Total factor productivity growth in English agriculture

Maddison, David; Rehdanz, Katrin

DOI:
10.1093/oep/gpy055

Total factor productivity growth in English agriculture: 1690-1914

By David Maddison[a] and Katrin Rehdanz[b]

[a] Department of Economics, University of Birmingham, Birmingham, B15 2TT; e-mail: d.j.maddison@bham.ac.uk
[b] Department of Economics, University of Kiel, Kiel, Germany

Abstract

The rate of TFP growth in agriculture is sometimes thought of as facilitating the wider industrial revolution. We use data on rents, prices, wages, the cost of inventories and the user-cost of man-made capital to analyse productivity change in agriculture in England 1690-1914. Adopting an approach based on the profit function we find that the rate of profit augmentation was 0.4 percent whilst the output and input-based rates of TFP growth were 0.1 and 0.2 percent respectively. We cannot reject the null hypothesis that the profit function for agriculture is stable. At least in economic terms agriculture exhibited steady progress rather than revolutionary change.

JEL code: B31, Q15

Introduction

The rate of total factor productivity (TFP) growth in agriculture is often deemed to be a fundamental part of the explanation about how the wider industrial revolution came to occur. The importance of TFP in this context can be most readily appreciated by imagining things in terms of a race between food production achieved under conditions of diminishing returns and population growth.[1] The basic assumption is that, immediately prior to the industrial revolution, the rate of TFP growth in agriculture was more than sufficient to feed the growing population thereby permitting labour shedding and industrialisation to occur.[2]

Despite several empirical studies of the historical rate of TFP growth in agriculture there is however little evidence that the rate of TFP growth actually changed. Partly this is because it is impossible to obtain the data necessary to measure the historical rate of TFP growth in quite the same way that it is measured today. But even using humbler measures of TFP growth no-one has presented a statistical test of the hypothesis that the rate of TFP growth was constant during the so-called 'agricultural revolution'. In this paper we both measure and explicitly test the constancy of the historical rate of TFP growth in agriculture.[3]

The rate of TFP growth in agriculture is nowadays typically calculated using index numbers. These indices are then compared and any unexplained component attributed to growth in TFP. Although it is not the purpose of this paper to review these techniques greater attention is focussed on those procedures which do not impose any a priori restrictions on the structure of production e.g. the Tornqvist-Theil index. For a detailed explanation of the calculation of TFP in the USA using the Tornqvist-Theil index see Ball (1985).

---

[1] For an opposing point of view see Weisdorf (2006) who argues that it was the rate of TFP growth in industry that generated a release of labour from agriculture. This occurred because agricultural households were also involved in the production of non-agricultural commodities, an activity that became relatively less efficient with TFP growth in the industrial sector prompting some agricultural households to focus wholly on agricultural production, but many others to abandon agriculture altogether.

[2] More specifically with a growing population a positive rate of TFP growth is necessary for what Dixit (1973) refers to as the 'viability' of the economy. In this model industrialisation can occur when the TFP growth rate exceeds $N \times (1 - \alpha)$ where N is the population growth rate and α is the elasticity of output with respect to labour.

[3] The growing application of modern time series econometric techniques to historical data was recently reviewed by Greasley and Oxley (2010). But although there are contained in their review many examples of researchers using such techniques to analyse historical time-series data there are surprisingly no examples involving agriculture.

Because of the lack of historical survey data rather than using the Tornqvist-Theil or indeed any other index, this paper adopts an econometric approach based on the profit function. Because the profit function is derived from the production function it encapsulates all of the same information. From the estimated parameters of the profit function we can therefore retrieve estimates of the historical rate of TFP growth and factor shares.

In order to implement this approach we must assume that the rents achieved by agricultural land are a good indicator of the profitability of agriculture. Given the variety of historical rental agreements encountered (see below) this is no small assumption. Here however, we take advantage of a unique dataset on agricultural rents containing only 'rack' or 'economic' rents to create an index covering 1690-1914. These data, which have not previously been analysed for this purpose, are then combined with other information on agricultural prices, wages, the cost of inventories and the user-cost of man-made capital.

To anticipate our main findings it appears that using an 'output-based' definition, the rate of TFP growth was both modest and stable over a period of 225 years and that there was, in the terms in which we will define it, no agricultural revolution only steady progress. Such findings conform to more modern views of the wider industrial revolution i.e. gradual change rather than revolutionary progress, see e.g. Broadberry et al (2015).

The remainder of the paper is structured as follows. Section 2 reviews existing estimates of the historical rate of TFP growth in agriculture. The theoretical framework of our paper is presented in section 3. The data employed in our analysis is described in section 4 while section 5 tests for the existence of cointegration between the variables in the profit function and estimates the parameters of the profit function. Section 6 discusses the robustness of the results, presents additional findings and offers a comparison with current rates of TFP growth and contemporaneous evidence on factor shares. Section 7 concludes.

2 The agricultural revolution

Among historians there has been enduring disagreement over when and even whether any agricultural revolution occurred.[4] The classic account of the agricultural revolution is found in Prothero (1912) who dates the agricultural revolution 1760-1830, whilst Chambers and Mingay (1966) favour the longer period 1750-1880. In contrast, Kerridge (1967) argues that the agricultural revolution occurred 1560-1767, with most achieved prior to 1673. Jones (1981) argues that the agricultural revolution got underway during the commonwealth and restoration periods i.e. 1649-1688, whereas Thompson (1968) suggests that there have been two agricultural revolutions: the first occurring 1660-1750 and the second 1815-1880. More recently, Clark (1993) argues that there was in fact little or no change in the rate of TFP growth in agriculture 1700-1850.

Before proceeding any further, following Overton (1996a) it is crucial to note the absence of any shared understanding as to the meaning of the phrase 'agricultural revolution'. For some contributors this might refer to a period during which there was a historically unprecedented rate of TFP growth. For others it might refer to a period during which there was an unparalleled rate of growth in agricultural output. One could also argue that the phrase could

[4] This section draws heavily on Overton (1996a).

describe a period of rapid change in agricultural institutions e.g. the enclosure of open fields irrespective of any wider impact on TFP.

In what follows we view agriculture as having undergone a revolution only if there is rapid change in the production set.[5] Note that this definition neglects any agricultural revolution characterised by changes in the input mix brought about solely by changes in relative prices.

Below we review existing estimates of the historical rate of TFP growth, all of which have been obtained using the technique of growth accounting rather than econometric estimation.[6] Growth accounting involves totally differentiating either a Cobb-Douglas cost function or a Cobb-Douglas production function with respect to time. Beginning with the following cost function:

$$LnP_t = -TFP_t + \alpha_1 LnW_t + \alpha_2 LnR_t + \alpha_3 LnU_t \tag{1}$$

where P is prices, W is wages, R is rents and U is the user-cost of capital. Totally differentiating the cost function with respect to time and rearranging yields the rate of growth of TFP:

$$\frac{\Delta TFP_t}{TFP_t} = \alpha_1 \frac{\Delta W_t}{W_t} + \alpha_2 \frac{\Delta R_t}{R_t} + \alpha_3 \frac{\Delta U_t}{U_t} - \frac{\Delta P_t}{P_t} \tag{2}$$

The approach is analogous in the case of the production function and the weights α correspond to the respective shares of the factor inputs. The unobserved rate of TFP growth emerges as the 'Solow' residual.[7]

To many researchers it has seemed easier to infer the historical rate of TFP growth in agriculture using information on the prices rather than the quantities of inputs and outputs. The reason is that it is harder to obtain reliable information on the quantities of agricultural inputs and outputs. For example, any attempt to calculate the quantity of labour inputs must make assumptions about the number of full-time workers, part-time workers, family workers, seasonal workers and the relative contributions of men, women and children. For a discussion of the limitations of current estimates of agricultural output see Kelly and O'Grada (2013). By contrast, considerable information is available on the prices of agricultural outputs and to a lesser extent, the costs of agricultural inputs.

Despite these challenges, using the production function approach Crafts (1985) reports a number of estimates based on this approach whilst McCloskey (1981), Hueckel (1981), Allen (1992), Mokyr (1993) and Clark (2002a) all prefer the cost function approach. Their estimates are presented in Table 1. [8,9]

---

[5] This is of course equivalent to the statement that there was an agricultural revolution if the parameters of the profit-function including the rate of profit augmentation exhibit significant change over time, since these are derived from the production function.

[6] For an example of growth accounting in the context of the wider British industrial revolution see Antra and Voth (2003) whose preferred economy-wide estimates are 0.4 percent over the period 1770-1830.

[7] Crafts (2003) discusses the limitations of the growth accounting approach e.g. the assumption of constant returns to scale, the assumption of neutral technical progress and the assumption of a unitary elasticity of substitution between factors of production.

[8] Empirical evidence is available from farm records detailing changes over time in the quantities of agricultural produce per unit of land. Good examples of such estimates can be found in Bennett (1935) and more recently in

Table 1. Estimates of the rate of TFP growth in English agriculture

Author	Method	Period	Rate of TFP growth (%)	Input factor shares
Crafts (1985)	Production Function	1761-1800 1801-1831 1831-1861	0.2 0.9 1.0	Land 0.4, labour 0.4, and capital 0.2
McCloskey (1981)	Cost Function	1780-1860	0.45	Labour 0.75 and land 0.25
Hueckel (1981)	Cost Function	1790-1815 1816-1846 1847-1870	0.2 0.3 0.5	Labour 0.77 and land 0.23
Mokyr (1993) (a)	Cost Function	1797-1827 1797-1835 1805-1827 1805-1835	0.02-0.13 0.27-0.37 0.15-0.21 0.18-0.42	Labour 0.67-0.75 and land 0.33-0.25
Mokyr (1993) (b)	Cost Function	1790-1820 1820-1850	-0.39-0.32 0.36-0.98	
Allen (1992)	Cost Function	1600-1800	0.2	Capital 0.13, labour 0.27, land 0.40 and miscellaneous 0.20
Clark (2002a)	Cost Function	1525-1865 1765-1865	0.13 0.27	Labour 0.41, land 0.41 and capital 0.18

Source: See text. Note: Mokyr (a) uses the Williamson (1982) wage data and the Gayer et al. (1953) price data whilst Mokyr (b) uses the Bowley (1937) and Wood (1899) wage data and the Gayer et al. (1953) price data. The range of estimates provided by Mokyr in the penultimate column is the result of assuming that the input factor share of labour varies between 0.67 and 0.75. Allen (1992) refers only to the rate of TFP growth in the South Midlands.

These studies provide estimates of the rate of TFP growth over different periods. Some appear to suggest that the rate of TFP growth picked up e.g. Crafts (1985). The periods identified by these studies differ and critically, none provides a statistical test of the hypothesis that the rate of TFP growth was constant. Note too that over shorter periods unusual production conditions might obscure otherwise significant changes in TFP.[10]

Another limitation of these estimates relates to their dependency on extraneous estimates of input shares. It is clear from Table 1 that there are major differences between studies concerning what factor inputs are to be included, let alone their actual shares. The work of Mokyr (1993) illustrates the sensitivity of estimates of the TFP growth rate to changes in input shares. Notable for his especially careful derivation of factor input shares is Allen

Turner (1982). Bennett's data for example, point to an increase in output of wheat per acre from 11 bushels per acre in 1688 to 17 bushels per acre in 1760. Such estimates however provide only a partial account since they do not consider changes in other inputs e.g. whether the increase in bushels of wheat per acre is actually the result of an increase in labour inputs.

[9] In a similar exercise Mundlak (2005) provides estimates of the rate of TFP growth in US agriculture of 0.20 percent per annum for 1800-1840, 0.56 percent per annum for 1840-1880 and 0.15 percent for 1880-1900.

[10] For example, from 1745-1759 Britain experienced a foot and mouth epidemic during which a policy of slaughtering infected animals was implemented and severe restrictions placed on the movement of animals (Mullett, 1946).

(1992) whose estimates refer only to the South Midlands. His estimates of the relative shares of inputs come from reworking the farm accounts provided by Young (1771).

Care must be exercised in to avoid the mismeasurement of the rate of TFP growth. For example, in a study of US agriculture 1940-1960 Griliches (1963) demonstrates that incorrect factor shares, the omission of important inputs and changes in the quality of inputs show up as spurious growth in TFP.

Turning to the supposed causes of improvements in TFP during the agricultural revolution, most historians e.g. Overton (1996b) appear to include selective breeding, the introduction of new crops and cropping practices, enclosure, regional specialisation and the eventual mechanisation of agriculture. Regional specialisation is potentially of great importance to agriculture especially if as is the case in England there are significant geographical variations in conditions of agricultural production. But whether the gains from regional specialisation can be realised depends on the existence of transport infrastructure; see e.g. Kelly (1997) for a discussion of the role played by canals. Enclosure refers to the process whereby scattered pieces of open land were consolidated into larger plots and common rights held over land were extinguished. It is frequently argued that the mediaeval organisation of farmland into open fields required consensus for change to occur and stifled improvements. For a description of the manner in which the open field system operated and its shortcomings see Turner (1980). The agricultural revolution is also frequently presented as if it were the work of a handful of great agricultural pioneers. Thus, we are reminded that Jethro Tull invented the seed drill in 1701 and that the 'Norfolk rotation' of turnips-barley-clover-wheat associated with Thomas Coke avoided the need for a period of fallow. According to Overton (1986) however, the contribution of both of these individuals in particular has been overblown.

Several empirical studies seek to estimate the productivity gains brought about by particular innovations. McCloskey (1975) takes the observed increases in rent following enclosure as an indicator of the productivity benefits whilst Allen (1988) presents evidence on changes in the size distribution of farms and the resulting economies. Brunt (2004) tests the importance of particular cultivation techniques to 18th century agriculture and Allen (2008) examines the hypothesis that the use of nitrogen played a decisive role in the transformation of agriculture. Finally, Ang *et al.* (2013) analyse the extent to which improvements in labour productivity during the period 1620-1850 were driven by R&D as measured by the number of agricultural patents.

How does measured agricultural productivity in Britain compare with elsewhere? Van Zanden (1991) compares agricultural productivity across 16 different countries from 1870-1914 when for the first time agricultural census data became available. Van Zanden aggregates agricultural outputs using world prices, whilst simultaneously using information on the percentage of the male labour force employed in agriculture and the amount of agricultural land. Judging by either measures of labour or land productivity it appears that a core of countries bordering on the North Sea were the most productive: Denmark, Britain, the Netherlands, Belgium and France.

Over time however, things changed and from 1870-1910 productivity growth in Britain was only 0.19 percent compared to an average of 0.65 percent over all 16 countries. These estimates are based on the assumption of a Cobb-Douglas production function with shares of 0.35, 0.5 and 0.15 for labour, land and livestock respectively. Van Zanden attributes the

relatively superior performance of other Northern European countries to their greater use of chemical fertilisers and concentrated feeds, as well as to the use of technologies such as the centrifugal cream separator. He also describes the importance of state-sponsored extension services and credit and marketing cooperatives, things which were either wholly or entirely absent in Britain.

For an estimate of TFP growth rates in county Armagh in Ireland over the period 1765-1789 to 1820-1844 see Solar and Hens (2013). They find that over this long period of time the TFP growth rate was negative, with estimates ranging from -0.1 to -0.34 percent per annum.[11] The authors attribute this change to the fall in the size of agricultural holdings, itself possibly a consequence of the rapidly increasing population.

3 The modern theory of rent and different measures of the TFP growth rate

As a prelude to what follows, in this section we present the way that economic analysis formulates the Ricardian theory of rent.[12] Let Q represent the quantities of agricultural output obtainable from cultivating a unit area of land, L the amount of labour and K the quantity of capital employed. The variable T represents a time trend, F is the production set and π is profit. The variables P, W, R and U are as previously defined. The constrained maximisation problem of a tenant farmer operating under conditions of perfect certainty is represented by the following Lagrangian where λ is the lagrange multiplier:

$$Max\ \mathcal{L} = PQ - WL - UK + \lambda F(Q, L, K, T) \tag{3}$$

Solving for the optimal levels of L, K and the implied level of output Q results in the profit function given by:

$$\pi = \pi(P, W, U, T) \tag{4}$$

Assuming perfect competition among tenant farmers the surplus from agricultural production is however entirely absorbed by the rent paid to the landowner such that:

$$\pi(P, W, U, T) - R = 0 \tag{5}$$

The profit function is linear homogeneous and monotonically increasing in P, and monotonically decreasing in W and U.

Following Karagiannis and Mergos (2000), we now establish a link between the rate of profit augmentation (r^{π}) and output and input-based measures of TFP growth (r^{o} and r^{i} respectively). By definition:

$$\pi = TR - TC \tag{6}$$

[11] The finding of negative rates of TFP growth in agriculture is not actually unusual. In the vast collection of estimates contained in Federico (2005) for example for many Less Developed Countries post WWII there are estimates pointing to a negative rate of TFP growth.

[12] The Ricardian theory of rent has recently been much used to value the attributes of farmland e.g. Mendelsohn and Dinar (2003).

Where *TR* is total revenue and *TC* is total cost. Taking the derivative of profits with respect to time and dividing by profits yields the rate of profit augmentation:

$$\frac{\partial\pi/\partial T}{\pi} = \frac{\partial TR/\partial T - \partial TC/\partial T}{\pi} = r^{\pi} \tag{7}$$

Assuming that the time derivative of *TC* with respect to *T* is zero (i.e. adopting an output-based measure of the rate of TFP growth) yields:

$$r^{o} = \frac{\partial TR/\partial T}{TR} = \frac{\pi r^{\pi}}{TR} \tag{8}$$

Which using Hotelling's Lemma yields:

$$r^{o} = \frac{\pi r^{\pi}}{PQ} = \frac{\pi r^{\pi}}{P\partial\pi/\partial P} \tag{9}$$

Or more concisely:

$$r^{o} = \frac{r^{\pi}}{\varepsilon_{\pi P}} \tag{10}$$

where $\varepsilon_{\pi P}$ is the elasticity of profit with respect to price. Thus, the rate of profit augmentation is linked to the output-based rate of TFP growth by a simple expression involving the elasticity of profits with respect to the price of output. The derivation of the relationship between the rate of profit augmentation and the input-based rate of TFP growth, achieved by assuming that the time derivative of total revenue is equal to zero is, analogously, given by the expression:

$$r^{i} = -\frac{r^{\pi}}{\varepsilon_{\pi W} + \varepsilon_{\pi U}} \tag{11}$$

where $\varepsilon_{\pi W}$ is the elasticity of profits with respect to wages and $\varepsilon_{\pi U}$ is the elasticity of profits with respect to the user-cost of capital.

The output-based measure of TFP growth addresses the following question: how much more revenue can be obtained with unchanged production costs per acre as a consequence of technological progress? The input-based measure of TFP growth addresses the following question: by how much can production costs per acre be reduced as a consequence of technological progress whilst holding revenue constant? Which of these concepts is of relevance depends, of course, on the question but none of the earlier studies differentiated between the input and the output-based measures of the rate of TFP growth or the rate of profit augmentation.[13] They dealt exclusively with the output-based rate of TFP growth.

[13] It is also possible to obtain from the profit function a measure of the elasticity of output with respect to factor inputs. For example, the definition of the elasticity of output with respect to the labour input is:

$$\rho = \frac{\partial Q}{\partial L}\frac{L}{Q}$$

The transformation function is:

4 Data

Turner *et al*. (1997) provide data on historical agricultural rents for the period 1690-1914. More specifically, they present information on assessed and received rents from large estates or parts thereof.[14] Assessed rents represent the bargain struck between landowner and tenant whereas received rents is the amount actually collected. It is possible that the received rents include abatements as well as debts carried forward from previous years. It is important to understand that 'estates' here refers to the unit of ownership not the unit of production. These data refer only to England and, of critical importance for our purposes, is the fact that the authors claim to have carefully excluded those agreements in which the rent was set by custom and supported by a system of entry fines, or where the land was subject to service obligations or where the length of the lease was in terms of named lives. Such rental agreements, although historically not uncommon, obviously do not provide a good measure of the current profitability of agriculture whereas according to Turner *et al*. (1997) their data contain only 'economic' or 'rack' rents.[15,16,17]

In total there are 5,771 observations providing information on either received or assessed rents per acre pertaining to 77,134,487 acres over the entire 225 year period. There are 5,354 observations on received rents and 4,794 observations on assessed rents from 93 estates. The

---

$$F(Q, L, K, T) = 0$$

By the implicit function theorem:

$$\frac{\partial F}{\partial L} + \frac{\partial F}{\partial Q}\frac{\partial Q}{\partial L} = 0$$

which implies:

$$\rho = -\frac{\partial F/\partial L\, L}{\partial F/\partial Q\, Q}$$

Combining the first order conditions:

$$\frac{-W}{P} = \frac{\partial F/\partial L}{\partial F/\partial Q}$$

we finally obtain:

$$\rho = \frac{WL}{PQ} = -\frac{\partial \pi/\partial W\, W}{\partial \pi/\partial P\, P} = -\frac{\varepsilon_{\pi W}}{\varepsilon_{\pi P}}$$

where we have, in the last step, made use of Hotelling's Lemma.

[14] For example the Guys Hospital estate is divided into holdings in Lincolnshire, Herefordshire and Essex.

[15] The historical importance of agricultural land as a component of wealth as revealed by rents is discussed by McLaughlin et al. (2014).

[16] For a discussion of traditional types of tenancy see Clay (1985).

[17] Despite this the authors concede that it is possible that a component of the rent paid actually represents payments for capital investment in the land e.g. drainage and also for the use of agricultural buildings and equipment. Likewise it is possible that some rents include payments for the use of woodland. No information is available about burdens upon the land e.g. local rates and tithes. The data includes both enclosed and unenclosed land.

largest estate is the 290,000 acres under the control of the ecclesiastical commissioners whereas the smallest a mere 767 acres. Some estates include land crossing county boundaries and in some cases scattered across many different counties. The amount of land attributed to particular estates fluctuates because of acquisitions and disposals. Out of the 43 counties of England 34 are explicitly covered.

Apart from Turner *et al*. (1997) other rental price indices are available especially Clark (2002b) whose index is based on land held by charities. But this index includes land which was not let for an economic rent which is something that the preceding section makes clear is fundamental to our analysis. It is for this reason that we use the rental price index based on Turner *et al*. (1997). For a discussion on the strengths and weaknesses of the Turner *et al*. data see Clark (1998) and Turner *et al.* (1998).

Following the recommendation of Turner *et al*. (1997) in what follows we analyse rents received rather than rents assessed. Not only are rents received much more likely to measure the profitability of agriculture, as noted above more information is available on rents received rather than rents assessed (there are in fact several years for which no observations are available for assessed rent). Turner *et al*. (1997) refer to rents received as the 'best and most sensitive indicator [available]'.

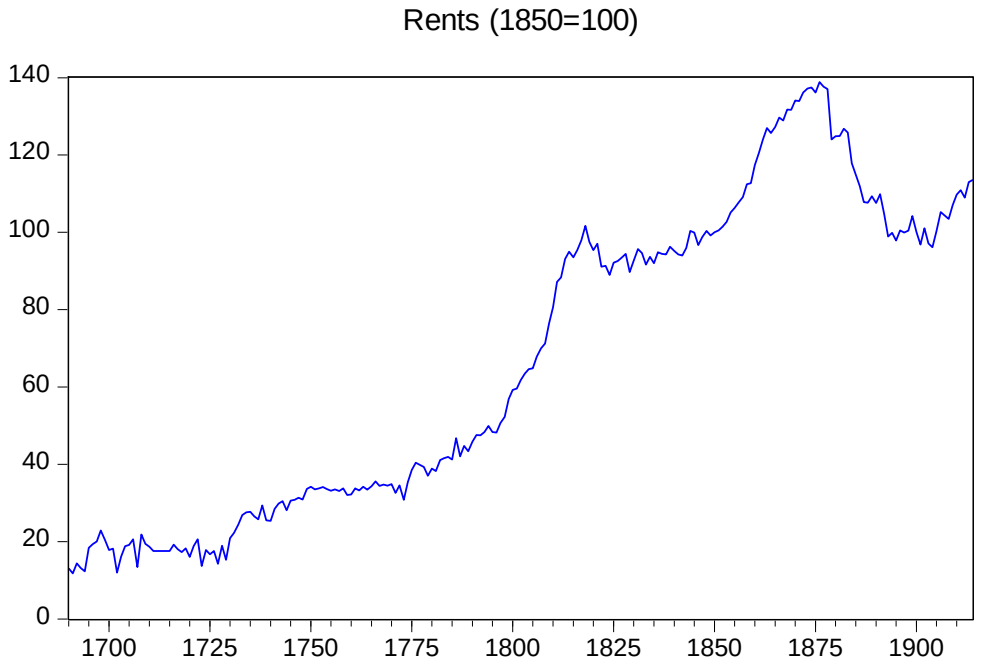
Using information on rents received, in contrast to Turner *et al*. (1997) we create a hedonic price index for rent using the following hedonic price equation:

$$LnR = \sum_{i=1}^{i=93} \alpha_i ESTATE_i + \sum_{t=1690}^{t=1849} \beta_t YEAR_t + \sum_{t=1851}^{t=1914} \beta_t YEAR_t + \varepsilon \tag{12}$$

Where *R* continues to refer to the rents received per acre, *ESTATE* is a dummy variable which takes the value unity if the observation refers to estate *i* and *YEAR* is a dummy variable which takes the value unity if the observation refers to year *t*. The exponents of the β coefficients are used to create the hedonic price index which is presented in such a way that it takes the value 100 in the year 1850. The parameters of the estimated hedonic rent equation (not shown) reveal considerable heterogeneity across the different estates i.e. the α parameters differ greatly. It is the need to control for this heterogeneity which leads us to prefer the hedonic price index to the area-weighted index in Turner *et al*. (1997).

The resulting hedonic price index is displayed in Figure 1. This figure illustrates well the devastating effect on agricultural rents of the European grain invasion from 1870 onwards when low-cost imports from the New World reduced the price of corn see e.g. O'Rourke (1997).

The methods that we use to produce a hedonic rental index are not dissimilar to those employed by Solar and Hens (2013). In fact, even though they deal with a shorter time period and only one Irish county they possess a similar number of observations (almost 5,000) although these refer to agricultural holdings rather than estates. They also possess information on the identity of the estate as well as the plot size and the length of the lease.



Turning to prices, Clark (2004) provides an annual price series for 26 agricultural commodities in England from 1209-1914. These are obtained by splicing together numerous existing price indices and adding new information. His overall price index is formed using 'net' rather than 'gross' output shares and therefore attaches correspondingly less weight to the price of agricultural outputs that are themselves consumed as part of agricultural production activities e.g. oats for horses. Clark also presents three sub-indices for arable, pastoral and wood products. The single most important item is wheat which attracts a share of 53 percent of the arable price index at the start of the data period, falling to 22 percent by the end of the data period. Overall, the arable index comprises 60 percent of the overall price index at the start of the data period falling to 32 percent by the end of the data period, with the importance of pastoral products rising from 30 percent to 68 percent over the same time period.

Clark (2007) also provides a documented history of agricultural wage rates in England from 1209-1869. After 1869 wage rates are taken from Fox (1903) and from 1902-1914 agricultural wage rates are taken from Bowley (1937). These are spliced together to form a single series for wages.

We include in our profit function the opportunity cost of agricultural inventories, *I*. The cost of agricultural inventories is calculated by multiplying the price of agricultural output described above by the rate of interest plus a risk premium. The rate of interest is the rate of return on consols which is taken from Mitchell and Deane (1962). This series goes back only as far as 1756, but we have extended it using the results of Clark (1988) who notes that, in the period when they overlap, the return on consols matched the return on perpetual rent charges. Young (1771) refers to interest of 4 percent on the stock of animals which compares with the contemporaneous rate of return on consols of 3.5 percent reported by Mitchell and Deane (1962). We therefore infer a risk premium of 0.5 percent although this risk premium would probably have fluctuated substantially over time. For evidence on variations in risk premiums over time albeit in another context see Arnott and Bernstein (2002).

To obtain a proxy for the user-cost of man-made capital, *M* in the form of equipment we concatenate various historical price series for manufactured iron. The series from Clark (2006) for the period 1690-1869 is extended using Sauerbeck (1886 and various years thereafter). The resulting series is then multiplied by the rate of return on consols plus a 0.5 percent risk premium and an assumed ten percent rate of depreciation.

Turning finally to taxes and tithes, using information from the Royal Commission on Agriculture (1897) Turner *et al*. (1997) suggest that, on the basis of the sample of farms considered by the Commission, rents should be increased by 12.5 per cent to reflect better the profits from agriculture. However, in what follows only changes in the rate of taxation would affect the calculations. We assume no change in the rate of taxes and tithes. Summary statistics of the data are displayed in Table 2.

Table 2. Data

Variables	Mean	Std. Dev.	Min.	Max.
R_t (1850=100)	66.983	40.048	11.766	138.845
P_t (1850=100)	78.150	24.035	44.300	152.400
I_t	3.346	1.256	1.597	8.534
W_t (d/day)	17.817	7.237	9.19	33.788
M_t	0.490	0.179	0.201	1.308

Source: See text.

5 Regression analysis

Prior to analysing the data it is necessary to select a functional form for the profit function. Primarily because of the age of the data, but also the ease with which its parameters can be interpreted, we employ the Cobb-Douglas profit function.[18] The Cobb-Douglas profit function is given by:

$$LnR_t = \alpha + \beta T_t + \gamma_1 LnP_t + \gamma_2 LnW_t + \gamma_3 LnI_t + \gamma_4 LnM_t \tag{13}$$

In this equation we have used *R* to substitute for π. Note carefully that the parameter β represents the rate of profit augmentation not TFP growth. Note also that increasing the rent by a constant factor to represent taxation would alter only the constant α rather than any of the parameters of interest. The restrictions associated with linear homogeneity are:

$$\gamma_1 + \gamma_2 + \gamma_3 + \gamma_4 = 1 \tag{14}$$

The elasticity of profits with respect to prices is given by γ_1 and the elasticity of profits with respect to wages, the cost of inventories and the cost of man-made capital by γ_2, γ_3 and γ_4 respectively. In order that the profit function is convex with respect to prices it is required that $\gamma_1 \geq 1$.

[18] Cropper *et al*. (1988) find that flexible functional forms perform best when all variables are included in hedonic models but simpler functional forms such as the log-log model perform best in the presence of omitted variables. Given the age of the data we are using we regard this as grounds for using the Cobb-Douglas functional form.

We now examine the time-series properties of the variables included in the model using the Augmented Dickey Fuller (ADF) test. The results of this test are displayed in Table 3. These indicate that all variables are I(1) irrespective of the inclusion of a time trend. We also used a test for stationarity in which the null hypothesis is stationarity rather than non-stationarity. These tests (results not shown) uniformly indicate that the hypothesis of stationarity can be rejected when the data is in levels. Our conclusion that the data are all non-stationary is also unaffected by allowing for the possibility of a break in either the intercept or the time trend (results not shown).[19]

Table 3. ADF tests of stationarity

	No Trend	**Trend**
$Ln(R_t)$	-1.895	-1.643
$\Delta Ln(R_t)$	-3.713***	-3.852**
$Ln(P_t)$	-1.780	-1.929
$\Delta Ln(P_t)$	-12.474***	-12.471***
$Ln(I_t)$	-1.673	-1.801
$\Delta Ln(I_t)$	-10.591***	-10.492***
$Ln(W_t)$	0.296	-3.236*
$\Delta Ln(W_t)$	-9.430***	-9.471***
$Ln(M_t)$	-1.294	-2.314
$\Delta Ln(M_t)$	-10.849***	-10.825***

Source: Authors' calculations. Note: * means significant at the 10 percent level of confidence ** means significant at the 5 percent level of confidence and *** means significant at the 1 percent level of confidence. The optimal lag length is determined according to the Akaike criterion.

Irrespective of the imposition of linear homogeneity, the τ and the z variants of the Engle-Granger test statistics are statistically significant at the one percent level of confidence enabling us unambiguously to reject the null hypothesis of no cointegration. Given the non-stationary nature of the data we estimate the parameters of the profit function using the Dynamic Ordinary Least Squares (DOLS) technique of Saikkonen (1991).[20] The reason is that this estimation technique supports a direct test of parameter constancy appropriate for nonstationary data (see below). Later, we re-estimate the model using a quite different estimation technique to provide a cross-check.

The results are displayed in Table 4. In Model 1 we do not impose linear homogeneity whereas in Model 2 this is imposed. Both models are then assessed using the Hansen L_c test appropriate for use in regressions with I(1) parameters (Hansen, 1992). The Hansen L_c test allows the parameters of the model potentially to follow a Martingale process. As argued by Hansen, as a test of parameter stability this is appropriate when as here there is no prior information about the date at which any change in the regression parameters might have occurred and no reason to suppose that changes occurred anything other than gradually.[21]

[19] For a recent demonstration of the importance of allowing for the presence of structural breaks in stationarity testing using spot prices for crude oil and petroleum products see Sun and Shi (2015).

[20] According to the Monte Carlo analysis of Kao and Chiang (2000) the DOLS technique outperforms the alternative Fully Modified Ordinary Least Squares technique in terms of its finite sample properties.

[21] It is perhaps worthwhile here explaining Hansen's L_c test for parameter stability given that it plays an important role in our claim that there was no agricultural revolution. Compared to the time series linear regression with i = 1…k stochastic regressors and deterministic regressors:

Table 4. Estimates of the profit function
Dependent Variable = $Ln(R_t)$
No. Obs. = 225
Method = DOLS

	Model 1	Model 2
$Ln(P_t)$	3.242	3.184
	(10.196)	(14.313)
$Ln(W_t)$	-0.421	-0.681
	(-1.338)	(-5.325)
$Ln(I_t)$	-1.409	-1.263
	(-6.266)	(-8.594)
$Ln(M_t)$	-0.146	-0.238
	(-1.052)	(-2.117)
TREND	0.003	0.004
	(1.622)	(4.944)
CONSTANT	-8.490	-8.065
	(-8.716)	(-13.937)
Engle-Granger τ-statistic	-6.287***	-6.358***
Engle-Granger z-statistic	-68.437***	-69.717***
Hansen L_C statistic	0.013	0.012
Test of linear homogeneity	$\chi^2(1)=0.874$	Imposed

Source: Authors' calculations. Note: figures in parentheses are t-statistics. * means significant at the 10 percent level of confidence and ** means significant at the 5 percent level of confidence and *** means significant at the 1 percent level of confidence. T-statistics are heteroscedasticity and autocorrelation consistent (Bartlett kernel and Newey-West fixed bandwidth = 5 and without pre-whitening). The number of leads and lags is determined according to the Akaike criterion.

In all cases the coefficients are signed as expected such that an increase in prices increases profits whereas an increase in wages, the cost of agricultural inventories or the user-cost of man-made capital, reduces profits. The elasticity of profit with respect to the price of output moreover exceeds unity which conforms to theoretical expectations. Furthermore the null hypothesis of linear homogeneity cannot be rejected, even at the ten percent level of confidence. Turning to the Hansen L_c test statistic, we observe that it is in both models statistically insignificant even at the ten percent level of confidence. The estimated rate of profit augmentation appears to be 0.4 percent.

$$Y_t = \beta_1 X_{1t} + \beta_2 X_{2t} + \cdots + \beta_k X_{kt} + \varepsilon_t$$

The Hansen L_c test for parameter stability allows the β coefficients to be time-varying such that:

$$\beta_{it+1} = \beta_{it} + \eta_{it}$$

Where it is assumed that:

$$\eta_{it} \sim N(0,\ \sigma_i^2)$$

The null hypotheses is $\sigma_i^2 = 0$ for all i and the alternative hypothesis is $\sigma_i^2 = 0$ for at least one i. Because it is a portmanteau test its statistical significance does not indicate which coefficients are time-varying. Note also that the test statistic can also be considered as a further test of cointegration since if the constant term follows an I(1) process then the equation cannot cointegrate.

As mentioned above we also estimate the parameters by means of an alternative approach to DOLS, albeit one that does not provide a direct test of parameter constancy. Using the Johansen (1988) methodology the cointegrating vector of the model where linear homogeneity is imposed is:

$$\left[(Ln(R_t) - Ln(W_t)) - 3.260(Ln(P_t) - Ln(W_t)) + 1.192(Ln(I_t) - Ln(W_t)) + 0.436(Ln(M_t) - Ln(W_t)) - 0.003TREND + 8.415\right]$$

The trace test and maximum eigenvalue test both reject the null hypothesis of no cointegration vector at the one percent level of confidence when the appropriate lag length is selected according to the Akaike criterion. All the explanatory variables in the cointegrating vector are moreover statistically significant at the one percent level of confidence and are remarkably similar to those in Model 2 obtained through DOLS.

Over the period 1690-1914 there obviously occurred a multitude of events from Jethro Tull's invention of the seed drill in 1701 and Joseph Foljambe's invention of the Rotherham plough in 1730 though to the first use of refrigerated shipping to transport frozen meat carcasses from New Zealand to the United Kingdom on the Dunedin in 1882. The very fact that there are so many events justifies our use of a test of structural stability appropriate when (a) there is no prior information about the date of any structural change and (b) any structural change occurred gradually.

Nevertheless, we also investigated whether the rate of profit augmentation changed during or around the time of three events: the peak year for open field arable enclosure (1801) when 86 parliamentary acts were passed, the period of the Corn Laws (1815-1846) and the grain invasion (1870). More on each of these topics can be found in Turner (1980), Barnes (1965) and O'Rourke (1997) respectively. We also allowed for the possibility that the rate of profit augmentation increased between 1760-1830, 1750-1990, 1560-1767, 1560-1767, 1660-1750 and 1815-1880. These dates refer respectively to the views of Prothero, Chambers and Mingay, Kerridge, and Thompson (who believed that there were two agricultural revolutions). None of these models however proved satisfactory, either because: (a) the coefficient on the additional time trend was not statistically significant, (b) the coefficient on the price of output was significantly less than unity, (c) the coefficient on the price of at least one input was significantly greater than zero or (d) the resulting profit function was not linear homogeneous.[22]

Estimates of the output and input-based rates of TFP growth as well as implied factor shares are presented in Table 5. These estimates are taken from Model 2 in which linear homogeneity has been imposed. Referring to the contents of Table 5, it appears that the output-based rate of TFP growth is a mere 0.1 percent, whereas the input-based rate of TFP growth is only 0.2 percent. Comparing our estimates for the rate of output-based TFP growth with those contained in Table 1 we see that our estimates are on the whole much lower, although not dissimilar to those presented by Clark (2002a).

[22] In those cases where linear homogeneity was acceptable this restriction was imposed and the equation was re-estimated. But in only one case did the variable representing the change in the rate of profit augmentation turn out to be statistically significant, and in that case the coefficient on the user-cost of capital was positive and statistically significant.

Table 5. Estimates of the output and input-based TFP growth rates and factor shares

Output-based TFP percentage growth rate	0.150
	(5.106)
Input-based TFP percentage growth rate	0.219
	(4.973)
Share of labour	0.214
	(7.554)
Share of agricultural inventories	0.396
	(14.473)
Share of man-made capital	0.074
	(2.064)
Share of land	0.314
	(14.313)

Source: Authors' calculations. Note: t-statistics are in parentheses. T-statistics are derived using the Delta method.

Overall, it is hard on the basis of these results to subscribe to the view that there was an agricultural revolution during 1690-1914. It seems more appropriate to say that agriculture exhibited steady progress than revolutionary change.

6 Discussion

Having found little evidence supporting the existence of an agricultural revolution, this section compares historical estimates of the rate of output-based TFP with present-day ones. We also gauge the plausibility of our estimates by comparing the implied factor shares with those derived from 'synthetic' farm accounts. We begin however, by assessing the robustness of our results to an alternative specification of the profit function, one including additional inputs.

Phillips (1989) notes that historically a significant quantity of agricultural land in England was subject to waterlogging and this both limited its use and increased the cost of cultivation. He presents evidence suggesting that from 1845-1899 some 4.5 million acres of land was under-drained. He also reports that in 1855 alone 2,800 brickyards made 420 million drainpipes. According to some e.g. Thompson (1968) the under-draining of farmland was responsible for a second agricultural revolution.

To investigate the importance of the under-draining we concatenate historical price series for bricks (as a proxy for the cost of tiles and then drainpipes which supplanted the use of stones in drainage activities). These data are from Clark (2006) for the period 1690-1867 and then extended forward using Maiwald (1954). The resulting series is then multiplied by the rate of return on consols plus an assumed 0.5 percent risk premium and a 10 percent rate of depreciation to obtain the user-costs. Note that this index also accounts for the user cost of brick buildings.

We denote the user-cost of drainage by *B*. This variable is included along with the other variables in Model 3 and Model 4 (where linear homogeneity is imposed), both of which are estimated using DOLS. The coefficients on $Ln(B_t)$ are unexpectedly signed but statistically

insignificant even at the 10 percent level of confidence. The remaining parameter estimates are little affected by the inclusion of this new variable.

It is possible that the user-costs of drainage and brick buildings are statistically insignificant because our measure provides a poor approximation of the 'true' user-cost. For example, the cylindrical drainpipe was anyway only invented in 1843 prior to which tiles and stones were the preferred materials. Furthermore, the cost of drainage systems was from 1847-1884 subsidised through low-cost loans from the Public Money Drainage Acts. But although loans provided by the Public Money Drainage Acts were at 3.5 percent this however still exceeds the average rate of return on consols which was 3.2 percent over 1847-1884 and the amounts of money that could be borrowed were quite limited. So it may be that for much of the period 1690-1914 the user-cost of drainage (and that of buildings) was simply irrelevant.

Table 6. Estimates of the profit function
Dependent Variable = $Ln(R_t)$
No. Obs. = 225
Method = DOLS

	Model 3	Model 4
$Ln(P_t)$	4.999	4.017
	(15.514)	(10.0771)
$Ln(W_t)$	-0.598	-0.935
	(-1.842)	(3.679)
$Ln(I_t)$	-2.045	-1.566
	(-13.404)	(-7.589)
$Ln(M_t)$	-0.934	-0.728
	(-4.649)	(-3.419)
$Ln(B_t)$	0.232	0.213
	(1.135)	(0.782)
TREND	-0.005	0.000
	(-3.141)	(0.298)
CONSTANT	-13.074	-10.109
	(-17.132)	(11.567)
Engle-Granger τ-statistic	-6.277***	-6.343***
Engle-Granger z-statistic	-68.300***	-69.487***
Hansen L_C statistic	0.048	0.026
Test of linear homogeneity	$\chi^2(1)$=8.536***	Imposed

Source: Authors' calculations. Note: figures in parentheses are t-statistics. * means significant at the 10 percent level of confidence and ** means significant at the 5 percent level of confidence and *** means significant at the 1 percent level of confidence. T-statistics are heteroscedasticity and autocorrelation consistent (Bartlett kernel and Newey-West fixed bandwidth = 5 and without pre-whitening). The number of leads and lags is determined according to the Akaike criterion.

We now turn to the issue of whether the factor shares in Table 4 are plausible starting with man-made capital. Why this factor share is so small can be better understood by considering: (a) when now-familiar items of agricultural equipment began to be more widely adopted and (b) when steam power began to supplant muscle power.

Walton (1993) presents evidence on the rates of adoption of various items of agricultural machinery in Oxfordshire. For the 12 items of machinery considered he uncovers low rates of

adoption, even in the second half of the 19th century. Mitchell and Deane (1962) moreover provide evidence that the number of horses used solely in agriculture did not begin to decline until after the start of the 20th century. Starting with 1.267 million in 1870 the number of horses had increased to a maximum of 1.572 million in 1905 and in 1914 still stood at 1.296 million. The use of steam power either for the purposes of haulage or as a mobile source of power started when Ransomes of Ipswich produced the first traction engine in 1841 and began commercial production a year later. Thus over the period 1690-1914 an enduringly small share of man-made capital seems not entirely implausible although our neglect of changes in the quality of capital goods should certainly be borne in mind.

Another way of verifying the extent to which man-made capital and indeed any other factor input formed a significant component of production costs is to examine contemporaneous farm accounts. Unfortunately such accounts tend to fall well short of modern-day accounting standards. Because of this and the limited extent to which the accounts of any individual farm are representative of the national picture Bowden (1990) writes: '…imperfections of the data mean that we cannot rely upon individual case histories… The development of notional farm accounts offers, based on piecemeal data, drawn from a variety of contemporary sources, one way of circumventing these difficulties.' Developing what he refers to as 'synthetic' accounts Bowden argues that for a 100 acre arable farm over the period 1700-1750 the user-cost of man-made capital in the form of equipment accounted for only 1 percent of the overall costs whereas for a cattle farm over the period 1730-1750 the user-costs of man-made capital accounted for only 2 percent of overall costs for a farm of the same size. These and other factor shares are displayed in Table 6.

Table 7. Estimated factor shares compared with those from Bowden

	This paper	Bowden	
Factor	95 percent CI	Arable farm 1700-1750	Cattle farm 1730-1750
Land	0.272-0.355	0.314	0.570
Labour	0.159-0.268	0.266	0.199
Man-made Capital	0.005-0.142	0.013	0.020
Other / Agric. Inventories	0.343-0.448	0.407	0.211

Source: Bowden (1990) and the authors' own calculations.

We would expect our factor shares to lie between those for an arable farm and those for a cattle farm since many farms would have been combinations of the two. The 95 percent confidence intervals (CI) for the factor shares derived from Model 2 are displayed in column 2. These overlap the range of Bowden's estimates displayed in columns 3 and 4 corresponding to the shares for arable and cattle farms. Also interesting is that the agriculturalist Marshall (1804) noted that according to prevailing opinion the produce of the farm should be equal to three 'rents': one for the landlord, one for the tenant for the expense of cultivation (i.e. labour) and another to the tenant as recompense for the capital employed. Our factor shares are not wholly dissimilar to Marshall's rule of thumb.

As mentioned in the introduction, modern analyses of the rate of TFP growth in agriculture have better information and can consequently make use of more advanced index-number techniques. Despite this mismatch in terms of data quality, our final task will be to compare our historical estimates with modern-day equivalents. Thirtle *et al*. (2004) contains a UK-based survey of post WW2 estimates of the rate of TFP growth, all of which lie in the range

1.0-2.0 percent.[23] Thus the rates of TFP growth during the period 1690-1914 are, by modern standards, anaemic. This is another reason not to refer to the period 1690-1914 as a period of agricultural revolution: it is an epithet best reserved for the post WW2 period. Hence we agree with O'Brien (1977) when he argues: '…terms like agrarian revolution are singularly inapposite descriptions of the pace and character of agrarian change before the advent of chemical fertilisers, electricity and the internal combustion engine.'

7 Conclusions

In this paper we construct a rental series representing the profitability of agriculture 1690-1914. Adopting a profit function approach, we detect a cointegrating relationship between this series, prices, wages and the cost of inventories and the user-cost of man-made capital. There is no evidence to suggest that this relationship is unstable. Distinguishing between different definitions of TFP, we find a statistically significant rate of profit augmentation of 0.4 percent. We also find an output-based rate of TFP growth of 0.1 percent and an input-based rate of TFP growth of 0.2 percent. We further find evidence of factor shares similar to those suggested by properly-construed contemporaneous accounts.

Our findings make it difficult to support the idea that there was, at least in terms of rapid changes to the production set, any agricultural revolution in the period 1690-1914. The confidence intervals for the output-based rate of TFP growth moreover preclude rates of growth similar to those seen today. Such changes as occurred 1690-1914 are far better described as steady progress and that the rate of output-based TFP growth is so much lower than estimates obtained using post-WW2 data further suggests that if the term agricultural revolution has to be used, it is best reserved for events occurring in the past 70 years. Future research should probably be directed towards obtaining estimates of the user-costs of man-made capital which incorporate changes in the quality of such goods.

Supplementary material

Supplementary material is available on the OUP website. This comprises data and replication files. Raw data on agricultural rents is available from: Turner, M., Beckett, J., Afton, B. (1997). *Agricultural Rent in England, 1690-1914*. [data collection]. UK Data Service. SN: 3691, http://doi.org/10.5255/UKDA-SN-3691-1.

Acknowledgements

The authors would like to thank the editor and two anonymous referees. Any remaining errors or omissions are the sole responsibility of the authors.

Bibliography

[23] Estimates for other countries for various periods 1800-2000 are contained in Federico (2005). Of particular note is that estimates from OECD countries for the post WWII period are generally larger than estimates from earlier time periods. Also of interest is the fact that there is a great variation in estimates covering the same country and same time-period. There are also a large number of developing countries for whom TFP growth is negative.

Allen, R. (1988) The Growth of Labour Productivity in Early Modern English Agriculture. *Explorations in Economic History* 25: 117-146.

Allen, R. (1992) *Enclosure and the Yeoman: The Agricultural Development of the South Midlands*. Clarendon Press: Oxford.

Allen, R. (2008) The Nitrogen Hypothesis and the English Agricultural Revolution: A Biological Analysis. *Journal of Economic History* 68:182-210.

Ang, J. Banerjee, R. and Madsen, J. (2013) Innovation and Productivity Advances in British Agriculture: 1620-1850. *Southern Economic Journal* 80: 162-186.

Antra, P. and Voth, H.-J. (2003) Factor Prices and Productivity Growth during the British Industrial Revolution. *Explorations in Economic History* 40: 52-77.

Arnott, R. and Bernstein, P. (2002) What Risk Premium is 'Normal'? *Financial Analysts Journal* 58: 64-85.

Ball, E. (1985) Output, Input and Productivity Measurement in U.S. Agriculture, 1948-79. *American Journal of Agricultural Economics* 67: 475-486.

Barnes, D. (1965). *A History of the English Corn Laws, from 1660-1846*. A.M. Kelly: University of Michigan.

Bennett, M. (1935) British Wheat Yields Per Acre for Seven Centuries. *Economic History* 3: 12-29.

Bowden, P. (1990) *Economic Change: Wages Profits and Rents 1500-1750.* Cambridge University Press: Cambridge.

Bowley, A. (1937) *Wages and Income in the United Kingdom since 1860*. Cambridge University Press: Cambridge.

Broadberry, S., Campbell, B. M. S., Klein, A., Overton, M. and van Leeuwen, B. (2015) *British Economic Growth, 1270-1870*. Cambridge University Press: Cambridge.

Brunt, L. (2004) Nature or Nurture? Explaining Wheat Yields in the Industrial Revolution Circa 1770. *The Journal of Economic History* 64: 193-225.

Chambers, J. and Mingay, G. (1966) *The Agricultural Revolution 1750-1880*. B. T. Batsford Ltd: London.

Clark, G. (1988) The Cost of Capital and the Medieval Agricultural Technique. *Explorations in Economic History* 25: 265-294.

Clark, G. (1993) Agriculture and the Industrial Revolution 1700-1850. In Mokyr, J. (ed.) (1993) *The Industrial Revolution: An Economic Perspective*. Westview Press: Boulder, Colorado.

Clark, G. (1998) Renting the Revolution. *Journal of Economic History* 58: 206-210.

Clark, G. (2002a) *The Agricultural and the Industrial Revolution: England, 1500-1912*. Mimeo. University of California, Davis CA.

Clark, G. (2002b) Land Rental Values and the Agrarian Economy: England and Wales, 1500-1914. *European Review of Economic History* 6: 281-308.

Clark, G. (2004) The Price History of English Agriculture, 1209-1914. *Research in Economic History* 22: 41-123.

Clark, G. (2006). Data available from: http://gpih.ucdavis.edu/.

Clark, G. (2007) The Long March of History: Farm Wages, Population, and Economic Growth, England 1209-1869. *Economic History Review* 60: 97-135.

Clay, C. (1985) Landlords and Estate Management in England. In Thirsk, J. (ed.) *The Agrarian History of England and Wales*. Cambridge University Press: Cambridge.

Crafts, N. (1985) *British Economic Growth during the Industrial Revolution*. Clarendon Press: Oxford.

Crafts, N. (2003) *Quantifying the Contribution of Technical Change to Economic Growth in Different Eras: A Review of the Evidence*. LSE Working Paper No. 79/03.

Cropper, M., Deck, L. and McConnell, K (1988) On the Choice of Functional Form for Hedonic Price Functions. *Review of Economics and Statistics* 70: 668-675.

Dixit, A. (1973) Models of Dual Economies. In Mirrlees, J. and Stern, N. (eds) *Models of Economic Growth*. John Wiley and Sons: New York.

Federico, G. (2005) *Feeding the World: An Economic History of Agriculture, 1800-2000*. Princeton University Press: Princeton.

Fox, A.W. (1903) Agricultural Wages in England and Wales during the Last Fifty Years. *Journal of the Royal Statistical Society* 66: 273-359.

Gayer, A., Rostow, W. and Schwartz, A. (1953) *The Growth and Fluctuation of the British Economy, 1790-1850*. Oxford: Clarendon Press.

Greasley, D. and Oxley, L. (2010) Cliometrics and Time Series Econometrics: Some Theory and Applications. *Journal of Economic Surveys* 24: 970-1042.

Griliches, Z. (1963) The Sources of Measured Productivity Growth: United States Agriculture, 1940-60. *Journal of Political Economy* 71: 331-346.

Hansen, B.E. (1992) Tests for Parameter Instability in Regressions with 1(1) Processes. *Journal of Business & Economic Statistics* 10: 321-335.

Hueckel, G. (1981) Agriculture during Industrialisation. In Floud, R. and McCloskey, D. (eds) *Economic History of Britain Volume 1: 1700-1860*. Cambridge University Press: Cambridge.

Johansen, S. (1988) Statistical analysis of cointegration vectors. *Journal of Economic Dynamics and Control* 12: 231-254

Jones, E. (1981) Agriculture 1700-80. In Floud, R. and Johnson, P. *The Cambridge Economic History of Modern Britain*. *Volume 1: Industrialisation, 1700-1860*. Cambridge University Press: Cambridge.

Kao, C. and Chiang, M. (2000) On the Estimation and Inference of a Cointegrated Regression in Panel Data. In Baltagi, B. (ed.) *Advances in Econometrics Volume 15: Nonstationary Panels, Panel Cointegration and Dynamic Panels*. Elsevier: Amsterdam.

Karagiannis, G. and Mergos, G. (2000) Total Factor Productivity Growth and Technical Change in a Profit Function Framework. *Journal of Productivity Analysis* 14: 31-51.

Kelly, M. (1997). The Dynamics of Smithian Growth. *The Quarterly Journal of Economics* 112: 939-945.

Kelly, M. and O'Grada, C. (2013) Numerare Est Errare: Agricultural Output and Food Supply in England Before and During the Industrial Revolution. *Journal of Economic History* 73: 1132-1163.

Kerridge, E. (1967) *The Agricultural Revolution*. Routledge: London.

McCloskey, D. (1975) The Economics of Enclosure: A Market Analysis. In *European Peasants and their Markets. Essays in Agrarian Economic History*. Parker, W. and Jones, E. (eds.) Princeton University Press: New Jersey.

McCloskey, D. (1981) The Industrial Revolution 1780-1860. In Floud, R. and Johnson, P. *The Cambridge Economic History of Modern Britain*. *Volume 1: Industrialisation, 1700-1860*. Cambridge University Press: Cambridge.

McLaughlin, E., Hanley, N., Greasley, D. Kunnas, J., Oxley, L. and Warde, P. (2014). Historical wealth accounts for Britain: progress and puzzles in measuring the sustainability of economic growth. *Oxford Review of Economic Policy* 30: 44-69.

Maiwald, K. (1954) An Index of Building Costs in the United Kingdom 1845-1938. *Economic History Review*. VII: 187-203.

Marshall, M. (1804) *On the Landed Property of England*. G. and W. Nicol: London.

Mendelsohn, R. and Dinar, A. (2003) Climate, Water and Agriculture. *Land Economics* 79: 328-341.

Mitchell, B. and Deane, P. (1962) *Abstract of British Historical Statistics* Cambridge University Press: Cambridge.

Mokyr, J. (ed) (1993) *The Industrial Revolution: An Economic Perspective*. Westview Press: Boulder, Colorado.

Mullett, C. (1946) The Cattle Distemper in Mid-Eighteenth Century England. *Agricultural History* XX: 144-65.

Mundlak, Y. (2005) Economic Growth: Lessons from Two Centuries of American Agriculture. *Journal of Economic Literature* 43: 989-1024.

O'Brien, P. (1977) Agriculture and the Industrial Revolution. *Economic History Review* 30: 166-181.

O'Rourke, K. (1997) The European Grain Invasion. *Journal of Economic History* 57: 775-802.

Overton, M. (1986) *Agricultural Revolution in England*. Cambridge University Press: Cambridge.

Overton, M. (1996a) Re-Establishing the English Agricultural Revolution. *The Agricultural History Review* 44: 1-20.

Overton, M. (1996b) *Agricultural Revolution in England. The Transformation of the Agrarian Economy 1500-1850*. Cambridge Studies in Historical Geography.

Phillips, A. (1989) *The Underdraining of Farmland in England in the Nineteenth Century*. Cambridge Studies in Historical Geography, Cambridge University Press: Cambridge.

Prothero, R. (1912) *English Farming Past and Present*. Longmans, Green and Co: London.

Saikkonen, P. (1991) Asymptotically Efficient Estimation of Cointegrating Regressions. *Econometric Theory* 7: 1-21.

Sauerbeck, A. (1886) Prices of Commodities and the Precious Metals. *Journal of the Statistical Society* XLIX: 592-648.

Solar, P. and Hens, L. (2013) Land Under Pressure: The Value of Irish Land in a Period of Rapid Population Growth 1730-1844. *Agricultural History Review* 61: 40-62.

Sun, J. and Shi, W. (2015). Breaks Trends and Unit Roots in Spot Prices for Crude Oil and Petroleum Products. *Energy Economics* 50: 169-177.

Thompson, F. (1968) The Second Agricultural Revolution: 1815-1880. *Economic History Review* 21: 62-77.

Thirtle, C., Lin, L., Holding, J., Jenkins, L. and Piesse, J. (2004) Explaining the decline in UK Agricultural Productivity Growth. *Journal of Agricultural Economics* 55: 343-366.

Turner, M. (1980) *English Parliamentary Enclosure*. William Dawson and Sons Ltd: Folkestone.

Turner, M. (1982) Agricultural Productivity in England in the Eighteenth Century. *Economic History Review* 35: 489-510.

Turner, M., Beckett, J. and Afton, B. (1997) *Agricultural Rent in England: 1690-1914*. Cambridge University Press: Cambridge.

Turner, M., Beckett, J. and Afton, B. (1998) Renting the Revolution: A reply to Clark. *Journal of Economic History* 58: 211-214.

Van Zanden, J. L. (1991) The First Green Revolution: The Growth of Production and Productivity in European Agriculture. *The Economic History Review* 44: 215-239.

Walton, J. (1993) Mechanization in Agriculture: A Study of the Adoption Process. In Fox, H. and Butlin, R. (eds.) *Change in the Countryside: Essays in Rural England 1500-1900*. Institute of British Geographers Special Publication No.10.

Weisdorf, J. (2006) From Domestic Manufacture to Industrial Revolution: Long Run Growth and Agricultural Development. *Oxford Economic Papers* 25: 264-287.

Williamson, J. (1982) The Structure of Pay in Britain, 1710-1911. *Research in Economic History* 7: 1-54.

Wood, G. (1899) The Course of Average Wages between 1790 and 1860. *Economic Journal* 9: 588-592.

Young, A. (1771). *The Farmer's Tour through the East of England*. London: printed for W. Strahan; W. Nicoll; B. Collins, Salisbury; and J. Balfour, Edinburgh.