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Roots of the Industrial Revolution

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Abstract

We analyze factors explaining the very different patterns of industrialization across the 42 counties of England between 1760 and 1830. Against the widespread view that high wages and cheap coal drove industrialization, we find that industrialization was restricted to low wage areas, while energy availability (coal or water) had little impact. Instead we find that industrialization can largely be explained by two related factors related to the human capability of the labour force. Instead of being composed of landless labourers, successful industrializers had large numbers of small farms, which are associated with better nutrition and height. Secondly, industrializing counties had a high density of population relative to agricultural land, indicating extensive rural industrial activity: counties that were already reliant on small scale industry, with the technical and entrepreneurial skills this generated, experienced the strongest industrial growth. Looking at 1830s France we find that the strongest predictor of industrialization again is quality of workers shown by height of the population, although market access and availability of water power were also important there.

Introduction.

This paper uses data for the 42 counties of England from the late eighteenth and early nineteenth centuries to examine systematically what differentiated regions that industrialized successfully from those that did not.[1] England in the mid-eighteenth century was a large and geographically diverse place, with the upland north and west differing systematically from the lowland south and east in wages, diet, landholding and occupation; and these factors turn out to be strong predictors of industrialization.

Against the influential view, based on comparisons with Continental Europe, that English industrialization was induced by cheap coal (Wrigley, 2010) and expensive labour (Allen, 2009); we find that industrialization only occurred in counties that had low wages in the mid-eighteenth century (although not all of these low wage areas industrialized: low wages are necessary but not sufficient); while proximity to coal has no explanatory power, reflecting the fact

[1]While the Industrial Revolution was very much a British phenomenon, we lack county-level data on Scotland and Wales in the eighteenth century and therefore restrict our analysis to England.

that the simple machinery of the early Industrial Revolution tended to be water powered. Given the importance of water power, high water flow does turn out to be a pre-requisite for industrialization but, again, not all areas with high flow industrialized.

Instead of wages and energy availability, the pattern of English industrialization is strongly explained by two aspects of human geography that are closely related to the capabilities and skills of the labour force. The first is the pattern of land-holding. While the fertile, arable counties of lowland England were populated largely by landless labourers who became increasingly reliant on public charity as the eighteenth century progressed; a substantial proportion of the people living in the agriculturally marginal, upland areas of northern England farmed tiny holdings and relied on industrial activities like weaving, spinning, or metal working to supplement their income. The ratio of these small-holdings to larger farms is strongly associated with quality of diet and with the biological standard of living of the population, measured by the height of military recruits. Whereas southern English labourers subsisted on a staple diet of expensive nut not very nutritious white bread; northerners relied on cheaper and more nutritious barley and oats, and consumed large quantities of dairy products. Although wages were lower in the north of England, the availability of small-holdings, greater opportunities for non-agricultural employment, more availability of meat and milk, and, probably, greater demand for female labour meant that the biological standard of living was higher.

The second important factor explaining industrialization is the density of population relative to agricultural land. In the mid-eighteenth century, the counties that went on to industrialize had the highest population densities outside London. These high populations densities did not translate into low agricultural wages, and show the extent to which some counties were already by the mid-eighteenth century becoming independent of farming and relying on simple manufacturing. In other words, areas that were highly industrialized in 1831 had been strongly reliant on industry in the 1760s.

Between them these two variables—the ratio of small to large farms; and the density of population relative to farmland—explain around two thirds of the variation of industrial employment across England in the 1830s, and this rises to four fifths when counties are weighted by population. We also find, contrary to the widespread view that education had no role in fostering early industrialization, that literacy has a substantial impact on industrial employment, although the associated standard error is large.

These findings remind us that the early Industrial Revolution was less about the sudden appearance of radically new technologies than about improving fairly familiar technologies to the stage where they became commercially viable, and lead us to model the evolution of an economy where ability to adopt technology depends on the human capability of workers, which depends in turn on their nutrition and access to training opportunities. The model combines two workhorses of economic growth: the Nelson and Phelps (1966) model where technology adoption depends on human capital; and the Ben-Porath (1967) model of human capital accumulation. We demonstrate that such a system leads generically to a sudden take-off or industrial revolution, and show how it can explain the very different evolution of northern and southern England during the late eighteenth and early nineteenth centuries.

We also consider the determinants of industrial employment across the 85 Departments of France in the late 1820s. We find that the strongest predictor of industrial employment is human capability as reflected in the height of the population, but access to water power is also important, and market access to a lesser extent.

The existing literature on the Industrial Revolution is, of course, large—for a recent survey see Kelly, Mokyr and Ó Gráda (2014)—but limited, as we have stressed, to comparisons between Britain and Continental Europe. Several recent papers have started to look at the geography of the Industrial Revolution in England, particularly Nuvolari, Verspagen and von Tunzelmann (2011) who analyse at the early diffusion of the steam engine, Horrell and Oxley (2012) who focus on nutrition, and Crafts and Wolf (2013) who examine the location of the cotton industry; but this is the first study to look at industrialization in general. The central role that we assign to human capability as a driving factor of the Industrial Revolution is in keeping with the rapidly growing Fetal Origins literature in Health and Development economics that stresses the lifelong impact on health, physical and cognitive development of childhood nutrition and exposure to disease: see Almond and Currie (2011) and Currie and Vogl (2013) for recent reviews.

The rest of the paper is as follows. In Section 1 we outline a model of growth where the human capability of workers determines a region's ability to adopt new technology, and show how this leads to a sudden take-off or industrial revolution. In Section 2 we look at factors determining the degree of industrialization across English counties in the early nineteenth century. Section 3 looks at the factors that explain French industrialization in the 1820s. Section 4 concludes.

1 A Model of Human Capability and Technological Take-off.

In this section we outline a model of growth where an economy's ability to implement new technology depends on the human capability of its workers, which is determined in turn by the investment of their parents in feeding and training them in some useful skill. We do not model the act of invention itself but rather on its adoption. The adoption of a new technique usually required a fair amount of tweaking and microinvention to adapt it to local circumstances. To adopt technology, a region thus needs workers with some minimum level of "competence," which is acquired by investment in human capability through childhood nutrition, and training in the form of master-apprentice contact. Output is a function of both the quantity of workers and their "quality" (human capability). The model combines the Nelson and Phelps (1966) model in which productivity growth depends on the difference between the actual techniques in use and the productivity of best-practise techniques; with the Ben-Porath (1967) model, which analyses the growth of human capability as a function of parental investment decisions.

The model concerns the diffusion of best-practice knowledge from elite scientists to the level of ordinary artisans where it can be incorporated into everyday production. We therefore define the state of the art level of international scientific knowledge by $\tilde{A}$ and assume that it grows exogenously. Within a given country, the level of technology in use is A. This level of technology evolves according to a Nelson-Phelps process, depending on the gap between scientific knowledge and the country's own technology; and on the level of skill of ordinary workers H:

$$\frac{A_t}{A_{t-1}} = \begin{cases} \left(\frac{\tilde{A}}{A_{t-1}}\right)^{\delta} H_{t-1}^{\epsilon} & \underline{A} < A_{t-1} < \tilde{A} \\ 1 & \text{otherwise} \end{cases} \tag{1}$$

where $0 < \delta, \epsilon < 1$. The technology in use in an economy cannot exceed the frontier value $\tilde{A}$, and cannot fall below a minimum level $\underline{A}$. To simplify notation in what follows, we assume that the minimum technological level is unity: $\underline{A} = 1$.

The human capability of each artisan evolves according to the Ben-Porath equation

$$\frac{H_t}{H_{t-1}} = I_{t-1}^{\lambda} H_{t-1}^{-\mu} \tag{2}$$

where $0 < \lambda, \mu < 1$. I_{t-1} denotes investment in the young generation of workers in period $t-1$ in the form of nutrition, basic schooling and training as an apprentice, and needs to equal $H_{t-1}^{\mu/\lambda}$ to maintain the existing level of human capability of the workforce.

To close this simple model we need to specify what determines the level of investment in the next generation of workers. We suppose that individuals have two periods in their lives: when young they receive investment from their parents; and when old they receive income as workers that they use to maximize utility which comes from their own consumption C_t and investment in their child (we assume constant population for now)

$$U(C_t, I_t) = C_t^{1-\gamma} I_t^{\gamma} \tag{3}$$

where $0 < \gamma < 1$. Workers supply one unit of labour inelastically, and live hand to mouth, making and receiving no bequests. It follows that parents invest a fraction γ of their income in their children.

Output in this economy comes from the production function

$$Y_t = A_t H_t^{\alpha} N_t^{1-\alpha} \tag{4}$$

where $0 < \alpha < 1$ and N is the number of workers. Every worker receives an income Y_t/N_t.

Each worker pays a share of his income to the government or landlords, receiving nothing in return. In addition, however, the government may tax the landlord class and redistribute this money to workers in the form of a Poor Law.

It follows that the disposable income of workers is $(1-\tau)\,Y/N$ where τ is the net rate of tax and rent after subtracting Poor Law transfers.

To analyse the evolution of useful knowledge A and human capability H it will be simpler, both for intuition and for drawing phase diagrams, to adopt the trick of using the inverse of human capability

$$M \equiv \frac{1}{H} \tag{5}$$

that we will refer to as misery, remembering that it refers to low levels of nutrition, health, schooling and other outcomes of childhood deprivation.

It follows that useful knowledge and misery evolve according to the log-linear system of difference equations

$$\begin{aligned} \Delta \log A_t =& \delta \log \tilde{A} - \delta \log A_{t-1} - \eta \log M_{t-1} \\ \Delta \log M_t =& \lambda \log \frac{N_t^{\alpha}}{\gamma\,(1-\tau)} - \lambda \log A_{t-1} - (\mu - \lambda\alpha) \log M_{t-1} \end{aligned} \tag{6}$$

Assuming that population is more than a handful of people so that $N_t^{\alpha} > \gamma\,(1-\tau)$, only one coefficient of this system has a sign that is not immediately obvious: the $(\mu - \lambda\alpha)$ term multiplying $\log M$ in the misery equation. If $\mu < \lambda\alpha$, the real wage at the technological minimum rises as population N or net taxes τ increase as (9) below shows. In addition, the misery process is unstable: a rise in misery lowers output and human capital investment, increasing misery next period in a self-reinforcing process so long as population remains stable. We therefore assume that $(\mu - \lambda\alpha)$ is positive.

The isoclines of the system, between the minimum and maximum levels of technology, are

$$\begin{aligned} \Delta \log A = 0 \qquad & \log M = \frac{\delta}{\eta} \log \tilde{A} - \frac{\delta}{\eta} \log A \\ \Delta \log M = 0 \qquad & \log M = \frac{\lambda}{\mu - \lambda\alpha} \log \frac{N_t^{\alpha}}{\gamma\,(1-\tau)} - \frac{\lambda}{\mu - \lambda\alpha} \log A \end{aligned} \tag{7}$$

The knowledge-misery system has four possible steady states depending on the relative position and slope of these isoclines.[2] In the phase diagrams we denote $N_t^{\alpha}/\gamma\,(1-\tau)$ by N^*.

In the first panel of Figure 1, the misery isocline lies everywhere above the knowledge isocline so that misery dominates. The only equilibrium is at point B, with the log of useful knowledge equal to its lower bound, which we have set at zero.

[2] There is also the case where the isoclines exactly coincide, making every point along them a steady state.

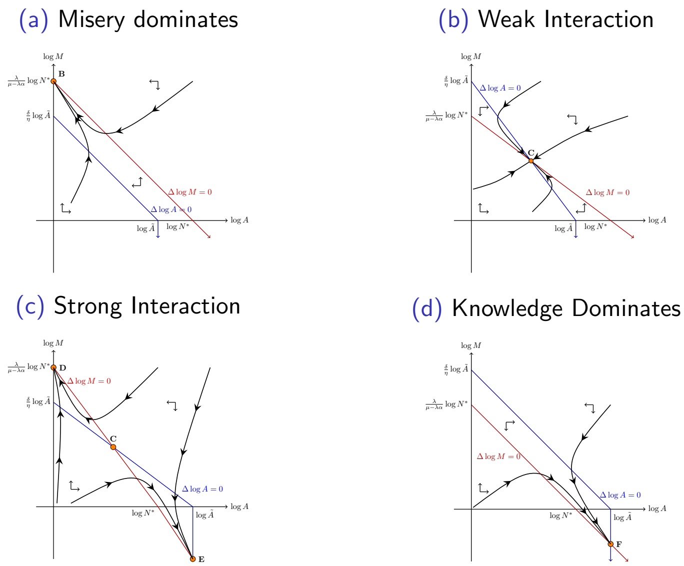


Figure 1: The four equilibria of the knowledge-misery system.

In the second and third panels the isoclines intersect at $C = \left(\overline{\log A}, \overline{\log M}\right)$ where

$$\begin{aligned}\overline{\log A} &= \frac{1}{\lambda\eta - \delta\left(\mu - \lambda\alpha\right)}\left[\lambda\eta \log \frac{N_t^{\alpha}}{\gamma\left(1-\tau\right)} - \delta\left(\mu - \lambda\alpha\right)\log \tilde{A}\right] \\ \overline{\log M} &= \frac{\delta\lambda}{\delta\left(\mu - \lambda\alpha\right) - \lambda\eta}\left[\log \frac{N_t^{\alpha}}{\gamma\left(1-\tau\right)} - \log \tilde{A}\right] \qquad (8)\end{aligned}$$

In the second panel, the own effect terms in (6) dominate the cross effect terms $\delta\left(\mu - \lambda\alpha\right) > \lambda\eta$ so the technology isocline is steeper. As a result, the intersection point C is globally stable.

In the third panel, cross effects dominate own effects $\delta\left(\mu - \lambda\alpha\right) < \lambda\eta$ so the misery curve is steeper. As a result, the intersection point $C = \left(\overline{\log A}, \overline{\log M}\right)$ is a saddle dividing the space into two basins of attraction, one converging on point D with technology at its lower bound, the other at point E where the misery isocline cuts the upper bound of technology $\log \tilde{A}$.

Finally, in the last panel of Figure 1, the knowledge isocline lies everywhere above the misery isocline, so the system converges to a steady state at point F where the misery isocline cuts the upper bound of technology $\log \tilde{A}$.

Intuitively, the evolution of useful knowledge and misery in (6) resembles an eco-system with two competing species: the growth of each species is retarded by the presence of the other. In the first panel of Figure 1, conditions are so favourable to the first "species", misery in our case, that its "population" will be high regardless of the second species which it always drives to its minimum level; with the converse holding in the fourth panel where knowledge dominates. In the second panel, the species have little impact on each other and both co-exist at positive levels, while in the third panel they have a strong impact on each other but the outcome depends on which species initially has a sufficiently large population to dominate the system. We now show how this simple interaction of knowledge and misery leads to a sudden take-off in knowledge: an Industrial Revolution.

1.1 England: North and South.

There are two regions that we shall call North and South. Each faces the same technological frontier $\tilde{A}$ that rises through time, reflecting the progress of scientific knowledge. As in the empirical results in Section, the North differs from the South in having better diet and more developed rural industry. As a result, a given level of parental investment in their children results in a higher level of capability. This means that the North has a higher value of λ in the Ben-Porath equation (2) giving it a steeper misery isocline. The important thing however is that the North starts out with a higher level of human capability H equivalent to lower misery at the base level of technology.

At the technological minimum where the system begins, workers in each region $i = N, S$ have log disposable income

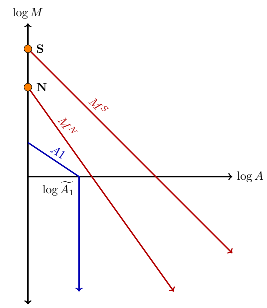
$$\log(1-\tau_i)\, w_i = \frac{1}{\mu - \lambda\alpha}\left[\log\gamma + \mu\log(1-\tau_i) - \alpha\mu\log N_i\right] \tag{9}$$

We abstract from things like better employment opportunities for women and suppose that workers North and South have equal disposable incomes: for instance workers in the South, as was the case in reality, were entitled to poorlaw payments reducing their net taxes τ and compensating for their lower λ.

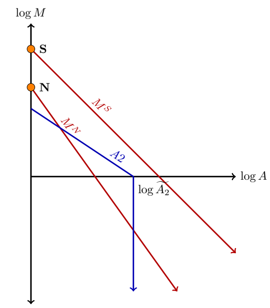
In Figure 2 we denote the Northern and Southern misery isoclines by M^N and M^S respectively, and the equilibrium of each economy by N and S. We want to see how these change as the technological frontier $\tilde{A}$ gradually rises through time.

Our starting point, in panel (a), is a stark Malthusian world with little knowledge: $\log\tilde{A}$ is arbitrarily small and the knowledge isocline $A1$ lies completely below the two misery isoclines. As a result, both economies are at an equilibrium at the lower bound of knowledge. As time passes scientific knowledge $\tilde{A}$ will rise exogenously, reflecting the progress of the Enlightenment, and this will be the driving force behind the model.

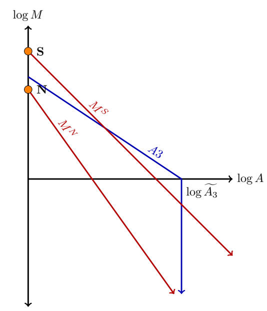
In panel (b) the knowledge frontier has risen so that the knowledge isocline $A2$ now intersects the Northern misery isocline. We suppose that misery and useful knowledge strongly affect each other $\delta(\mu - \lambda\alpha) < \lambda\eta$ so that the misery isocline is steeper: when the opposite holds the evolution of the system is broadly similar as we will see below. While a steady state exists at the knowledge frontier, as in the third panel of Figure 1, because the Northern economy is starting in the basin of attraction of the low knowledge equilibrium, it stays at this point. The rising technological frontier has no impact on production



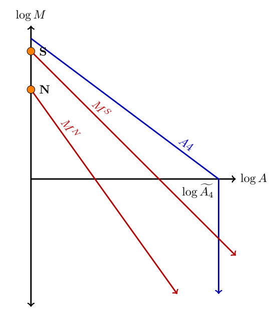
(a) Both at technological minimum.



(b) Rising technological frontier has no initial impact.



(c) North moves to technological frontier.



(d) South moves to technological frontier.

Figure 2: Impact of rising technological frontier $\tilde{A}$ on two economies with different isoclines.

technology because the level of human capability is too low to absorb it: the technological enlightenment has no impact down on the farm.

In the third panel of Figure 2, the continued gradual rise in scientific knowledge causes the technology isocline to move above the Northern misery isocline, but still to cut the Southern one from above. As a result, while the South stays at the minimum technology steady state at S, the North jumps to the technological frontier at N. A small rise in the knowledge frontier causes a sudden divergence between the economies to occur. Because Northern human capability is slightly higher than Southern, thanks to better diet and existing rural industrial activity, the North can start to apply technological knowledge to production, giving rise to a cumulative process of rising living standards, rising human capital, and rising production technology. A gradual rise in knowledge above a critical level causes the North to experience an industrial revolution, while the South appears mired in rural backwardness.

This divergence is not permanent however. As the knowledge frontier $\log \tilde{A}$ continues to rise in the last panel of Figure 2, the technology isocline $A4$ moves

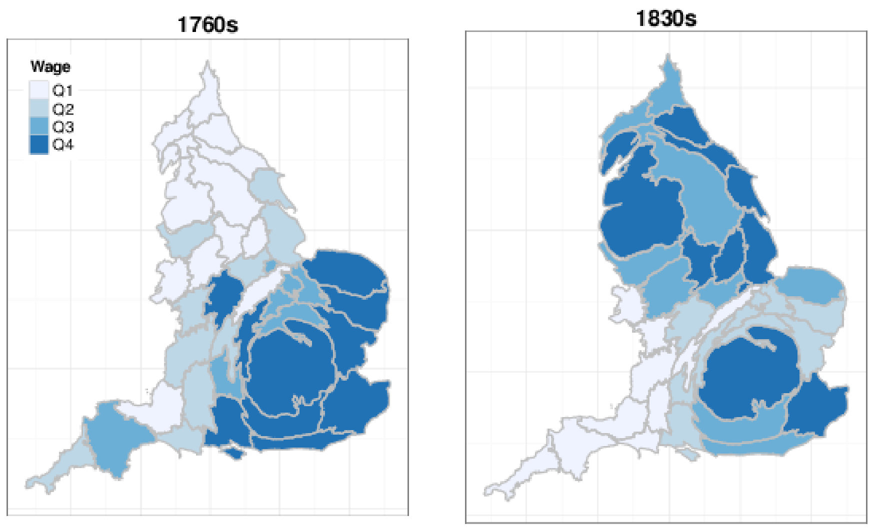


Figure 3: Cartograms of England in the 1760s and 1830s. The area of each county is scaled in proportion to its aggregate labour income (wage times population), and shaded according to its wage rate.

above the Southern misery isocline, causing the South to converge to the same technological frontier as the North.

If, on the other hand, misery and technology interact weakly $\delta\left(\mu-\lambda\alpha\right)>\lambda\eta$ so that the knowledge isocline is steeper, the evolution of the system is slightly different. When the technology isocline first rises above the North's misery isocline, it moves to a steady state where the two intersect, and the South will follow some time afterward. Both economies move steadily down along their misery isoclines as the knowledge isocline rises, until they reach the technological frontier.

2 Growth in England.

England is a large and geographically diverse country. Using data on its 42 counties from the late eighteenth and early nineteenth centuries allows us to examine systematically what differentiated regions that industrialized successfully from those that did not.

Pre-industrial England fell into three geographical regions: the lowland south and east, engaged in arable farming; the upland north and west with pastoral agriculture; and the urban giant of London that, by 1750, contained over 10 per cent of England's population and was the largest city in Europe (Wrigley, 2010, 61). In the eighteenth century, these regions differed systematically in terms of wages, diet, land holding, and occupational structure.

Figure 3 shows a map of England where the counties are re-scaled in proportion to their aggregate labour income (wage of agricultural labourers times population) in the 1760s and 1830s. Counties are shaded accorded to the wage rates of agricultural labourers in each period. Given the absence of any restrictions on mobility these are likely to have been close to the wages earned by labourers in other sectors

In the 1760s, Figure 3 shows that the English economy was dominated by London and its environs, and southern wages are higher than northern. The variation is substantial, with wages in the highest counties around fifty per cent higher those in in the lowest. Wages in the 1760s reflect soil fertility, with areas of old, hard rock having the lowest wages: the correlation between county wage and age of its dominant rock type (computed from worldgrids.org) is -0.7.

The reversal of fortune between northern and southern counties over the following two generations is apparent when the first panel of Figure 3 is compared with the second. The economic geography of England has been transformed, with northern counties that were in the bottom quartile of wages now in the top; and the aggregate income of the textile areas of Lancashire and West Yorkshire becoming as large as London's. In terms of wages, the industrializing counties of the north and midlands have not merely converged on the south-eastern ones, but overtaken them, with rises in nominal wages of 80 to 90 per cent in industrial counties, compared with 15 to 25 per cent in agricultural ones. Weighted by population, the average national wage rose 50 per cent in nominally, compared with a 50 per cent rise in the national CPI estimated by Clark (2011). Wage dispersion remains constant through time, with a coefficient of variation of 13 per cent in both the 1760s and 1833.

The varying labour demand that drove these wage rises drove very different rises in population. Between 1761 and 1831, while depressed agricultural counties in the south and east saw growth of only 25–33 per cent, the population of the industrial counties and those around London more than doubled, with that of Lancashire more than quadrupling.

To examine the determinants of industrialization we first need a measure of industrialization. We focus on two, that turn out to be strongly related. The first is the share of males over 20 employed in manufacturing and other non-agricultural labour in 1831 from Marshall (1833, 11).[3] The other measure of industrialization is the growth rate of aggregate money income between the 1760s and 1830s. As Figure 4 shows, these two measures are strongly related, with counties having the highest industrial employment in 1831 being those that grew fastest in terms of wages and population over the preceding two

[3]This is, all workers not listed as being employed in the categories agriculture, retail and handcrafts, capitalists and professionals, or without a specific occupation.

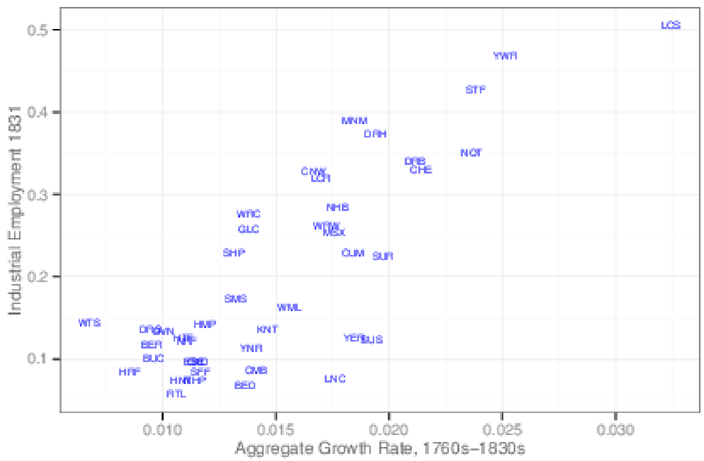


Figure 4: Measuring industrialization: aggregate growth rate from 1760s to 1830s versus industrial employment in 1831.

generations. This figure highlights the extent to which English growth in this period is tied to the growth of industry.

The geographical distribution of industrial employment in the 1830s is shown in the first panel of Figure 5, and can be seen to cluster strongly in the north-west and midlands. The other panels show the distribution of other county characteristics that we shall explain below. It can be seen that counties with a large number of small farms, and a large population in the eighteenth century relative to their farmland, are the most heavily industrialized, and these counties also have populations that were tall and well nourished in the late eighteenth century. Counties with low literacy levels in the late eighteenth century can be seen to have less industry in the early nineteenth century.

Figure 6 gives scatterplots of industrial employment share in 1831 against a number of explanatory variables. Starting with log wage in the late 1760s at the end of the first row, it can be seen that industrialization is associated with low wages. There are two revealing groups of outliers on the right. The first group is London, which corresponded roughly to Middlesex (MSX) and its neigbours Kent and Surrey, which have higher industrial employment than their high wages would predict. The other, again predictable, outlier is Warwickshire (WRW), centered on Birmingham which was already a major industrial area by the mid-eighteenth century. Overall, the scatter-plot shows a "lower-triangular" pattern, with some but not all low wage counties industrializing, while no high wage ones do. In other words, low wages appear necessary but not sufficient for industrialization.

The second row of Figure 6 gives measures of biological living standards and human capital. Nutrition is the score given to each county by Horrell and Oxley (2012) based on information on labourers' diet collected by Eden in 1795. It is

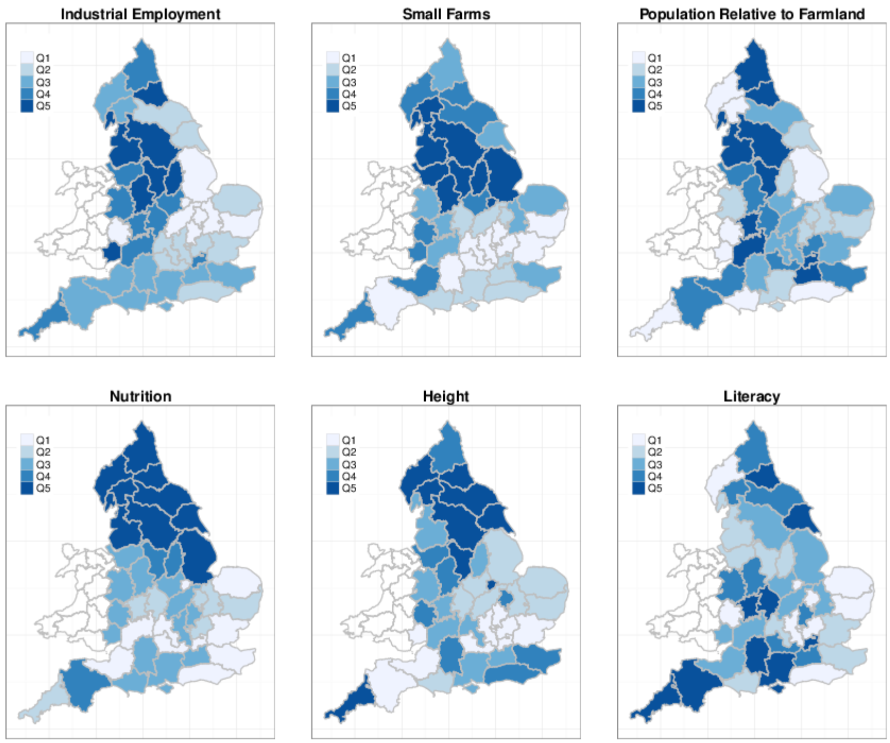


Figure 5: Map of county industrialization and characteristics.

immediately evident that, although wages were considerably lower in the north, nutrition was better. This reflects differences in diet, with southern labourers eating a staple of white bread, which was expensive and not very nutritious, whereas northerners relied on cheaper and more nourishing oats and barley boiled in milk. It can be seen that, apart from some well-nourished northern counties in the lower right, there is a positive correlation between nutrition and subsequent industrialization, but with Middlesex, as usual, an outlier. The superior diet of northerners is reflected in heights of military recruits in 1788 from Floud, Gregory and Wachter (1990). Although these data suffer from selection bias, being based on volunteers rather than conscripts, it is evident that northerners were on average around one inch taller than southerners. As a standard measure of human capital, we also include the percentage of convicts from each county around 1800 that were literate from Nicholas and Nicholas (1992, Table 3). As with wages the triangular pattern in the diagram shows that literacy appears necessary but not sufficient for industrialization.

Following Crafts and Wolf (2013), who find a strong impact of market size on the location of cotton firms in the 1830s, we include a gravity measure of market potential for each county in the 1760s. This is the aggregate labour income of other counties weighted by their distance in kilometers, with an exponent of -0.8, where the county is assumed to have a distance of 1 from itself. Changing this exponent did not alter the results materially. The diagram omits Middlesex which has a market potential nearly twice that of the second highest county.

Next we include measures of energy availability. Given the importance of water-wheels in powering the simple machinery of the early Industrial Revolution we compute a measure of water flow for each square kilometer on England based on the area that drains into it, multiplied by the tan of its slope, and assigning each county a value equal to the log of the 98th percentile of the flow across its squares.[4] The correlation between this measure of water flow and the number of water mills per capita around 1800 from Nuvolari, Verspagen and von Tunzelmann (2011) is 0.6. Leaving out the outlier of Monmouthshire, we again see a roughly lower triangular relationship between water availability and industrialization, where a large flow is necessary but not sufficient for industrial growth.

For coal, we measure the distance from the centroid of each county to the centroid of the nearest coal producing county, using the Von Tunzelmann (1978) list of county coal output around 1800.[5] The correlation between distance and price for the 28 counties that have data is 0.8.

The two variables most strongly related to industrialization both reflect human geography.[6] These are the ratio of small to large farms; and the density of population relative to farmland in the 1760s.

The agricultural counties of southern England had large arable farms worked by landless labourers who earned high wages in the 1760s but were increasingly reliant on public charity, in the form of the Speenhamland system of subsidized wages, by the 1790s. In northern England, by contrast, it was common for families to work small plots of land: Marshall (1833, 10) assigns these an average size of 10 acres: too small to support a family but a useful supplement to income from other activities, one that could generate some capital for small scale industrial activity like weaving or watch making, or fund the apprenticeship of children in learning useful skills. In addition, the dairy farming and small scale industry of northern areas probably generated greater demand for female labour than the wheat growing monoculture of the southeast, further increasing household income. So, while the wage cost of northern labour was lower than in the south, the biological standard of living shown by height and nutrition were certainly higher, and household income probably also higher.

We measure these small holdings as the ratio of farms that do not employ labourers to those that do from Marshall (1833, 10). These data are for 1831

[4]Slope and water flow are from USGS Hydro1k database: lta.cr.usgs.gov/HYDRO1K.

[5]We ignore the fact that coalfields were expensive to develop: particularly, for inland fields away from rivers, their transportation linkages. For example, as Crafts and Wolf (2013), the southwest Lancashire coalfield was only developed in response to the growing demand from the Manchester cotton industry, so that industrialization drove the development of coal rather than the other way around.

[6]The central role of landholding in understanding the Industrial Revolution is stressed in early studies of the Lancashire cotton industry such as Chapman (1904, 9–12) and Wadsworth and Mann (1931, 25–28, 314–324).

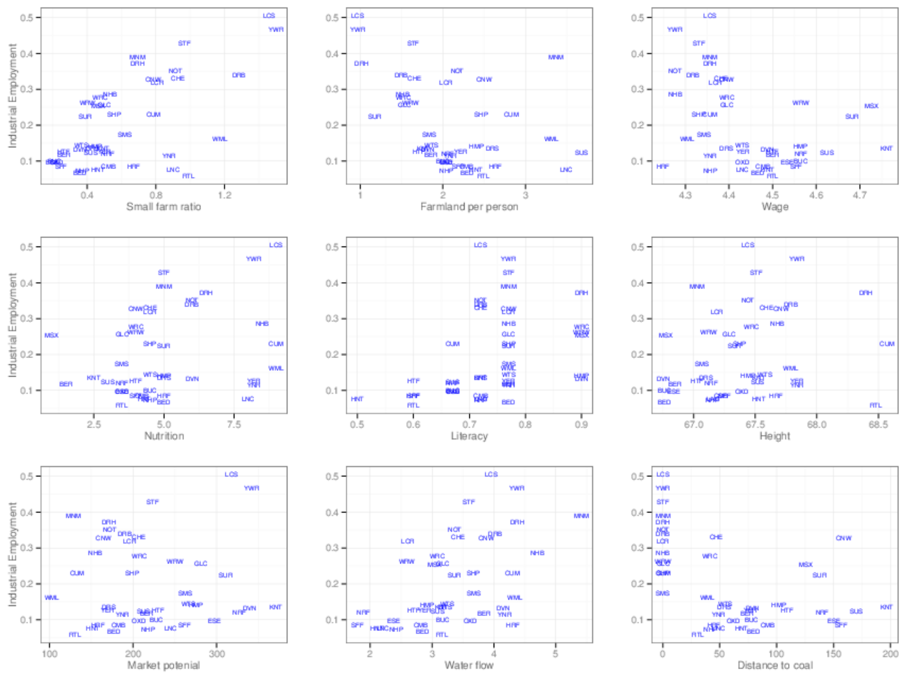


Figure 6: Relationship between county characteristics and industrial employment.

and may, in part, reflect the fact that northern labour had become too dear to employ in agriculture although there is considerable evidence that small farming supplemented with domestic industry existed in northern counties from at least the mid-eighteenth century.[7] However, it must be remembered that these farms without labourers were, according to Marshall, tiny: too small ever to have employed outside labour. In addition they occur in upland areas, which in England are associated with poor peat soil.[8] The correlation between ratio of

[7]Based on observations scattered through Arthur Young's (1771, 1772) Tours of England in the late 1760s, typical farms in the counties where small farms predominated in 1831 (Yorkshire, Lancashire, Cheshire, Derby, Nottinghamshire, Staffordshire, Cumberland, Westmoreland, Lincolnshire, Monmouthshire) ranged in value from £24 to £179, compared with a range from £62 to £399 elsewhere. Shaw-Taylor (2012, Tables 7–12) presents parish data from the seventeenth and early eighteenth centuries showing the south-east of England to have considerably larger farms than the north. More impressionistically, Daniel Defoe writing in the 1720s comments on the prevalence of small farms and part time industry in several of these areas (cited by Mantoux 2005, 51, 53, 66). Clark and Gray (2012) compute the ratio of small to large farms in 1831 for parishes in four counties and, finding it uncorrelated with literacy, conclude that "Geography is not destiny."

[8]Lowland England is composed predominantly of two types of clay soil (planosols and cambisols) that are equally suitable for farming, whereas upland areas have peat soil (histosol) that can only support rough grazing. The percentage of a county that is peat, derived from the worldgrids.org database, is therefore a useful measure of its agricultural potential.

small holdings to farms employing labourers to share of peat soil is 0.6. We employ peat soil as an instrument for small farms in the regressions below and find no change in coefficients, indicating that small farms are exogenous to industrialization. Other variables, again associated with poor soil, are almost equally strong instruments for percentage small farms—the tax value per square mile of land in 1290 from Nightingale (2004, Table 2), or age of the dominant rock type in the county—but do not offer additional explanatory power when peat soil is included.

The other population variable we consider is the amount of farmland (measured as non-peat soil) per capita in 1761. As Figure 5 shows, northern counties which had low population density relative to their overall area, actually had high densities relative to their agricultural potential. These high densities did not, however, result in low wages for agricultural labours: the correlation between the two variables is zero. In other words, the high populations of these areas were supported in the 1760s by non-agricultural activities, such as spinning, weaving, and metal working, that served to endow local populations with useful technical and entrepreneurial skills. This density relative to agricultural land therefore serves as a proxy for small scale industrial activity.

2.1 Regression Results.

Table 1 gives the results of regressions of industrial employment in 1831 on the explanatory variables just described. First we include log of wages in the 1760s, and the percentage of convicts that were literate. Next we include measures of energy availability: distance to nearest coal field, and log of water flow; followed by market potential. The next variables are nutritional quality and height of military recruits. Lastly, we include farmland per capita, and the ratio of small farms to those employing labourers.

Because the dependent variables are proportions, there is the possibility that the OLS residuals will be non-normal. However plots of the quantiles of the residuals did not show large deviations from normality; and the coefficients and standard errors did not change materially when we estimated the data using a beta regression and computed marginal effects at the mean value of the explanatory variables. For all regressions, the standard Cook's distance showed large leverage being exerted by one predictable county: Middlesex, which corresponds roughly to London. We therefore include a dummy for this county, although the estimated coefficients and standard errors do not change markedly as a result.

The 42 counties in our regression varied substantially by population in 1831, ranging from 20,000 in Rutland and 50,000 each in Huntingdonshire and Westmorland; to 1 million in West Yorkshire, and 1.3 million each in Lancashire and Middlesex. We therefore also report the results of regressions weighted by 1831 population.

Being regressions on spatial data, the expectation is that they will suffer from strong spatial autocorrelation. We therefore include a standard Moran's I test for the OLS residuals, where spatial weighting is based on an average

	Unweighted			Population Weighted		
(Intercept)	0.270	0.363	-0.093	-0.708	-0.229	-0.015
	(0.923)	(0.871)	(0.123)	(0.752)	(0.718)	(0.118)
Wage	-0.075	-0.091		0.194	0.094	
	(0.209)	(0.197)		(0.173)	(0.164)	
Literate	0.316	0.286	0.347*	0.163	0.183	0.226
	(0.171)	(0.162)	(0.145)	(0.159)	(0.147)	(0.136)
Nutrition	-0.009	-0.011		-0.009	-0.013	
	(0.009)	(0.008)		(0.007)	(0.007)	
Coal	0.000	0.000		0.000	0.000	
	(0.000)	(0.000)		(0.000)	(0.000)	
Water flow	0.022	0.026		0.016	0.011	
	(0.021)	(0.020)		(0.019)	(0.017)	
Market	0.000	0.000		-0.001**	0.000*	
	(0.000)	(0.000)		(0.000)	(0.000)	
Farmland	-0.090	-0.140*	-0.134**	-0.121**	-0.181***	-0.132***
	(0.049)	(0.051)	(0.041)	(0.037)	(0.041)	(0.035)
Small Farm	0.198***	0.192***	0.209***	0.296***	0.265***	0.229***
	(0.055)	(0.052)	(0.037)	(0.045)	(0.044)	(0.030)
London		-0.319*	-0.335*		-0.256*	-0.311**
		(0.141)	(0.133)		(0.098)	(0.096)
R^2	0.649	0.697	0.645	0.855	0.880	0.837
Num. obs.	42	42	42	42	42	42

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$

Table 1: Regressions of industrial employment share in 1831 on characteristics of 42 English counties.

of surrounding counties (Bivand, Pebesma and Gomez-Rubio, 2008, 259–272). The results do not indicate the presence of spatial autocorrelation. Similarly, a Breusch-Pagan test does not indicate heteroskedasticity.

To allow for the potential endogeneity of small farms, we regress them on percentage of a county that is peat soil. The explanatory power of this regression is satisfactory: the R^2 is 0.36 and the F-statistic is 22. When including the fitted value from this regression as an additional explanatory variable in the industrialization regressions, its p-value of 0.95 suggests that the ratio of small to large farms is not endogenous.

Looking at the regression results, it can be seen that the impacts of wages in the 1760s, water flow, proximity to coal, market potential, height, and nutrition are neither large or significant at conventional levels. Wages and coal proximity are strongly negatively correlated but the performance of each variable did not change if the other was excluded. The coefficient on literacy is large however, in the range 0.2–0.3 and is significant or close to significant at conventional levels in some regressions. However, it can be seen that the two most important variables are farmland per person, and, most strongly, the ratio of small to large farms. The explanatory power of these regressions is unusually large for cross-sectional regressions, ranging from around two thirds when each county is given equal weight, to four fifths when they are weighted by population.

The results are informative. We see that the two most important predictors of industrialization were small farms (which are associated with a high biological standard of living) and high population density relative to farmland, which indicates the extent of rural industrial employment. Between them, these two variables explain four fifths of industrial employment outside London in the early nineteenth century.

These results run counter to several well known explanations of the Industrial Revolution, based on traditional comparisons of England with France. First there is no support for Wrigley's (2010) contention that the availability of cheap mineral energy in the form of coal, gave England its decisive advantage. Similarly Allen's (2009) view that English industrialization reflected induced innovation driven by dear labour and cheap coal receives little support. Instead the results are consistent with the view that human capability and skills derived from existing industrial activity were central. Human capital is often dismissed as a source of industrialization on the grounds that English literacy was unimpressive by Continental European standards, but it can be seen that literacy tends to have a substantial impact on industrialization.

The irrelevance of coal to industrialization should come as no surprise with the heavy coal consumption of low pressure engines restricing the use of steam power during the first half of the nineteenth century: in 1830 total steam power of British industry was only 165,000 horsepower (Von Tunzelmann, 1978; Crafts, 2014). On the face of it, things improved considerably over the next 40 years. According to the 1871 Factory Returns summarized by Samuel (1977, Table 1), installed capacity of steam in 1870 was 280,000 horsepower in cotton, 165,000 HP powering blast furnaces, 45,000 HP each in worsed and woolens, and 37,000 HP each in iron and machinery making. However, these 6 sectors accounted for 84 per cent of installed steam capacity, with cotton and blast furnaces alone accounting for 61 per cent. However, outside blast furnaces and iron mills average steam power per establishment was low with the average cotton mill having only 100 HP, about the power of a very modest European family car, and other sectors even lower.

3 Human Capability and Industrialization in Early Nineteenth Century France.

France's early nineteenth century industrialization was, of course, less spectacular than England's, but we can still examine the factors that determined the widely differing levels of industrial employment across the 85 Departments of mainland France. Figure 7 maps the geographical distribution of height and literacy of 20 year old military conscripts from 1825–27; the percentage of these conscripts that had been in industrial employment; and the number of current patents per 10,000 population. It can be seen that all these variables show the same geographical pattern, being high in the north-east and along the Mediterranean coast; low in the south and west and, particularly, the centre.

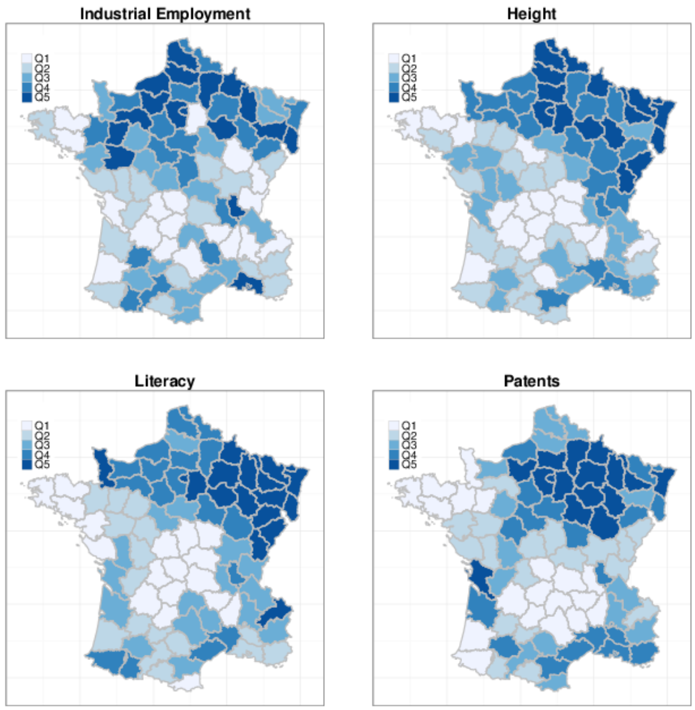


Figure 7: Map of industrial employment and characteristics of French Departments.

Height data for France are particularly useful: unlike the English data for military volunteers, they are based on all 20 year old males in France. As emphasized by Kelly, Mokyr and Ó Gráda (2014) the large discrepancy between France and England points to marked differences in biological standards of living. The average French male in the late 1820s was 164 cm (64.5 inches), around 5 centimetres (2 inches) shorter than his English counterpart and even this low average was a marked improvement on 1817 when, after a quarter century of almost continuous warfare, average height was 161.5 cm (63.5 inches), with nearly thirty per cent failing to reach the minimum height of 157 cm (62 inches).

Table 2 presents regressions of percentage of conscripts from industrial backgrounds on height, energy availability: namely log water flow; and distance to centroid of the nearest department with coal (where coal fields are taken from Rice and Hartmann (1939, 16)); and market potential (in the absence of wage data this is based solely on population where distance again receives a weight of -0.8)[9] Wages for industrial workers are only available starting in 1840 but still

[9]In estimating a gravity equation for 1820s France we do have one commodity that was shipped to Paris from every department of France: prostitutes. The number of prostitutes in Paris relative to their home department's population falls with the square root of distance.

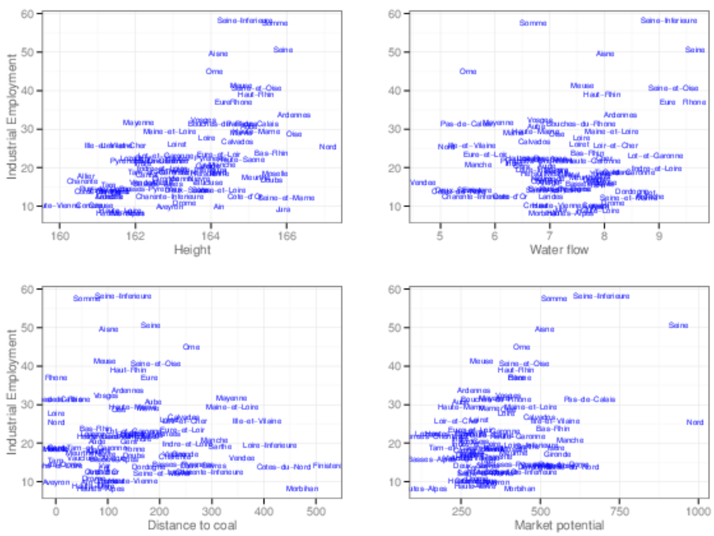


Figure 8: Relationship between departmental characteristics and industrial employment.

reflect agricultural productivity (the correlation with wheat output per day of labour input in 1852 is 0.4) showing the continuing dominance of agriculture in the French economy. This wage variable has a small and insignificant coefficient when added to industrial employment regressions, and did not affect the other coefficients.

In estimating regressions for industrial employment we face the clear possibility that height is endogenous: industrialization might have improved living standards which increased people's height. However, our data come from the late 1820s, fewer than fifteen years after Waterloo, when French industrialization was only starting. We instrument for height using soil fertility (the FAO prediction of wheat output per hectare with low inputs and no irrigation from gaez.fao.org: compared with French wheat output for 1852 this tends to underestimate wheat output). Excluding the large outlier of the mountainous department of Hautes-Alpes, the F-statistic for a regression of height on soil fertility is 16. If we add the predicted value of height based on soil fertility to the industrial employment regression, the p value is 0.47, indicating that height is explained by factors that do not drive industrialization.

The first column of Table 2 presents OLS results, (again the marginal effects computed from beta regressions are very similar). It can be seen that the strongest determinant of industrial employment is height. If literacy, which is strongly correlated with height, is used instead, the explanatory power of the regression falls somewhat. Water flow matters importantly for industrialization while proximity to coal appears to have been of little advantage to most industry. This is consistent with the traditional view that French industry remained heav-

	OLS	Weighted OLS	Spatial
(Intercept)	-4.864***	-5.386***	-4.864***
	(1.123)	(1.222)	(0.955)
Height	0.030***	0.032***	0.030***
	(0.007)	(0.007)	(0.006)
Water Flow	0.022*	0.033***	0.022*
	(0.010)	(0.009)	(0.008)
Coal Distance	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)
Market Potential	0.000*	0.000**	0.000**
	(0.000)	(0.000)	(0.000)
vec4			-0.222**
			(0.077)
vec5			-0.184*
			(0.077)
vec9			0.183*
			(0.077)
vec17			-0.184*
			(0.077)
vec1			0.130
			(0.077)
vec7			-0.127
			(0.077)
vec2			-0.120
			(0.077)
vec25			0.178*
			(0.077)
R^2	0.347	0.413	0.575
Num. obs.	85	85	85

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$

Table 2: Regressions for French industrial employment, 1825–1829.

ily reliant on water power into the late nineteenth century, developing highly efficient water turbines, and not relying on coal as much as British or German industry. Finally, market size exerts a larger force on industrial location than in England.

Looking at diagnostic statistics for the OLS regression, a Breusch-Pagan test with p value of 0.04 suggests heteroskedasticity, indicating possible misspecification, and in particular the data show strong spatial autocorrelation, with a Moran statistic having a p value of 0.001. To handle this we follow the semiparametric filtering approach of Tiefelsdorf and Griffith (2007) which takes the eigenvectors of the modified spatial weight matrix and adds these as explanatory variables to the regression until the Moran statistic indicates that spatial autocorrelation has disappeared: this is analogous to adding time lags until residuals behave as white noise. The third column of table 2 shows the results for this spatial autocorrelation adjusted regression: it can be seen that the magnitude and statistical significance of the regression coefficients are broadly unchanged.

4 Conclusions.

Existing analyses of the sources of the Industrial Revolution focus on comparisons between Britain and France, risking the sort of mono-causal explanation for which the field is notable: "Factor x (which, depending on the author, might be wages or institutional quality or availability of coal) was higher in Britain than in France in the eighteenth century. It follows that Factor x was the cause of the Industrial Revolution." However, for all their occasional ingenuity, such comparisons between England and France ultimately reduce to fitting a line through two data points, an exercise of uncertain usefulness.

This paper looked instead at the characteristics of the 42 counties of England in the late eighteenth and early nineteenth centuries, to see which determined the extent of industrial employment in 1831. Against the view that the Industrial Revolution represented a response to cheap coal and expensive labour we find that proximity to coal had no impact on industrialization (although water power did matter); and that industrialization was restricted to areas with low wages in the 1760s. Instead we find that industrialization is strongly determined by two characteristics strongly connected to the human capabilities of county populations: the ratio of small to large farms (which is strongly associated with nutrition and height of the population), and the extent of existing industrial activity measured by the ratio of population to farmland in the 1760s. Looking at France in the late 1820s, we also find that biological living standards as reflected in the height of military conscripts, is the dominant determinant of industrial location, although the results are weaker, reflecting the more geographically diffuse pattern of French industrialization.

Appendix. Data Sources and Construction.

England.

Wages of agricultural labourers for the 1760s and 1833 are taken from Hunt (1986) with one obvious error corrected (Nottinghamshire in the 1760s where wage is given as 9 shillings instead of the 6 shillings that Young records). Population data for 1761 and 1831 are taken from Wrigley (2007), while literacy of convicts is from Nicholas and Nicholas (1992, Table 3). Both of these exclude Monmouthshire, so we use Marshall's (1833) figure for 1750 population, and assume that illiteracy was the same there as in other counties of western England (21–25 per cent). Nutrition scores from 1795 are taken from Horrell and

Oxley (2012). We interpolate values for two missing eastern counties of Cambridgeshire and Huntingdonshire based on a penalized spline of values from neighbouring counties. The value of the lay subsidy per square mile in 1334 is from Glasscock (1973, Table 4.1).

France.

Wage is average industrial wage, 1839–40 used by Chanut et al. (1995) and kindly provided by Gilles Postel-Vinay, while agricultural productivity is wheat yield per hectare divided by man days per hectare from the 1852 *Enquete agricole* from Demonet (1990). All other variables are taken from the tables in Angeville (1836) with column numbers listed. All figures for military recruits are the average for 1825–1829. Height: average height in cm of accepted conscripts (V37). Literate: One minus percentage conscripts ignorant (V69). Industry: Proportion of military recruits from industrial occupations (V84).

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