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What Caused the Agricultural Revolution?

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Abstract

Explanations of changes in agricultural TFP during the agricultural revolution typically consist of a purely narrative account. Often these accounts present a timeline of key innovations or a discussion of the achievements of great agricultural pioneers. Using data drawn from a variety of sources we estimate agricultural TFP over the period 1690-1914. Applying causality tests appropriate for analyses involving nonstationary data we show that changes in the volume of agricultural output and the cumulative number of first editions of books on agriculture precede changes in TFP. By contrast the length of the canal network, measures of private R&D and the number of parliamentary acts of enclosure do not precede changes in TFP. Our findings appear to confirm the importance to the agricultural revolution of learning-by-doing and the improved dissemination and retention of knowledge.

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1 Introduction

The traditional story of the industrial revolution starts with a prior revolution in the agricultural sector. Improvements in agricultural TFP imply that the rate of growth of agricultural production, achieved under conditions of diminishing returns, exceeds the rate of population growth, thereby allowing labour to move from agriculture to industry. Other analyses view the agricultural and the industrial revolutions as largely parallel developments.[1]

Most explanations for the agricultural revolution defined in terms of improvements in TFP provide a purely narrative account. Not infrequently a timeline is presented[2] covering key agricultural contraptions and their inventors.[3] The agricultural revolution is also not infrequently presented as if it were the result of the life's work of a handful of agricultural pioneers.[4] Oftentimes however, their precise contribution and the practical significance of

[1] There exists no shared understanding regarding the meaning of the phrase agricultural revolution and in what follows we use the phrase merely as shorthand for those changes in agricultural TFP observed over a period of time of uncertain duration but terminating at the beginning of WW1. We do not wish to suggest that changes in agricultural TFP in this period were fast compared to the changes that occurred post WW2 or that there was a moment when the trend rate of growth of agricultural TFP accelerated.

[2] The classic account of the agricultural revolution is Prothero (1912) who dates the agricultural revolution 1760-1830. Chambers and Mingay (1966) favour the longer period 1750-1880 whilst 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 period 1649-1688 whereas Thompson (1968) suggests that there was not one but two agricultural revolutions the first occurring 1660-1750 and the second 1815-1880.

[3] For example, Jethro Tull designed the seed drill in 1701. The precise planting of seeds in neat rows prevented the wastage of seed and made crops easier to hoe. In 1730 the Rotherham plough was patented by Joseph Foljambe. This plough was much lighter incorporating an iron covering for the mouldboard enabling it to be pulled by fewer horses. The threshing machine was invented in 1786 by Andrew Meike thereby mechanising a task traditionally accounting for one quarter of all the labour employed by agriculture. And in 1843 John Read invented the cylindrical clay pipe thereby facilitating numerous drainage projects. According to Federico (2010) "All changes in TFP have routinely been attributed, more or less consciously, to technological progress".

[4] The New Leicester sheep bred by Robert Bakewell is often given as an example of the way in which animals were improved in order to gain weight more quickly and develop other desirable traits. The Norfolk rotation of turnips-barley-clover-wheat associated with Thomas Coke side-stepped the need for a period of fallow: the turnips provided fodder for sheep and the clover fixed atmospheric nitrogen. In his classic account of the agricultural revolution Prothero (1912) lists five great individuals: Tull, Townsend, Bakewell, Coke and Young.

their contraptions seems to have been exaggerated (see e.g. Overton, 1986). Furthermore elevating particular individuals' status or focussing attention onto a limited number of inventions ignores countless changes in agricultural practices and the efforts of multitudes of farmers.

Another factor potentially contributing to the agricultural revolution is the enclosure movement whereby up and down the country, small strips of land were consolidated into larger fields and customary rights were terminated. See, McCloskey (1972) and Allen (1992) for different views on the issue.[5]

A further explanation for improvements in agricultural TFP is Smithian growth although according to Federico (2010) this is an explanation researchers have largely overlooked. Smithian growth refers to improvements in TFP that occur due to better transport infrastructure. Better transport infrastructure supports regional specialisation showing up as productivity gains. For an extensive review of the putative causes of TFP growth in agriculture from 1800 to modern day see Federico (2010).

Our interest lies not in measuring the rate of TFP growth much less in determining the timing of any revolution – even though interesting information about both of these things emerges from our analysis. Our aim is to identify causes of the agricultural revolution by applying the concept of Granger-causality. This enables us to determine changes in what factors temporally precede changes agricultural TFP. And in so doing we investigate the contribution of all of the foregoing factors as well as that arising from other factors (the construction of transport infrastructure, a spurt in private R&D and institutional change) seldom discussed in the literature: learning-by-doing and the improved dissemination and retention of knowledge.

Our work uses data on agricultural prices, wages and rents, the rate of interest and the price of capital goods for the period 1690-1914. These are combined with information on factor shares from a contemporaneous source to obtain a series for agricultural TFP. We then use this series to identify the causal determinants of the agricultural revolution for which we compile fresh data on various factors potentially responsible for the agricultural revolution. We then investigate the issue of temporal precedence using a test of Granger-causality that accounts for the nonstationary nature of the data.

There are several papers relevant to our attempt to identify the causes of the agricultural revolution. Estimates are available of the rate of TFP growth during the agricultural revolution although this evidence is rudimentary with some contributors suggesting a change in agricultural TFP while others find only steady progress. Much of this evidence is surveyed by Overton (1996).

Hoffman (1997) is perhaps closest in spirit to the present paper if not in actual technique. In his study of French agriculture for the period 1450-1815 he investigates the existence of causal connections between agricultural TFP and population, farm size, enclosure and transport infrastructure but critically, does not employ any of the time series econometric techniques nowadays viewed as essential. Applying these techniques Oxley and Greasley

[5] McCloskey (1972) has suggested using differences in the rent achieved by enclosed versus unenclosed land to reveal the productivity advantages of enclosure. His results indeed suggest modest gains. This is contested by Allen (1992) who argues that the increase in rents associated with enclosure does not reflect productivity gains so much as a redistribution of the agricultural surplus in favour of the landowner and to the disadvantage of the tenant.

(1998) have used Granger-causality tests to investigate the antecedents of the British industrial revolution. The authors explore the causal connection between GDP per capita and exports, patent counts, population growth, domestic demand and imports. They find the industrial revolution was caused by patent counts.

Focussing on British agriculture, Brunt (2004) tests the importance of particular cultivation techniques and the use of certain items of machinery using data collected by the great agricultural writer Arthur Young during his famous tours. Quite recently Ang et al (2013) present a multivariate analysis of the historical rate of growth of labour productivity in agriculture. Their focus however is on using an econometric model to distinguish between different theories of growth involving private R&D activities rather than actually resolving what are the causal determinants of agricultural TFP.

In contrast to the relatively small number of studies touching on the historical determinants of TFP numerous researchers have analysed modern-day agricultural TFP see e.g. Thirtle et al (2004). Such analyses typically include some measure of public and private R&D expenditures as well as expenditures on agriculture extension. Dummy variables are used to signify important events e.g. changes in Government policy. Often the underlying purpose of these studies is to measure the long-run response of TFP with respect to spending on publicly-funded R&D and extension in order to calculate the benefit-cost ratio. In such exercises numerous factors e.g. the scale of agricultural production and the amount of transport infrastructure are often treated as constants whereas in a historical context they are better viewed as potential determinants of TFP. Nonetheless these studies certainly provide clues as to the kinds of things that might potentially Granger-cause agricultural TFP during the agricultural revolution.

To anticipate our main findings variables describing the quantity of agricultural output and the cumulative number of first editions of books on agriculture are statistically significant causes of historical changes in agricultural TFP whereas other more frequently discussed variables are not. And in one case we find that the direction of causality is opposite to that which might be expected. Our findings are robust to dummies denoting historical events and changes in the way that we estimate agricultural TFP.

The remainder of the paper is organised as follows. In the next section we describe our basic methodology and the source material used to determine the factor shares for agriculture and discuss factor price indices. Section three discusses further the putative causes of the agricultural revolution as well as important events impacting agricultural productivity. Section four presents the technique used for testing Granger-causality. Section five describes the results of the Granger-causality tests and section six considers the consequences of altering the factor shares thereby changing the series for agricultural TFP. The final section concludes with some ideas for future research and reflections on the limitations of the present exercise.

2 Analysis of agricultural TFP and data

2.1 Analysis of agricultural TFP

Modern-day analyses of agricultural TFP normally proceed in two steps. In the first step the rate of TFP growth in agriculture is calculated using index numbers. In this paper we essentially follow the same two-step procedure. However, while modern-day analyses use index number procedures which do not impose a priori restrictions on the structure of production,[6] we are dealing with a period in which there are no annual surveys. It is therefore necessary to make assumptions regarding technology. In particular, following others, we assume that the cost function for agriculture is Cobb-Douglas and that technical progress is of the Hicks-neutral variety. For an example of researchers making these assumptions to calculate the rate of TFP for the British economy as a whole for the period 1770-1860 see Antras and Voth (2003).

In order to implement the two step approach we require estimates of the factor shares and factor price indices. The next section, section 2.2, discusses the first of these. Discussion of the factor price indices follows in the ensuing section, section 2.3.

2.2 Factor shares

Estimates of factor shares are taken from Young (1771). We copy others such as Allen (1992) in utilising this source of information. But as Allen notes Young has no concept of the user cost of capital. For this reason like Allen we convert the value of stock in husbandry presented in Young into the user cost equivalent.[7]

Following Allen we also make a distinction between depreciable and non-depreciable assets. Depreciable assets include draught cattle and cows. These are depreciated at the rate of 10 percent per annum along with the prevailing 4 percent rate of interest mentioned by Young. Note that although we have inserted a 10 percent rate of depreciation Young also includes an element for the “wear and tear” of horses. This figure however implies a 70 percent rate of depreciation and has therefore been excluded from our calculations. Langdon (1982) discusses the economics of oxen, cart-horses and plough-horses. Using the historical information presented by Langdon it is possible to deduce rates of depreciation for oxen, cart horses and plough horses of 3, 11 and 14 percent respectively. Subsequently Young (1774) suggests that whereas there were 200 thousand oxen being used as draught animals there were 1.2 million horses. Combing these pieces of information the conventional assumption of a 10 percent rate of depreciation for draught animals appears not unrealistic. Non-depreciable assets namely “fatting beasts”, young calves, sheep, pigs and poultry are discounted using a 4 percent rate of interest without any element of depreciation. We revisit our assumption concerning the rate of depreciation of draught animals in a sensitivity analysis (section 5).

Turning now to estimates of man-made capital we observe that Young includes both implements and “farm furniture” which we interpret as buildings and other immovable structures. These estimates once more appear to refer to the price for outright purchase. These purchase price estimates are therefore once more subjected to a 10 percent rate of depreciation and a 4 percent rate of interest to obtain the user costs. Again Young includes a component for the repair of “half of the farm buildings”. If it is assumed that this component refers to “farm furniture” it implies only a very small rate of depreciation and it is in any case unclear why only half of the farm buildings have to be repaired and none of the implements. One distinct possibility is that these are included in the cost of the rent.

Young includes expenditures on feed and seed as well as a variety of labourers some of whom are live-in servants whereas others are hired help. For the live-in servants the costs of

[6] And it is for this reason that recently most attention has been on the Tornqvist index which is ‘exact’ for the translog production function. For a detailed explanation of the calculation of TFP in the US using the Tornqvist index see e.g. Ball (1985). In the second step the resulting index for TFP is subjected to further analysis.

[7] In fact Young provides high and low estimates of livestock. Here we use the lower estimate and investigate the effect of switching to the higher estimate in a later section.

accommodation have been included in the cost share of labour. Also included in Young's calculations is the typical share of land plus a variety of taxes. These include tithes, rates and taxes which in total amount to just over 15 percent of the costs of agricultural production. For simplicity we model these as if they were an ad-valorem tax on agricultural output.

The only remaining issue is whether it is appropriate to include as does Young the cost of working capital. Working capital is necessitated whenever there is a mismatch between the timing of outlays and the collection of receipts. Although the cost of working capital seldom features in modern-day analyses of cost functions it does seem inevitable that a farmer would need to borrow money (or forgo interest) in order to buy seed and feed and to pay his labourers. Somewhat less clear however, is the precise extent to which rents and taxes were payable in advance. Turner et al (1997) suggest that customs involving payment of rent varied widely and that sometimes this was spread over the agricultural cycle. Although Young includes a cost of 4 percent on all items representing the cost of working capital we ignore this cost component for the time being once more preferring to return to this assumption in a sensitivity analysis in section 6. Lastly, we have like Young ignored any costs associated with the upkeep of the farmer and his family.

Clearly it would be desirable to validate the estimates of factor shares arising from our reworking of Young by comparing them with others. But although there are other estimates these tend to be for individual farms rather than for the country as a whole and are not therefore necessarily representative of agriculture in general. There is also the enduring issue that such accounts like Young's typically fall short of modern accounting practices e.g. ignorance of the concept of user costs and ignoring the farmer's own consumption of agricultural produce.

One solution to these problems is provided by Bowden (1990) who provides a set of 'synthetic' farm accounts. These do not refer to any actual farm but combine information taken from the accounts of more than one farm where the accounts are in good shape.

Bowden provides cost share estimates for a notional 100 acre arable farm circa 1700-1750 as well as for an equivalently sized cattle farm circa 1730-1750. Comparing the two sets of estimates with those derived from Young writing a few years later (see Table 1) it is immediately clear that whereas Young includes a significant element for tithes, rates and taxes these do not appear in Bowden since it is there assumed that they are paid by the landlord. Bowden also includes the cost of manure and other soil dressings transported to the farm. Leaving aside these minor differences there is nonetheless a fair correspondence between Young and Bowden in the sense that the cost shares from Young are typically close to or in between the range of cost shares for the arable and pastoral farms described by Bowden.

Table 1. Estimates of factor shares

	Young	Bowden	
		Arable	Cattle
Rents	0.34	0.31	0.57
Taxes	0.16		
Depreciable livestock	0.03	0.02	0.01
Non-depreciable livestock	0.02	0.00	0.05
Feed and seed	0.17	0.24	0.06
Man-made capital	0.07	0.01	0.02

Labour	0.21	0.27	0.20
Manure		0.12	0.00
Miscellaneous		0.02	0.08

Source: See text. Note that figures do not sum to 1 because of rounding.

2.3 Factor price indices

Having determined the factor shares we now turn to consider the factor price indices. Starting with the price of output Clark (2004) provides an annual price series for 26 agricultural commodities in England from 1209-1914. These are obtained by joining together numerous existing price indices and adding new information. Because we are assuming that all tithes, rates and taxes are ad valorem taxes the price of output price index is also appropriate for this cost-share. Sub-indices are provided for arable and pastoral products.

Turner et al (1997) provide data on agricultural rents for 1690-1914. More specifically, they present information on assessed and received rents from large estates or parts thereof.[8,9] 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.

In total Turner et al 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 largest estate is the 290,000 acres under the control of the ecclesiastical commissioners whereas the smallest a mere 767 acres. The amount of land attributed to particular estates fluctuates through acquisitions and disposals. The data cover 5.5 percent of the agricultural land in England in 1887 although the temporal coverage is highly uneven.

More information is available on rents received rather than rents assessed and Turner et al refer to rents received as the "best and most sensitive indicator [available]". Using information on rents received we create a hedonic rental price index including dummy variables for each estate and for each year.

The price index for depreciable livestock is set equal to the price of pastoral products multiplied by the rate of return on consols plus an assumed 10 percent rate of depreciation to obtain a user price. The rate of return on consols comes from Mitchell and Deane (1962). This series goes back only as far as 1756 but we have extended it using estimates of the return on perpetual rent charges taken from Clark (1988) who notes that in the period when they overlap the return on perpetual rent charges almost exactly matches the return on consols. The price index for non-depreciable livestock is calculated as above but without the 10 percent rate of depreciation.

Our estimate of the cost of capital involves first creating an index of the price of investment goods. Constructing this index involves concatenating various historical price series for bricks, timber and iron. These data are taken from Clark (2004) and extended using data from Sauerbeck (1986) for iron and timber, and Maiwald (1954) for bricks. This price index is then

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

[9] Assessed rents represent the bargain struck between landowner and tenant whereas received rents the amount actually collected. It is possible that the received rents include abatements as well as debts carried forward from previous years.

multiplied by the rate of return on consols plus an assumed 10 percent rate of depreciation to obtain a user price.

Clark (2007) also provides agricultural wage rates in England from 1209-1869. After 1869 wage rates are taken from Fox (1903) who surveys wages from 125 farms in England and Wales. From 1902-1914 agricultural wage rates are taken from Bowley (1937). These are spliced together to form a single series for wages.

Combining all this information with our estimates of factor shares yields an index of TFP in agriculture. The path of TFP over time is displayed in Figure 1. The graph confirms a gradual improvement in TFP. The average rate of TFP growth over this period is however only 0.24 percent which is below some estimates contained in the survey of Overton (1996) but nevertheless accords well with the findings of Allen (1992) and Clarke (2002) who report estimates of 0.30 percent and 0.15 percent respectively. One reason why our estimates are below some of those contained in Overton is that other authors present estimates for the late 18th or early 19th centuries whereas ours go back to the 17th century when there was evidently little growth in TFP. Another possible reason is because earlier researchers tended not to include the user costs of biological and man-made capital focussing instead on land and labour.

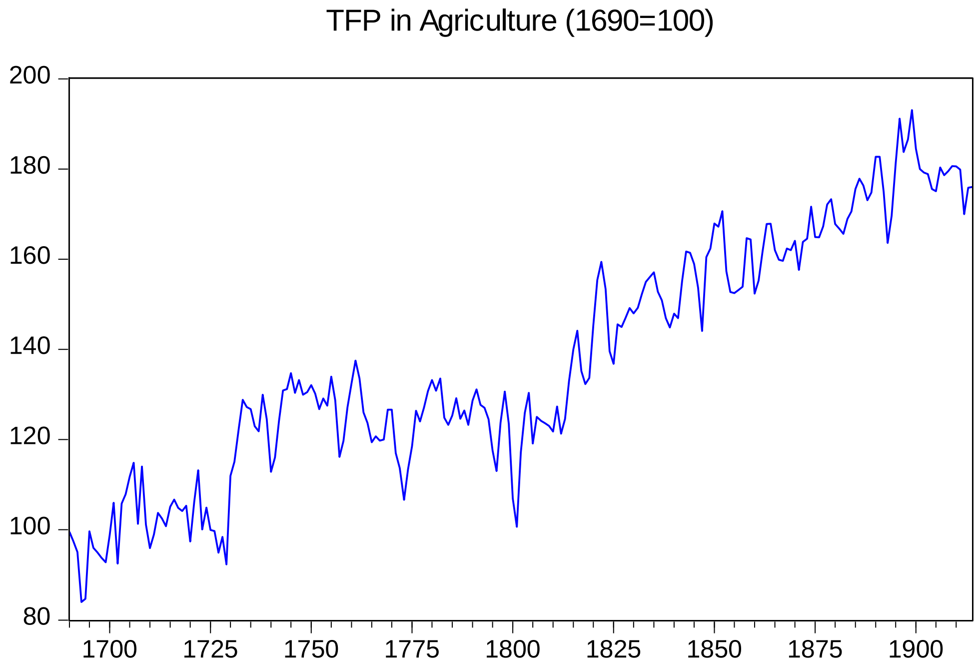

Figure 1. TFP in Agriculture (1690=100)

3 Factors causing the agricultural revolution

Having forged an index for agricultural TFP, we now proceed to the second stage of the exercise, where we use this to test whether particular factors Granger-caused agricultural TFP. More specifically, our interest lies in determining to what extent improvements in agricultural TFP were preceded by (1) the construction of transport infrastructure, (2) a spurt in private R&D, information retention and dissemination activities and (3) institutional change. We begin however, by discussing (4) a measure of agricultural output intended to capture so-called learning-by-doing effects, as a supplementary explanation of the agricultural revolution.

3.1 Learning-by-doing

Modern-day studies into the implications of learning-by-doing for the evolution of production costs are ubiquitous in manufacturing but curiously, not as a possible cause of historical TFP growth in agriculture. Indeed, only a small number of studies investigate whether learning-by-doing is a cause of modern-day improvements in agricultural TFP. In the context of TFP growth in US agriculture Luh and Stefanou (1993) find a substantial role for learning-by-doing over the period 1950-1982 whereas Gopinath and Roe (1997) find no significant role for learning-by-doing over the period 1948-1991.

Most of the empirical evidence on learning-by-doing in manufacturing is summarised in an article by Argote and Epple (1990). In this literature researchers commonly use cumulative production as a proxy for the unobservable stock of knowledge. More recent work however acknowledges 'organisational forgetting' caused by periods of reduced activity e.g. Benkard (2000). Following Argote et al (1990), we assume that the change in the stock of knowledge K_t depends positively on the quantity of output Q_t and negatively on the stock of knowledge:

$$K_{t+1} = Q_t + \rho K_t$$

Where $\rho < 1$which implies:

$$K_{t+1} = Q_t + \rho Q_{t-1} + \rho^2 Q_{t-2} + \cdots$$

Hence, the finding that lagged changes in agricultural output precede changes in agricultural TFP can be interpreted as evidence of learning-by-doing.[10]

For the scale of agricultural output we use estimates from Broadberry et al (2011). These data are available from 1207-1870. Estimates for arable production are made by combining evidence on the amount of arable land under cultivation and assumptions about its division between fallow and each of the main crops. These estimates are then combined with further information on evolving yields per acre net of seed sown. Further allowances are made for arable produce consumed by working animals whose number is determined using evidence on stocking densities. Estimates for pastoral production are also based on stocking densities. Assumptions about slaughter rates are used to obtain the proportions of animals producing meat, milk and wool and the resulting figures are then combined with evolving estimates of

[10] The paper of Argote et al refers to the construction of standardised "Liberty ships" in WW2. They find that the rate at which knowledge depreciates is so high that even output in the past 12 months would be a good measure of the stock of knowledge and a good predictor of the cost of producing further vessels.

the amount per animal of the same three products. For a critical review of the estimates of agricultural output provided by Broadberry et al and others see Kelly and O'Grada (2013).

3.2 The construction of transport infrastructure

Turning now to Smithian effects, regional specialisation is potentially of great importance to agriculture, especially if there are significant geographical variations in conditions of agricultural production. Whether the gains from regional specialisation can be realised however, depends on the existence of transport infrastructure. Kelly (1997) presents a theoretical model in which achieving a critical density of transport linkages results in rapid economic growth. Kelly further argues that it was the construction of 30,000 miles of waterways in China by the year 1000 which was responsible for the rapid economic growth as revealed by a subsequent surge in the real money supply.

The causal relationship between investments in transport infrastructure and improvements in agricultural TFP however, can run in either direction. With significant geographical variations in conditions of agricultural production, improvements in transport infrastructure, perhaps undertaken with other considerations in mind, can indeed cause regional specialisation in agriculture. But improvements in agricultural productivity can also make it profitable to transport agricultural produce greater distances than before in the isolated-state model of von Thünen (1826); privately-financed transport infrastructure is built because the potential traffic warrants it.

Modern-day analyses of agricultural TFP and transport infrastructure also tend to note the existence of an association between infrastructure and agricultural TFP e.g. Antle (1983) but do not determine the direction of any causal relationship – something which might, as argued, differ depending on whether transport infrastructure is built purely with commerce in mind and on the geographical variability of the conditions of agricultural production.

As an index of the scope for regional specialisation we use the length of the canal network in England. The classic account of the canal network is contained in the series *Canals of the British Isles* (various authors and various years). Each volume focusses on a different region of the British Isles and includes appendices containing information as to when named waterways of known lengths were opened. These waterways are classified in Boughey (1998) as either wholly artificial canals, 'canalised' rivers called 'navigations' or rivers that have undergone some alteration but without changing the actual course of the river e.g. dredging or the addition of a towpath. There are also a significant number of waterways built primarily for drainage purposes but navigable nonetheless. We include the volumes of the series for Eastern England, the East Midlands, North West England, South and South East England, South West England, the West Midlands, Yorkshire and the North East. We use this information to estimate the cumulative length of canals and navigations over the period 1500-1914; rivers and other sorts of waterways are ignored. A very small number of canals and navigations whose opening dates are unknown have been omitted.

Although we have only fragmentary evidence to show how much agricultural freight was carried by inland waterways, per mile tariffs for all manner of agricultural inputs and outputs are contained in Priestley (1831). For an illustration however, as to the actual importance of canals to agriculture Maw et al (2009) provide a detailed account of traffic on the Rochdale canal. Whereas in 1825 coal accounted for 30 percent of the tonnage compared to 14 percent for corn it was actually the latter that accounted for 32 percent of the tolls compared to only 5 percent for coal.[11] Corn was brought from as far afield as Lincolnshire, East Anglia and the Vale of York. Other agricultural outputs separately identified include wool and timber. Also separately identified was lime, itself an important input to agricultural production.

Apart from roads (ignored because of data availability) and railways (which eclipsed canals only towards the end of the period under investigation) another important form of transportation for agricultural produce was coastal shipping, and the importance of this trade is something to which we later return.

3.3 R&D expenditures, information retention and dissemination acitivities

As a proxy for private R&D expenditures we use patent counts related to agriculture. Although modern-day analyses of the determinants of TFP in agriculture typically utilise data on private R&D expenditures rather than patent counts patently there is a relationship between them: one represents the 'input' to research activity whilst the other represents the 'output'. Ideally, we should include public expenditures alongside private ones since public expenditure on agricultural R&D is nowadays significant and represents an attempt by Governments to overcome the market failures associated with the inability to appropriate fully the benefits of private research. But although there were agricultural research facilities in Rothamstead as early as 1843 this was a wholly private undertaking and according to Brassley (2000) public funds were made available for research into agriculture in the UK only after 1910.

For patent counts we use data taken from Woodcroft (1857), a source which is discussed at great length by Sullivan (1984). This book enables researchers to enumerate all patents pertaining to agriculture over the period 1617-1852. Unfortunately, the patent system was reformed in 1852 and there appears no easy way of extending the series beyond that date. Furthermore, despite data being available from 1617, Sullivan provides several good reasons to believe that the procedures used to evaluate patents might be consistent only from 1661 or even 1689. Sullivan presents a decadal count of patents which includes not only those directly relating to agriculture but also to agricultural produce, manure, dairy, farriery and drainage. In order to obtain an annual rather than a decadal series we have gone back to Woodford to obtain the annual number of patent counts listed under the exact same headings.

There are numerous well-known shortcomings associated with the use of patent counts e.g. the changing propensity of inventors to patent their inventions and the differing importance of patents. We have nothing further to add to these discussions. Furthermore, not every good idea could be patented; patents could not for example be issued for methods of organisation, distribution or for products for human consumption.

In the same article, Sullivan also proposes the publication of first editions of books as an alternative to the number of patents. Sullivan derives from Perkins (1932) the number of first editions of books published on the subject of agriculture. Data on books published is available from 1523-1900 which Sullivan also presents as a decadal count.[12] We have once more, gone back to Perkins (1932) to obtain an annual rather than a decadal series. We do however, look upon the publication of first editions of books somewhat differently to

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[11] The definition of corn used by the canal company included wheat, barley, oats, hops, beans, peas, malt, linseed, rapeseed, flour and bran.

[12] Sullivan presents evidence suggesting that the rate of literacy amongst yeomen was in excess of 80 percent during the period 1750-1850.

Sullivan for the following reasons. A significant number of modern-day analyses of agricultural TFP find that extension advice is a significant contributor to gains in agricultural TFP. We believe that the number of first editions of books plays a role similar to extension since both involve the *dissemination* of knowledge as opposed to its *creation*. Books also assist with the retention of knowledge. MacDonald (1979) discusses the diffusion of knowledge among Northumberland farmers during the agricultural revolution. Observed methods include informational spillovers, membership of agricultural societies and attendance at agricultural shows and the written word: both private correspondence and books and periodicals.

3.4 Institutional change

Finally, we turn our attention to the issue of institutional change. As noted, a widely held view is that historical gains in TFP in agriculture were aided by enclosure. Enclosure of course, refers to the process whereby scattered pieces of open land were consolidated into larger plots and common rights held over land were extinguished.[13] According to Wordie (1983) by 1700 only 29 percent of land in England remained unenclosed, but during the frenzied period 1700-1850 approximately 21 percent of the land in England was enclosed.

Enclosure occurred in a number of ways. Enclosure could come about by private agreement but it could also involve private parliamentary acts, of which there were several thousand. Information on parliamentary acts of enclosure is contained in Tate (1978) who comprehensively lists parliamentary acts of enclosure in England over the period 1604-1914. Using the information in Tate we have counted the number of parliamentary acts of enclosure in each year and have cumulated them.

Note carefully that we use the cumulative count of acts of parliament rather than the area of land to which each act refers as a measure of institutional change. The reason lies in the work of Chapman (1987). His detailed analysis of a sample of enclosures suggests that estimates of the amount of land enclosed based on figures relating to either the act or the award can be "wildly inaccurate". Chapman also draws attention to the changing target of enclosures: initially from arable to wasteland.

3.5 Other factors

Apart from the combined influences of learning-by-doing, Smithian growth, private R&D activity, dissemination and knowledge retention and institutional change agricultural TFP also has been impacted by a large number of one-off events. These include major conflicts as well as other diverse events impinging on agricultural production. Whilst it is important to account for these the list of events potentially impacting agricultural TFP is almost endless. In what follows therefore, we claim only to have identified the more obvious ones.

A number of authors have argued that the Napoleonic wars of 1792-1815 adversely affected agricultural production, even though no battles were fought on British soil. Various mechanisms might be involved including interruptions to regional trade. There is evidence, during the period of the Napoleonic conflict, of the disintegration of national markets and

[13] More specifically open fields were individually cultivated whilst under the plough but communally grazed whilst under pasture. But then as now there were still owners, tenants and owner-occupiers. Beyond the open fields were wasteland used for grazing. There were also closed fields and complicated patterns of duties and privileges. 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).

increased variation in prices across regional markets e.g. Jacks (2011). Chandler and Beckett (2003) also state that the size of the British army swelled from 40,000 to 250,000 men over the period 1793-1813, something which might have had a direct impact on agricultural knowledge retention through labour turnover. We therefore include as a control a dummy variable covering the period of the Napoleonic conflict.

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). We create a dummy variable covering this period of time whilst noting the existence of numerous albeit more minor outbreaks of contagious animal diseases e.g. the cattle plague of 1714 which is, from contemporaneous descriptions of the symptoms, now thought to have been rinderpest.

Apart from animal diseases, agricultural production has very occasionally been affected by volcanic eruptions, such as the Laki and Grimsvötn eruptions in Iceland during 1783-1785. Contemporaneous accounts suggest agricultural production activities were severely disrupted. There was an increase in the death rates of outdoor workers and cattle. The sulphur dioxide injected into the atmosphere harmed vegetation. There were reports of damage to crops, trees and even fish-death. For a discussion of the effects of these eruptions on Britain see Grattan and Brayshay (1995). We include a dummy variable covering the period of these eruptions noting the existence of other important volcanic eruptions in the southern hemisphere e.g. Tambora in 1815 and Krakatau in 1883.

There is evidence from the Central England temperature record that average temperatures in Britain changed markedly, following the end of the so-called little ice age. Current analyses of the impact of climate change on agriculture suggest temperature changes of this magnitude might significantly impact agricultural production, even today. In order to control for changes in the climate we have used the Central England temperature record to create a 30 year smoothed average of temperatures.[14] This confirms the existence of a period of rapid warming from 1690-1730 of about 1°C, followed by an almost equally sharp reversal.

Finally, we create a dummy variable to account for the existence of trade restrictions, specifically the Corn Laws of 1815-1846 which might have adversely impacted agricultural TFP. We are aware that despite 1815-1846 being commonly referred to as the era of the Corn Laws there were in fact trade restrictions before 1815 (Barnes, 1965). Also, although the repeal of the Corn Laws occurred in 1846 the sliding scale of charges continued until 1849. And even during the period of the Corn Laws proper the exact nature of the controls was significantly revised, significantly in 1822 and again in 1828.

Given the above a dummy variable taking the value unity from 1815-1846 is a crude way of controlling for trade restrictions. More appealing might seem the use of ad-valorem equivalent tariffs as presented by Sharp (2010). These express the duty obtained on corn as a percentage of the domestic value, although as Sharp notes, the trade restrictions were not actually in the form of an ad-valorem tariff but rather involved the use of sliding scales. Unfortunately, from 1815 until the temporary acts of 1825 it is impossible to calculate the ad-valorem equivalent since either no corn was imported or, if it was imported, it paid no duty.

[14] These data are from the Meteorological Office: http://www.metoffice.gov.uk/hadobs/hadcet/data/download.html

The other means of measuring the extent of trade restrictions during the era of the Corn Laws discussed by Sharp appear just as crude as using a dummy variable. For an example of a modern attempt to discern the effects of openness to trade on agricultural TFP see Yoo et al (2012).

3.6 Summary statistics

Summary statistics on acts of enclosure, patent counts, miles of canals and agricultural output are presented in Table 2. The table reports data from 1690-1914 apart from agricultural output which refers to the period 1690-1870, for patents which refers to the period 1690-1852 and for books which refers to the period 1690-1900.

Table 2. Data on output, canals, patents, books and parliamentary acts of enclosure

Variable	Mean	Std. Dev.	Min.	Max.
OUTPUT	197.809	84.20374	72.16	409.4
CANALS	1579.668	1112.919	251.875	2845.709
PATENTS	218.7117	173.7254	64	877
BOOKS	1012.237	872.5527	120	2853
ENCLOSURE	2564.551	2209.42	7	5365

Source: see text.

4 Methodology to test for Granger-causality

Having described our data, we now describe the methodology of Toda and Yamamoto (1995) used to test for Granger-causality. Employing this methodology, we test for temporal precedence between our index of TFP and agricultural output, the length of the canal network, cumulative patent counts, cumulative first editions of books on agriculture and the cumulative number of parliamentary acts of enclosure.

The Toda-Yamamoto methodology entails first investigating the time-series properties of the data with the specific aim of identifying the highest order of integration of the variables included. Once this has been done, the next step is to run a Vector Auto Regression (VAR) in *levels* irrespective of what is found in the first step of the methodology regarding the order(s) of integration. The lag length of the VAR is determined by some information criteria and may need to be further increased in order to deal with any problems of autocorrelation. Let the number of lags so chosen be denoted m. Next, the lag length of the VAR is further augmented by additional lags the number of which is determined by the highest order of integration encountered. Let this be denoted by n such that the lag length of the VAR is now $m + n$. The test of causality involves testing for each variable in turn the statistical significance of the first m lags.

The advantages of the Toda-Yamamoto methodology over other approaches to causality testing are two-fold. The first advantage of this methodology is that it avoids pretest bias. More specifically, depending on the outcome of a test for cointegration the appropriate test of Granger-causality could involve either a Vector Error Correction framework or alternatively, if no cointegrating relationship is detected, data which is nonstationary should be differenced and analysed as a VAR. And it is the possibility of making a mistake at precisely this stage that causes pretest bias and the evidence moreover, suggests that this bias can sometimes be substantial. The Toda-Yamamoto test avoids pretest bias because it can be used irrespective of whether the data cointegrates or not. The second advantage of the Toda-Yamamoto test is that it allows one to include deterministic regressors, such as the dummy variables identifying periods of conflict etc. discussed earlier.

5 Results

As a first step in the implementation of the Toda-Yamamoto methodology, we use the Augmented Dickey-Fuller (ADF) test to establish the time series properties of the data. The results, displayed in Table 3, clearly suggest that most variables are I(1) irrespective of whether or not a time trend is included. By contrast, the log of TFP and the log of agricultural output are either I(1) or I(0), depending on whether a time trend is included.

Table 3. ADF tests of stationarity

	No Trend	Trend
Ln TFP	-1.804	-5.458***
Δ Ln TFP	-11.483***	-11.489***
Ln OUTPUT	-0.479	-5.639***
Δ Ln OUTPUT	-14.438***	-14.321***
Ln CANALS	-1.447	0.242
Δ Ln CANALS	-9.248***	-9.418***
Ln PATENTS	2.939	1.081
Δ Ln PATENTS	-4.356***	-5.228***
Ln BOOKS	-0.841	-0.757
Δ Ln BOOKS	-6.360***	-6.395***
Ln ENCLOSURE	-2.491	-0.638
Δ Ln ENCLOSURE	-2.588*	-3.524**

*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.*

For the first model, we exclude the control variables i.e. the dummies indicating the occurrence of conflict, cattle plague, volcanic eruptions etc. Assuming a maximum lag length of 8, the optimal number of lags for the VAR indicated by the Akaike Information Criterion is $m = 5$. We further check for evidence of autocorrelation.[15] Following the next step of the Toda-Yamamoto procedure, we then proceed to add the $n = 1$ additional lags to the $m = 5$ already being considered that being the highest order of integration encountered. Finally, we test the statistical significance of the first 5 lags of each variable in turn in order to test the null hypothesis of no Granger-causality using the 'modified' Wald test. Note that the time period for these tests is 1690-1852 rather than 1690-1914, because of the limitations posed by the patent data. The results are displayed in Table 4.

Table 4. Multivariate Toda-Yamamoto tests of causality

Causal relationship assumed to be absent	No further controls	All controls	1690-1870
OUTPUT → TFP	32.199***	27.579***	20.492***
CANALS → TFP	9.430*	6.847	6.362
PATENTS → TFP	14.647**	9.235*	

[15] The Schwarz Information Criterion points to a shorter lag length of m = 1 but this lag length exhibits significant first order autocorrelation.

BOOKS → TFP	20.236***	15.194***	14.454**
ENCLOSURE → TFP	8.235	4.716	2.669

*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 most notable finding to emerge from Table 4 (first column) is that the null hypothesis that agricultural output does not Granger cause TFP can be rejected, even at the one percent level of confidence. Despite this, learning-by-doing has hitherto been entirely ignored as an explanation for improvements in TFP during the agricultural revolution. Also statistically significant at the one percent level of confidence is the cumulative sum of first editions of books published on agriculture. This finding appears to confirm the views of Sullivan (1984) who first proposed using the publication of the first editions of books as a means of measuring of technical change in agriculture, one that is in his view at least as good as patent count data and in some respects better. This, he argues, is because books could express ideas that could not be patented. Our interpretation is that books are both a means of disseminating and retaining knowledge. It is nonetheless also possible to reject, albeit only at the 5 percent level of confidence, the null hypothesis that changes in the cumulative number of patents did not Granger-cause agricultural TFP. The hypothesis that cumulative length of the canal network caused TFP can be rejected albeit only at the ten percent level of confidence. By contrast, there is no evidence that cumulative enclosure caused TFP, although this could of course be a consequence of data inadequacies.

In the next model (second column), we include the full set of controls i.e. controls for cattle plague, the Laki eruption, the Napoleonic conflict, the period of the Corn Laws and climate change. Output and the cumulative number of first editions of books published on agriculture remain statistically significant causes of TFP at the one percent level of confidence whereas the statistical significance of cumulative patent counts drops from the five to the ten percent level of confidence.

The preceding tests of causality are, of course, limited in that the data for patent counts is available only up to 1852, whereas data for agricultural output is available up until 1870. The variable describing the cumulative number of patent counts as a measure of R&D is however, statistically significant only at the 10 percent level of confidence in the model containing the full set of controls. We therefore drop this variable and conduct a Toda-Yamamoto test on the remaining variables. The amount of data available for analysis is now extended by 18 years. Once more, we see that agricultural output is statistically significant at the 1 percent level of confidence. The statistical significance of the cumulative sum of first editions of books published on agriculture drops to the 5 percent level of confidence.

We also present in Table 5 multivariate tests of reverse causality for all three specifications. This table is provided mainly for the sake of completeness; it is not the goal of our analysis to identify those factors temporally preceding agricultural output, the cumulative length of the canal network, agricultural patents, first editions of books published on agriculture or acts of enclosure.

The results indicate that the null hypothesis that TFP caused changes in the cumulative length of canals can be rejected at the 5 percent level of confidence. No other variables are statistically significant, not even at the 10 percent level of confidence.

Notwithstanding the fact that if our aim been to explain the extent of the canal network we would have chosen a different set of explanatory variables our interpretation of this finding is that improvements in TFP made it profitable to cultivate land further from population centres thereby generating a demand for transportation services and associated infrastructure. Realising any potential gains from regional specialisation, on the other hand, would have required the canal network to be constructed first.

Table 5. Multivariate Toda-Yamamoto tests of reverse causality

Causal relationship assumed to be absent	No further controls	All controls	1690-1870
TFP → OUTPUT	6.331	5.953	3.767
TFP → CANALS	11.684**	13.465**	13.033**
TFP → PATENTS	2.771	3.932	
TFP → BOOKS	2.113	2.462	1.228
TFP → ENCLOSURE	6.841	6.142	6.188

*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.*

6 Discussion

In this section we investigate alternative assumptions concerning factor shares in order to assess whether our results which indicate that learning-by-doing and the cumulative number of first editions of books on agriculture are causal determinants of TFP are robust. Throughout we adhere to the Toda-Yamamoto methodology outlined earlier: establishing the correct lag length, checking for autocorrelation and using the 'modified' Wald test on the first m lags. The results are displayed in Table 6 and in Table 7 for reverse causality.

The first sensitivity analysis involves looking at the effect of choosing the higher bound value from the two estimates Young (1771) provides for the value of livestock in husbandry. Briefly, Young presents a lower bound estimate of £39.686m and an upper bound estimate of £61.452m. The effect of this change is to increase the share attributable to the user cost of livestock from 0.042 used in the benchmark model, to 0.065. This change however, has almost no effect on the average rate of TFP growth over the period and the quantity of agricultural output and the cumulative number of first editions of books on agriculture are both still significant at the one percent level of confidence.

In the second sensitivity analysis we drop our assumption that the rate of depreciation for horses is 10 percent per annum and despite our reservations, use instead the 70 percent suggested by Young. This increases the factor share for horses from 0.014 to 0.072 which represents a substantial change. Once more however, there appears to be little impact on the results; not only is the average rate of TFP growth unaffected the statistical significance of output and the cumulative number of first editions of books on agriculture does not change either. Both remain statistically significant at the one percent level of confidence.

In the final sensitivity analysis we include an element for the cost of working capital. More specifically, we make the assumption that half the rent and half the taxes, as well as half the cost of the feed and half the cost of labour would have had to be paid in advance. Contrariwise we assume that the full cost of seed has to be paid in advance. These assumptions result in a share for working capital equal to 0.019 which once again fails to alter any of the previous conclusions about either the average rate of TFP or the variables responsible for changes to TFP.

Table 6. Multivariate Toda-Yamamoto tests of causality

Causal relationship assumed to be absent	Increase the user cost of livestock	Increase depreciation for horses	Include financial capital
OUTPUT → TFP	28.297***	29.482***	27.254***
CANALS → TFP	6.654	6.772	6.362
PATENTS → TFP	9.638*	9.938*	9.558*
BOOKS → TFP	15.202***	15.206***	15.200***
ENCLOSURE → TFP	4.616	4.596	4.596

*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.*

Table 7. Multivariate Toda-Yamamoto tests of reverse causality

Causal relationship assumed to be absent	User cost of livestock increased	Depreciation for horses increased	Financial capital included
TFP → OUTPUT	5.836	5.614	6.049
TFP → CANALS	13.422**	13.283**	13.492**
TFP → PATENTS	3.856	3.750	3.989
TFP → BOOKS	2.568	2.734	2.426
TFP → ENCLOSURE	5.999	5.777	6.150

*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.*

7 Conclusions

Inspired by modern-day attempts to explain the rate of TFP in agriculture, this paper explores the causal determinants of agricultural TFP around the time of the agricultural revolution. In so doing, it combines time series data pertaining to agriculture over the period 1690-1914 with information on factor shares in agriculture obtained from a unique contemporaneous source. Together, these are used to create a series for agricultural TFP which shows that, over the period in question, the TFP growth rate was on average 0.24 percent per annum. This series for TFP is then combined with other historical data to determine which, out of a set of variables, Granger-cause TFP. Putative causes of the agricultural revolution are further supplemented by a search through the historical record to identify events that might have impacted agricultural TFP.

Results confirm that changes in agricultural output and the cumulative number of first editions of books on agriculture precede changes in agricultural TFP. Thus the story of the agricultural revolution is consistent with learning-by-doing and improved dissemination and retention of knowledge. The finding that the quantity of output itself caused changes in TFP is something seldom discussed in relation to agriculture let alone in relation to the agricultural revolution. Despite this, evidence for learning-by-doing in other sectors in much later time periods is quite ubiquitous.

The existence of a relationship between transport infrastructure and agricultural TFP also receives some empirical support. The causal relationship however runs, not from the construction of canals to improved TFP through regional specialisation, but from improved

TFP to the construction of canals. The appropriate way of thinking about the relationship between transport infrastructure and agricultural TFP might therefore be one in which improvements in agricultural TFP generates a demand for transport services. Again, this is different from the traditional story in which transport infrastructure facilitates regional specialisation. Nonetheless, we do not wish to push this explanation too hard because our analysis was primarily aimed at explaining agricultural TFP and many other factors not included in our analysis were certainly involved in the expansion of the canal network e.g. incipient economic growth.

Very slim evidence is found to support the contestation that the agricultural revolution was caused by private R&D or the institution of private property i.e. enclosure. It may nonetheless be that these were both important causes of the agricultural revolution but that the variables used to measure these things were inadequate.

Apart of course from improving the underlying data future work might attempt to collect time series data on average farm sizes in order to determine the causal role of farm amalgamation in improving TFP. It would also be interesting to try to compile a series on the openness to trade in agricultural commodities since according to some studies this too might be expected to impact TFP.

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