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A quantitative model of the British industrial revolution, 1780-1850

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Abstract

A simple aggregative model is calibrated to data from Great Britain in 1850 and used to study the role of growing foreign trade, the declining cost of power, and technical change in manufacturing over the period 1780-1850. The model shows that growth in trade played an important role in redistributing income away from land and toward labor, as it reduced the share of agriculture and increased the share of manufactured goods in aggregate output. Both types of technical change contributed significantly to growth, but the change in manufacturing was about three times as important as that in the energy sector.

The British Industrial Revolution marked the beginning of the modern economic era: the faster growth, rapid real wage increases, and dramatic shifts in the allocation of labor and composition of output across sectors that began during that period have continued ever since. But our understanding of the factors underlying the economic events of this period is very incomplete. Technical change was clearly important, but its pace and exact location are still unclear. The steam engine played a major role, but its contribution would have been modest without the many complementary innovations it stimulated, particularly in the spinning and weaving of cotton. And technical change occurred in other sectors as well, including metallurgy and chemicals. Indeed, an orthodox view of the period is that technical change was widespread throughout the economy, occurring in virtually all

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branches of manufacturing and in agriculture as well—that it was not the "age of steam" but rather the "age of invention." But this characterization leaves open the issue of where the important innovations occurred.

The role of foreign trade during this period has also been hotly debated. Britain was a very open economy even at the beginning of the period, and her foreign trade grew enormously as she industrialized. Was the larger volume of trade vital in precipitating rapid growth, or is it more accurately viewed as a passive by-product of the enhanced productivity in manufacturing?[1]

These questions are, inherently, both quantitative in nature and macroeconomic is scope. The goal of the analysis here is to address at least some of them using a simple quantitative model of the type that has become standard in macroeconomics in recent years. Calibrated models have proved extraordinarily useful for addressing many questions where an economy-wide picture is needed. Studies of monetary policy, fiscal policy, international trade, labor market policies, and economic growth have benefitted enormously from having simple quantitative models as the basis for discussion. These models provide a discipline, especially for analyzing quantitative issues, that is hard to impose otherwise. They reveal logical flaws and expose claims that are quantitatively fallacious in a way that verbal arguments and partial equilibrium models often cannot.

A simple quantitative framework seems particularly useful for studying an historical period for which the evidence is scattered, partial, and subject to large errors. A calibrated theoretical model provides a consistency check on shaky data and in addition offers useful guidance for future work, by showing which particular types of data would be most helpful in sharpening the focus of the overall picture.

The framework used here is a variant of a standard growth model, calibrated so that the industrial steady state roughly matches evidence for the British economy around 1850. Population growth is pegged at its historical level and, along Malthusian lines (and to permit existence of a steady state), technical change in agriculture is assumed to be just rapid enough to offset it. The Industrial Revolution is then modeled as having consisted of three events: a dramatic improvement in the technology for producing energy, a moderate improvement in the technology for producing manufactured goods, and a large increase in the volume of foreign trade. The steady state with these three changes is computed and compared with British data from around 1780. The unit of analysis is Great Britain (England, Wales, and Scotland) throughout.

Before proceeding, it is useful to say a few words about the choice of

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[1] For more detatiled discussions of these issues, see Cuenca-Esteban (1997), Engerman (1994), Harley (1999), Harley and Crafts (2000), McCloskey (1985), Mokyr (1999), and Temin (1997).

dates and the focus on steady states. An unfortunate but unavoidable fact is that the early 1800's were a period of substantial upheaval for the British economy. The country was fighting a long and expensive series of wars with France that drained resources and disrupted trade. In addition, there were several years of devastating crop failures in the early 1800's. Thus, it is clear that any serious attempt to fit a transition path would have to deal with these extraordinary shocks: the very high level of government spending and the substantial fraction of the labor force drawn into military service; the interruptions to foreign trade; and the wild gyrations in food supplies and prices. Such a study would be enormously interesting, but it is beyond the ambitions of the present paper.

Instead, the analysis here focuses on benchmark years before and after this interval of turmoil, years when the exogenous shocks to the economy were (relatively) mild, and it models these two years as steady states. The early year for the study, 1780, is early enough so that mechanization in industry (cotton textiles) was just getting started, so it is a reasonable date for calibrating the pre-industrial economy. But it is late enough so that steam engines were beginning to enter the market for mechanical power, so fairly reliable sources are available for estimating the cost of power.

The later year, 1850, is late enough so that the economy had recovered from the devastating wars with France and mechanization in manufacturing was widespread. It is also late enough so that data from the fairly reliable 1851 Census of Population can be used.

To facilitate comparison with the evidence, the model here has three final outputs. The first consists of agriculture, forestry, and fishing; the second of manufacturing, mining, and industry (including construction); and the third of trade and transport (or commerce), housing, services (domestic and personal, professional, and government), and all other. These will be referred to throughout as agriculture, manufacturing, and 'other.' This is the way much of the data is available, except that many sources distinguish two or three categories within 'other.' For our purposes here a further refinement is not useful and would add several parameters to the model. The breakdown into these three sectors is enough to allow us to look for the major change in the composition of output that was the hallmark of the early industrial revolution: a substantial rise in manufacturing that was offset by a decline in agriculture.

The model includes three primary inputs: land, labor, and capital. In addition, energy (mechanical power used in industry, to be precise) is explicitly included as an intermediate good. It is produced with capital and labor and used in the production of manufactured goods.

In comparing the pre-industrial and industrial steady states in the model with the evidence for 1780 and 1850, we will be particularly interested in the increase in total output, sectoral shifts in its composition, and changes in factor returns. That is, we will want to compare the changes in the model with those suggested by the evidence. This is an exercise that is bound to fail in the sense that part of the growth and some of the sectoral shifts will remain unaccounted for. Nevertheless, it is an interesting first step toward understanding the role of various factors in explaining the dramatic changes that occurred.

We will then use the model to examine the importance of various economic factors in contributing to growth during the Industrial Revolution. With a quantitative model in hand, it is easy to calculate the fraction of total growth—overall and in particular categories—that can be attributed to the increase in foreign trade, the decline in the cost of power, and the technical change in manufacturing generally. Stated a little differently, the first question is: if foreign trade had *not* expanded during this period, how much would overall growth have been hampered by the need to rely on domestic sources for food? The model below can give at least a rough answer to this question. Similarly, within the context of the model, it will be quite straightforward to ask how much growth would have been hampered if there had been no change in the price of energy or no technical change in manufacturing.

The Industrial Revolution has been the subject of a number of recent papers adopting an aggregative theoretical framework. Hansen and Prescott (2002) and Jones (2001) focus on explaining the rather abrupt transition from a world with virtually no per capita income growth to one with sustained growth. Galor and Weil (2000) and Lucas (2001) also address this question, and in addition look at its connections with the demographic transition and the rise in human capital. All of these papers take a very broad and primarily theoretical approach, and in some sense all can be viewed as attempts to identify types of technical change that are compatible with the long run trends. This paper takes a narrower and more empirical approach, focusing on the macroeconomic changes in Britain over a comparatively short time period.

More closely related is Harley and Crafts (2000), where the authors use a computable general equilibrium (CGE) model to study this period. Their approach, which focuses on the composition of manufactured exports, is very complementary to the one taken here. Harley and Crafts calibrate a CGE model with seven sectors (agriculture, services, and five branches of industry) to data from 1840. They look at the volume and composition of foreign trade in 1770 and 1840, and focus on questions about the rates of technical change in various sectors. They conclude that the observed growth in food imports is consistent with technical change in agriculture that is substantial but still too little to offset the diminishing returns provoked by a limited supply of land. They also conclude that the volume and composition of manufactured exports is consistent with the view that technical change in manufacturing was concentrated in a few industries. For plausible demand elasticities, the growing demand for food imports could stimulate export growth even in manufacturing sectors where technical change was absent or very small.

The rest of this paper is organized as follows. Section 1 provides a little historical background, and the relevant data for the British economy during the period under study are discussed in Section 2. The theoretical model is described in Section 3 and the basic numerical results are presented in Section 4. The counterfactual exercises, calculating the relative importance of foreign trade and of the two types of technical change, are carried out in Section 5; and in Section 6 some conclusions are drawn.

1 Historical background

The model developed below includes exogenous improvements in the technologies for energy and manufactured goods, so it is useful to begin with brief descriptions of these sources of change.[2] The changes in foreign trade will be discussed later.

Before 1770 very little mechanization had taken place in the textile industry, and an industrial plant of any type had a very low power requirement, usually no more than 5-7 horsepower. The main sources of power were water wheels, windmills, horses, and man (or woman) power, with the water wheel being by far the most important. The undershot wheel was simple, robust, and cheap to construct, and until the mid-eighteenth century it was the most commonly used. Overshot wheels were about twice as efficient, but they had other drawbacks. The breast wheel, introduced by John Smeaton in the 1750's, combined most of the efficiency of the overshot wheel with some of the practical advantage of the undershot wheel, and it spread quickly. Other improvements were made as well, and the efficiency of water wheels in harnessing the potential power from a given stream rose significantly. But by the late 1700's overcrowding was a severe problem, at least on favorable streams in desirable areas, and the potential for further increases in power was limited.

A useful starting date for the early wave of mechanization is 1771, when Arkwright built the first cotton mill with mechanized spinning. Many of the cotton mills built in the 1770's, 80's and 90's followed Arkwright's design closely, and they typically used either 10 or 20 horsepower, supplied by a waterwheel. Even though the new technology spread rapidly, however, the total volume of cotton textile output was small, and "the total import of cotton in 1795 could have been carded and spun with 5,000 h.p." (Chapman, 1970, p. 2)

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[2] The material here draws on Mokyr (1985, 1990) and Reynolds (1983).

Although earlier devices were employed in mining, the use of the steam engine in manufacturing came with James Watt. Boulton and Watt formed their partnership in 1775, to exploit Watt's patent on the separate condenser, and over the next 25 years (the patent was extended) they built on the order of 450-500 engines. Competing firms built steam engines with other designs, as well as 'pirate' engines that infringed on Watt's patent, but Boulton and Watt had a little over a quarter of the market during the life of Watt's patent. Their first orders for rotative engines, the type used in the cotton industry, came in 1783. Production of that type grew quickly, and subsequent innovations further improved efficiency.

By 1850 two big changes had occurred in British industry: further innovations in spinning and weaving cotton, as well as developments in other industries, had enormously increased the total power in use, and the steam engine had displaced the waterwheel as the most important source of power. The growth in total horsepower came from increases in both average power per mill—which grew to 20 to 30 horsepower, while large mills used 100 or more—and the number of mills. By 1850 a total of 500,000 horsepower in steam engines were installed in Britain.[3] The textile industry alone employed 133,000 horsepower, of which 81% came from steam.[4]

2 Data

There are no national income and product accounts for this period, so the first challenge in calibrating a model is to find enough data to make the exercise possible (and interesting). The only comprehensive set of figures for this period is in the pioneering work of Deane and Cole (1969). But like other pioneers they attracted followers, and as a result some of their estimates have been very substantially revised. Of particular importance for our purposes here, it is widely agreed that their figures significantly overstate real income growth for the period we are studying. Consequently we will draw on other sources for estimates of real wage growth, as well as for information about the capital stock, resources in agriculture, and the size and composition of foreign trade.

In the rest of this section the data sources will be described in more detail and a set of figures will be constructed. The constructed figures should be viewed as an estimate of a smooth trend for the period, with no attempt to account for short-run fluctuations.

Before proceeding, another issue that deserves a little discussion is an

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[3] Tann (1988, Table 7.5). Von Tunzelmann (1978, pp. 29-30) reports the same number. Many of the large engines were pumping engines used in mining, however, so the total in other industries was substantially lower.

[4] Mitchell (1962, pp. 185, 198, 203, 210).

important maintained assumption: that capital and labor markets in Great Britain were sufficiently well integrated so that they can be treated as single units. Economic historians have debated this issue at considerable length, with both sides receiving some support. Obviously there were regional variations in wages and prices, but it is not clear that these were larger than in other economies where calibrated macroeconomic models have been used successfully.[5]

2.1 *Sectoral allocation of inputs and composition of output*

Table 1 displays estimates of the allocation of (raw and weighted) labor and capital across sectors and of the sectoral composition of output, aggregated to conform with the model to be developed below. The sectoral allocations for 1850 will be used in calibrating the model, so that information is particularly critical.

Raw labor: For the allocation of raw labor, two sources are used. The last six columns, for 1801-1851, are from Deane and Cole (1969), and are based on Census of Population data. The authors warn that these are 'highly unsatisfactory' for the first half of the nineteenth century. They view the 1851 Census as the first for which the figures are reliable, and those figures are used in the calibration.

The first column, with an estimate for 1755, is based on the figures in Lindert (1980).[6] Lindert's work is based on burial records from a sample of parishes, which report occupational information for deceased men. Lindert uses these records to sort the deceased into 14 categories, and this information is then combined with census data for 1831 and other demographic information to form estimates of the occupational structure of the living population in 1755.

The share figures in Table 1 were calculated from Lindert's, following the procedure used in Crafts (1985a, pp. 14-15). To begin, twelve categories are aggregated in the obvious way to form three groups: agriculture constitutes one; mining, manufacturing, apprentices, and building trades are aggregated to form a second; and professions, commerce, maritime, army, servants, other services, and titled form the third. The small category called 'poor, pensioners' is omitted, as being out of the workforce. The large category called 'laborers' is then allocated 60% to agriculture and the rest to industry, a split that Crafts suggests on the basis of the 1831 census figures.

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[5] Williamson (1990, Ch. 7) looks at this issue using a multisector applied general equilibrium model. He concludes that the effects of imperfections in capital and labor markets were substantial, especially for barriers in the capital market, but his figures seem rather problematic (cf. Mokyr, 1999, p. 82).

[6] The data are for England and Wales only, but evidence for later years suggests that Scotland was not much different, so we will ignore this issue.

Table 1: Sectoral allocations
(shares)

	1760	1780	1790	1800	1810	1820	1830	1840	1850
Allocation of labor (raw)									
agriculture	.31[a]	.33[b]	.35[b]	.36	.33	.28	.25	.22	.22
manufacturing	.29[a]	.30[b]	.30[b]	.30	.30	.38	.41	.41	.43
other	.40[a]	.37[b]	.35[b]	.34	.37	.34	.34	.37	.35
Allocation of labor (weighted)									
agriculture		.22[c]	.24[c]	.25	.26	.22	.19	.18	.16
manufacturing		.22[c]	.22[c]	.22	.21	.28	.33	.36	.37
other		.56[c]	.54[c]	.53	.54	.50	.48	.46	.47
Allocation of capital									
agriculture	.33	.30	.30	.32	.28	.26	.21	.18	.15
manufacturing	.08	.09	.10	.10	.10	.11	.14	.16	.18
other	.59	.61	.61	.58	.61	.63	.65	.66	.68
(dwellings)	(.30)	(.30)	(.29)	(.27)	(.30)	(.31)	(.33)	(.32)	(.27)
Gross inv./GNP	8%	13%	14%	10%	14%	14%	13%	13%	13%
Composition of GDP									
agriculture	.37	.36[b]	.35[b]	.33	.36	.26	.23	.22	.20
manufacturing	.20	.20[b]	.21[b]	.23	.21	.32	.34	.34	.34
other	.43	.44[b]	.44[b]	.44	.43	.42	.43	.44	.46
(housing services)				(.053)	(.057)	(.062)	(.065)	(.082)	(.081)

[a]*1755;* [b]*interpolated;* [c]*constructed. 'Agriculture' includes forestry and fishing; 'manufacturing' includes mining and industry; and 'other' includes trade and transport (or commerce), housing, and all services--domestic, personal, professional, and government.*

Sources: For raw labor, the 1755 figures are constructed from Lindert (1980, Table 3), as described in the text, and the 1800-1850 figures are from Deane and Cole (1969, Table 30, p. 142); for weighted labor, the 1780-90 figures are constructed as described in the text, and the figures for 1800-1850 are from Dean and Cole (1969, Table 34, p. 152); the capital stock figures are from Feinstein (1988, Appendix, XIII, p. 452); the investment ratios are from Feinstein (1981, Table 7.2); and for GDP the first column is from Crafts (1994, Table 3.1), and the 1800-1850 figures are from Deane and Cole (1969, Table 37, p. 166).

The burial information for women is not very useful, since the vast majority are identified simply as 'wives' or 'widows.' The question, then, is whether the employment shares across sectors were different for women and men. Following Crafts, the shares for men are adjusted by adding 10% to the 'other' sector, on the grounds that women were more heavily represented in domestic service.[7]

The figures for 1780 and 1790 are then constructed by interpolation, using the figures for 1755 and 1800. These figures must be viewed as rough estimates, but since they are not used in the calibration, errors here are not critical.

Weighted labor: A conceptually more appropriate way to measure the allocation of labor across sectors is to weight the number employed in each sector by average hours and an average wage rate for that sector. Thus, a better measure of the distribution of 'weighted' labor input is the distribution of earnings across sectors.

For 1801-1851 this information is available in Deane and Cole (1969), and their figures are displayed in Table 1 as weighted labor. For 1780, a commensurate figure was constructed as follows.

The figures for raw and weighted labor across sectors for 1801-1851 can be combined to back out a set of implicit weights for each year. These weights change gradually over time, with the weight on agricultural labor showing a hump shape, the weight on manufacturing labor increasing, and the weight on labor in the 'other' sector declining. The weights for 1800 were applied to the raw labor figures for 1780 and 1790 to construct estimates of the weighted labor allocation for those years. Since the 1780 figure is used only as a check on the fit of the calibrated model, this simple method of adjustment seems adequate.

No adjustment is made here for changes in labor quality over time. Schooling, the most obvious source of changes in labor quality, was unimportant for this period. Matthews, Feinstein, and Odling-Smee (1982, Appendix E, Tables E.1 and E.2) report average years of schooling in England and Wales for birth cohorts and for the workforce. For birth cohorts from 1805 and earlier, the average is 2.3 years, and this rises gradually to 4.2 for the 1826-1835 birth cohort. The composition of the workforce changes even more slowly and with a lag, so by 1871 the average years of schooling for males in the workforce was only 4.2.

Similarly, in his review of the role of education in explaining growth at this time, Mitch (1999) concludes that it was very minor. He cites Schofield's

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[7] Notice that this procedure is not the same as saying that women represented only 10% of the workforce and all of them were employed in service: it says that compared with men, women were more heavily concentrated in the service sector, and that the 10% adjustment takes care of this difference.

(1973) study that looked at literacy rates as proxied by signature rates at marriage. These grew very little (from 60% to 65% for grooms and 40% to 50% for brides) between 1780 and 1830. Thus, ignoring education seems fairly innocuous. Other aspects of human capital (like health) may have improved, but a quantitative assessment would be difficult.

GDP: No direct information on the structure of GDP is available, but reasonable conjectures have been made based on the allocation of labor, and these are displayed in Table 1. The last six columns are again from Deane and Cole (1969). For 1801 the records are very incomplete, so their figures for that year are tentative. But income-tax assessments are available from 1842-3 on, and for 1851 they combine this data with the occupational information from the Census.

For the earlier period the estimates are from Crafts (1994, Table 3.1). They are based on the Social Tables in Lindert and Williamson (1982), which in turn are based on the burial records used in Lindert (1980). Crafts gives figures for 1760, 1800, and 1840, and these show a slightly smaller decline in agriculture compared with Deane and Cole's figures. The figures in Table 1 for 1780 and 1790 are interpolated.

Capital stock: Feinstein (1988, Tables XIII, XIV) provides detailed estimates of the real capital stock, by sector and by type of asset, by decade. These are constructed from disaggregated information on investment in specific types of assets. The figures in Table 1 are constructed by simply aggregating his figures to conform with our three-sector structure and calculating shares. The main change over this period is that agriculture's share declines by half, with approximately equal parts of the released capital being absorbed by agriculture and the 'other' sector. Notice that housing has a fairly constant share of about 30% over the whole period.

Capital stock figures are inherently more difficult to construct than estimates of labor and output, especially for a period when investment was not measured in any systematic way. Consequently, the capital stock figures should probably be viewed as more susceptible to error than the labor and GDP estimates.

Investment: In addition, Feinstein (1981, Table 7.2) provides estimates for total (gross) investment in Britain as a share of GNP, and these are also displayed in Table 1. These figures are decade averages. Investment's share rose from 8% - 10% during the 1760's and 1770's to 13% in the 1780's, and then—except for the 1810's, at the height of the wars with France—fluctuated around 13-14% for the entire period.

As a consistency check, it is useful to note that investment in buildings is roughly the same when calculated two different ways. Feinstein estimates investment in buildings to be about 73% of the total, while investment's share in GDP is about 13%. Using these two figures, we find that the share of building investment in GDP is about (.73)(.13) $\approx$ 0.095. Alternatively, Crafts (1985a, Table 2.3) estimates building to be about 26.5% of total industry in 1831, while industry (cf. Table 1) is about 34% of GDP. Using these two figures, the share of building investment in GDP is about (.26)(.34) $\approx$ 0.090, so the two estimates match fairly well.

Farm land: Finally, Feinstein (1981, Table 7.1) provides estimates of the value of farm land as a fraction of total capital assets: 47% in 1760 and 21% in 1860. Interpolating gives figures of 42% for 1780 and 24% for 1850.

2.2 *Earnings and land rents*

Earnings: There is an enormous amount of controversy among economic historians about the extent of real wage growth during the period under study here.[8] Consequently, it is useful to begin with a brief overview of the main points of contention.

As usual, there are two components in the construction of a real wage series: a series for average nominal wages and one for a cost-of-living index (COLI). There is relatively little controversy about nominal wages, at least for blue collar workers, because the data is fairly good. Two of the important primary sources, Gilboy (1934, 1936) and Bowley and Wood (1898-1910), have been around for a long time, and virtually all nominal wage series use them heavily.[9]

The more serious differences have been about the COLI for this period, and there are controversies about all aspects of its construction: the price series for individual commodity categories—food, clothing and rent; the appropriate budget shares; and whether to use fixed or varying weights.

A good starting point is Flinn (1974), who surveys a number of price index series and nominal wages series compiled by various historians. He concludes that "Very broadly, prices moved in a rising and falling arc over the century 1750-1850 with a peak in 1812-1813," with inflation picking up in the early 1790's and continuing during extended period of the wars with France. Flinn concludes that before 1815 the substantial price increases were roughly matched by increases in money wages, with no significant change either way in real wages. In the next decades, however, there were substantial price declines that were not matched by nominal wage cuts. Hence there was a significant increase in the real wage—perhaps 25-40% in total—between 1815 and 1850.

In a very ambitious but controversial paper, Lindert and Williamson (1983, 1985) construct average nominal wage series separately for blue collar

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[8] See von Tunzelmann (1979) for an analysis that shows why there is so much room for disagreement.

[9] See Flinn (1974) for a complete bibliography.

and white collar workers and also construct a new COLI series. Their blue collar wage series is similar to those calculated by others. The innovations are the white collar series and the COLI. In a broad qualitative sense their conclusions agree with Flinn's impression, but their estimates of overall real wage growth are enormous: their "best-guess" for real wage growth over the period 1755-1850 is 155%, with almost all of the growth coming after 1820. Even their most pessimistic view is that real wages doubled over this period.

Their figures were quickly criticized by Crafts (1985b), Mokyr (1988), and others. Mokyr shows that very large wage increases seem incompatible with the evidence on imports of small luxury items: sugar, tea, and tobacco. These goods were entirely imported, so customs records provide fairly good evidence on total supply (except for smuggling). Moreover, these products have fairly high income elasticities, so one can back out estimates of income growth from increases in per capita consumption, controlling for price changes. Mokyr concludes that these estimates show very little income growth between 1791 and 1851, with the little that there was occurring in the 1840's.

Finally, in a recent contribution Feinstein (1998) offers his own series for both nominal blue collar earnings and the cost of living. His nominal earnings series is very similar to Lindert and Williamson's, as it should be, since both are based on the same underlying data series. His COLI series is quite different, however. He criticizes the Lindert-Williamson index on a number of grounds: the series used for rents, the series used for clothing, the weights used in the food component, and the overall weights (fixed for the entire period) used to construct the series. His objections seem valid and his final numbers seem more plausible, so we will use Feinstein's figures here. Mokyr (1999) presents a slightly revised version of Feinstein's series, and those figures are displayed in Table 2. They show an increase in real earnings for blue collar workers of 37%, with most of the change coming after 1830. The figure of 37% will be used to calibrate the extent of technical change in the manufacturing sector.

Two issues remain: what to do about a wage index for white collar workers and how to weight the two.[10] Feinstein provides no figures for white collar earnings. Mitch (1999, Table 5.2) reviews evidence on the premium for skilled over unskilled labor, and presents estimates for the period 1755-1851, using several alternative classification schemes. Most of these show very little change over the period of interest here, and the ones that do change

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[10] Lindert and Williamson (1983) construct estimates for white collar earnings and for weights, but their figures seem suspect on two grounds. First, they show real earnings for white collar workers rising by a factor of 4.5 (yes, a 350% increase) for the period 1781-1851, with virtually all of the gains coming after 1815. In addition, backing out the (implicit) weights for the two groups, one finds that the weight on white collar workers *falls* over time, from 39% in 1781 to 28% in 1835. It is difficult to decide which claim strains credulity more severely.

Table 2: Earnings and land rents
(current prices)

	1780	1790	1800	1810	1820	1830	1840	1850
average nominal earnings	100	107.4	154.6	188.7	166.5	154.5	164.9	166.4
cost of living index	100	101.4	153.8	181.8	150.9	135.1	140.2	121.5
average real earnings	100	106	103	104	111	114	118	137
rental rate for farm land (£ per acre)	0.674	0.796	1.064	1.543	1.241	1.220	1.148	1.170
total rents on farm land (mil. £)	£ 25	£ 30	£ 39	£ 57	£ 46	£ 45	£ 43	£ 43

Sources for Table 2: Nominal earnings, COLI and real earnings from Mokyr (1999, Table 1.5), are five-year averages centered around indicated year, computed from Feinstein (1998, Appendix Table 1). Rental rates are ten-year averages during the subsequent decade, from Clark (1999, Table 6). Total rents are calculated using the figure for total agricultural land in England and Wales in 1888 from Clark (1999, Table 3), and an adjustment factor from Allen (1994, p. 9) to incorporate Scotland.

show a falling skill premium. Hence it seems reasonable to assume that the rates of real wage growth were about the same for the two groups.

There is still the issue of weights, however. Even if earnings grew at about the same rate within each group, the overall average could grow more rapidly if the composition of the labor force shifted toward higher skill groups. But as noted above, schooling and literacy rates increased only a little during the period under study here. Therefore, the skill mix will be assumed to have remained constant.

Land rents: Although agriculture's role was shrinking rapidly during this period, it was still an important sector of the economy. Consequently land rents are a significant, if declining, share of national income. The best available evidence on this component of national income seems to be in Clark (1999b, Table 6), who estimates land rents for England and Wales using a hedonic model and data on rental rates for land held by charities. The regressions use indicator variables for time, geographical region, various types of structures, and other features of the plot. Using this information, Clark constructs average rental rates for several geographic regions and for the country as a whole. By his estimates, average nominal rents (in current £/acre) grew from 0.674 in 1780-84 to 1.170 in 1850/54.

Clark also provides information on the acreage under cultivation, by region, for 1888. Since this area was fairly constant over time, we can use the 1888 figure of 29.4 mil. acres for our period as well.[11] Clark's acreage figure is for England and Wales only, but Allen (1994, p. 97) notes that by the middle of the nineteenth century, England and Wales accounted for 80% of British farm land and 89% of agricultural output. We will use the 80% figure to boost the total acreage to 29.4 / 0.80 = 37 million. Table 2 displays Clark's series for average rental rates and an estimated series for total land rents.

2.3 *National income and factor shares*

Deane and Cole (1969, Tables 34 and 72) offer estimates of total national income and total earnings, in nominal terms by decade, from 1801 on, and their figures are displayed in the last two lines of Table 3. But their figures do not go back far enough for our purposes, and, more importantly, their figure for 1851 seems very suspicious.

Looking at a number of sources, it appears that prices fell by 10-15% during the 1840's and then rose by the same amount during the 1850's.[12]

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[11] There were some enclosures during this period: see Holderness (1988) for more detail. But these can be viewed as investments that increase productivity rather than increases in acerage.

[12] For example, Feinstein's COLI index falls 13% and then returns to its original level; Clark's agricultural price deflator falls 8% and then rises 15%; the national income deflator

Table 3: National Income and factor shares
(mil. £ at current prices and shares)

	1780	1790	1800	1810	1820	1830	1840	1850	1860
Total earnings	£ 55	£ 66	£106	£147	£151	£162	£194	£219	
National income	£123	£146	£234	£319	£328	£351	£414	£467	
Agricultural land rents	£ 25	£ 30	£ 39	£ 57	£ 46	£ 45	£ 43	£ 43	
Factor shares									
labor	.45	.45	.45	.46	.46	.46	.47	.47	
land	.20	.20	.17	.18	.14	.13	.10	.09	
capital	.35	.35	.38	.36	.40	.41	.43	.44	
(wages & salaries)			£104	£140	£133	£148	£191	£247	£315
(national income)			£232	£301	£291	£340	£452	£523	£668

Sources for Table 3: Total earnings are constructed by multiplying the average nominal earnings index in Table 2 by population and using a scale factor to adjust units. National income is constructed from total earnings by assuming the indicated values for labor's share. Agricultural land rents are from Table 2, and shares for land and capital are calculated. The last two lines are from Dean and Cole (1969, Tables 34 and 72).

Using Deane and Cole's figures for national income in current prices in 1840, 1850, and 1860, and assuming a 10% price decrease during the 1840's that is exactly reversed during the 1850's, these figures imply that real national income grew by 29% over the 1840's and by only 16% over the 1850's. Alternatively Deane and Cole's 1850 figure for national income may be overstated. A nominal income figure of £495 for 1850 equalizes the real growth rates over the two decades if the price decline was 10%, or a figure of £467 if the price decline was 15%.

Similarly, using Deane and Cole's figures for total nominal earnings for 1840, 1850, and 1860 and making the same assumption about prices, we find that real earnings grew by 44% during the 1840's and by only 15% over the 1850's. A nominal earnings figure of £221 in 1850 equalizes the real growth rates over the two decades if the price decline was 10%, or a figure of £208 if the price decline was 15%.

Feinstein's nominal earnings series can also be used to construct estimates of total nominal earnings and total national income for 1850. First multiply the average nominal (blue collar) earnings series for 1780-1850 from Table 2 by population. Then divide the resulting series for 1800-1840 by Deane and Cole's series for wages and salaries to form the ratios, and average these ratios to determine a (constant) scaling factor. Then multiply the (average earnings × population) series by this scaling factor to construct an estimated series for total nominal earnings over the whole period. This series is displayed in the first line of Table 3.

A series for total (nominal) national income can then be constructed using estimates of labor's share. Deane and Cole's figures put labor's share at 45% in 1801 and 47% in 1851, with fluctuations around these figures during the intervening years. The constructed series for national income in Table 3 uses a smooth series for labor's share that rises gradually from 45% to 47%.

Notice that the two constructed series are quite close to the Deane and Cole figures for 1800-1840. Moreover, the crucial 1850 figures of £219 for total earnings and £467 for national income are very similar to those calculated by interpolating between Deane and Cole's values for 1840 and 1860 and assuming a 10-15% price change that is reversed.

Total (nominal) agricultural land rents were constructed in Table 2. Land's share in Table 3 is computed directly, and capital's share is the residual.

2.4 *Output and input growth*

Except for real earnings, Tables 1 - 3 say nothing about real growth rates. Table 4 displays estimates of growth rates for outputs and inputs, in aggregate

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in Deane and Cole falls 8% and then rises 11%; and the capital stock deflator implicit in Feinstein and Pollard falls 16% and then rises 10%.

and by sector.

GDP and industrial output: The consensus among economic historians is that growth during the early years of the industrial revolution was much slower than Deane and Cole had originally thought, so the real growth rates for aggregate output and industrial value added in Table 4 are based primarily on information from Crafts and Harley (1992).

The composition of industrial output changed dramatically over the period we are studying, with large increases in cotton textiles and building, and large declines in wool and leather. Not surprisingly, these huge shifts were accompanied by large changes in relative prices, so the task of constructing an index for the increase in overall industrial output over this period is far from easy.

Using Fisher and Divisia price indices, Harley (1982) offers estimates of the increase in industrial production for two subperiods. The two estimates agree quite well with each other: according to either index, industrial production grew at an annual rate of about 1.6% over the period 1770-1815 and about 3.1% over the period 1815-1840.

Crafts (1985a, Table 2.6) does similar calculations and arrives at very similar conclusions. Using Fisher and Divisia indexes, he computes average annual growth rates of 2.0-2.1% for 1780-1800 and 3.0-3.1% for 1801-31, so the two weighting procedures give estimates that are very close to each other and also quite similar to Harley's. The growth rate figures in Table 4, from their later joint work, incorporate minor revisions.

Crafts and Harley do not offer a figure for GDP growth rate for 1830-50, so for this period Deane and Cole's figure of 2.3% is used.

Capital stock: Feinstein's (1988) capital stock figures were used to calculate the real growth rates in Table 4, by sector and in total. Notice that the aggregate capital stock grows at about the same rate as GDP, so the capital/output ratio is roughly constant.

Agriculture: For agriculture, Allen (1994) provides indexes for total output and for inputs of labor and land, for 1750, 1800, and 1850. The figures in Table 4 were calculated assuming a constant growth rate between 1750 and 1800. Allen also provides figures for capital input, which show significantly slower growth compared with Feinstein's figures–only 60% over the whole period instead of 100%.

Labor supply: The figure for total labor supply growth is simply total population growth over the period, computed from the figures in Wrigley and Schofield (1981, Table 7.8). The latter are widely accepted as being of very high quality, although they are for England only. The authors report that population was 7.042 million in 1781 and 16.736 million in 1851, for a total increase by a factor of 2.38 over 70 years. The population growth rate was very similar at the beginning and end of the period, and a little higher

Table 4: Output and input growth
(total change over 1780-1850, factor)

	output	capital	labor	land
aggregate GDP	3.38	3.69	2.38	1.08
agriculture	1.80	1.99 (1.59)	1.21	1.08
industry	6.07	9.05		
other	3.45	3.90		
per capita GDP	1.42	1.55	1.00	
agriculture	0.76	0.84 (0.67)	0.51	
industry	2.55	3.80		
other	1.45	1.64		

Sources for Table 4: Aggregate GDP computed using growth rates for 1780-1830 from Crafts and Harley (1992, Tables 4) and for 1830-50 from Dean and Cole (1969, Table 72); industrial output from Crafts and Harley (1992, Table A3.1); capital stock from Feinstein (1988, Table XIII); total labor supply from population in Wrigley and Scofield (1981, Table 7.8); agricultural output, capital (in parentheses), labor, and land from Allen (1994, Tables 5.1-5.4); and output of 'other' calculated using sectoral shares in Table 1. All per capita figures calculated.

during the middle years. Scotland and Wales were modest proportions of the British total and their growth rates were similar to the English, so multiplying the English population by 1.25 gives about the right figure for Great Britain.

The remaining issue, then, is whether it is reasonable to assume that aggregate labor supply was approximately proportional to the total population over this period. In principle, adjustments could be made for the fraction of the population of working age, the fraction of that group in the labor force, and the average work week of the employed.[13]

The evidence on the last two points is limited, and what there is suggests no need for adjustment. Figures constructed from the 1801 and 1851 census data suggest little change in the labor force participation rate over that period, and for the eighteenth century there is no direct evidence. Nor is there very good evidence about the average number of hours worked per week. Some work suggests that it may have increased in London, but remained constant in agriculture.[14]

For information about the fraction of the population of working age, we can use Wrigley and Schofield's (1981, p. 447) estimates of the dependency rate, an index of the ratio of those aged 0-14 and 60 or over, to those aged 15-59. The movements in this index reflect the pattern in the population growth rate, rising from 902 in 1780 to 1000 in 1826, and then falling to 868 in 1851. Although the changes are substantial, the ratio is about the same at the beginning and end of the period. Hence the fluctuation does not matter much for the calculations here, and there is little harm in assuming the fraction of the population of working age remained constant.

2.5 *The energy sector*

Cost of power: To estimate the decline in the marginal cost of power supplied to the manufacturing sector between 1780 and 1850, we can look at cost figures for any competitive power source at each date. Evidently both water and steam were competitive at both dates, so we can use either. Estimating unit costs for power from waterwheels is quite difficult, however, since construction costs tended to be very site-specific and records have survived for only a small number of mills. Consequently we will focus on the cost of power from steam, for which much better information is available. The decline in the unit cost of power will be used in the simulations to calibrate technical change in the energy sector.

Many of the available figures for the earlier period are for 1795, so we will look at costs for that year and assume that they were not much different in

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[13] Since the goal here is to construct trend figures, fluctuations in the unemployment rate can be ignored.

[14] See Mokyr (1999, p. 91-93) for a discussion of the evidence.

1780. Tann (Table 7.6) reports estimates of average retail prices for Boulton and Watt rotative engines of various sizes, sold between 1788 and 1795. Cost per horsepower fell with the size of the engine, especially for smaller engines. For a 10 horsepower engine, which was a common size, it was £48 per horsepower. For engines of 20-40 horsepower it was roughly constant, at about £40 per horsepower. In addition, Boulton and Watt added an annual premium charged on Watt's patent. In 1795 the premium rate was £3.8 per horsepower per year for the remaining five years of the patent, payable at the time of purchase, for a total of £19. There were also costs for an engine house, framework, delivery and erection. For a medium size engine, around 30 horsepower, Tann's figures suggest a total of about £19 per horsepower. So for a 30 horsepower engine, the capital cost per horsepower was approximately

$$\begin{aligned} 40+19+19 &= \pounds\mathit{78}, \\ \text{engine}+\text{royalties}+\text{other} &= \text{total}, \end{aligned}$$

and for smaller engines the total would be a little higher. Allowing 10% for interest and depreciation, the annual capital cost was around £7.8.

Von Tunzelmann (1978, Tables 4.10 and 4.11) also reports figures for a 30 horsepower Watt rotative engine built in 1795. His estimate of the capital cost is £72 per horsepower, which agrees well with Tann's figure. To turn this into an annual figure he uses an interest rate of 6% and applies separate depreciation rates for the engine, the boiler, and the building, arriving at an annual capital cost of £7.5 per horsepower per year.

Finally, von Tunzelmann estimates annual material (coal) and labor costs to be £255+53= £308, or £10.3 per horsepower. Thus, the total cost of power from a Watt rotative engine in 1795 was about

$$\pounds 7.5 + 10.3 = \pounds 17.8$$

per horsepower per year.

Von Tunzelmann (pp. 150-151) also estimates that the annual cost per horsepower using steam was £11 in the mid 1850's. If nominal prices rose by about 20% over this period, then the real cost of power fell almost in half between 1795 and 1850. In the simulations below, the decline will be assumed to be 50% between 1780 and 1850.

Inputs in the energy sector: To calibrate the model we will also need estimates of the total capital and labor inputs employed in energy production in 1850. This consists of direct labor and capital plus the appropriate fraction of factors employed in mining. The last year for which von Tunzelmann gives a breakdown of energy costs (Table 4.11) for steam engines is 1835. At that time direct capital costs were about 35% of the total, direct labor was about 15%, and coal was the remaining 50%.

Coal accounted for around 60% of the value of the mining industry in 1850, and around 60% of the coal was used in domestic industry (Deane and Cole, pp. 214-219), so about 36% of the labor and capital employed in mining can be attributed to the energy sector. In 1851, about 10% of the workforce in industry was employed in mining (Deane and Cole, Table 31, p. 143). Since industry employed about 37% of the (weighted) labor force (cf. Table 1), the fraction of the workforce employed in mining coal used in energy for industry was

$$(0.37)\,(0.10)\,(0.36) = 0.013, \quad \text{(weighted)}.$$

Since about 1.25% of the total capital stock in 1850 was in the mining sector (Feinstein, Table XIII), a similar calculation for the fraction of the capital stock employed in mining coal used in energy production for industry gives

$$(0.0125)\,(0.35) = 0.0044.$$

But coal accounts for only half the cost of energy from steam, and some allowance should be made for other sources of power, principally waterwheels. Both of these additional components display a much higher fraction of capital in total costs.

Since capital and labor have approximately equal shares in national income, a percentage point increase in the use of either factor has about the same effect on total cost. Hence about three quarters of the cost of coal is for labor and about one quarter is for capital. If those proportions are reversed in the other half of the costs for steam, then total inputs of capital and labor in steam production are about $0.013 + 0.0044 \approx 0.0174$, or about 1.7% of each factor. Adding a little for water wheels gives perhaps 1.8% of the total (weighted) labor force and 2% of the total capital stock in energy production. The figure for raw labor would be a little higher.

2.6 *International trade*

The volume of foreign trade was quite large during this period, and its role in stimulating the industrial revolution in Britain has been much debated by historians. Table 5, which contains figures from Davis (1979), displays the main features about this trade from 1785 to 1855: Britain imported food and raw materials and exported manufactured goods, and the volume of trade—large at all times—grew significantly over the period.

For our purposes it is most convenient to look at food imports and manufactured exports as shares of domestic production in 1780 and 1850. Davis does not provide figures for either of those years, and foreign trade grew very rapidly during the 1780's and the 1840's. But Mitchell (1962) contains estimates of total trade for those years, and we can use the information in Table 5 to calculate shares of those totals.

Table 5: Overseas trade
(mil. £ sterling and shares)

	1784-6	1794-6	1804-6	1814-6	1824-6	1834-6	1844-6	1854-6
Total exports	£ 12.7	£ 21.8	£ 37.5	£ 44.5	£ 35.3	£ 46.2	£ 58.4	£ 102.5
Cotton goods	.06	.16	.42	.42	.48	.49	.44	.34
Woolen goods	.29	.23	.16	.18	.16	.15	.14	.11
Other textiles	.11	.11	.07	.08	.09	.10	.11	.13
Other manufactures	.38	.37	.24	.18	.19	.18	.19	.24
Foodstuffs and raw materials	.16	.13	.10	.15	.08	.09	.12	.19
Total imports	£20.4	£34.3	£50.6	£64.7	£ 57.0	£70.3	£82.0	£151.6
Foodstuffs	.42	.48	.42	.43	.36	.29	.33	.36
Raw materials	.47	.45	.54	.56	.62	.68	.62	.59
Manufactures	.11	.07	.03	.01	.02	.03	.04	.05

Source for Table 5: Davis (1979, Tables 2 and 23).

Figures for total exports and imports in 1780 and 1850 are displayed in the first two rows of Table 6. The third row, the difference, is evidently income from abroad. (Britain's empire was already a profitable venture!) The rest of the figures in Table 6 are constructed using information from Tables 1 and 3 about total income and the sectoral composition of output, and from Table 5 about the composition of exports and imports.

The information for manufacturing in Table 1 is for value added, so combining the figures there on the composition of output and the figures in Table 3 for national income, we find that nominal (domestic) value added in manufacturing in 1780 was about $.20 \times £123 = £24.6$. Then, using the share figures for 1784-6 from Table 5 and total imports for 1780, we find that the value of raw materials imports was $0.47 \times £15.3 = £7.2$. Assuming that all of these were used in the manufacturing sector and neglecting domestic raw materials, the sum, £31.8, is the total value of manufacturing output. Drawing again on the share figures in Table 5, exports of manufactured goods in 1780 were $.84 \times £8.9 = £7.5$, so about $£7.5/£31.8 \approx 24\%$ of manufacturing output was exported. Hence exports of value added were $.24 \times £24.6 = £5.9$ and retained imports of raw materials were $.76 \times £7.2 = £5.5$. Similar calculations for 1850 and for agricultural imports for both years are also displayed in Table 6.

Table 6 shows very clearly that domestic consumption of food and manufactured goods was quite different from domestic production of those goods, in both years. In addition, imports of raw materials were very substantial over the whole period, and there was a significant inflow of income from abroad.

Since land is an important fixed factor—especially for an island kingdom like Great Britain, agriculture is a sector where diminishing returns puts a very serious limitation on production. Thus, there is good reason to expect that the Industrial Revolution in Britain might have looked quite different if food imports had not grown. In addition the export-producing sector, manufacturing, is the sector that enjoyed substantial technical change. Hence it is reasonable to suppose that Britain's growth during the Industrial Revolution was significantly enhanced by her ability to export manufactured goods. Since our main purpose here is to assess the role of various factors in contributing to growth during the Industrial Revolution, including food imports and exports of manufactured goods in the model is crucial.

It is fairly straightforward to do this in a mechanical way. Notice that food imports are roughly equal to exports of value added in manufacturing. Thus, a simple way to capture the most important aspect of the trade data for our purposes is to assume that value added in manufacturing is exported in exchange for food, to assume that this part of trade is balanced, and to ignore income from abroad and raw materials. This strategy allows us to

Table 6: Manufacturing exports and food imports
(mil. £ sterling and shares)

	1780	1850
total exports	£ 8.9	£ 69.8
total imports	£ 15.3	£104.6
difference (income from abroad)	£ 6.4	£ 34.8
manufactured goods		
domestic value added	£ 24.6	£158.8
imported raw materials	£ 7.2	£ 63.3
total	£ 31.8	£222.1
exported manufactures	£ 7.5	£ 59.0
share of exports in total	0.24	0.27
ratio of imported raw materials to VA	0.29	0.40
exports of value added in mfg.	£ 5.9	£ 42.9
retained imports of raw materials	£ 5.5	£ 46.2
agricultural goods		
domestic production	£ 44.3	£ 93.4
imports	£ 6.4	£ 36.1
total	£ 50.7	£129.5
share of imports in total	0.13	0.28

Sources for Table 6: Total exports and imports for 1780 constructed by extrapolating backward from Davis's figures using total growth between 1779_81 and 1784_86 computed from the official figures in Mitchell (1962, p. 281), 1.43 for exports and 1.34 for imports, and ignoring price changes. For 1850, the figures are declared values from Imlah (1958), as reported by Mitchell (p. 283), averaged over three years. All other figures are constructed as described in the text.

capture one of the most critical aspect of trade for industrialization: Britain's ability to feed her population by exporting manufactured goods.

This approach begs the question of how the level of trade was in fact determined. Presumably technical change in manufacturing and energy increased Britain's comparative advantage in producing manufactured goods, and it was this change that prompted the increased volume of trade. But to make the volume of trade endogenous, we would need data on the price of manufactured goods relative to foodstuffs in Britain and in her trading partners, as well as some estimate of the price elasticity of world demand for manufactures. This more ambitious approach may be feasible, and would be an interesting area for future work. As we will see below, the more mechanical approach taken here puts a severe limit on what the model can say about trading opportunities as a source of growth.

In any case, a remaining question is what to do about income from abroad and imported raw materials. We could include them explicitly, but each raises some problems. For the former, it is not clear that all of the 'difference' item is income from abroad: it may also include shipping costs and it certainly includes measurement errors. Absent firmer information about its status, it seems safer to omit it. For the latter, incorporating raw materials would require adding a parameter to the production function for manufactured goods and a price for raw material imports. Although not impossible, it is not obvious how these could be estimated and it is not clear what is to be gained by including them.[15]

2.7 *Government*

Although the government sector does not appear explicitly in the model developed below, it is useful to get a rough idea of its size, so we know what is being neglected. Table 7 displays total government revenue and expenditure, and their main constituent items, for 1780, 1801, 1815, and 1850.

Total revenue and primary expenditures (i.e., excluding debt service) are also shown as fractions of total national income. Government spending was about 13-14% of national income in 1780 and 1801, and rose to 24% in 1815, at the peak of the wars with France.[16] By 1850 the wars were over

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[15] Since the ratio of imported raw materials to value added in manufacturing does not change too much between the two dates, another interpretation is also possible. If imported raw materials are used in fixed proportion to domestic value added in manufacturing, and those raw materials are financed by income from abroad, then we can also rescale units in the the manufacturing sector of the model to adjust for the omission of the raw materials component.

[16] Williamson (1984) concludes that growth was very slow before 1830, in large part because of the effects of the wars with France. In his view 'crowding out' was a dominant force affecting the standard of living.

Table 7: Government revenue and expenditure
(mil. £ current)

	1780	1801	1815	1850
Total revenue	£ 12.5	£ 31.6	£ 77.9	£ 57.1
customs, excise, stamps, and post office	9.5	20.0	53.0	46.5
land, assessed, property and income taxes	2.5	5.1	22.5	10.1
Total expenditure	£ 22.6	£ 51.0	£108.3	£ 50.6
debt charges	6.0	16.7	30.0	28.5
civil government	1.3	2.1	5.8	7.0
military	14.8	31.7	72.4	15.1
National income	£123	£234	£323	£467
revenue / nat. inc.	10.2%	13.5%	24.1%	12.2%
gov't. exp. / nat. inc.	13.1%	14.4%	24.2%	4.7%

Sources for Table 7: Revenue and expenditure figures from Mitchell and Deane (1962, pp. 388 - 397). The 1780 and 1801 figures are for Great Britain, the 1815 and 1850 figures for the U.K. National income (constructed) from Table 3.

and government spending fell to about 5% of national income, although the burden of the accumulated debt remained. Including the public sector would be an interesting area for further research.

3 The model economy

The British economy is represented using a fairly standard growth model with three final goods—agricultural, manufactured, and 'other'; one intermediate good—energy; three primary factors—capital, labor, and land; and balanced trade consisting of exports of manufactured goods and imports of food. Raw materials are ignored.

Technical change in agriculture, which can be viewed as land-augmenting, is assumed to proceed at a constant rate. We will assume, along Malthusian lines, that it just offsets (constant) population growth. This assumption allows us to focus on steady states where the technology-augmented supply of land per capita is constant.[17]

The simulations below involve comparing two such steady states, constructed to represent 1780 and 1850. The Industrial Revolution is modelled as consisting of improvements in the technologies for energy and manufactured goods and an increase in the level of foreign trade.

All of the production functions display constant returns to scale and, with one exception, they are Cobb-Douglas. The exception is that capital and energy are assumed to be complementary in the production of manufactured goods. Thus, capital and energy in that sector are aggregated using a CES function with an elasticity of substitution less than unity. The assumption that energy production displays constant returns to scale in capital and labor inputs is reasonable if the availability of coal (in the ground) does not constrain the production of power.

3.1 *Technology*

It is convenient to set up the model in terms of per capita quantities. Agricultural goods are produced using capital (k_a), land (ℓ_a), and labor (n_a) as inputs; manufactured goods using capital (k_m), energy (e_m), and labor (n_m); 'other' goods and energy using only capital (k_o and k_e) and labor (n_o and n_e). Time is continuous, $t \geq 0$, and on a per capita basis the production functions for the four sectors are

$$\begin{aligned} y_a(t) &= e^{\eta t} b_a k_a^{\beta}(t) \ell_a^{\gamma}(t) n_a^{1-\beta-\gamma}(t), \qquad (1) \\ y_m(t) &= b_m F\left[k_m(t), e_m(t)\right]^{\alpha} n_m^{1-\alpha}(t), \end{aligned}$$

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[17] See Clark (1991 and 1999a) for more detailed discussions of productivity growth in British agriculture.

$$\begin{aligned} F(k,e) &= \left[(1-\theta)\,k^{1-1/\epsilon} + \theta e^{1-1/\epsilon}\right]^{\epsilon/(\epsilon-1)}, \\ y_o(t) &= b_o k_o^{\phi}(t) n_o^{1-\phi}(t), \\ y_e(t) &= b_e k_e^{\psi}(t) n_e^{1-\psi}(t), \end{aligned}$$

where $b_a, b_m, b_o, b_e, \eta, \beta, \gamma > 0$, $\beta + \gamma < 1$, and $0 < \alpha, \epsilon, \phi, \psi < 1$. Note that F is a CES function with elasticity of substitution ϵ that aggregates capital and energy in manufacturing, and that η is the (exogenous, constant) rate of technical change in agriculture. To permit the existence of steady states, we will assume throughout that $\eta = \gamma\nu$, where γ is land's share and $\nu > 0$ is the (constant) rate of population growth. We will also assume that all firms behave competitively in all markets.

There are four market clearing conditions for produced goods:

$$\begin{aligned} \dot{k}(t) + (\delta + \nu)\,k(t) + c_m(t) &= y_m(t) - x_m(t), \\ c_a(t) &= y_a(t) + i_a(t), \\ c_o(t) &= y_o(t), \\ e_m(t) &= y_e(t). \end{aligned} \tag{2}$$

Output of manufactured goods, net of exports, is used for both consumption and investment. Capital depreciates at the constant rate $\delta > 0$, and investment must also offset population growth. Food consumption is met from domestic production plus imports. All output in the 'other' sectors is consumed, and all output of the energy sector is used as an input in manufacturing.

There are also three market clearing conditions for primary inputs:

$$\begin{aligned} k_a(t) + k_m(t) + k_o(t) + k_e(t) &= k(t), \\ n_a(t) + n_m(t) + n_o(t) + n_e(t) &= 1, \\ \ell_a(t) &= e^{-\nu t}\ell_0, \end{aligned} \tag{3}$$

where labor supply per capita is normalized at unity and where ℓ_0 is the initial supply of land per capita. Since physical capital is malleable in the long run and we are interested only in steady states, capital in the four sectors can be aggregated.

Finally, there is foreign trade. When calibrating the model, food imports i_a are fixed at a level chosen to match the data, and exports of manufactured goods are assumed to adjust. Balanced trade of this type at domestic prices may reduce welfare, however, so an allowance needs to be made to ensure that there are some gains from trade. This is done by assuming that the international price of agricultural goods is only $(1-\pi)$ times the domestic price, so the exports needed to pay for imports are

$$x_m(t) = (1-\pi)\,p_a(t) i_a(t). \tag{4}$$

The parameter π is fixed at the lowest level consistent with trade being welfare-enhancing, at the margin.

In solving for the steady state, it is convenient to normalize the price of manufactured goods to be unity at all dates, $p_m(t) \equiv 1$. Then let $\{R_k, R_\ell, w, p_a, p_o, p_e\}$ denote the rental prices for capital and land, the wage, and the prices of agricultural goods, other goods, and energy, respectively.

3.2 *Preferences*

Since all of the action comes from the technology side, the household structure and preferences are quite simple. There is an infinitely lived representative household whose size grows at the fixed rate ν. The household's preferences are additively separable over time, with a fixed rate of time preference ρ, so its intertemporal utility function is

$$\int_0^\infty e^{-(\rho-\nu)t} u\left(c_a(t), c_m(t), c_o(t)\right) dt.$$

A key feature of preferences that we want to capture is the declining income share for food. To this end, we will follow Laitner (2000) and assume that instantaneous utility has the following very simple form. Individuals consume only agricultural goods up to a threshold c_a^*, so at low levels of income only food is consumed; and after the threshold is attained, all additional consumption expenditures are for non-agricultural goods.[18] In particular,

$$u\left(c_a, c_m, c_o\right) = \begin{cases} c_a - c_a^*, & \text{if } \ c_a < c_a^*, \\ \left[c_m^\zeta c_o^{1-\zeta}\right]^{1-\sigma} / (1-\sigma), & \text{if } \ c_a \geq c_a^*, \end{cases}$$

where $\sigma > 0$.

We are interested only in the phase where manufactured and 'other' goods are consumed and $c_a = c_a^*$. In that regime the dynasty's problem is to maximize discounted lifetime utility,

$$\max_{\{k, c_m, c_o\}} \int_0^\infty e^{-(\rho-\nu)t} \frac{\left[c_m^\zeta(t) c_o^{1-\zeta}(t)\right]^{1-\sigma}}{1-\sigma} dt, \tag{5}$$

subject to the budget constraint

$$\dot{k} = \left(R_k - \delta - \nu\right) k + w + R_\ell \ell_0 e^{-\nu t} - p_a c_a^* + \pi p_a i_a - c_m - p_o c_o,$$

and a transversality condition, given all prices (including π), the import level i_a, and the initial conditions k_0, ℓ_0.

Equations (1)-(5), together with assumptions that firms maximize profits and markets are perfectly competitive, provide a complete description of the model. The Appendix shows in detail how the steady states are calculated.

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[18] This view also seems quite consistent with the evidence on food consumption. See Clark, Huberman, and Lindert (1995).

4 Calibration and numerical results

It is routine to show that for fixed parameter values the model has a unique steady state. The simulations below involve comparing two such steady states. The first uses parameters calibrated to the data for Britain in 1850, while the second is a 'backcast' for 1780 calculated after changing three of the parameters: the share of imports in the total food supply, the level parameter for the energy technology, and the level parameter for the manufacturing technology. Food imports are calibrated directly from the data; technical change in the energy sector is calibrated to fit the estimated fall of 50% in the cost of energy between the two dates; and technical change in manufacturing is calibrated to fit the estimated real wage growth of 37%.

There is some latitude in choosing which aspects of the 1850 data to use in calibrating the model, so as a robustness check on the substantive conclusions the model is calibrated two different ways. The baseline calibration uses the composition of output across sectors and the allocation of weighted labor across sectors. The alternate calibration uses the allocation of capital and raw labor (slightly adjusted) across sectors. Both calibrations use factor shares, the share of investment, and the allocation of factors to energy production.

The parameter values used in the simulations are displayed in Table 8. Those common to both calibrations are displayed in the first panel. Without loss of generality the level parameters for the manufacturing and 'other' sector technologies are normalized at unity, as is food consumption. Since we are comparing steady states, the elasticity of intertemporal substitution $1/\sigma$ plays no role, although it would be important in determining the speed of adjustment along the transition path. The population growth rate is set at its historical average for the period, $\nu = 0.012$.

The elasticity parameter in the capital-energy aggregate, $\varepsilon = 0.50$, is a value suggested by modern data. Some experiments with this parameter will be discussed below. The share and level parameters for energy in the capital-energy aggregate, θ and b_e, enter as the product $\theta b_e^{1-1/\varepsilon}$, so one can be fixed. It is convenient to set $\theta = 0.02$ and to adjust b_e.

The depreciation rate is set at $\delta = 0.05$, which is a little higher than the average figure of 3.5% implicit in Feinstein's figures. The share of imports in the total food supply is set at its historical level for each year: $\iota_a = 0.28$ for 1850 and $\hat{\iota}_a = 0.13$ for 1780.

4.1 *Baseline calibration*

For the baseline model, the parameters $(b_a, \beta, \gamma, \alpha, \phi, \rho, \zeta)$ are calibrated to fit the 1850 figures for the allocation of weighted labor across sectors, the composition of output across sectors, factor shares in income, and the share of investment in total output (seven independent figures). The parameters

Table 8:
Parameter value

Common

b_m=1.00, b_o=1.00, c_a^*=1.00, σ =* * * , ν =0.012
ε =0.50, θ =0.02, δ =0.05, i_a=0.28 $\hat{\iota}_a$=0.13

Baseline

b_a=1.67, β =0.17, γ =0.45, η =0.0054
α =0.51, ϕ =0.52, ρ =0.14, ζ =0.20, π =0.00
b_e=8.00, ψ =0.50, $\hat{b}_e$=3.09, $\hat{b}_m$=0.81

Alternate

b_a=1.58, β =0.28, γ =0.39, η =0.00468
α =0.30, ϕ =0.62, ρ =0.14, ζ =0.13, π =0.10
b_e=1.30, ψ =0.50, $\hat{b}_e$=0.53, $\hat{b}_m$=0.78

(b_e, ψ) for the technology in the energy sector are calibrated to the data on the shares of capital and labor (2.0% and 1.8%) allocated to that sector.

The rate of technical change in agriculture, $\eta = \gamma\nu$, is the product of land's share and the population growth rate. In this calibration the marginal gains from trade are positive even when imports are purchased at their full domestic price, so $\pi = 0.00$.

The data and the simulated values for the baseline model are displayed in Table 9, with boldface type indicating values used in the calibration. The parameter values in Table 8 for the baseline calibration look reasonable.

In agriculture the factor shares are 45% for land, 38% for labor, and 17% for capital, which is not far from the 40-40-20 split suggested by Crafts (1985, p. 83). Note that land's share is simply the factor share of land, 9%, divided by agriculture's share of output, 20%. The level parameter in agriculture plays a large role in determining the share of GDP generated in that sector. Since demand for food is inelastic, higher productivity reduces the relative price of food and hence reduces agricultures's share in total output.

In manufacturing the share for the capital-energy aggregate is 51%, and in the 'other' sector, which includes housing, capital's share is 52%. Both values seem high compared with modern figures. This difference could reflect differences in the technologies, or it could result from errors in the data used to calculate capital's share in national income. If the returns to land or labor or both are understated, then the error appears as an overestimate of the (residual) income share of 44% allocated to capital. Capital's share in the energy sector is 50%.

On the preference side, the rate of time discount is $\rho = 0.14$, so the interest rate is 14%. This rather high value is needed to match the share of investment. The weight on manufactured goods in discretionary consumption, $\zeta = 0.20$, is important in matching the share of 'other' goods in total output.

4.1.1 *The fit of the baseline model*

The figures in Table 9 for the allocation of capital across sectors, for exports of manufactured goods, and for land's share in total wealth in 1850 provide independent checks on the model. The model allocates substantially more capital to manufacturing than the data suggest, and less to both of the other sectors. Part of the difference is clearly attributable to housing. According to Feinstein's figures, the stock of dwellings accounts for 27% of the capital stock (cf. Table 1 above), but according to Deane and Cole's figures housing services account for only about 8% of national product (1969, Table 37). If capital's share in national income is 44%, then housing should be about $0.27 \times 0.44 \approx 12\%$ of national product (to match the capital stock figure), or

Table 9: Baseline simulation results

	MODEL		DATA	
	1780	1850	1780	1850
Allocation of capital				
share in agr.	0.14	0.08	0.30	0.15
share in mfg.	0.33	0.37	0.09	0.18
share in other	0.53	0.55	0.61	0.68
share in energy	0.024	**0.020**	n.a.	**0.020**
Allocation of labor (weighted)				
share in agr.	0.27	**0.16**	0.22	**0.16**
share in mfg.	0.32	**0.37**	0.22	**0.37**
share in other	0.42	**0.47**	0.56	**0.47**
share in energy	0.021	**0.018**	n.a.	**0.018**
Composition of GDP				
share of food	0.32	**0.20**	0.36	**0.20**
share of mfg.	0.28	**0.34**	0.20	**0.34**
share of other	0.40	**0.46**	0.44	**0.46**
Factor shares				
labor	0.46	**0.47**	0.45	**0.47**
land	0.14	**0.09**	0.20	**0.09**
capital	0.40	**0.44**	0.35	**0.44**
Investment/GDP	0.13	**0.14**	0.13	**0.13**
Imports/agr. goods	**0.13**	**0.28**	**0.13**	**0.28**
Exports/mfg. goods	0.17	0.23	0.24	0.27
Farm land/total wealth	0.30	0.20	0.42	0.24
Food exp./ wage	0.80	0.58	0.69	0.62
Composition of cons.				
share of food	0.42	0.32	n.a.	n.a.
share of mfg.	0.12	0.14	n.a.	n.a.
share of other	0.46	0.54	n.a.	n.a.
Capital/output	2.1	2.3	n.a.	n.a.
in mfg.	2.3	2.4	n.a.	n.a.

Table 9: Baseline simulation results (cont.)

(change over whole period)

	MODEL	DATA
Quantities (per capita)		
GDP	41%	42%
agr. goods	-17%	-24%
mfg. goods	98%	155%
(energy)	(192%)	(n.a.)
consumption	32%	n.a.
agr. goods	0%	n.a.
mfg. goods	89%	n.a.
other goods	47%	n.a.
capital stock	81%	55%
Factor returns (in agr. goods)		
wage	37%	37%
land rents	-17%	-36%
Prices		
mfg. goods rel. to agr. goods	-18%	n.a.
other goods rel. to mfg. goods	28%	n.a.
energy rel. to mfg. goods	-50%	-50%

dwellings should be only 0.08/0.44 ≈ 18% of the capital stock (to match the estimate of housing services). Or perhaps capital's share in income should be only 0.08/0.27 ≈ 30%.

The share of exports in total output of the manufacturing sector fits fairly well, 23% in the model and 27% in the data. And the share of farm land in total wealth also fits quite well, 20% in the model and 24% in the data.

The ratio of food expenditures to the wage is a rough measure of the real wage. Food consumption (per capita) in the model is inelastic and is normalized to be one unit. Hence the ratio in the model, 0.80 in 1780 and 0.58 in 1850, is simply the price of agricultural goods divided by the wage rate. The 'data' values of 0.69 and 0.62 are from the budget shares for food that Feinstein (1998, Table 1) uses to construct his COLI for blue-collar workers.[19]

For the 1780 simulation three parameters are changed. The share of imports in the total food supply is reduced to its historical level, $\hat{\iota}_a = 0.13$; the level parameter in the energy sector is reduced to $\hat{b}_e = 3.09$, which exactly doubles the cost of energy; and the level parameter in manufacturing is cut to $\hat{b}_m = 0.81$, which reduces the real wage in terms of agricultural goods by 37%. The 'grain wage' is used because Feinstein's CPI—which is for blue collar workers—puts most of its weight (70-80%) on food and drink.

The model's predictions for the 1780 economy are not bad. The model captures the major differences in the composition of GDP—a higher share for agriculture at the earlier date, at the expense of both manufacturing and the 'other' sector. But the model understates the magnitude of the changes in agriculture and manufacturing, and substantially overstates the change in the 'other' sector. The model also captures correctly the main change in the distribution of income across factors—a higher share for land rents at the expense of capital, but understates the magnitude of the change.

In terms of the allocation of factors, most of the changes are in the right direction. The model correctly predicts that the capital allocation in the earlier year was higher in agriculture and lower in the other two sectors, but the levels show the same problem as in the later year. The model correctly predicts that the labor allocation in the earlier year was higher for agriculture and lower for manufacturing. The model misses entirely on the labor allocation for the 'other' sector, however, predicting a substantially smaller share for the earlier year while the data show a much larger share.

The composition of consumption looks reasonable for both years, as do the capital/output ratios, although I could not find independent estimates against which to check the model predictions.

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[19] The former is Feinsteins's reported value for 1788/92, the latter is interpolated using his values for 1828/32 and 1858/62.

4.1.2 *Growth predictions of the baseline model*

Table 9 also displays the model's predictions and the data for total growth over the 70-year period. The model is calibrated to fit the 37% increase in the real wage and the 50% drop in the price of energy, but the other figures provide a check.

The model fits the estimated value of GDP growth quite closely, 41% in the model versus the 42% suggested by the growth rates in Crafts and Harley. The model also captures much of the decline in agricultural output per capita, showing a 17% decline as opposed to the 24% decline in Allen's figures. Output of manufactured goods increases by 94% in the model as opposed to the 155% suggested by Crafts and Harley. And the capital stock in the model increases by 86%, as opposed to the 55% in Feinstein's figures.

The model shows a substantial decline in land rents, 17%, but it is much less than the decline suggested by the data. Using the figure of 42% for growth in real GDP per capita and the factor shares of 20% and 9% for land from Table 3, gives a decline of 36% in land rents per capita: $1.42 \times 0.09 / 0.20 = 0.64$. Using the nominal land rents and price (COLI) in Table 2, and adjusting for population growth, gives a decline of 40% in land rents: $43/(1.21 \times 25 \times 2.38) = 0.60$.

4.2 *Alternate calibration*

Given the range of error likely in the data, calibrating in two ways—to different parts of the data—provides a robustness check on the conclusions from the model. For the alternate simulation the parameters $(b_a, \beta, \gamma, \alpha, \phi, \rho, \zeta)$ are calibrated to fit the data on the allocation of (adjusted) raw labor and capital across sectors, factor shares, and the share of investment.

The adjustment to raw labor is computed by downweighting labor in agriculture to 67% of its raw value, but making no adjustment to change the relative weights in manufacturing and the 'other' sector. This downweighting in agriculture is suggested by a comparison of wages for unskilled workers in agriculture and industry: the wages for the former were about 1/3 lower.[20] It (coincidentally) puts the share of labor in agriculture in 1850 at the precisely the same level as before (16%), but tilts the remaining share much more heavily toward manufacturing. Allocating labor this way offsets the fact that the capital allocation is tilted very heavily toward the 'other' sector (68%).

The alternate parameter values are displayed in the bottom panel of Table 8, and the figures from the alternate calibration are compared with the data in Table 10. As before, the figures used in the calibration are indicated in

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[20] See Clark (1999c).

Table 10: Alternate simulation results

	MODEL		DATA	
	1780	1850	1780	1850
Allocation of capital				
share in agr.	0.25	**0.15**	0.30	**0.15**
share in mfg.	0.15	**0.18**	0.09	**0.18**
share in other	0.60	**0.67**	0.61	**0.68**
share in energy	0.023	**0.020**	n.a.	**0.020**
Allocation of labor				
share in agr.	0.27	**0.16**	0.25	**0.16**
share in mfg.	0.40	**0.46**	0.34	**0.46**
share in other	0.33	**0.38**	0.42	**0.38**
share in energy	0.021	**0.019**	n.a.	**0.019**
Composition of GDP				
share of food	0.36	0.23	0.36	0.20
share of mfg.	0.24	0.29	0.20	0.34
share of other	0.39	0.47	0.44	0.46
Factor shares				
labor	0.45	**0.47**	0.45	**0.47**
land	0.14	**0.09**	0.20	**0.09**
capital	0.41	**0.44**	0.35	**0.44**
Investment/GDP	0.13	**0.14**	0.13	**0.13**
Imports/agr. goods	**0.13**	**0.28**	**0.13**	**0.28**
Exports/mfg. goods	0.20	0.28	0.24	0.27
Farm land/total wealth	0.29	0.20	0.42	0.24
Food exp./ wage	0.93	0.64	0.69	0.62
Composition of cons.				
share of food	0.48	0.37	n.a.	n.a.
share of mfg.	0.07	0.08	n.a.	n.a.
share of other	0.45	0.55	n.a.	n.a.
Capital/output	2.2	2.3	n.a.	n.a.
in mfg.	1.2	1.3	n.a.	n.a.

Table 10: Alternate simulation results (cont.)
(change over whole period)

	MODEL	DATA
Quantities (per capita)		
GDP	31%	42%
agr. goods	-17%	-24%
mfg. goods	77%	155%
(energy)	(171%)	(n.a.)
consumption	27%	n.a.
agr. goods	0%	n.a.
mfg. goods	74%	n.a.
other goods	49%	n.a.
capital stock	55%	55%
Factor returns (in agr. goods)		
wage	37%	37%
land rents	-17%	-36%
Prices		
mfg. goods rel. to agr. goods	-10%	n.a.
other goods rel. to mfg. goods	17%	n.a.
energy rel. to mfg. goods	-50%	-50%

boldface.

The alternate calibration changes the share parameters for capital in a fairly significant way: capital's share increases to 28% in agriculture and to 62% in the 'other' sector and falls to 30% in manufacturing. These large changes are needed to fit the data on the allocation of capital across sectors, which show a very high proportion of the total stock in the 'other' sector. The other notable change is that a relative price wedge of $\pi = 0.10$ is now needed to make the gains from trade positive at the margin.

The alternate parametrization fits the 1850 data on the composition of GDP, manufacturing exports, farm land value, and real wage fairly well. The model also does quite well overall in fitting the 1780 data. The model still predicts, incorrectly, that the allocation of labor to the 'other' sector was smaller rather than larger in the earlier year.

With the alternate parameters the model produces less growth, making the predictions for output growth a little worse than for the baseline parameters and making the prediction for growth in the capital stock a little better (perfect, in fact).

5 Counterfactual experiments

The model here incorporates three sources of exogenous change to explain growth between 1780 and 1850: an increase in food imports, paid for with exports of manufactured goods; technical change in the energy sector; and technical change in manufacturing. Within the context of the model, it is straightforward to calculate the role of each factor in contributing to overall growth by shutting them down, one at a time, and recalculating the 1850 steady state. This experiment is conducted for both calibrations, and the results are displayed in Tables 11 and 12. We will begin with Table 11.

The top panel shows the changes in production and consumption of each commodity, in the capital stock, and in the returns to labor and land. The first column shows the total change predicted by the model, with all three factors included, and the next three columns show the fraction of the total change that disappears as each exogenous change is eliminated, one at a time. The last column is the sum of the preceding three, and the fact that the most of the sums are close to one means that the model is fairly linear.

The lower panel in Table 11 shows relative price changes. In each row the indicated relative price is normalized by its level in the 1780 steady state. Thus, the first two lines show that in the baseline simulation for 1850 the prices of agricultural and 'other' goods rose relative to manufactured goods, by 22% and 28% respectively. The last line displays the 50% decline in the relative price of energy to which the model was calibrated.

First consider the contribution of the growth in food imports to the

Table 11: Sources of change: baseline calibration

(total change and attribution to sources)

	total change	import growth	tech. ch. in energy	tech. ch. in mfg.	SUM
Quantities (per capita)					
prod. of agr. goods	-17%	1.00	0.00	0.00	1.00
prod. of mfg. goods	98%	0.27	0.24	0.67	1.17
cons. of mfg. goods	89%	0.08	0.27	0.79	1.13
prod. of other goods	47%	0.11	0.25	0.72	1.08
prod. of energy	192%	0.20	0.71	0.38	1.29
capital stock	81%	0.08	0.29	0.77	1.14
Factor returns (in agr. goods)					
wage	37%	0.53	0.13	0.44	1.10
returns to land	-17%	1.00	0.00	0.00	1.00

	1780	1850 w/o import growth	1850 w/o tech. ch. in energy	1850 w/o tech. ch. in mfg.	1850
Normalized relative prices					
agr. / mfg. goods	1.00	1.43	1.13	0.92	1.22
other / mfg. goods	1.00	1.28	1.21	1.05	1.28
energy / mfg. goods	1.00	0.50	1.22	0.41	0.50

Table 12: Sources of change: alternate calibration

(total change and attribution to sources)

	total change	import growth	tech. ch. in energy	tech. ch. in mfg.	SUM
Quantities (per capita)					
prod. of agr. goods	-17%	1.00	0.00	0.00	1.00
prod. of mfg. goods	77%	0.28	0.20	0.64	1.12
cons. of mfg. goods	74%	0.02	0.26	0.82	1.10
prod. of other goods	49%	0.03	0.24	0.79	1.06
prod. of energy	171%	0.19	0.74	0.32	1.25
capital stock	55%	-0.07	0.29	0.87	1.09
Factor returns (in agr. goods)					
wage	37%	0.42	0.14	0.54	1.10
returns to land	-17%	1.00	0.00	0.00	1.00

	1780	1850 w/o import growth	1850 w/o tech. ch. in energy	1850 w/o tech. ch. in mfg.	1850
Normalized relative prices					
agr. / mfg. goods	1.00	1.26	1.06	0.93	1.11
other / mfg. goods	1.00	1.17	1.14	1.03	1.17
energy / mfg. goods	1.00	0.50	1.18	0.42	0.50

changes between 1780 and 1850 predicted by the model. Not surprisingly, it is important in changing the composition of production, accounting for 100% of the decline in the production of agricultural goods, for roughly 27% of the increase in the production of manufactured goods, and for about 20% of the increase in energy production. Since food demand in the model is completely inelastic, output in the agricultural sector would have had to have taken up all of the slack in the absence of the larger food imports. The imports are paid for with exports of manufactured goods, and the latter use energy as an input. The growth in agricultural imports also explains 100% of the decline in the returns to land displayed by the model, for obvious reasons.

Perhaps most interestingly, the growth in food imports explains about half of the 37% increase in the real ('grain') wage. Two factors are at work here. First, higher food imports shift the composition of output away from agriculture and toward manufacturing. Since the latter sector is more labor-intensive, this change raises the wage rate. In addition, the increase in food imports keeps the relative price of agricultural goods from increasing sharply. In the model the relative price increase would have been 43% in the absence of import growth, instead of the 22% that occurs with import growth.

Note that food imports play a very small role in explaining the substantial growth in consumption of manufactured and other goods and in the capital stock. This fact is not really a prediction of the model, but rather a symptom of its limitations. Recall that the "gains from trade" parameter was set at $\pi = 0$ in the baseline calibration, and set at the lowest level consistent with nonnegative gains from trade in the alternate calibration. None of the evidence used in calibrating the model is really helpful for pegging the size of the gains from trade, so they are simply fixed at a low level. Data on the world and domestic prices of traded goods would be needed to get a more accurate estimate of the contribution of expanded trade to consumption growth.

By default, the model attributes virtually all of the growth in consumption and the capital stock to technical change in energy and in manufacturing. The model predicts sizable increases in the consumption of manufactured and other goods, 89% and 47% respectively; in the production of manufactured goods and energy, 98% and 192% respectively; and in the size of the capital stock, 81%. (Note that the returns to capital move one-for-one with the stock, since the rate of return is the same at both dates.) In almost every case, technical change in manufacturing is about three times as important as technical change in the energy sector in explaining the growth. The exception is the increase in energy production, where technical change in the energy sector was about twice as important as technical change in manufacturing.

In the absence of technical change in the energy sector, the price of energy would have risen 22% instead of declining 50%, dampening the decline in the relative price of manufactured goods. Hence the prices of agricultural and 'other' goods relative to manufactured goods would have risen less sharply, by only 13% and 22%, respectively.

In the absence of technical change in manufacturing, the relative prices of food and 'other' goods would not have displayed substantial increases: the former would have fallen by 8%, while the latter would have risen only 5%. In addition, the relative price of energy would have fallen even more sharply than it did, by 59% instead of 50%.

Turning to Table 12 we see a picture that is very similar. The main differences are that the total increases in consumption and production are somewhat smaller, and the decline in the relative price of manufactured goods is more modest. But the attribution of the changes to the three factors is altered very little. This is a pleasant surprise: the model parameters are quite different for the two calibrations, so it was not at all obvious that they would deliver conclusions that are so similar.

Several additional experiments (not reported here) were also conducted, using the baseline parameters except for a higher elasticity of substitution between capital and energy in the production of manufactured goods. Specifically, elasticities of $\epsilon = 0.80$, 0.90, and 0.99 were used. In each case θ and b_e were also changed, to keep the share of capital and labor inputs in the energy sector constant, and $\hat{b}_e$ was changed to maintain the 50% decline in the price of energy.

The only major alteration these simulations produced in Table 11 was to magnify the increase in the production of energy, from 190% to 250%, 265% and 280% in the three cases. Total growth in production, consumption, and the capital stock was dampened very slightly (by about 2 - 4 percentage points), and the attribution of growth to the three exogenous factors changed very little.

6 Conclusions

The main contribution of this paper has been to build a simple quantitative model that is roughly consistent with the available evidence on the British economy at the time of the Industrial Revolution. Within the context of the model, the Industrial Revolution is represented by three changes: a large increase in food imports, paid for with exports of manufactured goods; a dramatic improvement in the technology for producing mechanical energy; and a substantial improvement in the technology for producing manufactured goods.

Substantively, the calibrated model has allowed us to examine the relative importance of these three changes in explaining overall growth during this period, as well as the large changes in the distribution of income across factors. The model shows, not surprisingly, that the growth in food imports was very important in changing the composition of output away from agriculture and toward manufacturing, and in reducing the factor share of land. A less obvious conclusion is that the increase in foreign trade was also very important in raising the real wage, explaining roughly half of real wage growth over the period. Without data on the terms of trade, however, the model cannot provide an estimate of the importance of trade growth in contributing to overall income growth.

The model also indicates that technical change in manufacturing was much more important than technical change in the energy sector in contributing to overall output growth. Specifically, the former accounts for roughly three quarters of the growth in capital and consumption, while the latter accounts for about one quarter.

The model examined here is very simple, and the list of possible refinements and extensions is almost endless. For the reasons noted above, a more detailed treatment of foreign trade would be very desirable. Specifically, data on prices in world markets is needed in order to estimate the importance of gains from trade in contributing to growth. A careful treatment of income from abroad and imported raw materials would also be very useful.

Additional sectors could be added to address specific issues. One obvious possibility is to model the cotton textile industry in more detail. That industry grew much more rapidly than other parts of manufacturing during this period, and the price of cotton cloth declined dramatically. Consequently the index number problem is especially severe in constructing an aggregate index for manufacturing. On a theoretical (and computational) level, it would be fairly straightforward to split manufacturing into cotton (or 'fast-growing industries') and the rest, thus avoiding the most severe part of the index number issue.

Another possibility is to incorporate a separate sector for housing. As was noted above, the capital stock and imputed output (service) flows for this sector appear to be inconsistent with each other. Reconciling them would significantly enhance the fit of the model.

An even more ambitious project would be to look at the transition path. As noted above, this exercise would be quite challenging because of the large shocks (wars and crop failures) during this period, but the same factors would make such a project extremely interesting.

The exercise carried out here also makes a methodological point: that data on the allocation of inputs across sectors, the composition of output across sectors, and the factor shares in income can be used to calibrate parameters for Cobb-Douglas technologies in a multi-sector model. This type of exercise could be quite fruitful in many contexts: to study other historical periods, or to look at less developed modern economies, where detailed sector-level data is not available.

Quantitative models like the one analyzed here also have the virtue of highlighting which pieces of evidence fit together to form a coherent picture of the whole, and which seem hard to reconcile. Thus, they can help guide future data collection efforts, by indicating the areas where the existing data seems most suspect or most fragile. For throwing fresh light on old questions and for framing new ones, quantitative models offer a novel and potentially fertile approach to the study of historical questions.

Appendix

This Appendix shows how the equilibria are computed.

A. Behavior of firms

Using the production functions in (1) it is straightforward to compute output prices and input demands. Three sectors have Cobb-Douglas technologies. The technology for manufactured goods is also Cobb-Douglas when written in terms of the composite input $F(k,e)$. The composite input has price P_{ke} defined by

$$P_{ke} \equiv \min\left[R_k k + p_e e\right] \text{ s.t. } F\left(k,e\right) = 1,$$

and we will let (k^*, e^*) denote the cost-minimizing input pair. Note that (P_{ke}, k^*, e^*) are functions of (R_k, p_e).

Since all of the technologies are Cobb-Douglas, all of the output prices and input demands have the same form. In particular, producers of manufactured goods, agricultural goods, 'other' goods, and energy break even if

$$p_m = \Gamma_m P_{ke}^{\alpha} w^{1-\alpha}, \tag{A1}$$

$$p_a = e^{-\eta t}\Gamma_a R_k^{\beta} R_\ell^{\gamma} w^{1-\beta-\gamma}.$$

$$p_o = \Gamma_o R_k^{\phi} w^{1-\phi},$$

$$p_e = \Gamma_e R_k^{\psi} w^{1-\psi},$$

where

$$\Gamma_m \equiv \left[b_m \alpha^{\alpha}\left(1-\alpha\right)^{1-\alpha}\right]^{-1},$$

$$\Gamma_a \equiv \left[b_a \beta^{\beta} \gamma^{\gamma}\left(1-\beta-\gamma\right)^{1-\beta-\gamma}\right]^{-1},$$

$$\Gamma_o \equiv \left[b_o \phi^{\phi}\left(1-\phi\right)^{1-\phi}\right]^{-1},$$

$$\Gamma_e \equiv \left[b_e \psi^{\psi}\left(1-\psi\right)^{1-\psi}\right]^{-1},$$

and they choose input levels

$$k_m = \alpha k^* \frac{y_m}{P_{ke}}, \tag{A2}$$

$$e_m = \alpha e^* \frac{y_m}{P_{ke}},$$

$$n_m = \left(1-\alpha\right)\frac{y_m}{w},$$

$$k_a = \beta \frac{p_a y_a}{R_k},$$

$$\ell_a = \gamma \frac{p_a y_a}{R_\ell},$$

$$n_a = (1-\beta-\gamma)\frac{p_a y_a}{w},$$

$$k_o = \phi \frac{p_o y_o}{R_k},$$

$$n_o = (1-\phi)\frac{p_o y_o}{w},$$

$$k_e = \psi \frac{p_e y_e}{R_k},$$

$$n_e = (1-\psi)\frac{p_e y_e}{w}.$$

The aggregator function F is CES, with an elasticity of substitution ϵ that lies (strictly) between zero and one:

$$F(k,e) = \left[(1-\theta)k^{1-1/\epsilon} + \theta e^{1-1/\epsilon}\right]^{\epsilon/(\epsilon-1)}.$$

Consequently, it is straightforward to show that the price of the composite is

$$P_{ke} = \left[(1-\theta)^\epsilon R_k^{1-\epsilon} + \theta^\epsilon p_e^{1-\epsilon}\right]^{1/(1-\epsilon)}, \tag{A3}$$

and the optimal inputs are

$$k^* = \left(\frac{1-\theta}{R_k}P_{ke}\right)^\epsilon, \qquad e^* = \left(\frac{\theta}{p_e}P_{ke}\right)^\epsilon. \tag{A4}$$

B. Household behavior

The static portion of the household's problem in (5) is

$$\max c_m^\zeta c_o^{1-\zeta} \ \text{ s.t. } \ c_m + p_o c_o \le x,$$

so

$$\frac{c_m}{\zeta} = \frac{p_o c_o}{1-\zeta}. \tag{A5}$$

In a Malthusian steady state population growth exactly offsets technical change in agriculture $(\nu = \eta/\gamma)$, and all prices and all per capita quantities are constant. Hence $\dot{k} = 0$, the interest rate is

$$R_k = \rho + \delta, \tag{A6}$$

and the transversality condition for the household's problem holds if $\rho - \nu > 0$.

C. Competitive equilibrium

The steady state conditions (2)-(5) and (A1)-(A6), with $\dot{k} = 0$, can be simplified a little. By Walras Law the household's budget constraint can be dropped. And since the outputs y_a and y_o always appear multiplied by their prices, it is convenient to define $v_a \equiv p_a y_a$ and $v_o = p_o y_o$. Substituting from the factor demand equations (A2) into the resource constraints (3) and simplifying the remaining conditions, we get the system of (fifteen) equations

$$1 = \Gamma_m P_{ke}^{\alpha} w^{1-\alpha}, \tag{A7}$$

$$p_a = e^{-\eta t} \Gamma_a R_k^{\beta} R_\ell^{\gamma} w^{1-\beta-\gamma},$$

$$p_o = \Gamma_o R_k^{\phi} w^{1-\phi},$$

$$p_e = \Gamma_e R_k^{\psi} w^{1-\psi},$$

$$P_{ke} = \left[(1-\theta)^{\epsilon} R_k^{1-\epsilon} + \theta^{\epsilon} p_e^{1-\epsilon} \right]^{1/(1-\epsilon)},$$

$$R_k k = \alpha k^* y_m \frac{R_k}{P_{ke}} + \beta v_a + \phi v_o + \psi v_e,$$

$$w = (1-\alpha) y_m + (1-\beta-\gamma) v_a + (1-\phi) v_o + (1-\psi) v_e,$$

$$e^{-\nu t} R_\ell \ell_0 = \gamma v_a,$$

$$v_e = \alpha e^* y_m \frac{p_e}{P_{ke}},$$

$$v_a = p_a \left(c_a^* - \iota_a \right),$$

$$v_o = \frac{1-\zeta}{\zeta} c_m,$$

$$k_m^* = \left(\frac{1-\theta}{R_k} P_{ke} \right)^{\epsilon},$$

$$e^* = \left(\frac{\theta}{p_e} P_{ke} \right)^{\epsilon},$$

$$c_m = y_m - (1-\pi) p_a \iota_a - (\delta + \nu) k,$$

$$R_k = \rho + \delta,$$

to determine the (seven) prices $\{R_k, R_\ell, w, p_a, p_o, p_e, P_{ke}\}$ and (eight) quantities $\{k, y_m, c_m, v_e, v_a, v_o, k_m^*, e^*\}$. For the pre-IR economy we solve the same system, using the constants $\hat{b}_m$ and $\hat{\iota}_a$ in place of b_m and ι_a, pegging $\hat{p}_e$ at the desired multiple (twice) its level in the post-IR economy, and backing out $\hat{b}_e$.

The third price equation in (A7) determines p_o, which does not appear elsewhere, so we can set that one aside. We can also use the third resource constraint to eliminate R_ℓ, so the remaining four price equations are

$$P_{ke} = w^{1-1/\alpha}\Gamma_m^{-1/\alpha}, \tag{A8}$$

$$p_a = \left[\Gamma_a \ell_0^{-\gamma} \left(\gamma c_A\right)^\gamma R_k^\beta w^\mu\right]^{1/(1-\gamma)},$$

$$p_e = \Gamma_e R_k^\psi w^{1-\psi},$$

$$P_{ke} = \left[(1-\theta)^\epsilon R_k^{1-\epsilon} + \theta^\epsilon p_e^{1-\epsilon}\right]^{1/(1-\epsilon)}.$$

For the post-IR steady state, first substitute for P_{ke} and p_e in the last equation to get

$$w^{1-1/\alpha} = \Gamma_m^{1/\alpha}\left[(1-\theta)^\epsilon R_k^{1-\epsilon} + \theta^\epsilon \left(\Gamma_e R_k^\psi w^{1-\psi}\right)^{1-\epsilon}\right]^{1/(1-\epsilon)}.$$

Since R_k is known, this equation can be solved for w. Then calculate p_a, p_e, P_{ke}, k_m^*, and e^*.

To calculate quantities, use the market clearing conditions for energy, agricultural goods, and 'other' goods to eliminate v_e, v_a, and v_o in the resource constraints for capital and labor. Use the equation for v_e as it is; define $c_A \equiv c_a^* - i_a$, and use $v_a = p_a c_A$ to eliminate v_a. Use the next-to-last equation (household demand) to substitute for c_m in the equation for v_o, so

$$v_o = \frac{1-\zeta}{\zeta}\left[y_m - (1-\pi)\, p_a i_a\right] - Z_0 k,$$

where

$$Z_0 \equiv \frac{1-\zeta}{\zeta}\left(\delta + \nu\right).$$

Use this equation to eliminate v_o. The resource constraints for capital and labor then provide a pair of linear equations in k and y_m,

$$\begin{pmatrix} Q_5 & -\left(R_k + \phi Z_0\right) \\ Q_6 & -(1-\phi)\, Z_0 \end{pmatrix} \begin{pmatrix} y_m \\ k \end{pmatrix} = \begin{pmatrix} \phi \chi p_a i_a - \beta p_a c_A \\ w + (1-\phi)\, \chi p_a i_a - \mu p_a c_A \end{pmatrix},$$

where

$$Q_5 \equiv \alpha \frac{R_k k_m^*}{P_{ke}} + \phi \frac{1-\zeta}{\zeta} + \psi \alpha \frac{p_e e^*}{P_{ke}},$$

$$Q_6 \equiv (1-\alpha) + (1-\phi)\frac{1-\zeta}{\zeta} + (1-\psi)\, \alpha \frac{p_e e^*}{P_{ke}},$$

$$\chi \equiv \frac{1-\zeta}{\zeta}(1-\pi).$$

For the pre-IR steady state, set the level parameter in manufacturing to its new level $\hat{b}_m$ and calculate $\hat{\Gamma}_m$; set agricultural imports to their new level $\hat{\imath}_a$, and define $\hat{c}_a \equiv c_a^* - \hat{\imath}_a$; and set the energy price $\hat{p}_e$ equal to the desired multiple of its post-IR level. Then use the fourth equation in (A8) to calculate $\hat{P}_{ke}$, the first to determine $\hat{w}$, and the third to back out $\hat{b}_e$ from $\hat{\Gamma}_e$.

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