PRODUCTIVITY GROWTH DURING THE ENGLISH INDUSTRIAL REVOLUTION: A DUAL APPROACH

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Abstract

This paper presents new estimates of total factor productivity growth in Britain for the period 1770-1860. We use a dual technique recently popularized by Hsieh (1999), and argue that the estimates we derive from factor prices are of similar quality to quantity-based calculations. Our results provide further evidence, derived from this independent set of sources, that productivity growth during the British Industrial Revolution was relatively slow. During the years 1770-1800, TFP growth was close to zero, according to our estimates. The period 1800-1830 experienced an acceleration of productivity growth. The Crafts-Harley view of the Industrial Revolution is thus reinforced. We also consider alternative explanations of slow productivity growth, and reject the interpretation that focuses on the introduction of steam as a general purpose technology.

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Key words: British Industrial Revolution, productivity growth, Dual measurement of productivity, general purpose technology.

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> “*We are coming now rather into the region of guess-work,” said Dr. Mortimer.*
> “*Say, rather, into the region where we balance probabilities and choose the most likely. It is the scientific use of the imagination, but we have always some material basis on which to start our speculation.”*
>
> - Arthur Conan Doyle, *The Hound of Baskerville*

1. Introduction

How rapid was productivity growth during the Industrial Revolution? Since the pioneering studies of Ashton (1948) as well as Deane and Cole (1962), this question has been central to the economic history of Britain, 1750-1850. It is also of wider interest for the speed and timing of productivity changes following major inventions. After the introduction of electric motors and the computer, for example, the productivity performance remained sluggish for decades. When it did pick up, however, total factor productivity (TFP) increases were rapid and widespread. These later examples may not be aberrations, but perhaps part of a regular pattern if we can also prove convincingly that England did not become much more efficient during the first few decades of the Industrial Revolution.[1]

Crafts and Harley have estimated modest rates of output growth during the Industrial Revolution.[2] Crafts found that Deane and Cole (1962) had chosen an inappropriate price index with which to deflate the nominal income series in the national accounts, thus overstating growth. He also compiled alternative indices for agricultural, industrial and service output. His finding of substantially slower growth was reinforced by Harley, who argued that that the earlier estimates of industrial production by Hoffmann (1955) had seriously overestimated growth (by giving much too high a weight to the revolutionary cotton sector). Since rates of input growth have not been similarly revised downwards, their results also imply that the Solow residual was only growing relatively slowly during the late eighteenth and early nineteenth century.[3]

Deane and Cole did not provide any estimates of total factor productivity growth during the industrial revolution. Later work by Feinstein (1981), however, showed that Deane and Cole’s estimates implied remarkably rapid total factor productivity growth, especially for the period 1760-1801.[4] Using the standard, primal approach to growth accounting, Feinstein estimated annual productivity growth of 0.2% for the period 1760-1800 and of 1.3% for the period 1801-1830. The

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[1] David 1990.
[2] Crafts 1985, Harley 1982, Crafts and Harley 1992.
[3] Voth (1998) revises the labour input figures based on a sharp rise in working hours.

latest estimates by Crafts and Harley, based on their revised output series, imply increases of only 0.1 per cent p.a. during 1760-1800 and 0.35 per cent p.a. during 1800-1830 (table 1). The new orthodoxy thus holds that both output and productivity growth were slow during the English Industrial Revolution. Also, advances were heavily concentrated in the ‘revolutionizing sectors’ such as cotton and iron manufacturing. These sectors were too small to have a sizeable impact on the manufacturing sector as a whole (and the economy at large) until the middle of the 19th century. What was 'revolutionary' about the Industrial Revolution was neither the speed of output growth nor its source, but a broad structural transformation, reallocating labour from agriculture to industry.

Table 1: Previous Estimates of Productivity Growth in England, 1760-1831

	DY/Y	**DK/K**	**DL/L**	**DT/T**	**TFP Growth**
Feinstein (1981)					
1760-1800	1.1	1	0.8	-	0.2
1801-1831	2.7	1.4	1.4	-	1.3
Crafts (1985)					
1760-1800	1	1	0.8	0.2	0.2
1801-1831	2	1.5	1.4	0.4	0.7
Crafts/Harley (1992)					
1760-1801	1	1	0.8	-	0.1
1801-1831	1.9	1.7	1.4	-	0.35

The new orthodoxy established by Crafts and Harley has attracted criticism from different perspectives. All contributors to the literature on the speed of output and productivity growth emphasize the fragility of the underlying data and accept difficulty in deriving estimates. As Feinstein said of his estimates of capital formation – “*we are able to proceed only by reliance on conjecture and speculation*.”[5] Some critics of the dominant view argue that data revisions and changes in procedure should substantially modify it; others doubt the value of the exercise as such, given the limitations of the data and the number of non-quantitative aspects necessarily excluded. Berg and Hudson firmly fall into the second category. They emphasize demographic change, regional specialization, organizational changes and the evolution of female and child labour as areas that showed truly ‘revolutionary’ change. They also voice a general distrust of aggregate, quantity-based output and TFP calculations, and point to some potential sources of fragility of the estimates derived – such as the assumption of constant returns to scale.[6] Their plea for the inclusion of non-quantitative evidence, and their sceptical evaluation of Crafts's and Harley's data work is in part a continuation of Julian Hoppit's critique. He emphasized the difficulties of applying appropriate weights to the output series of individual industries. This is normally based on value-added, evidence on which is relatively fragile.[7]

[4] Feinstein’s revisions of Deane and Cole’s estimates concentrated on the figures on capital formation. See Feinstein and Pollard (1988) for more on this issue.
[5] Feinstein 1981.
[6] Berg and Hudson 1992.
[7] Hoppit 1990.

Other critics have attempted to rework the original data, or to add new evidence. R.V. Jackson argues for higher weights for faster-growing industries.[8] Based on a reexamination of the Crafts-Harley data set, he challenges the view that industrial output growth did not accelerate until the second decade of the nineteenth century.[9] His series of industrial output suggests a break in the trend rate of growth as early as the 1780s. Overall, however, his index is not too different from the one proposed by Crafts and Harley, and they have accepted his estimates as a possible alternative interpretation of the data.[10] Cuenca Esteban (1994, 1995) has attempted to use additional information on the price of cotton goods derived from contemporary customs estimates to argue that Crafts and Harley have understated the growth of cotton output. Overall output growth for England would be markedly higher if his corrected figures for textile production are used. Crafts and Harley have defended their estimates vigorously, and Cuenca Esteban's alternative index has failed to convince the majority of other scholars.[11]

Finally, Temin has used a novel approach to examine the plausibility of the hypothesis that growth was slow and highly concentrated. He analysed the pattern of British trade during the period. Using a Ricardian model, Temin argues that slow (and heavily concentrated) productivity growth should have turned England into a net importer of most manufactured goods.[12] Since Britain continued to export most industrial goods, he rejects the notion of limited and minimal productivity advances.

The marked improvements in quantity-based national accounts over the past 20 years – especially in the case of capital inputs and overall output measurement – have therefore not led to an unquestioned consensus. Independent of the merits of individual challenges, continuing debate over the core elements of the Crafts-Harley view shows that what is needed are new estimates based on a different methodology and independent data. In this paper, we use a dual approach to derive independent estimates of TFP growth during the English Industrial Revolution. Using information from factor prices, we show that there is clear evidence of slow productivity growth. Section 2 briefly introduces the dual approach to TFP accounting, and argues that in the case of historical data, it will yield estimates that are at least as reliable as those derived from the primal approach. We then discuss the data sources used in our calculations. Section 3 presents our new estimates of TFP growth, and confronts these with existing calculations. In Section 4, we conduct a number of sensitivity tests. We then discuss briefly some of the possible reasons for slow growth in Section 5, and also offer an explanation that reconciles this fact with the observed pattern of foreign trade. Section 6 concludes.

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[8] Jackson 1990 also argues that there is a mistake in Crafts's original calculation of the output in commerce, which Crafts and Harley (1992) accept.
[9] Jackson 1992. Crafts and Harley (1992) contend that, contrary to Jackson's argument, any revision would have to be downwards.
[10] Crafts and Harley 1992.
[11] Harley and Crafts 1995.

2. A Dual Approach to Productivity during the Industrial Revolution

Using input and output prices (instead of quantities) to measure changes in productivity is not a novel idea. Griliches and Jorgenson (1967) demonstrate the equivalence of the primal and dual approaches to growth accounting. An early application of the dual approach to economic history can be found in McCloskey (1972), who inferred changes in agricultural productivity during the industrial revolution from movements in rents paid for land.[13] Recently, Clark (1999a) has extended McCloskey's technique by also considering changes in farm wages and return on farm capital, deriving overall measures of productivity change in agriculture.

The dual approach has also been used to measure productivity in manufacturing during the Industrial Revolution. McCloskey (1981) analysed output and input price data in several industrial sectors to infer annual productivity change between 1780 and 1860. McCloskey summarized the intuition behind the dual approach: "*We do not know annual quantities of china plates and steam coal, admittedly, and probably never can. On the other hand, we know practically anything we choose about price. … The technique is to measure physical productivity change by the changes in prices … The degree to which the price of the cloth fell relative to the price of the inputs is therefore a measure of productivity change.*"[14] Productivity advances will eventually bid up the price of factors of production, as they must in a competitive economy. The extent to which capital, labour and land can receive higher payments is a direct measure of the pace of productivity advances.

The same argument can be made for the economy as a whole. If the remuneration of all factors of production increases, overall output must be growing. The same intuition lies behind the use of value-added in constructing national accounts. Note that, in some ways, using the dual approach to measure productivity growth for the economy as a whole is less problematic than for individual sectors. In the case of cotton, for example, one could argue about the extent to which a gradual erosion of the high rents captured by the first generation of producers was responsible to the output price decline relative to inputs. If cotton producers earned higher than average returns on their capital, we would be in danger of overestimating the rate of productivity change.[15] For the economy as a whole, of course, the influence of sector-specific rents or innovation premia will be much smaller – and estimating the rental price of capital is correspondingly less problematic.

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[12] Temin 1997. Crafts and Harley (1998) use a CGE-model to show that, in a more flexible framework than the Ricardian one employed by Temin, the trade data can be reconciled with concentrated (and slow) productivity growth.
[13] McCloskey 1972, p. 32-33.
[14] McCloskey 1994, p. 250-1.
[15] Assuming that measures of the return on capital for the economy as a whole are used in calculating sectoral productivity growth.

We will assume that there are only three factors of production in the economy: labor (L), capital (K) and land (T). Thus, at any given date t, output (Y) will be a function of K, L and T at date t:

$$Y_t = F\,(K_t, L_t, T_t) \qquad (1)$$

Following Hsieh (1999), our derivation of the dual estimates of productivity growth is based on the national income accounting identity that the (real) value of national output has to be equal to the (real) payments to the factors, i.e.:

$$Y_t = r_t K_t + w_t L_t + q_t T_t \qquad (2)$$

where w, r and q are real wages, the real rental rate of capital and real agricultural rents respectively.[16] Taking logarithms and differentiating with respect to time we obtain the following expression

$$\hat{Y} = \eta_K(\hat{r} + \hat{K}) + \eta_L(\hat{w} + \hat{L}) + \eta_T(\hat{q} + \hat{T}) \qquad (3)$$

where hats indicate growth rates and η is the share of income going to each factor. Rearranging we obtain:

$$\hat{Y} - \eta_K\hat{K} - \eta_L\hat{L} - \eta_T\hat{T} = \eta_K\hat{r} + \eta_L\hat{w} + \eta_T\hat{q} \qquad (4)$$

Note that the left-hand side of equation (4) is just the usual (primal) expression for the Solow residual, that is, the difference between the growth rate of output and a weighted-sum of the growth rates of factor inputs, with the weights being the shares of each input in total income. The right-hand side of equation (5), our dual measure of total factor productivity growth, is equal to the weighted-sum of the growth rates of real factor prices.[17] Summarizing, we have obtained

$$TFP_{\Pr imal} = TFP_{Dual} = \eta_K\hat{r} + \eta_L\hat{w} + \eta_T\hat{q} \qquad (5)$$

which will be the expression we will use throughout this paper to obtain our measures of productivity growth in England between 1770 and 1860. Although it should be clear from the above derivation, we should stress the fact that the equality between the primal and dual

[16] Notice that no assumption is needed (other than that labor, capital and land are the only three factors of production) to obtain equation (2).

[17] If we had used nominal values, this would be equal to the difference between the weighted-sum of growth rates and the growth rate of output prices.

approaches to growth accounting simply follows from an identity. As Hsieh writes: "*No other assumptions are needed for this result: one does not need any assumptions about the form of the production function, bias of technological change, or relationship between factor prices and their social marginal return*" (1999, p. 135)

This however does not imply that our measure of productivity is flawless. In fact, in order for the right-hand side of equation (5) to truthfully measure total factor productivity we further need to assume perfect competition and constant returns to scale. In the presence of imperfect competition or increasing returns to scale, factors of production would not be paid the value of their marginal product and dual estimates of total factor productivity could be shown to be biased. However, and this is a crucial point, if the above assumptions are violated, primal measures of productivity will be biased by the same amount since, as it is discussed above, primal and dual estimates are always equal to each other.[18]

Hence, any difference between the primal and dual approaches has to stem from an inconsistency between the national accounts and the data on factor prices. This paper presents measures of productivity that are qualitatively and quantitatively consistent with the recent work by Crafts and Harley. Their revisions have made extensive use of the primal approach to growth accounting. As discussed in the introduction, our claim is that factor price data can provide important independent confirmation of their findings, thus adding further credence to them.

Previous studies have mostly analysed particular sectors of the economy (e.g. agriculture, cotton), using input and output price data from these particular sectors to infer productivity changes. The difference between this previous 'dual' literature and this paper is one of scope. Our approach focuses on the economy as a whole. Recent contributions by Feinstein (1998), Turner, Beckett and Afton (1997) and Clark (1998, 1999b) have provided aggregate national series for wages and rents in England during the industrial revolution.[19] We take advantage of these contributions to construct a dual estimate of aggregate total factor productivity growth in England in the period 1770-1831. The next section describes the data in more detail, and presents the most important results.

3. Data and Results

Our approach requires data on the evolution of prices, the rental cost of capital, the cost of labour, and the return to land.

[18] In the primal approach, the bias would come from the fact that, if factors are not paid their marginal product, factor shares are no longer equal to the elasticity of output with respect to each factor. Cf. Crafts and Harley (1992) in response to this kind of criticism by Berg and Hudson (1992).

[19] See section 3 of this paper for more on these contributions.

Choosing a series for wages is easier than for any other components that we require. Feinstein's (1998) series is the seminal contribution to the literature, replacing the earlier indices compiled by Lindert and Williamson (1983). Feinstein’s estimates of average nominal earnings in Great Britain relate to manual (blue-collar) workers and exclude salaried (white-collar) workers. Lindert and Williamson (1983) restricted their study to England, but on the other hand also considered white-collar workers. Feinstein's new index is considerably more comprehensive, covering 24 different occupations or industries that employed 4 out of 5 Britons in 1851. Although these two studies sustain opposite views on the living standards issue, Lindert and Williamson’s nominal wage series for blue-collar workers is remarkably similar to the Feinstein data. Most of the difference between these authors’ views arises as a result of the use of different price indices.

It could be argued that a rising proportion of unskilled workers in the workforce exerted downward pressure on wages as measured by real wage indices.[20] Feinstein's series implicitly assumes that all changes in skill are incorporated in the level of average earnings.[21] Controlling for the possible effects of changes in the skill composition of the workforce would clearly be desirable. Hsieh eliminates the effect of changes in the skill composition of the workforce on wages by obtaining wage series for each skill category. These are then simply weighted by their relative contribution in the base year, thus eliminating any upward bias from rapid human capital formation.

We do not correct wage changes for human capital formation. This is for a number of reasons. First, the size and trend of skill premia during the Industrial Revolution are highly controversial. Second, there is little evidence that the skills of the workforce fell rapidly. Schofield found that the percentage of men who could not sign their names – thus classified as illiterate – fell slightly on average between 1754 and 1844. This was true of all occupations with the exception of husbandmen (cf. Table 2). The changes are small, and are unlikely to account for much of the increase in real wages. More importantly, the bias is against our results. Given that the workforce by the end of the period was (marginally) better trained, the true underlying improvement in productivity net of human capital growth must have been even less than the aggregate real wage indices suggest.

[20] We thank Daron Acemoglu for this suggestion.
[21] Feinstein 1996.

Table 2: Illiteracy by occupational group

	1754-84	1785-1814	1815-1844	% change
textiles	20	39	16	-4
metal	22	29	19	-3
transport	31	38	30	-1
yeomen and farmers	19	18	17	-2
husbandmen	46	56	52	6
average	36	39	35	-1

Source: Mitch 1993.

Feinstein's new price index (1995, 1998) also represents an improvement on earlier work, and is used for our baseline estimates. The range of commodities covered is wider than in earlier studies (incorporating items such as milk, beer, potatoes and cheese), uses new information on the price of cotton cloth, and includes a national measure of rent. The new series implies markedly slower growth of real wages largely because prices fell less between 1801 and 1850 than Lindert and Williamson (1983) assumed.

The series for land rental values is potentially more problematic. In his study of dual TFP growth in East Asia, Hsieh only used data on wages and the rate of return on capital data, thus ignoring the effect of any change on the amount paid to all other factors of production. This simplification is more innocent the lower the share of payments to other factors as a percentage of total income. In eighteenth century England, agricultural income represented around 40% of total income.[22] Nevertheless, payments to land (i.e. agricultural rents) are only a fraction of agricultural income. Based on self-admitted ‘crude estimates’, Clark has estimated the share of rents in total agricultural income to be around 40%.[23] This results in a share of rents in total income of around 15%, which is exactly the same figure proposed by Crafts (1985).

As for data on land rents, we are fortunate in being able to choose from the contributions by Turner, Beckett and Afton (1997) and by Clark (1998, 1999b). Their series originate from distinct pieces of evidence: Turner, Beckett and Afton draw their data from estate archives and from previous series constructed for the Royal Commission on Agriculture, whereas Clark uses reports of the Charity Commission on land held by charities in England and Wales. The series they obtain are also significantly different in levels. In particular, for the period 1770-1831, Clark estimates higher nominal rents for all years. This discrepancy has sparked a bitter discussion between the two sets of authors,[24] but as Allen (1998, p. 23-25) has recently pointed out, the two series have both virtues and flaws. However, since our dual calculation of total factor productivity requires data on

[22] This share is 43% in Deane and Cole (1962, p. 78). Crafts (1985) considered this figure to be too high and proposed instead a share of 37% (p.16).
[23] Clark 1999b, p. 36.

the growth rate of rents rather than levels, we can anticipate that whether we choose Turner, Beckett and Afton or Clark's series will not affect our results much. We will use the latter in our benchmark estimates and the former in our sensitivity tests.

A more difficult question is whether rents are really a good indicator of the return to land. In particular, as we have pointed out in the section on methodology, in order for our dual estimates of productivity growth to be accurate (i.e. unbiased), the assumption that each factor is paid the value of its marginal product needs to be satisfied. Allen (1994) argues that since rents "*were not adjusted annually and so could fall behind changes in land values, […] price calculations can give spurious measures of productivity change*" (p. 111). While this may be correct, the same assumption – that factors are paid the value of their marginal product – is also necessary for primal estimates of productivity to be unbiased.[25] Furthermore, even in the case in which rents were adjusted sluggishly, as long as a more or less constant proportion of rents where adjusted annually, any increase in the value of land would lead, in the long run, to a proportional increase in rents.[26] Since in this paper we compute productivity growth over thirty-year periods, it is most likely that the growth rate of rents is not affected.

The rental cost of capital can be calculated in two ways. The first one is to infer rental rates of capital from the capital share in total income. In particular, the rental rate of capital would be equal to the capital share divided by the capital-output ratio. By proceeding in this way, however, we would be relying on factor quantity data and it is precisely the consistency of this data that we aim to test in this paper. Furthermore, since the capital share is usually computed as a residual (what is left from income after payments to labor and land), using this approach would yield measures of rental rates on capital subject to several potential biases.

We follow the example of Hsieh and attempt to construct a more direct measure of the rental cost of capital. For this, we require information for three separate components – real interest rates, the relative cost of capital, and depreciation rates. The standard Hall-Jorgenson formula for the rental price is:

$$r = \frac{R}{P} = \frac{P_k}{P}(i - p + d) \qquad (6)$$

[24] See Clark (1999) and Turner, Beckett and Afton (1998). Clark asserts that Turner, Beckett and Afton's series is "*obviously deficient*" (p. 210), while the latter respond that Clark's findings are still "*unpublished and therefore untested*" (p. 211). Clark's evidence has also been questioned by Chapman (1999). Cf. the reply by Clark (1999d).

[25] See section 2 on methodology.

[26] The situation is analogous to the response of prices to an exogenous increase in money supply in a macroeconomic model with staggered adjustment of individual prices. In this type of models, money is neutral in the long run and unless one introduces 'real rigidities', inflation is likely to catch with money growth quite fast. See Chapter 6 in Romer (1996) for an introduction to these models.

where P_k/P is the relative price of capital, i is the interest rate, is inflation, and δ is the depreciation rate. The relative price of capital is taken from Feinstein (1978), who provides separate series for dwellings, agricultural works, and for plant and machinery.[27] For the depreciation rates, we calculate the average annual rates from the estimates of capital formation in Feinstein and Pollard (1988).

A potentially more delicate question is the choice of interest rate. We would ideally like to use interest rates for private sector borrowing, such as the loan rate charged by country banks. Such information is presently not available. We use the yield on Consols instead. Three Percent Consols, the largest component of the British government's funded debt, paid a fixed nominal interest rate of 3 per cent and were – in principle – callable. Their price fluctuated in response to changes in the supply and demand of capital, inflation, and the perceived riskiness of government bonds. Mitchell (1988, p. 678) presents a series for the yield on Three Percent Consols starting in 1756. There is every reason to assume that private-sector borrowing was more expensive than that of the government. As long as the spread of private over public borrowing was relatively constant, however, we will still be able to infer trends over time from the yield on Consols.

The potentially most damaging problem could arise from the usury laws – English law imposed an upper limit on interest rates. In times of high government borrowing, such as during wartime, private investment might have been 'crowded out'. At the time of Waterloo, Britain's public debt was valued at 2.3 times GDP, a ratio far higher than, for example, in the UK or US after World War II. Because public borrowing drove out private-sector investment, the nation's capital stock by 1810 was markedly smaller than it would have been without the wars with France. This would make the use of interest rates on Consols highly problematic – their yield would not only be lower than private sector borrowing rates, but the differential would vary over time (possibly dramatically so). Thus, the interest rate on Consols used may not just be artificially low, but may also mask very high rates of interest for private borrowing during wartime (Williamson 1984). Recent results by Clark (1999c), however, strongly suggest that this was not the case. He shows that charities obtained yields on their assets that were broadly similar to the Consol yields. Also, the rates of return on mortgages by the Sun Life insurance are very similar to Consol yields and the charity returns.[28] The Sun Fire Insurance, just like other insurance companies, invested some of premium income in private debt.[29] Mortgages tended to be relatively long-dated, often with maturities of 10 years or above. However, since the interest rate was subject to renegotiation, mortgage rates were not similar to long-term commercial interest rates. As Table 3 shows, the

[27] We weight these according to their contribution to the total stock of domestic reproducible fixed assets (Feinstein 1981, table IV, p. 433).
[28] John 1953. The rates are from the Sun Fire Insurance, Minutes of the General Meeting and Minutes of Quarterly Meetings.
[29] Mortgages constituted around 50% of 'stock account' balances (Mirowski 1981, p. 562).

premium that could be earned from investing in mortgages was relatively small. Between the first decade we consider, the 1770s, and the turn of the century, nominal rates increased somewhat.

Table 3: Interest rates in England, 1750-1799

	Charity returns	3% Consols	Sun fire office mortgage rate
1750-59	4.31	3.40	4.30
1760-69	4.53	3.60	4.70
1770-79	4.65	3.74	4.10
1780-89	4.68	4.65	4.85
1790-99	4.82	4.54	4.65

Sources: See text.

Movements over time in the rate of interest did not differ greatly – the yield on Consols acted as the benchmark for other long-term interest-bearing assets, offering a lower yield on account of the low perceived default risk.[30] There is therefore no empirical evidence to suggest that the rate of return on private assets was significantly different from the yield on Consols.

According to Neal, the prices of Consols "*became the best barometer of the schedules of loanable funds for all activities in the British Isles by the Seven Years Wars (1756-63)*".[31] There is therefore a number of reasons why we believe that movements in Consol rates can usefully serve as a proxy for changes in the price of private borrowing. There is clear evidence that Consol rates acted as an important reference rate for a considerable part of economic activity. Public utility investment rose and fell in line with the yield on Consols, most notably in the case of turnpike construction (Presnell 1960). As McCloskey, using the case of enclosures as an example, argued, "*the interest rate relevant to local projects was determined by what was happening in wider capital markets, as is plain for example in the sharp rises and falls of enclosure in the countryside with each fall and rise in the rate of Consols*" (1994, p. 254). Further evidence of these interactions can be found in Neal (1994, p. 179), who shows that the yield on Consols had a significant effect on the number of bankruptcies in England between 1723 and 1826. Neal (1994) has also argued that capital markets were more integrated than had previously been accepted: "*… an active and widespread… credit market, centred on London and radiating inland, operated throughout Britain during the entire eighteenth century. […] This meant that local firms in diverse parts of the kingdom could borrow exclusively from local savers and yet all pay interest rates that moved in accord with those available in the London money market*".[32]

[30] The correlation coefficient between changes in Consol yields and the interest rate on Sun mortgages is 0.76.
[31] Neal 1994, p. 156.
[32] Neal 1994, p. 154.

Because credit markets were relatively integrated, arbitrage ensured interest rates charged by local country banks had to move in with interest rates that were paid in the London money market.

Having discussed the methodological assumptions underlying the dual approach to productivity measurement as well as the data sources used, we now turn to the main result. Table 4 gives our preferred estimates of TFP growth during the Industrial Revolution, and compares them to the latest estimates offered by Crafts and Harley.[33] We follow Crafts (1985) in using factor shares of 0.5 for labour, 0.35 for capital, and 0.15 for land.

Table 4: Estimates of Productivity Growth in England, 1770-1851

	r/r	**w/w**	**q/q**		**TFP Growth**
Preferred Estimate					
1770-1801	-0.28	0.40	0.13		0.12
1801-1831	0.83	0.34	0.20		0.49
1831-1860	0.74	0.56	0.11		0.56
	Y/Y	**K/K**	**L/L**	**T/T**	
Crafts/Harley (1992)					
1760-1801	1	1	0.8	-	0.1
1801-1831	1.9	1.7	1.4	-	0.35
Crafts/Harley (1992) – three – factors					
1760-1800	1	1	0.8	0.2	0.19
1801-1831	1.9	1.7	1.4	0.4	0.50
1831-1860*	2.5	2.0	1.4	0.6	1.0

Sources: See text. Crafts and Harley 1992.
* taken directly from Crafts 1985.

The rental cost of capital is falling for the first period 1770-1801, according to our estimates. This, combined with very slow growth in real wages and the real value of rents, is largely responsible for our result of slow TFP growth. The best standard of comparison is the latest set of estimates from Crafts and Harley. They, however, use a two-factor model (for capital and labour only) to derive their estimates. Much of the downward revision of TFP estimates from Crafts (1985) to Crafts and Harley (1992) is the result of this change in procedure, which indirectly increases the weights on factors with higher rates of growth. Since we use information on changes in the real value of rent, wages and capital, we need to combine Crafts's (1985) three-factor approach with the new data on input and output quantities. The last estimate in Table 4 gives the figures for such an approach. The baseline Crafts-Harley estimate becomes 0.19 for 1760-1801 and 0.5 per cent p.a. for 1801-31. These figures are marginally higher than the original Crafts-Harley figures, largely as a result of

[33] Note that, since the new Feinstein wage series is only available from the 1770s onwards, we can only present estimates from this data onwards.

the lower weight on capital. Our own result for the first period is 0.07 percent lower, whereas the difference in the second period is a mere 0.01 per cent.[34]

Overall, our preferred estimates agree almost exactly with those favoured by Crafts and Harley. Our estimates of price changes would have to be wrong by several orders of magnitudes to restore the most ‘optimistic’ estimates in the TFP literature.[35] For the period 1831-60, we also find significantly positive TFP growth, just as Crafts (1985) argued, if at a lower level.

4. Sensitivity tests

We have already emphasized that the quality of the underlying data and the difficulties in fixing appropriate weights in aggregating the series, allows us to construct no more than ‘*controlled conjectures*’ (Feinstein 1996). How sensitive are our results to the various assumptions used in constructing them? Here, we analyse the impact of using (i) alternative factor shares (ii) alternative series for the rental cost of agricultural land, (iii) three different measures of the cost of capital, or (iv) another price series.[36]

Crafts and Harley (1992) only use capital and labour for the TFP calculations, assigning an elasticity of 0.5 to each. Setting η_L=η_K=0.5 generates our alternative estimate 2. A reasonable upper bound on the factor share assigned to labour is 0.7.[37] We assign a share of 0.2 to capital and 0.1 to rents to derive alternative estimate 3. Table 5 compares the results with our preferred estimate (1).

Table 5: Sensitivity tests – alternative factor shares

estimate	1	2	3
η_K	0.35	0.5	0.2
η_L	0.5	0.5	0.7
η_T	0.15	-	0.1
TFP			
1771-1800	0.12%	0.06%	0.24%
1801-1830	0.49%	0.58%	0.49%
1831-1860	0.56%	0.65%	0.62%

[34] For the first period, 100% of the downward revision is a result of assigning a greater weight to capital (capital grows at 1% p.a., land at 0.2% p.a.; increasing the weight on capital from 0.35 to 0.5 reduces the TFP measure). In the second period, growth would be 0.15% p.a. more rapid if Crafts's original three-factor approach had been pursued (TFP=0.5% p.a. instead of 0.35%).
[35] Those by Feinstein 1981. Converting his figures to our three-factor approach, using the factor shares of 0.5, 0.35, and 0.15 for labour, capital and land, respectively, as well as the estimates of land in use from Crafts 1985, suggests TFP growth of 0.3 and 1.45 for 1760-1801 and 1801-1831.
[36] Note that the appendix also contains alternative estimates derived from introducing rational expectations in our cost of capital computations.
[37] Nelson (1964) assumes that the likely upper bound is η_L= 0.75 for the US in the twentieth century. This almost certainly includes a large component for human capital (cf. Mankiw, Romer and Weil 1992).

Assigning weights of 0.5 (estimate 2) each to capital and labour has only a marginal impact on our estimates. The TFP growth rate for 1771-1800 falls to 0.06 per cent, which would reinforce our interpretation that growth was slow. The acceleration after 1801 is somewhat more rapid than in our preferred estimate, while the TFP growth rate after 1831 now increases somewhat. The alternative estimate (3) shows a sharper divergence from our baseline estimate, suggesting a TFP growth rate for 1771-1800 that is exactly twice as high. If this calculation was true, it would signal a return to the orders of magnitude calculated for this period by Feinstein (1981) and Crafts (1985).[38] For the second period, the range of alternative results is never higher than 0.58 per cent p.a. Even the most 'optimistic' of these estimates is still considerably below the level of 1.3 per cent originally calculated by Feinstein. The range of possible estimates therefore remains too low to lend credence to the rates implied by Cuenca Esteban or Berg and Hudson.

We decided to use the nominal rental cost of land, as calculated by Clark, which we deflate by the Feinstein price series. Two main alternatives suggest themselves, as argued in our data section. The first alternative is to use the rental series provided by Turner, Beckett and Afton (1997, 1998). We decided to accept some of the recent criticisms by Clark (1998, 1999b), and used his estimates. Nonetheless, it is possible to argue that Turner, Beckett and Afton produced superior calculations (Allen 1998). Table 6, estimate 2 shows the impact of using their figures. The upward revision for the first period is small indeed, a mere 0.03 per cent p.a. – clearly no more than any sensible estimate of the likely margin of error. The difference for the second period is somewhat larger, adding 0.24 per cent p.a. to our preferred estimate and returning the order of magnitude to that of Crafts (1985).

[38] As we argued above, the latest revision down to 0.1% p.a. really reflects a change in the weighting procedure applied by Crafts and Harley, and is not the result of data revisions.

Table 6: Sensitivity tests – alternative rent, cost of capital, and price indices

estimate			**r/r**	**w/w**	**q/q**	**TFP Growth**
preferred						
	1	1770-1801	-0.28	0.40	0.13	0.12
		1801-1831	0.83	0.34	0.20	0.49
		1831-1860	0.74	0.56	0.11	0.56
Turner, Beckett and Afton series for agricultural rents						
	2	1770-1801	-0.28	0.40	0.32	0.15
		1801-1831	0.83	0.34	1.80	0.73
		1831-1860	0.74	0.56	0.45	0.61
Clark real rent series						
	3	1770-1801	-0.28	0.40	-0.16	0.08
		1801-1831	0.83	0.34	1.15	0.63
		1831-1860	0.74	0.56	-0.20	0.51
Clark charity returns						
	4	1770-1801	-1.51	0.40	0.13	-0.31
		1801-1831	2.39	0.34	0.20	1.05
share price index						
	5	1770-1801	-1.50	0.40	0.13	-0.31
		1801-1831	1.10	0.34	0.85	0.58
		1831-1860	-0.30	0.50	-0.25	0.11
Feinstein wholesale price index						
	6	1770-1801	0.50	-1.47	-0.97	-0.70
		1801-1831	1.56	1.33	3.02	1.66

We could also have used the real rent series provided by Clark. He deflates the rental series by the price of 11 farm commodities (entering with varying weights).[39] By using the price of agricultural products instead of a general price index, we would generate a measure of what part of national income accrued to land in terms of its own product. While deflating by output prices in this fashion is undoubtedly correct when trying to calculate the productivity of agriculture (based on a dual approach), it is probably not sensible for the economy as a whole. As we are trying to assess productivity change in the aggregate, we need to derive a general measure of the increase of product accruing to factors of production in terms of all outputs. Nonetheless, estimate 3 gives the results for using his real rental cost of land series. TFP growth during the first period is even slower than in our preferred estimate, by one third. Growth after 1801 is somewhat more rapid, suggesting a rate that is approximately 0.1 per cent p.a. higher. The two main findings – very slow growth during the initial decades, combined with a moderate acceleration after 1800 – are not overturned by using either the Turner, Beckett and Afton series or the Clark real rent series.

[39] Clark 1999b, appendix.

Our cost of capital series, based on Consol yields, is arguably less robust than other data sources. We use two alternatives – the yield on Charity assets, and stock returns. Estimate 4 gives the results for using the charity series from Clark (1999c). Since he provides no data after 1839, we can only compare the results with our for the first two periods. The swings in the cost of capital become more extreme, largely as a result of very low (real) returns during the first decade of the nineteenth century. This initially leads to negative TFP estimates for the period 1770-1800. The recovery from the artificially depressed level drives up the rate of TFP growth after 1801. While the point estimates differ from those of our preferred estimate, the broad pattern of initially slow growth, followed by a gradual acceleration, is also clearly visible.

This is also true of the second alternative cost of capital series. We are ultimately interested in assessing the value of the part of national product accruing to capital. One short-cut around the problems discussed above is to simply examine the evolution of share values over the period. Share prices constitute an indicator of the value of total product accruing to capital owners. We combine the Mirowski and the Gayer, Rostow and Schwarz stock price indices.[40] This, of course, is not without difficulty – prior to 1811, we are largely restricted to the prices of Bank of England and the East India Company stock. These can hardly be regarded as representative of the corporate sector as a whole. Even after 1811, the stock index compiled by Gayer, Rostow and Schwarz is not without biases. Canals, docks, and waterworks dominate in the earlier years; later, mining companies, railways and banks begin to comprise a significant part of the overall index. We spliced the average price of Bank of England and East India company stock (unweighted) onto the Gayer, Schwarz and Rostow series. We do not argue that the combined index's movements provide an exact indicator to the fortunes of England's businesses and the return on capital that they produced.[41] However, as Mirowski has demonstrated, regressions of stock prices on the profits of the respective firms strongly suggest that the direction of change was similar, even if stock markets over- or underreacted.[42] Markets were efficient in this sense. We will therefore use the data as an additional check on the potential divergence between the Consol rate as a proxy for the rental cost of capital and other possible measures.

Stock prices declined in real terms between the 1770s and the 1810s, with the downward trend only being interrupted by a brief recovery in the 1790s. It is only from the 1820s onwards that stock prices increase at or above the rate of inflation. The direction of (real) price changes is almost identical in the two series, even if the rates of return are not. We again find that the real rental price

[40] Mirowski 1981, Gayer, Schwarz and Rostow 1953, vol. 1, p. 363.
[41] In addition to differences in coverage, Gayer, Schwarz and Rostow also weight individual stocks by their market capitalization. Cf. Gayer, Schwarz and Rostow 1953, vol. 1, p. 363.
[42] Mirowski 1981, p. 574-5. The exception is stock in the East India Company. Note, however, that the profit figures for the London Assurance Company and the Million Bank were derived from internal records, whereas Mirowski relied on published material for the EIC. It is possible that published information on profits was less accurate than the internal accounts – leaving open the possibility of stock prices tracking actual profits relatively accurately.

of capital declined sharply in the initial phases of industrialization, and that positive returns only started to be visible from the early 19th century onwards. When combined with our other estimates, we find that TFP was falling during the last three decades of the eighteenth century. For the second period, we find TFP growth of 0.58 per cent p.a., marginally above our preferred estimate. In the ultimate period, the rise in TFP is somewhat smaller than if we use the Consol yields, depreciation rates and the change in the relative price of capital.

We believe that the Feinstein (1998) price series is superior to the alternatives. It could however be argued that use of the wholesale price index would be more appropriate; this is the method followed by Hsieh (1999). We use the set of wholesale prices in Feinstein (1978) to test for the impact that the use of an alternative price series might have on our estimates. Since his series stops in the 1850s, we cannot provide comparative estimates for the third period. Wholesale prices are more volatile than the consumer price series – the peak in prices around 1800 is about 20 per cent higher, and the subsequent decline is sharper than in the consumer price series. Since we only have decade averages for wholesale prices, adjusting for price changes can only be done in an imperfect manner. We use the average annual change of the wholesale price index between the 1760s and the 1770s in our calculations of the real rental cost of capital, which does not necessarily lead to the same result as using average annual inflation during the 1770s would.

This alternative series (Table 6, estimate 6), suggests a sharper reduction in TFP during the first thirty years than in our baseline estimate. For the years 1801-31, growth appears relatively rapid when the wholesale price index is used. We believe that the quality of the wholesale price series – and the difficulty of adjusting for price changes – make these results less plausible than any of the others, and that there are good a priori reasons for not attaching too a high a weight to them.

Overall, the sensitivity checks do not suggest that our estimates are overly fragile.[43] The two crucial elements of the Crafts-Harley view are vindicated. First, independent of the indices for capital cost, rental cost, or overall prices used, we find that productivity growth was very slow during the last three decades of the eighteenth century. If anything, alternative data sources suggest even lower – and possibly even negative – rates of productivity change. This, it could be argued, is not as implausible as it might appear at first glance. These negative TFP figures are in the same range as Voth's recent revisions, who incorporated changes in hours worked in his labour input figures (thereby revising them sharply upwards). Thus, even our most pessimistic estimates are compatible with primal productivity calculations.[44] Second, we find an acceleration to more rapid but still moderate rates of TFP growth during the period 1801-1831. Here, all our alternative

[43] We also test for the possible effect of expectations, again with similar results (cf. Appendix).
[44] Voth 1998, 2000.

estimates – with one exception – suggest rates at or slightly above the 0.5 per cent p.a. argued for by Crafts and Harley.

Table 8: Counterfactual factor price changes

		Δr/r	Δw/w	Δq/q	TFP Growth
preferred	1770-1801	-0.28	0.4	0.13	0.12
	1801-1831	0.83	0.34	0.85	0.59
counterfactual	1770-1801	1.6	0.4	1.6	1
	1801-1831	2.65	0.34	2.65	1.5
difference	1770-1801	1.88	0	1.47	0.88
	1801-1831	1.82	0	1.8	0.91

One further way of examining the robustness of our findings is to ask how high factor price increases would have to be in order to restore the 'fast growth' hypothesis. Table 8 offers such a calculation. We believe that it is highly unlikely that a convincing case for revising real wages substantially upwards will be made. Therefore, higher productivity growth estimates would have to be result of faster growth in the rental rate of capital and land. For ease of presentation, we assume $\Delta q/q = \Delta r/r$. Also, we believe that the lowest possible rates of productivity growth needed to restore the view that growth was relatively 'fast' are one per cent p.a. 1771-1801 and 1.5 per cent p.a. 1801-31. By historical standards – e.g. the post-war boom in OECD countries etc. – these would still be very low. The counterfactual estimate in Table 8 shows how large the increases in factor costs would nonetheless have to be. During the first period, the rental cost of capital and of land would have to grow at 1.6 per cent p.a.; during the second period, the corresponding figure is 2.65 per cent. The differences from our preferred estimates are very large. Also, even the most optimistic estimates derived from alternative data sources or using altered assumptions are insufficient to yield TFP growth rates on this order of magnitude. While the fragility of the data must be emphasized, it is hard to see how the evidence from dual productivity estimates could be reconciled with the view that productivity change during Britain's industrial revolution was relatively rapid.

5. Explanations of slow growth

How can the evidence in favour of slow productivity growth be squared with the data on foreign trade? This is the question that Temin asked. Since he finds strong evidence that Britain became an exporter of all manufactured goods, and not just of a handful of 'revolutionary products', he argues that TFP growth must have been relatively widespread. This would also suggest that aggregate growth rates must have been underestimated. One of the central underlying assumptions in the Ricardian model of trade as used by Temin is that the relative price of factors of production does not change.

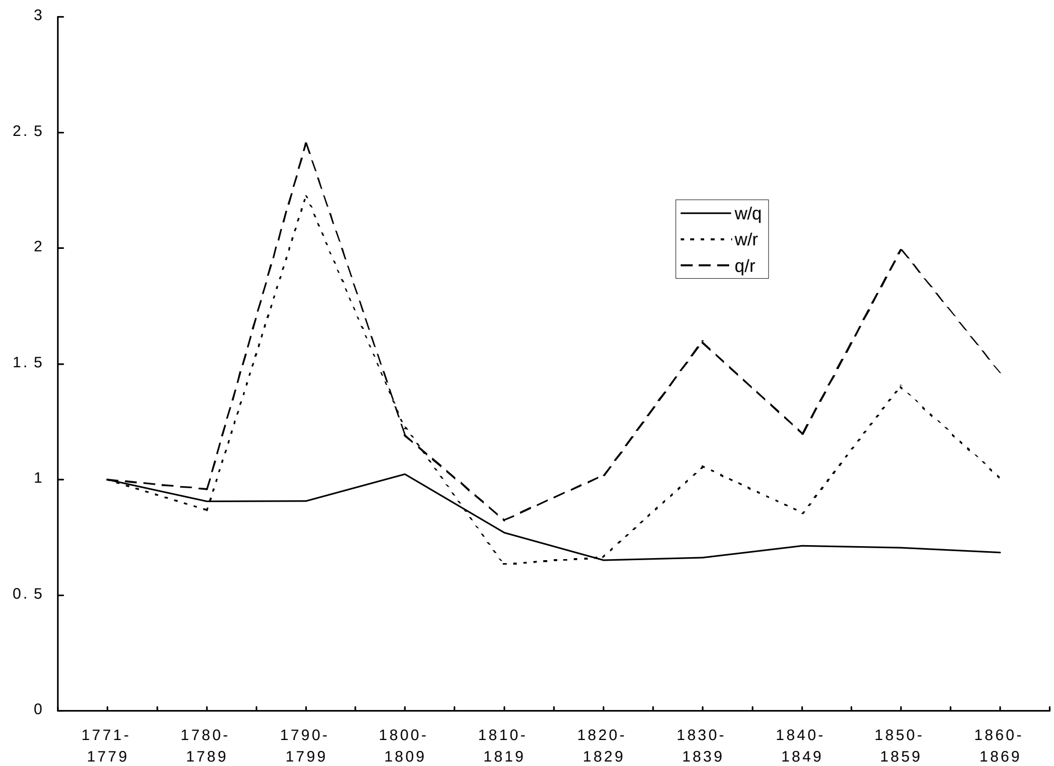

Figure 1: Relative price of factors of production

Plotting the relative price of factors of production over time reveals just how strongly this assumption was violated during this period. The ratio of prices often varies dramatically from one decade to the next. The coefficient of variation for relative prices is 18 per cent for the most stable series (w/q) and 42 per cent for the most volatile one (q/r). The data used in the calculation of our dual productivity estimates therefore also demonstrates why the foreign trade data in itself – interpreted in the framework of a Ricardian model – is not necessarily at variance with the Crafts-Harley view of the industrial revolution.

This, however, does not explain why growth – and, more specifically, productivity growth – was slow during the first decades of Britain's industrial transformation. Williamson's crowding-out hypothesis, as was argued already, is difficult to square with evidence on private-sector rates of return. Two alternatives suggest themselves. Much recent writing on productivity growth has focused on general purpose technologies (GPT). These are characterized by high potential for technical improvement and can be universally applied in the production process. They also often show strong innovational complementarities, and are therefore subject to network externalities (David and Wright 2001, Hornstein and Krusell 1996, Greenwood and Yorukoglu 1997, Bresnahan and Trajtenberg 1995, Greenwood and Jovanovic 1998). As these authors argue, there might well be good reasons why an acceleration of productivity growth typically follows the widespread adoption of new technology only with a lag of several decades.

Amongst the best-known historical examples is the introduction of electric motors. As David (1990) has shown, the benefits of electrification only became apparent in the 1920s, more than 20 years after the widespread adoption of electric lighting and the use of electric motors. David and Wright (2001) argue that a similar process may be responsible for the absence of measurable productivity growth following the IT-revolution. What the new technologies have in common is both their considerable potential for productivity growth, as well as the difficulty to adopt them efficiently without a wholesale redesign of manufacturing processes. Also, the need for simultaneous adoption of network technologies amongst numerous users (which then allows the building of public electricity grids, high-speed computer links etc.) slows down penetration. General-purpose technologies such as the dynamo or the microprocessor will therefore lead to lags between adoption and productivity growth.

Analogies between more recent examples of general purpose technologies and the steam engine have been noted before (David 1990, Bresnahan and Trajtenberg 1995). The use of the steam engine – and of coal in iron smelting etc – was clearly subject to the same kind of network effects. Coal transport itself remained a major hurdle until English transport networks had improved sufficiently; the required fixed costs of investment could only be recouped if enough users switched to the new power source. More importantly, the use of steam power required central workshops and factory buildings, which in turn caused a need to reorganize the workforce. Many of the problems associated with a wholesale switch to the new power source could only be overcome with the growth of the railways. The question that therefore needs to be addressed is if technological breakthroughs during the industrial revolution such as the steam engine and the spinning jenny were directly responsible for slow growth? We would thereby turn the 'old hat' view – that saw rapid growth being brought about by new inventions as central – on its head.[45]

If the GPT explanation is correct, three implications should follow (Comin 2000). First, those sectors that invest heavily in the new general purpose technology should experience particularly slow productivity growth. Since the 'cost of learning' to operate the new machinery is crucial, and only the wholesale adoption of the new technology will allow it to fulfil its potential, adoption in isolated industries should leave them particularly exposed to negative side-effects. Second, productivity growth in the economy (or the particular sub-sector adopting new technology) as a whole should be relatively even. In his AEA Presidential Address, Arnold Harberger (1998) distinguished between 'mushroom' and 'yeast-like' processes of productivity growth. In the case of 'yeast-like' processes, most sectors advance at a more or less equal pace. 'Mushroom-style' productivity growth, on the other hand, is dominated by one (or only a handful) of industries racing ahead due to sector-specific inventions. As David and Wright (2001) argue, the GPT interpretation requires that growth is 'yeast-like' when it does take off. Finally, as Comin (2000) has argued, the GPT approach has clear implications for the relative importance of embodied and disembodied technological change. Solow (1959) was the first to distinguish between embodied and disembodied technological change. The former can *"be introduced into the production process only through gross investment in new plant and equipment"* (Solow 1959). If the GPT interpretation is correct, slow productivity growth should be largely caused by slow embodied technological change. Disembodied technological change, on the other hand, ought to be unaffected.

Britain's industrial revolution does not appear to be a good example of general production techniques slowing down productivity growth. First, the sectors that adopted new technology early and vigorously were also the ones that recorded the highest TFP growth rates (Crafts 1985). The modernizing part of the economy only comprised a very limited number of sectors, principally comprised of cotton, iron, woollens, and transport. It was in these sectors that steam – as the principal GPT – and other new technologies such as the spinning jenny and the Arkwright machine were used. Growth in 'all other sectors' needs to be calculated as a residual from aggregate measures after the deduction of productivity growth in the fast-growing sectors, for which we have relatively direct information. Crafts (1985) shows that the entire rest of the economy outside the modernizing sector and agriculture cannot have experienced productivity growth at more than 0.08 per cent p.a. Since our dual productivity estimates confirm that growth overall was as slow as argued by Crafts and Harley, we also therefore also confirm just how uneven productivity growth was in English economy, 1770-1860. Productivity growth was not widespread enough to push up

[45] Temin (1998) popularized the term 'old hat' view of the industrial revolution.

factor prices in the economy as a whole.[46] Our confirmation of the new orthodoxy further re-inforces the hypothesis that productivity growth followed a ‘mushroom’ style pattern, in Harberger's parlance. This also suggests that the GPT interpretation is possibly not applicable to the industrial revolution.

Distinguishing embodied from disembodied technological change is not straightforward. Nelson (1964) focuses on the age of capital. Assuming a constant rate of productivity change λ embodied in new capital goods, he argues that changes in effective capital stock J can be approximated as

$$\frac{\Delta J}{J} = \frac{\Delta K}{K} + l - l\Delta a \qquad (7)$$

where Δa is the change in the average of the capital stock. In other words, the rate of new investment (and of retiring old capital) is crucial in determining embodied technological change, as this influences a, the gap between ‘best practice’ and the state of technology embodied in capital of average age. Estimates of the average age of English capital stock are not directly available. Nonetheless, we can use the information in Feinstein (1988) to calculate rough measures of the average age. Feinstein argued that the useful life of buildings and works was 80-100 years, that plant, machinery, and equipment had a life of 25-40 years, and that rolling stock and vehicles could be used for 10-20 years. If we assume that most of the investment in manufacturing was in plant and machinery, and that the average useful life of capital in the transport and railway sector was between that for rolling stock and plant (e.g. 30 years), then the rising proportion of the English capital stock coming from these sectors inevitably drives down the average age of capital. Even under conservative assumptions, a fall of 20 per cent appears possible.[47] This would suggest that, of the 0.5 per cent average productivity improvement p.a. between 1770 and 1860, a substantial proportion could have been accounted for by embodiment effects.

An alternative approach was suggested by Jorgenson (1966), who identified the rate of decline of the quality-adjusted price of new capital equipment with embodied TFP growth. Again, comprehensive and direct evidence on a satisfactory and consistent basis is not available. Steam engines are nonetheless at the very centre of the GPT interpretation, and we have some scattered evidence on the evolution of their prices. Also, since we have information on the horsepower provided by these machines, we have a rough-and-ready way to adjust for quality changes (thereby abstracting from improvements in reliability etc.). The real price per horse power provided by a 20 hp steam engine declined by 14 per cent between 1790 and 1830, or at a rate of 0.38 per cent p.a.[48]

[46] Also, contrary to the arguments of Cuenca Esteban, the revolutionizing sectors were not large enough to affect the rental cost of capital, of land, or of labour significantly.
[47] Details of calculations available upon request.
[48] Tann 1988.

This is somewhat higher the figure derived above from changes in age of overall capital stock. Of course, given the limitations of the data, no more than a very rough approximation of a TFP decomposition can be undertaken. Nonetheless, we find no evidence of the pattern that the GPT would predict, namely a large role of disembodied technological change and only a very small contribution from embodied technological improvements. Combined with the yeast-vs.-mushroom evidence and the fact that the industries that adopted the new GPT fastest did not suffer the greatest slowdown, this strongly suggests that the introduction of steam during the industrial revolution is not an example that can be added to the GPT list.

If the peculiarities of GPT diffusion do not account for slow growth, what does? Comin (2000) argues that an increase in uncertainty in the 1970s quickly rendered old capital stock unproductive, while new capital stock retained its usefulness. What slowed down productivity growth was not the network effects of computers, but a rapid collapse in (disembodied) productivity growth. Note that, even if new capital goods are highly productive, investments may nonetheless be delayed because of the rise in uncertainty (Dixit and Pindyck 1994). A similar interpretation can be advanced for Britain's industrial revolution. Growing volatility of the price of financial assets points towards a more uncertain environment.[49] Share price volatility trended up between the middle of the eighteenth and the early decades of the nineteenth century, reaching a decade-average of over 40 per cent in 1820s. The price of Consols also indicates a strong rise in uncertainty, with average price changes becoming markedly more extreme between 1750 and 1800.

[49] This is the type of evidence considered by Comin (2000) in the case of the 1970s productivity slowdown.

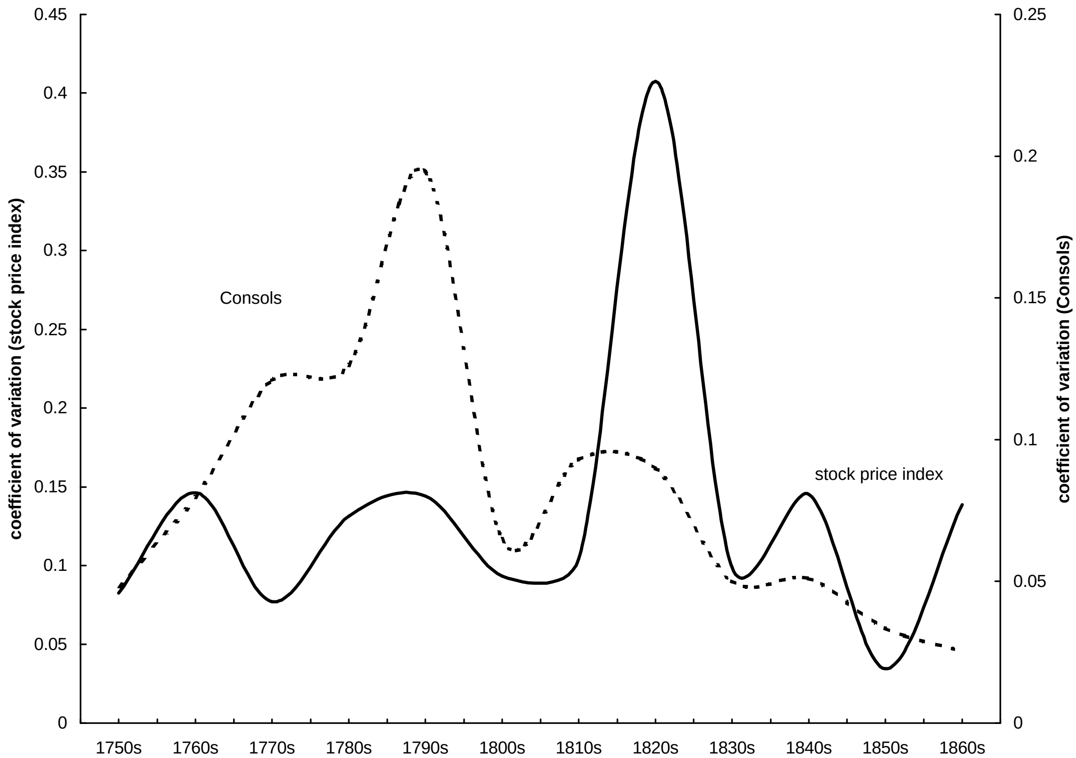

Figure 2: Coefficient of variation: Consol prices and stock price index 1750-1860

Rising uncertainty mattered because it increased the 'value to wait' for firms that considered new investments. The slow rise of the investment ratio during the industrial revolution (Feinstein 1981) may be partly explained by this. Also, the sluggish performance of 'all other sectors' may be a direct result of rising uncertainty. If the new, uncertain environment rendered old capital less productive, and required new, more flexible forms of capital, it is easy to see why the more traditional sectors saw little or no productivity growth. Williamson (1984) argued that Britain's wars were primarily responsible for slow growth because public borrowing drove out private investment. If our interpretation is correct, it may still be true that the many wars of the eighteenth century are partly to blame for sluggish growth; the mechanism may, however, be a very different one, linking a more politically unstable environment to greater uncertainty in the economy.

5. Conclusions

Critics of productivity and growth estimates during the industrial revolution often imply that the quantity-based calculations available so far are little more than a house of cards. In particular, some scholars have argued that output and productivity growth during the English industrial revolution must have been more rapid than the current orthodoxy has claimed (Berg and Hudson 1992, Cuenca Esteban 1994, Temin 1998).

This paper has attempted to show that, despite the difficulties of interpretation and the problems of the sources, the Crafts-Harley view is compatible with independent evidence using a different approach. We explicitly base our productivity calculations on changes in factor prices, and thereby offer confirmation of the main findings by Crafts and Harley from a new and independent source. The quality of our estimates can only be as high as the limited nature of our sources allowed. Yet, as Feinstein (1996) reminds us:

"The case for quantification in the face of the multitude of gaps and uncertainties in the available data is not that it provides definitive estimates. It is, rather, that it helps to establish orders of magnitude, and to test how robust or vulnerable the estimates are to different assumptions and judgements the statistician is forced to make in the face of a lack of satisfactory evidence."

It is in this spirit that our results need to be interpreted. Productivity growth was very slow during the last decades of the eighteenth century, and may even have been zero. This is compatible with the Crafts-Harley view, and reinforces recent findings that further downward revisions of primal TFP calculations due to higher labour input may well be in order (Voth 1998, 2000). There was no 'take-off' in the sense of Rostow. What acceleration there was occurred after 1800, and was mild. The efficiency with which the economy combined factors of production never increased at a rate markedly faster than one per cent before 1830, and probably much less than that.

The dual approach also highlights the close connection between productivity growth on the one hand and the course of living standards on the other. Some scholars appear comfortable with a pessimistic view of changes in living standards, while at the same time arguing for higher productivity growth (and the Industrial Revolution as a radical discontinuity).[50] These are contradictory positions, as dual measurement of productivity growth makes clear. Unless the labour share in national income moved very sharply – for which there appears to be no reliable evidence – real wage growth in the long run has to follow the trend rate of TFP increases.[51]

Having argued that even a house of cards can be remarkably stable if the numerous, independent elements support each other, we also examine the possible causes of slow growth. Neither 'crowding out' nor the approach that views the adoption of the steam engine as another example of a general purpose technology slowing down productivity are compatible with the evidence. Instead, we argue that rising uncertainty may be largely responsible for the unusually sluggish productivity of the First Industrial Nation, and that political causes are likely to have played an important role in creating this uncertainty.

[50] Cf. Berg and Hudson 1992, for example.
[51] Feinstein 1988b. Note however that recent work has argued that the capital share may well have moved up (Feinstein 1998b).

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Appendix: Expectations formation and factor prices

Expectations can have an impact on our estimates in two ways. First, if agents anticipate the relative price of capital goods to change, we need to modify the standard Hall-Jorgenson formula (Collins and Williamson 2000). Second, ex ante and ex post rental rates of capital and wages might diverge.

The simple Ramsey-Cass-Koopmans model of growth takes the rental rate of capital to be equal to the real interest rate plus depreciation. The basic underlying assumption of the model is that output and capital are *de facto* the same good, i.e. the proportion of output that is saved every period is transformed one to one into capital for the following period. This implies that in this model, the price of capital relative to output is 1 by construction.

In reality, however, the existence of adjustment costs and other such 'imperfections', cause the relative price of capital to vary over time. Hall and Jorgenson (1967) derived an expression for the rental rate of capital in such environments. They start with the nonarbitrage condition that the relative price of a new capital good (i.e. its price relative to the numeraire output) has to be equal to the discounted value of all future services derived from this capital good:

$$v(t)=\int_{t}^{\infty} e^{-(i-p+\ddot{a})(s-t)} r(s)ds \qquad (1)$$

$$v(t)=\frac{p_K(t)}{p(t)} \qquad (2)$$

Differentiating this formula with respect to the time of acquisition (t) and assuming static expectations about the price of investment we get the so-called Hall-Jorgenson formula:

$$r = v(i-p+\ddot{a}) \qquad (3)$$

which states that the real rental rate of capital is equal to the relative price of capital times the real interest plus depreciation.

Now if expectations are not static, that is if people expect the relative price of capital to vary through time, then (assuming perfect foresight) differentiation of (1) yields:

$$r = v(i-p+\ddot{a}) - \dot{v} \qquad (4)$$

which can be expressed as:

$$r = v(i - p + \ddot{a} - \frac{\dot{v}}{v}) \qquad (5)$$

Hence non-static expectations add a corrective term to equation (3) equivalent to the change in the relative price of capital over the period.

Table A.1: Impact of expectations about relative price of capital on TFP estimates

estimate			**r/r**	**w/w**	**q/q**	**TFP Growth**
preferred						
	1	1770-1800	-0.28	0.40	0.13	0.12
		1801-1830	0.83	0.34	0.20	0.49
		1831-1860	0.74	0.56	0.11	0.56
relative price of capital corrected						
	2	1770-1800	-1.85	0.40	0.13	-0.43
		1801-1830	2.10	0.34	0.20	0.94
		1831-1860	-0.04	0.56	0.11	0.70

Table A.1 demonstrates that some of our conclusions would even be strengthened if we assume rational expectations about the future evolution of the relative price of capital goods. TFP growth in the first period would now be strongly negative, and the acceleration after 1830 would be even sharper. For the final period, we find almost identical growth rates of productivity.

It is standard practice in contemporary economic studies to use ex post real interest rates and wage rates in the calculation of the cost of capital and labour. To what extent can we be certain that ex post and ex ante factor priced did not diverge at the time of the Industrial Revolution? If accidental shocks to the value of money determined the distribution of income generated by production, we may impart an important bias to our estimates. Since we average for periods of 10 years, the chances that one-off changes in inflation will have a significant impact are small. At the same time, money wages and interest rates showed substantial nominal inertia at the time. As part of the sensitivity analyses carried out in the main part of this paper, we estimate the ex ante rate of inflation. We follow the approach of Barro and Sala-i-Martin, estimating ARMA (1,1) models of inflation.[52] Thus, only past inflation enters the expectations formation process. Barro and Sala-i-Martin show that their model estimates track inflationary expectations as indicated in surveys relatively well.[53] Similar models have been widely used in historical studies as well – such as in an

[52] Barro and Sala-i-Martin 1990, p. 15-7.
[53] Barro and Sala-i-Martin 1990, Figure 1, p. 16.

analysis of expected inflation during the Great Depression in the U.S.[54] The obvious alternative would have been to extract expectations from Mishkin-style regressions. Implementation of this appraoch requires the assumption that economic data such as growth rates are made available to economic agents in a timely fashion – clearly an unrealistic assumption for the eighteenth and early nineteenth centuries.

We derive the following ARMA model, using the Feinstein price series as a dependent variable:

P=132.98 + 0.85 AR(1) –0.54 MA(1)
(15.96) (16.9) (-6.5)

where P is the price level, AR is the lagged dependent variable, MA is the movering average component, and t-statistics are given in parentheses. Barro and Sala-i-Martin (1990) report a range of estimates close to 0.9 for the AR component and between –0.4 and -0.8 for the MA(1) coefficient. Our results fall firmly in that range.

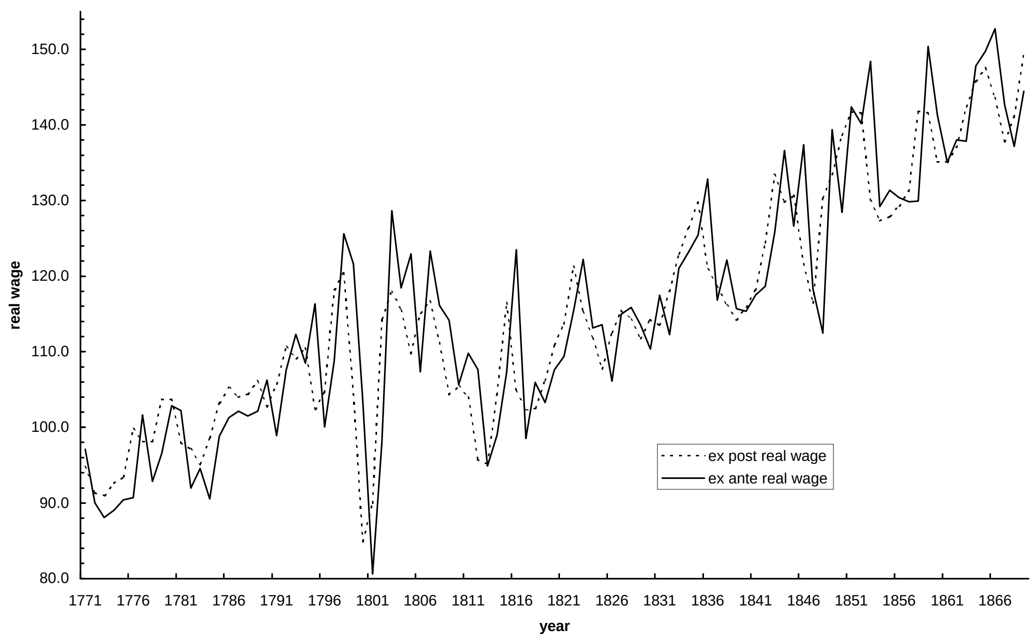

Figure A.1: Ex ante and ex post real wage

[54] Cecchetti 1991.

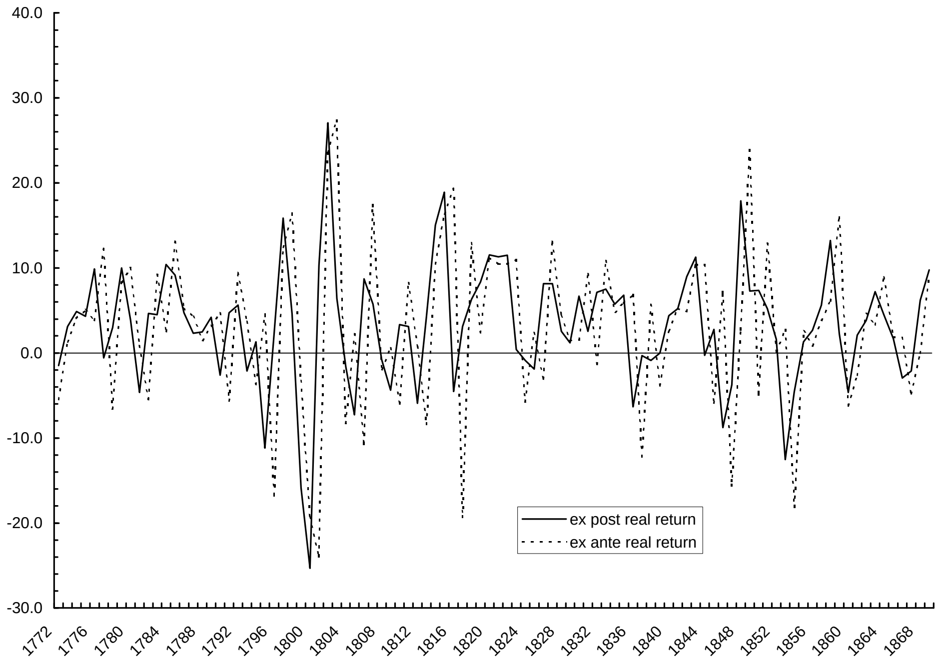

Figure A.2: Ex ante and ex post real interest rates

The series show the familiar one-period lag following large price changes. Ex ante real wages and real interest rates are somewhat more stable than the ex post rates. Because we use decade averages, the impact of moving to ex ante figures for our estimates is relatively small.

Table A.2: Ex post and ex ante real interest rates

	ex post real rate	ex ante real rate	difference
1770-9	4.1	2.8	1.3
1780-9	4.2	4.4	-0.3
1790-9	0.3	2.2	-1.9
1800-9	1.9	0.7	1.2
1810-9	5.2	3.7	1.5
1820-9	5.2	5.6	-0.4
1830-9	2.9	2.7	0.1
1840-9	4.5	4.6	-0.1
1850-9	4.8	3.8	1.0
1960-9	2.6	1.6	1.0

This suggests that the fall in the real interest rate between the 1770s and the 1800s would only be 0.09 per cent smaller if we used ex ante rates. The acceleration of TFP growth would be marginally larger for the period 1800-30, and somewhat smaller for the years 1830-50.

Table A.3: Impact of ex-ante interest rates on TFP estimates

estimate			r/r	w/w	q/q	TFP Growth
preferred						
	1	1770-1800	-0.28	0.40	0.13	0.12
		1801-1830	0.83	0.34	0.20	0.49
		1831-1860	0.74	0.56	0.11	0.56
ex ante interest rates	2	1770-1800	-1.12	0.40	0.13	-0.17
		1801-1830	1.92	0.34	0.20	0.87
		1831-1860	-0.04	0.56	0.11	0.29

Just as in the case of earlier sensitivity analysis, we find that the possible use of alternative time series broadly strengthens our conclusions. With ex ante interest rates, productivity growth during the first period would be even slower, and the acceleration thereafter even sharper. Nonetheless, even in the second period, England's productivity performance remains relatively sluggish.