequent repairs that required substantial expertise.

The traditional millwright, then, may not have been quite as learned and sophisticated as Fairbairn's description suggests, but neither was he as ignorant as Desaguliers may have thought. We should locate him in the upper tail of the distribution of artisanal skills. Before the Industrial Revolution these skills were largely tacit and transmitted through personal contact, that is, apprenticeship (Humphries, 2003). Cookson (1994, p. 46) shows that there was a social as well as a technical distinction between

---

[41] In Vol. II of his celebrated *Course of Experimental Philosophy* Desaguliers berated the ignorance of "engineers and "projectors" who set up ruinous waterworks but who hardly know "how to measure the quantity of water required to turn an undershot or overshot mill" (1763, Vol. II, pp. 414-15).

[42] Terry Reynolds, in his classic account of the history of the watermill, summarizes this view by expressing doubt whether before 1750 the typical millwright could do any of the things that Fairbairn listed and cites approvingly a 1775 writer who noted that the construction of water mills was "for the most part left to people not well skilled in the principles of mechanics." He also notes that any systematic analysis of efficiency and construction based on hydraulics before the early eighteenth century would have been unthank-able as the earliest serious theoretical works on the subject date from that period, and would have unlikely to have been read by the bulk of practical millwrights (Reynolds, 1983, pp. 191-95).

[43] Tann (1974, p. 80) equally stresses that the work was "a branch of carpentry" yet cites approving the anonymous 1747 source that stressed the diversity of mills and the knowledge requirements that this diversity imposed on wrights.

[44] Oddly enough, Winchester (2018) in his popular depiction of rise of precision engineering makes no mention of millwrights.

[45] For the technical details see e.g. Holt (1988, p. 117).

millwrights and lower-level artisans such as smiths and carpenters.[46] During the Industrial Revolution, millwrights were a kind of labor aristocracy, comparable to mule operators. The Industrial Revolution decisively changed the roles of millwrights in the industrializing regions, and the profession morphed into something we would call today mechanical engineering (MacLeod and Nuvolari, 2009).[47] The transition was characteristic of what the Industrial Revolution was all about: formal expertise and professionalization slowly evolved from highly-skilled craftsmanship.[48] Watermills were slowly being replaced by steam and hence traditional millwrighting skills were gradually becoming obsolete. But the transition of industrial power sources from water to steam was slow and uneven and not complete until the second half of the nineteenth century. At least in the early stages of the Industrial Revolution, many traditional upper-tail skills were still needed. In the cotton industry, the transition to factories was achieved through reliance on traditional millwrights, who installed the new equipment (Tann, 1974, p. 83). Cookson (2018, p. 69) reminds us that the vast bulk of eighteenth-century machines were still made of wood and required the high-end specialized carpentry skills that millwrights possessed. Only after 1790, with the sharp decline in the price of iron, did iron slowly replace wood and demanded new skills. Yet highly skilled artisans thinking of themselves as millwrights did not disappear, even as they had to transform to make room for more specialized engineers.[49]

The concept of the millwright as an all-around technically competent craftsman thus remained paramount during the Industrial Revolution. Textile engineering installations categorized their equipment as either "millwright's work" or "clockmaker's work" and these concept "were soon enshrined in insurance policies" (Cookson, 2018, p. 68). The exact meaning of the term "millwright" was evolving, but Cookson (2018, p. 72) points out that their role as professional consultants, akin to coal viewers, remained of central importance to the textile industry. A prime example here is the career of Thomas Cheek Hewes. Hewes had employed Fairbairn in the 1810s, and while he

---

[46] Yorkshire millwrights in the late eighteenth century enjoyed relatively high status, as suggested by the form of address, the title 'Mr' used in many instances. Cookson also cites none less than the great mechanical engineer Henry Maudslay himself to the effect that millwrights considered themselves superior to mere "engineers" and thought it was a disgrace to work with them (2018, p. 76).

[47] The transitional occupation was known as "specialist millwright/engineers," such as Smeaton, Jessop, Telford and others, whose "group identity brought about the establishment of the Society of Civil Engineers" (Byrom, 2017. p. 92).

[48] In the 1820s handbooks in engineering started to appear, codifying what until then was mostly tacit and informal knowledge. The best-known is doubtless John Nicholson, *Millwright's Guide* (1830), a rather detailed treatise, which tried to make best-practices in water power accessible. It was published as part of a series expressly designed to be adapted to the daily business of the "operative artist."

[49] In his lectures written in the 1850s, Fairbairn (born in 1789) reminisced on the position of millwrights in his younger years in the early decades of the Industrial Revolution: "a good millwright was a man of large resources; he was generally well educated ... he had a knowledge of mill machinery, pumps, and cranes, and could turn his hand to the bench or the forge with equal adroitness and facility. This was the class of men with whom I associated in early life — proud of their calling, fertile in resources, and aware of their value in a country where the industrial arts were rapidly developing. It was then that the millwright in his character of 'jack-of-all-trades' was in his element ... It was no wonder, therefore, that at the commencement of the new movements in practical science, occasioned by the inventions of Watt and Arkwright, the millwright should assume a position of importance" (Fairbairn, 1860, pp. 212-13).

specialized in waterwheels rather than steam engines, he was a significant inventor, introducing water works of the suspension type using governors (an idea borrowed from Watt). Despite his training as a traditional millwright, he was one of the pioneers of the use of iron in the construction of waterwheels. In part thanks to his work, water power survived far longer as a source of energy than the advent of steam might have suggested (Chrimes, 2002a).[50] He supplied machinery to a number of Lancashire textile machinery and eventually supplied machinery nationwide. By 1824 he employed about 140 workers, and was a pioneer in using iron axles and wheels. Similarly, Peter Ewart (1767-1824) was apprenticed to John Rennie himself and partnered with textile industrialists such as Samuel Oldknow and Samuel Greg. All the same, an abundance of millwrights in a region was not a sufficient condition for rapid industrialization. The west counties, where much of the woolen industries were still located by 1750, gradually lost their position to Yorkshire in the last third of the eighteenth century (Jones, 2010, pp. 47-70).

Despite its symbiotic relationship with water power, the woolen industry was quite heterogeneous across England (Jenkins and Ponting, 1987, pp. 1-11). The regional contrast between Yorkshire and the west counties (especially Gloucestershire and Wiltshire) was striking. The West Country had overall more fertile soils, and as regional specialization became more pronounced in the late eighteenth and nineteenth centuries, the small-scale domestic industry — a classic instance of "proto-industry" — of Yorkshire grew faster than their competitors further south. Regional specialization mercilessly led to a "great reversal," the remarkable switch from a polycentric textile sector that was spread in disparate regions to a heavy concentration of the textile industry in the north-west. Yet at the start of the eighteenth century this would have been hard to foresee, as the woolen industries were still thriving in the English South (Jones, 2010). In the eighteenth century, however, output in the wool industries in the West Country and East Anglia was, as far as we can tell, more or less stagnant, whereas that in Yorkshire grew rapidly.[51] In that development, skilled workers played a central role.

---

[50] Despite the possibility that they had a falling out, Fairbairn (1860, p. 229) graciously credited Hewes with the construction of much improved water wheels made entirely out of iron.

[51] Deane (1957, p. 220) has estimated that the proportion of total wool output of all kinds in Yorkshire rose from one-third in 1772 to three-fifths by the end of the eighteenth century. Pat Hudson has estimated that the share of the West Riding of Yorkshire in national wool production rose in the eighteenth century from 20 percent to 60 percent (Hudson, 1992, p.116). Other sources, while fragmentary, seem to be consistent with this trend for the earlier eighteenth century. For more details, see Ó Gráda, 2019.