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ESTIMATING ENGLISH WHEAT PRODUCTION IN THE INDUSTRIAL REVOLUTION

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Abstract

Wheat was the single most important product of the British economy during the Industrial Revolution, being both the largest component of national income and the primary determinant of caloric intake. This paper offers new estimates of annual wheat production during industrialisation. Whereas other researchers infer wheat production indirectly from demand equations, we estimate production directly from output equations. Our estimates are based on a new time series model of wheat yields, encompassing both environmental and technological variables. We trace the impact of war and population growth on wheat yields, mediated through changes in the economic incentives for wheat cultivation. We test the accuracy of our new wheat output series by modelling the market price of wheat in England between 1700 and 1825.

Keywords: Technology, climate, agriculture.

JEL Classification: N5, O3, Q1, Q2.

ESTIMATING ENGLISH WHEAT PRODUCTION IN THE INDUSTRIAL REVOLUTION[1]

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I. Introduction. In this paper we construct annual estimates of English wheat output during the Industrial Revolution. Our estimates bear directly on two important branches of the literature on industrialisation. First, wheat was by far the most valuable crop produced by the agricultural sector, so estimates of national income are substantially influenced by estimates of total wheat production. Second, there has been considerable debate about the caloric intake of labourers during industrialisation. Wheat was by far the most important element in the English diet. If we have direct estimates of wheat production then we can easily calculate the per capita consumption of wheat (since we have good data on imports and exports).[2]

There are two approaches to estimating the output of wheat: either we can estimate the supply of wheat or we can estimate the demand for wheat. Since supply and demand will be equal in equilibrium, these two methods should give the same answer. All the recent estimates of wheat production have relied on the demand-side approach. In this paper we present a new output series based on the supply-side approach.

The basic demand-side approach takes the consumption of wheat as a simple function of population.[3] However, Crafts noted that the total quantity demanded is a function of population, income per head and the market price of wheat.[4] There is good data available on both population and prices - and by making certain assumptions about the price and income elasticities of wheat, it is possible to solve iteratively for both wheat consumption and income per head.[5] Crafts' estimates of total wheat consumption are more precise because they use a more sophisticated model to harness a lot more data (i.e. annual prices).[6]

The basic supply-side approach estimates the output of wheat as a simple product of land inputs and 'representative' yield data.[7] This paper makes two improvements to this method of estimation. First, the quantity of land in wheat production is a function of both the arable acreage and the crop rotation in use. We compile new data on crop rotation through the eighteenth and nineteenth centuries. Second, the weakest link in the computational chain has traditionally been the yield data. There is very little yield data available before the 1860s. Moreover, the vagaries of weather make the annual yield fluctuation

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[2] Deane P and W A Cole, *British Economic Growth, 1688-1959* (Cambridge, 1962).

[3] Fussell G E and M Compton, *Economic History, a supplement of the Economic Journal*, Vol. 3 (1939).

[4] Crafts N F R, 'English Economic Growth in the Eighteenth Century: a re-examination of Deane and Cole's Estimates,' *Economic History Review*, Vol. 29 (1976), 226-235.

[5] Population figures are available in Wrigley E A and R S Schofield, *A Population History of England, 1541-1871*. Price data is widely available, for example in Mitchell B R, *British Historical Statistics*, (Cambridge, 1988). Crafts takes estimates of price and income elasticities from Mellor J W, *The Economics of Agricultural Development*, (Ithaca, 1966).

[6] Crafts N F R and C K Harley, 'Output Growth and the British Industrial Revolution: a re-statement of the Crafts-Harley View,' *Economic History Review*, Vol. 45 (1992), 703-30.

[7] Deane P and W A Cole, *British Economic Growth, 1688-1959* (Cambridge, 1962).

extremely high (around ±40 per cent). Runs of good or bad weather mean that even over periods of 5 or 10 years the average yield can be substantially different from the 'representative' yield. In this paper we model the wheat yield much more fully - taking into account weather, labour, capital and technology. We can therefore construct a series for total wheat output which is much more precise and reliable than those presented by earlier researchers.

In the next Section we estimate a time series model of English wheat yields. We find that the new time series model is consistent with the cross-sectional model presented previously and it successfully predicts good and bad harvests over the period 1728-1870.[8] In Section III we use the time series model to construct annual data for wheat yields which successfully simulates the available benchmark data. In Section IV we estimate annual total wheat output for the period 1700 to 1870. We test the new output series against price data by estimating a price equation for the English wheat market. Section V concludes.

II. A Time Series Model of English Wheat Yields. A time series model of wheat yields is an essential extension to our earlier cross-sectional model. The annual fluctuation of weather variables in England is much greater than the cross-sectional variation.[9] So we cannot simply use a cross-sectional model to predict annual yields because we would be predicting a long way out of sample (which would cause substantial errors). We therefore estimate a new model based on annual yield data for 1815-59 compiled by the Liverpool corn merchants.[10] As with the cross-sectional model, we use monthly weather data for the growing season running up to each harvest.[11]

The difficulty of estimating a time series model is that we do not have annual data on all the relevant variables (fertiliser, crop rotation, et cetera). But in fact this is not a serious problem. The annual fluctuation in wheat yields is overwhelmingly determined by the annual variation in weather. This is partly because crop yields are very sensitive to the impact of weather; but it is also because the year-on-year fluctuation of weather is much greater than the year-on-year fluctuation of other inputs (such as technology or the capital stock). Hence we would expect any time series model of wheat yields to focus almost exclusively on weather variables.[12] We control for the possibility of increasing capitalisation and technological change by adding a time trend to our model.[13] We therefore estimate the model in Table 1 below.

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[8] Brunt L, 'Nature or Nurture? Explaining English Wheat Yields in the Agricultural Revolution,' *Oxford University Discussion Papers in Economic and Social History*, No. 19 (Oxford, 1997).

[9] For example, in August the wettest place in England (Kendal in Cumbria) receives 3 times as much rainfall as the driest place (Hadleigh in Norfolk); but the wettest August on record (1878) received 330 times as much rainfall as the driest year (1730).

[10] The series is reproduced in Thirsk J (ed.), *The Agrarian History of England and Wales*, Vol. 6, Statistical Appendix, p1051. The authors note that the Liverpool yield series is 'liable to substantial positive bias' but the series successfully captures the annual variation. In order to estimate coefficients which are not biased upwards we chose to deflate the Liverpool series. The mean for the Liverpool series was 40 bushels, whereas a more realistic level for the period would be 25 bushels - so we simply multiplied all the yields by 0.625.

[11] The temperature series is taken from Manley G, 'Central England Temperatures: Monthly Means 1659 to 1973,' *Quarterly Journal of the Royal Meteorological Society*, Vol. 100 (1974), 389-405. The rainfall data is taken from Wales-Smith B G, 'Monthly and Annual Totals of Rainfall Representative of Kew, Surrey, 1697 to 1970,' *Meteorological Magazine*, Vol. 100 (1971), 345-363.

[12] This is the approach taken by biologists. Chmielewski F-M and J M Potts, 'The Relationship between Crop Yields from an Experiment in Southern England and Long-term Climate Variations,' *Agricultural and Forest Meteorology*, Vol. 73 (1995), 43-66. Nicholls N, 'Increased Australian Wheat Yield due to Recent Climate Trend,' *Nature*, Vol. 387 (1997), 484-5.

[13] We first tested for a unit root in order to establish that a time trend was a reasonable functional form. The unit root was rejected at the 5 per cent level.

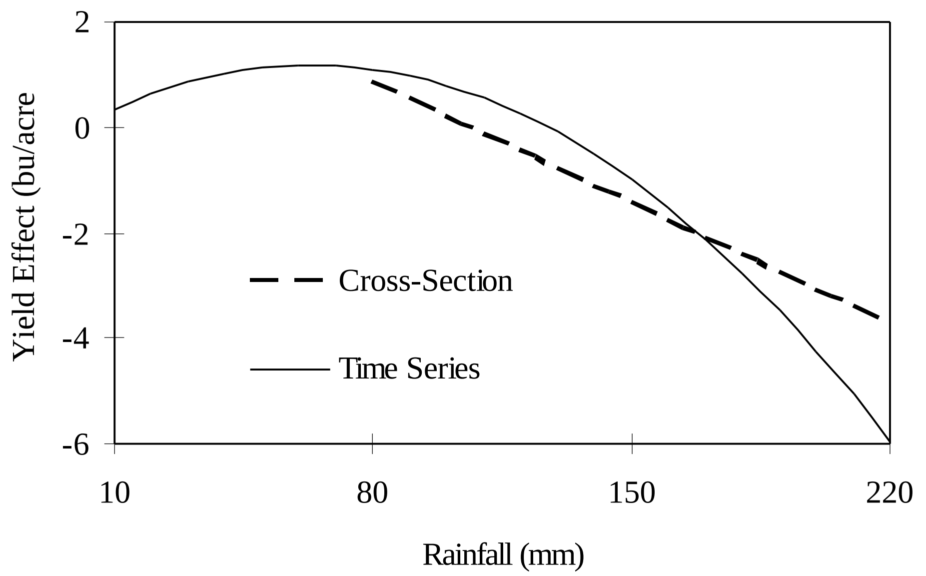
Table 1. A Model of English Wheat Yields, 1815-1859 (bu/acre).

Variables Explaining WHEAT YIELD	Coefficient	t-statistic
July-August Rainfall	0.037	0.81
July-August Rainfall Squared	-2.917	-1.70
July-August Temperature Change (Cube Root)	0.835	1.95*
December-January Mean Temperature	21.560	1.77
December-March Rainfall	-0.021	-1.99*
Year	0.294	6.67**
R^2	**0.79**	
Adjusted R^2	**0.75**	
SE of the Equation	**3.03**	
F-statistic	**23.50**	
Durbin-Watson	**1.63**	
N	**45**	

Note: ** are significant at the 1 per cent level; * are significant at the 5 per cent level. The other variables are not significant due to multi-collinearity; we decided to retain them after an F-test showed that they had high explanatory power.

The weather variables retained in the time series model are essentially those which are significant in our cross-sectional model and the estimated effects are similar. The specification is slightly different because the weather variables take on more extreme values over time. For example, a quadratic is used to describe the effect of July-August Rainfall in the time series model, whereas a linear relationship holds in cross-section. This is simply because all the cross-sectional observations lie above the turning point described by the time series data. If we plot the two estimated curves then we find that they are congruent when measured over the same range, as demonstrated in Figure 1 below.

Figure 1. The Effect of Rainfall on Wheat Yields: a Comparison of Time and Space.



Notice that the cross-section curve is slightly flatter than the time series (that is, yields are less responsive to rainfall in the cross-section). This is exactly what we would expect because the cross-section estimates are based on 'normal' yields responding to 'normal' weather. So in the cross-section the farmers can partly off-set excessive rainfall by adapting their farming practices (such as choosing varieties of wheat with high resilience to rainfall). By contrast, in the time series the farmers plant their seed in October and they have no knowledge of the rainfall that will actually fall in the following summer - so they are less able to adapt.

It is impossible to test our model directly against measured yield data because there are no such series available before the 1870s, even for a short period. However, we can verify our model against other sources. The time series model effectively breaks down the change in wheat yields into two components. First, there is an upward trend which is determined by factors such as capital and technology (which we cannot model explicitly here due to the lack of detailed data). Second, there is a substantial fluctuation around the trend caused by the annual variation in weather. Separating out these two effects allows us to test our model.

We use the model to estimate the effect of weather on the wheat yield in each year from 1697 to 1870. By ignoring the trend we are calculating the extent to which the wheat yield in any particular year was above or below 'normal'. (Of course, a 'bad' year around 1870 could still have a higher yield than a 'good' year around 1700 because the level of yields was trending upwards.) The series thus produced is comparable to the harvest assessments made by Jones.[14] On the basis of qualitative evidence, Jones assessed all the harvests between 1728 and 1911 and noted whether they were above or below average. We used his assessment to grade all the wheat harvests up to 1870 on a scale of 1 to 5. Average years were given a grade of 3; 'good' years earned a grade of 4; and 'very good' or 'bumper' years were graded 5; grade 2 years were 'bad'; and grade 1 years were 'very bad'. We correlated the annual estimates based on Jones' research with the new yield series generated by our model. The results are graphed in Figure 2 overleaf. The correlation between the two series is 0.40 (p=0.014). Given the coarse nature of one of the data series (i.e. a simple scale of 1 to 5) we find this result very encouraging and worth testing more fully.[15]

We have now estimated a time series weather model for the period 1815-59 which is consistent with our cross-sectional findings for the late eighteenth century. The new model successfully predicts good and bad harvest in the period 1728 to 1870. In the next Section we model more fully the upward trend in yields and hence produce a more accurate annual yield series, which we test against benchmark estimates.

III. Estimating Annual Yields. In order to accurately model wheat yields over time we need to take into account both the effect of weather and the effect of man-made factors (capital, technology, and so on). In the previous section we estimated the annual impact of weather on wheat yields. So in order to construct an annual estimate of the wheat yield, it merely remains to calculate the influence of man-made factors in each year. Clearly, calculating the effects of specific man-made factors would be preferable to relying on a simple linear trend, as we were forced to do when estimating the time series model. We have already modelled the response of wheat yields to man-made factors in another paper and we can use those results to assist us in this paper, as follows.[16]

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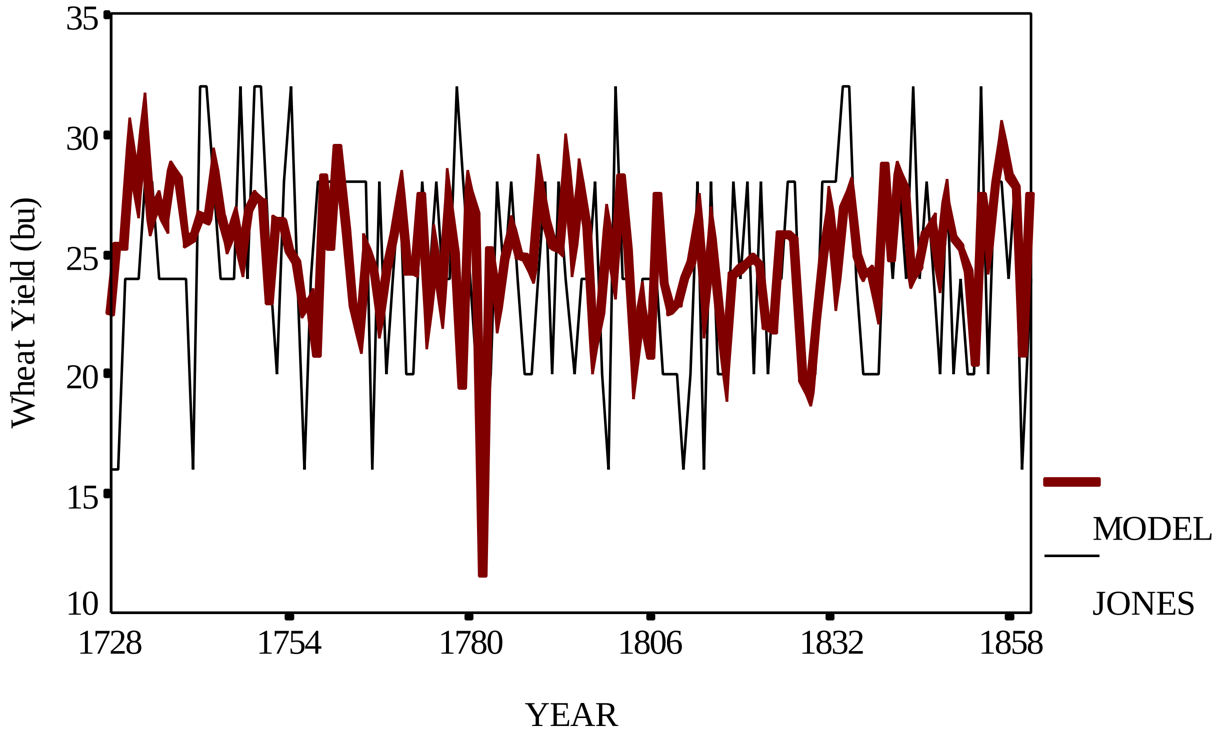
[14] Jones E L, *Seasons and Prices* (Chichester, 1964).

[15] The exceptionally large outlier predicted by the model in 1782 is probably due to inaccurate weather data because the rainfall data is contaminated for that particular year. See Wales-Smith B G, 'Monthly and Annual Totals of Rainfall Representative of Kew, Surrey, 1697 to 1970,' *Meteorological Magazine*, Vol. 100 (1971), 360.

[16] Brunt L, 'Nature or Nurture? Explaining English Wheat Yields in the Agricultural Revolution,' *Oxford University Discussion Papers in Economic and Social History*, No. 19 (Oxford, 1997).

Figure 2. Weather Shocks to English Wheat Yields, 1728-1861 (bu/acre).

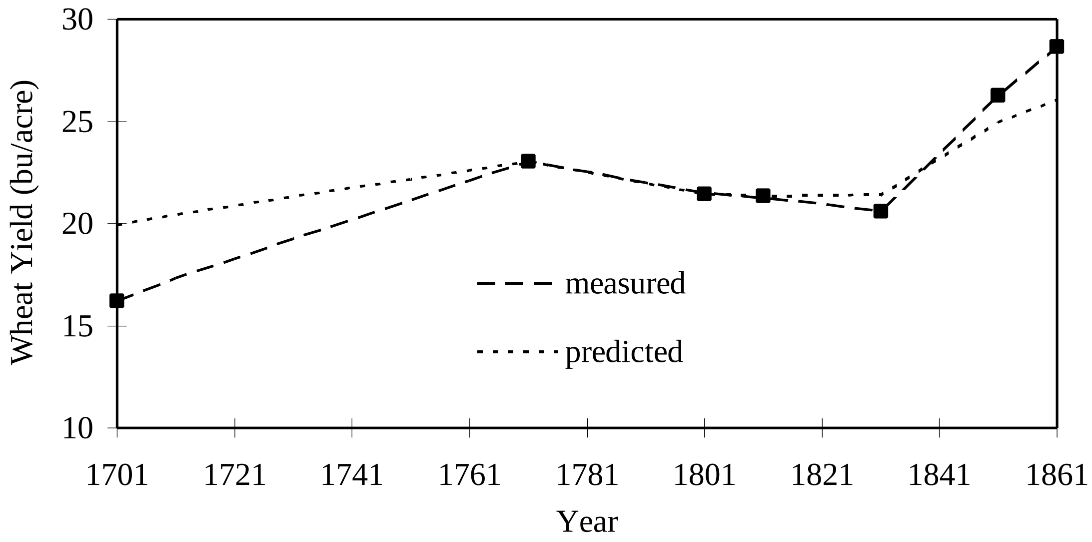


There are benchmark data available for each of the man-made factors which feature in the technology model formulated in our earlier paper (such as crop rotation, fertiliser use, drainage and machinery inputs). We interpolate linearly between the benchmarks in order to generate annual series for each input. We then take these annual series and calculate the effect of each input by imposing the coefficients derived in our earlier paper. This process allows us to estimate changes in the trend growth of wheat yields over the period. We combine this new estimate of the man-made trend with our annual estimate of weather shocks, as generated by the model outlined above. This combination generates an annual wheat yield series for the period 1698 to 1860.

We noted above that there were no annual series of wheat yields against which we could test our model. However, there are benchmark estimates available from a variety of sources. In general, the available sources represent survey data rather than census data - that is to say, they record yields in an average year rather than any particular year. For example, there are probate inventories from the 1690s; wartime surveys around 1800; Caird's survey of 1850; the Mark Lane Express of 1860. In consequence, we constructed benchmark estimates based on average wheat yields harvested over the preceding five years. We find a very high correlation between our benchmark estimates and the measured yield data over the period: the correlation is 0.95 (p=0.001). This is demonstrated clearly in Figure 3 overleaf.

It will be seen that the model predicts very well through the middle of the period but is less accurate towards the limits. In particular, it over-predicts around 1700 and under-predicts around 1860. This can be largely explained by two factors.

Figure 3. The Rise and Fall of English Wheat Yields, 1700-1861 (bu/acre).



The model over-predicts by 3.6 bushels around 1700 (19.8 bushels rather than the 16.2 bushels actually measured). The most plausible reason for this discrepancy is missing weather data. The available weather series only start in 1697, so the estimate for 1700 is based on the weather data for only the three preceding years. Moreover, it is generally thought that the weather of the 1690s was particularly poor.[17] If the weather effect of 1695 and 1696 were one standard deviation below average then the predicted value for 1700 would fall from 19.8 to 18.8 bushels; if the weather effect was two standard deviations below average then the predicted value for 1700 would fall to 17.8 bushels. The over-prediction of the model would thus be reduced to only 10 per cent, which we consider to be fairly satisfactory given the limitations of the data.

The progressive under-prediction from the 1850s onwards is probably due to the effect of new fertilisers which started to appear in bulk in the 1850s, in particular guano. These fertilisers are thought to have been particularly effective because they were rich in phosphorus and potassium, which were scarce elements in traditional nitrogen-rich fertilisers. These fertilisers do not appear in our model because they were not available in 1770, so we have no direct estimate of their effect on yields. However, on-going research using data from the Rothamsted Experimental Station suggests that guano imports are the primary cause of our yield under-estimate after 1845. In the future we will to be able to correct for the effect of guano explicitly on the basis of the Rothamsted study.

One of the striking aspects of the yield series graphed in Figure 2 above is that yields fell during the late eighteenth century. Indeed, this has lad a number of commentators to doubt the accuracy of the 1771 estimates (taken from Arthur Young).[18] But if we break down the changes in yields over the period then we see exactly why yields evolved in such an unexpected manner.

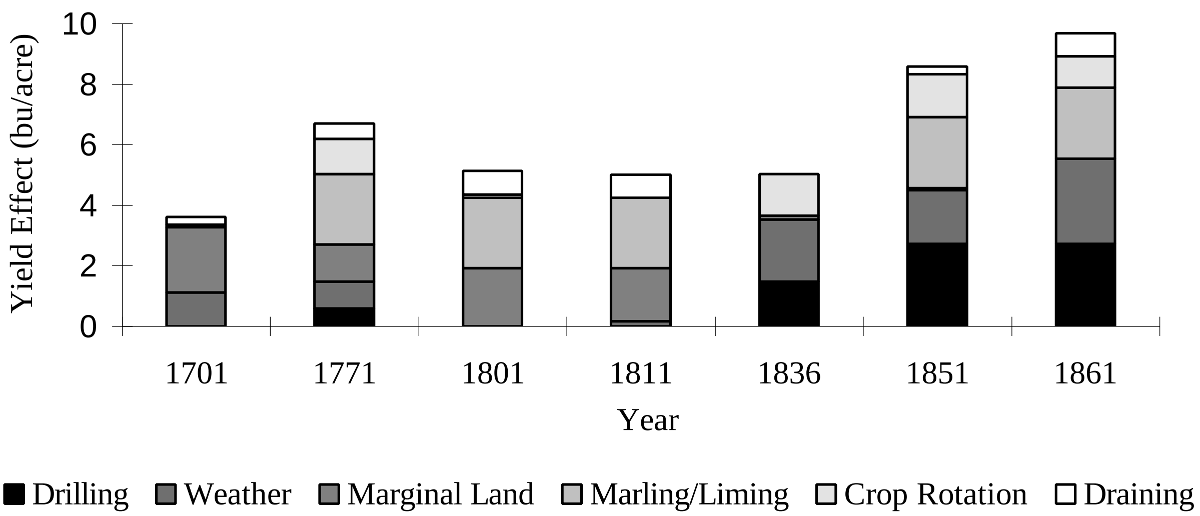
[17] Overton M, *The Agricultural Revolution in England* (Cambridge, 1996), 77.
[18] For example, see Kerridge E, 'Arthur Young and William Marshall,' *History Studies*, Vol. 1 (1968), 43-53.

Table 2. Sources of the Change in English Wheat Yields, 1700-1860 (bu/acre).

	1700	1771	1801	1816	1836	1851	1861
Drainage	-0.56	-0.26	0.00	0.00	-0.75	-0.33	-0.03
Drilling & Hoeing	0.00	0.59	0.00	0.15	1.62	2.58	2.50
Crop Rotation	-4.60	-3.46	-4.57	-4.68	-3.23	-3.18	-3.33
Marginal Land	0.00	-0.94	-0.25	-0.42	-2.04	-2.10	-2.13
Fertilisers	0.32	2.71	2.69	1.66	1.71	3.20	3.48
Weather	-1.66	-1.88	-2.32	-2.05	-0.71	-1.00	0.04
Predicted Yield	**19.81**	**23.08**	**21.87**	**20.97**	**22.91**	**25.48**	**26.86**
Measured Yield	*16.20*	*23.08*	*21.50*	*21.26*	*20.6*	*26.26*	*28.65*

It may be useful to summarise these fluctuations graphically, which we do in Figure 4 below. (In order to facilitate comparisons between factors and across years we have taken the lowest value for each factor and normalised it to zero, so that all the contributions appear to be positive on the graph. For example, the weather effect for 1801 has been set to zero so that we can see how much higher the yield was in other years due to more benign weather. This is just a graphical device to help us focus our attention on the *change* in yields over time rather than the level *per se*).

Figure 4. Sources of the Change in English Wheat Yields, 1700-1860 (bu/acre).



Decomposing the change in wheat yields into its component parts reveals a great deal of information about the historical causes of productivity change in English agriculture. However, it is quite complicated to interpret these changes because there are many causes and many interactions within the data. To draw out the finer points we will now discuss each component in some detail.

One of the most important factors determining the wheat yield is the crop rotation employed. Crops need to be rotated in order to put nutrients back into the soil. In general, cultivating grain crops reduces the fertility of the soil (and hence the yield) and growing vegetables and fallow crops increases the fertility of the soil (and hence the yield). As turnips replaced fallow between 1701 and 1771, there was upward pressure on wheat yields because turnips were a more effective source of nutrients than fallow. By 1771 the effect of crop rotation reached a peak because the average crop rotation featured a large proportion of turnips and a relatively small proportion of grain crops - so the wheat yield was correspondingly high. But as the price of wheat rose dramatically though the Revolutionary and Napoleonic Wars (1793 onwards) farmers grew a higher proportion of wheat and accepted a lower wheat yield per acre. In the post-war depression the proportion of wheat in the rotation shrank dramatically (thus improving yields) but thereafter increased in response to rising prices. Two aspects of this process need to be stressed.

First, the change in crop rotation was a rational response to temporarily high prices. The soil is effectively a 'nutrient bank' where the farmer can either make a deposit or a withdrawal. When wheat prices were temporarily high during the Napoleonic Wars it was optimal for the farmer to make a withdrawal (i.e. grow more wheat in the rotation) and run down the quality of the soil. After the war when wheat prices fell again it was optimal to make a deposit (i.e. grow less wheat in the rotation) and improve the quality of the soil. This behaviour is clearly demonstrated in Table 3 below.

Table 3. Crop Proportions in English Agriculture, 1700-1870.

Crop	1700	1771	1801	1816	1836	1851	1861
Wheat	**19.60**	**19.13**	**24.56**	**27.50**	**23.00**	**24.85**	**24.79**
Barley	24.24	17.62	16.44	7.49	13.00	18.84	15.32
Oats	9.63	16.68	20.74	25.00	12.00	9.20	13.29
Peas	12.42	8.62	5.97	5.13	3.14	3.03	2.40
Beans	4.12	2.90	3.55	3.05	1.86	1.80	3.76
Turnips	0.00	12.42	6.93	10.00	11.00	16.01	15.28
Clover	0.00	10.34	10.00	10.00	22.00	19.91	19.32
Fallow	30.00	12.28	11.81	11.81	12.00	6.32	6.59

Sources: 1700: Mean percentages taken from the sample of counties prepared by Overton from probate inventories (reproduced in Overton M, *Agricultural Revolution in England* (Cambridge, 1996). Since there was no data on fallow we have added an estimate (assumed equal to 1770) and adjusted the other percentages accordingly. The other percentages are not particularly sensitive to adjustments of the fallow percentage.
1771: Taken from Arthur Young's *Tours*.
1801: The 1801 crop returns as reproduced in Overton M, *Agricultural Revolution in England* (Cambridge, 1996). Since the 1801 returns do not include data on fallow, we have assumed that they occupied the same percentage as in 1816 and deflated the other percentages accordingly.
1816: Comber W T, *An Inquiry into the State of the National Subsistence* (London, 1808).
1836: Kain R J P and Prince, *The Tithe Surveys of England and Wales* (Cambridge, 1986), as reproduced in Overton M, *Agricultural Revolution in England* (Cambridge, 1996).
1851: British Government, *Agricultural Census* (Sample Returns for 1854), as reproduced in J Thirsk (ed.) *The Agrarian History of England and Wales*, Vol. 6 (Cambridge, 1989), 1042-3.
1861: British Government, *Agricultural Census* (Returns for 1871), as reproduced in Overton M, *Agricultural Revolution in England* (Cambridge, 1996).

The second point to note is that variations in total wheat output are much more sensitive to changes in crop rotation than changes in arable acreage. There are two methods of raising wheat output by 25 per cent. One option is to keep the same crop rotation and increase the arable acreage by 25 per cent. This is clearly very costly because it involves a high fixed cost for bringing new land into production (even if the farmer simply ploughs up his pasture land). Moreover, since the new land is likely to be of lower quality it will require an acreage increase in excess of 25 per cent (we address this issue in more detail below). The second option is to keep the same arable acreage and grow 25 per cent wheat instead of 20 per cent wheat. This point has been largely over-looked in the literature on the Agricultural Revolution but it bears on a number of important issues. For example, Chambers and Mingay estimated changes in the quantity of farm land as a function of changes in the population (assuming a stable amount of wheat consumption per capita).[19] Since the crop rotation varied substantially over time, this is clearly a flawed line of reasoning.

Our model shows that taking marginal land into production has a significant adverse effect on the average yield. We assume in our calculations that changes in arable area are achieved by moving marginal land into or out of production. This affects the average yield through two mechanisms. First, the natural fertility of marginal land is lower and therefore the yield is around 8 bushels below average.[20] As total production rises through the nineteenth century this drives down average yields by around 2 bushels, as demonstrated in Table 2 above. Second, marginal land is likely to be poorly drained. Over time, there were increases in both the acreage of marginal land in production and the acreage of land which had been artificially drained. Whether the overall drainage situation became better or worse depended on whether marginal land or drainage was increasing at a faster rate. Between 1700 and 1800 drainage was increasing faster and wheat yields were consequently pushed upwards (again see Table 2 above). The increasing use of marginal land began to push yields down substantially in the 1830s; but the invention of cheap clay pipes in the 1840s precipitated a massive increase in the quantity of land drainage.[21] Thereafter the adverse affect of poor natural drainage was progressively reduced (even though ever more marginal land was being brought into production) until poor drainage was eliminated by about 1870 (when artificial drainage projects ceased).

Our simulations show that fertilisers were one of the most important factors influencing the wheat yield, especially liming and marling. This is partly because wheat yields are very sensitive to applications of fertiliser, so that even small changes in the rate of use have a significant effect on yields. But also the effect of some fertilisers is particularly marked on marginal land - so as ever more marginal land was brought into production after 1700, the impact of fertiliser rose and rose. For example, paring and burning raised the yield on Grade 3 land (the most marginal type) by 2 bushels.[22] In fact, approximately one half of the adverse effect of marginal land - fully 1 bushel per acre - was off-set by the increasing use of fertilisers.

We showed in an earlier paper that the returns to seed drilling and horse-hoeing were very high (around 9 bushels per acre). There was a widespread take-up of drills during the first half of the nineteenth century - a period sometimes referred to as the ‘Age of High Farming’ due to its high level of capitalisation and technological efficiency. Walton estimates that the proportion of farmers using drills rose from 3 per cent in 1815 to 35 per cent in 1860, which would result in an average increase of more than 2 bushels per acre (as in Table 2 above).[23] It is also worth noting that Walton finds a temporary move to drilling in the 1770s, when he estimates that around seven per cent of farmers used a drill. This is remarkably close to the eight per cent of farmers using a drill in the Young data set (which is entirely independent of Walton’s sample). This would partly explain the exceptionally wheat high yields which Young found in 1770, since drills were adding 0.6 bushels per acre on average.[24]

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[19] Chambers J D and G E Mingay, *The Agricultural Revolution, 1750-1880* (Batsford, 1966), 34.

[20] We assume that marginal land was of Grade 3 quality, neither sandy or clay, in need of drainage, and growing an average crop rotation. See Brunt L, ‘Nature or Nurture,’ for detailed analysis.

[21] Trafford B D, ‘Field Drainage,’ *Journal of the Royal Agricultural Society of England*, Vol. 131 (1970), 129-152.

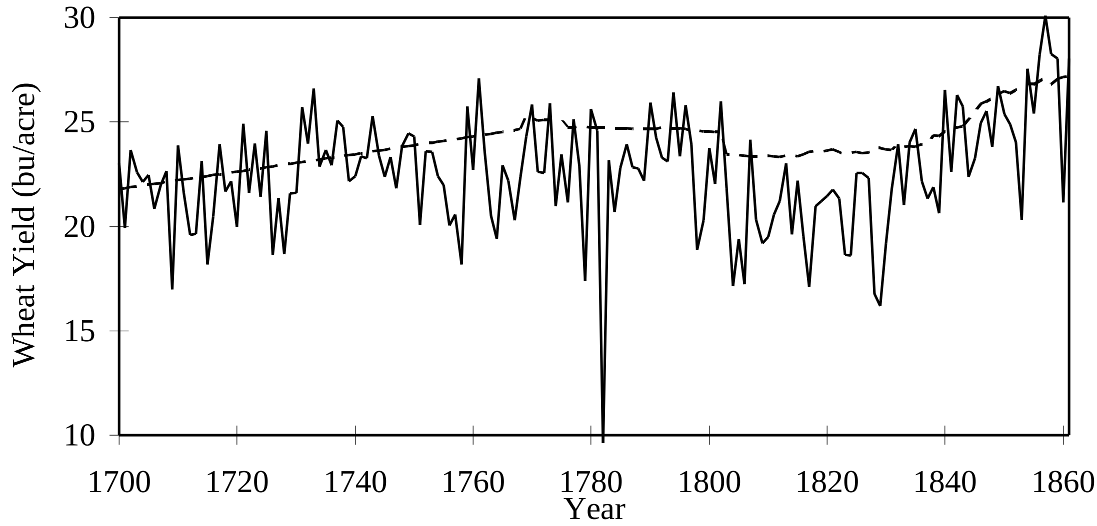
[22] Paring and burning involves tearing out scrub vegetation which has invaded the fields and burning the debris, thus returning nitrogen-rich compounds to the soil.

[23] Walton J R, ‘A Study of the Adoption Process,’ in Fox H S A and R A Butlin (eds.) *Change in the Countryside: essays on rural England 1500-1900*, (Institute of British Geographers Special Publication 10). Not everyone who used a seed drill subsequently used a horse-hoe. We have assumed that the ratio of horse-hoeing to seed-drilling was constant through the period. The qualitative evidence suggests that in reality the ratio increased, so the total effect is probably more marked than we have estimated.

[24] One might wonder why the use of drills declined after 1770 if they were so effective. The decline might well have been due to the increasing price of labour during the war. A similar effect was noted in technologically advanced Californian

One of the most important results of our model is that variations in weather cause substantial fluctuations in the wheat yield, even when averaged over periods as long as five or ten years. In consequence, benchmark data can be very misleading and need to be treated with some caution. For example, our model predicts an increase in yields from 17.8 bushels around 1700 to 26.9 bushels around 1860 - an increase of 51 per cent. But we know that the weather was particularly poor in the 1690s and particularly good in the late 1850s. If we control for the effect of weather then our model suggests that the 'real' change in yields over the period was from 21.5 bushels to 26.8 bushels - an increase of only 25 per cent. Given the magnitude of the annual fluctuations in wheat yields, our model probably gives a more reliable prediction of 'normal' yields in any particular year than actual measured data. In Figure 5 below we graph both the underlying wheat yield (determined by capital, technology, etc.) and the actual wheat yield realised in response to weather shocks.

Figure 5. English Wheat Yields in the Absence of Weather Shocks (bu/acre).



Although our model suggests that the underlying increase in wheat yields over the period 1700 to 1860 was much more modest than the prima facie increase, we should nonetheless be wary of drawing direct conclusions about productivity growth. For example, there was little increase in the wheat yield because improvements in technology were being partially offset by the rising proportion of wheat in the crop rotation. So the productivity of land *across the whole crop rotation* had risen substantially because a high-value product (wheat) had replaced a low-value product (fallow). But this increase in the productivity of land was *not* reflected in higher wheat yields per acre, and in fact they were *inversely* correlated. This really brings home the point that in order to fully understand changes in productivity we need to consider a wide range of agricultural factors in the context of a model which is internally consistent. Otherwise it is easy to be misled.

In this Section we have shown that our model replicates accurately the evolution of wheat yields between 1700 and 1860. In the next Section we put our new yield series to work by estimating the total output of wheat in England in each year from 1700 to 1860. This enables us to run further tests on our

agriculture in the nineteenth century. See Olmstead A L and P Rhode, 'An Overview of California Agricultural Mechanization, 1870-1930,' *Agricultural History*, Vol. 62 (1988), 86-112.

model using price data, which for the eighteenth century is the only annual indicator available regarding the state of the wheat market.

IV. Estimating Annual Output. In order to calculate the annual output of wheat we need to know the yield per acre and the number of acres in wheat cultivation. The number of acres in wheat cultivation is a product of the total arable acreage and the proportion of land under wheat (i.e. the crop rotation). For the period 1700 to 1860 we now have detailed information on yields and crop rotation but only sketchy data on total arable acreage. So let us turn to a consideration of total arable acreage.

Any figures for total arable acreage are controversial but the plausible range of values is fortunately relatively limited. Whereas the annual variation in wheat yields is in the order of ±40 per cent, the range of arable acreage estimates is only ±10 per cent. So any error in our estimate of total wheat output (induced by our estimate of arable acreage) is likely to be correspondingly modest. We also have a model of wheat yields to help us in our task. Estimates of arable acreage have traditionally been based on a straight choice by the researcher between competing estimates (for example, that of Comber for 1808 versus that of Stevenson for 1812). This is a rather ad hoc way of proceeding based on our like or dislike of particular historical commentators. But now we can use the wheat yield model to work through all the implications of our data choices for acreage and yields simultaneously. For example, if we postulate an increase in wheat acreage between two dates then the addition of marginal land to production will put downward pressure on yields. We must be able to reconcile this effect with our estimate of changes in wheat yields over the same period. This forces us to make data choices which are internally consistent. Considering the available sources and taking all these effects into account, we have adopted the estimates of arable acreage reproduced in Table 4 overleaf.

Calculating total wheat output is very straightforward given the arable acreage, crop rotation and wheat yield. There was a substantial increase in output over the period 1700 to 1840, roughly keeping pace with the rise in population. In Figure 6 overleaf we graph annual estimates of per capita wheat output (net of imports and exports).[25]

There are two striking features of Figure 6. First, per capita wheat consumption fluctuated wildly from year to year (even allowing for international trade). This is simply a function of the high variability of wheat yields. Consumers must have substituted into and out of wheat products on an annual basis in response to the harvest. Second, there was a dip in wheat consumption during the Napoleonic Wars and in the post-war depression. The dip would be slightly off-set by the changing age structure of the population (more children relative to adult consumers) but the basic result is robust to this adjustment. This is consistent with recent demand-side estimates by Allen, who also finds a decline in per capita agricultural production over the same period.[26]

Table 4. Acreage of Arable and Pasture in England, 1700-1870.

Year	Arable (acres)	Pasture (acres)	Total (acres)	% Arable
1700	11 000 000	10 000 000	21 000 000	52.38
1769	12 762 900	14 237 100	27 000 000	47.27
1779	12 607 705			
1801	11 350 501	16 796 458	28 146 959	40.33

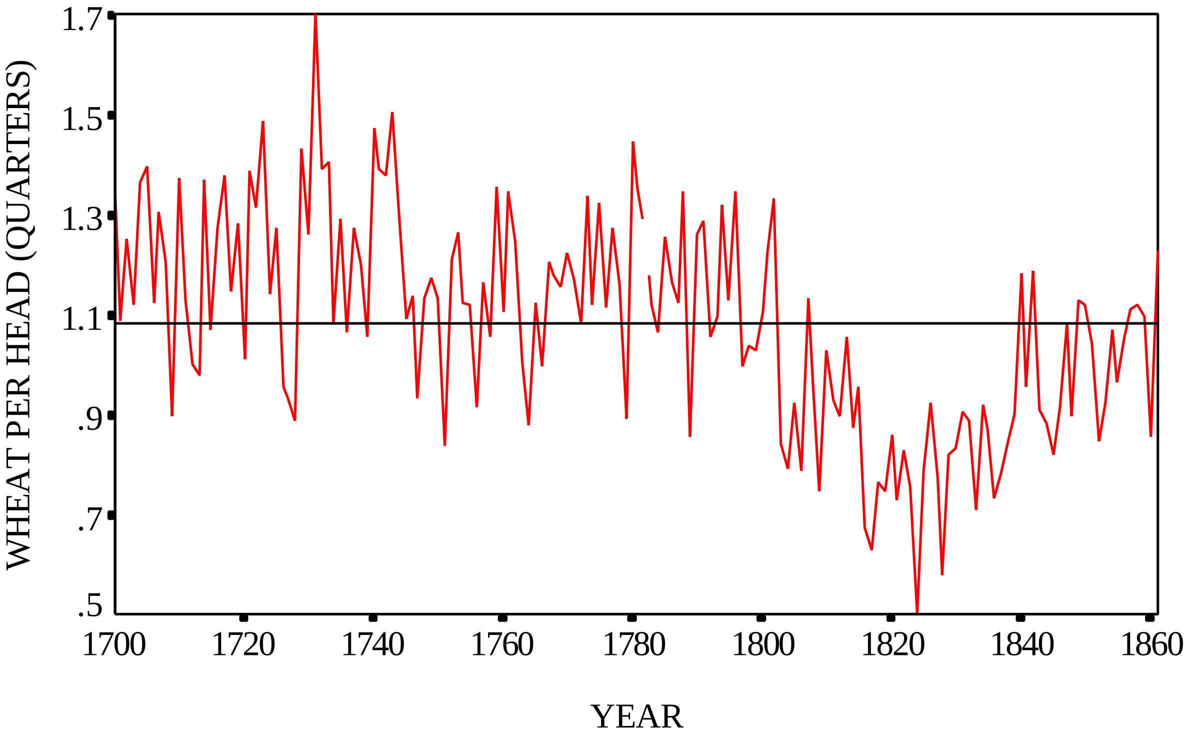
[25] We end the output series in 1840 because the wheat yield estimates are almost certainly too low thereafter. As discussed above, the underestimate probably grows over time due to the impact of guano.

[26] Allen R C, 'Agricultural Output and Productivity in Europe, 1300-1800,' University of British Columbia, Department of Economics Discussion Paper 98-14.

1808	11 575 000	17 495 000	29 070 000	39.82
1836	15 092 555	16 363 409	31 455 964	47.98
1850	13 667 000	13 332 000	26 999 000	50.62
1854	15 261 842	12 392 137	27 653 979	55.19
1866	14 290 759	10 255 748	24 546 507	58.22
1871	14 900 000	11 400 000	26 300 000	56.65

Sources: 1700: King G, *Natural and Political Observations… upon the State and Condition of England* (London, 1696).
1769: Young A, *The Farmer's Tour of the East of England* (London, 1771) estimates total agricultural area at 27 000 000 acres (broken down into 10 300 000 arable and 16 700 000 pastoral). We accept his total figure but not his arable-pastoral ratio. Instead, we calculate the arable-pastoral ratio from the detailed minutes of the *Tours*, based on the survey of 400 farms. This arable-pastoral ratio is more plausible in the light of both earlier and later figures; and it gives a more plausible arable total.
1779: Young A, *Political Arithmetic* (London, 1779), 27.
1801: Capper B P, *A Statistical Account of the Population and Cultivation...of England and Wales* (London, 1801), 66-73.
1808: Comber W T, *An Inquiry into the State of the National Subsistence* (London, 1808).
1836: Kain R J P and Prince, *The Tithe Surveys of England and Wales* (Cambridge, 1986), as reproduced in M Overton.
1850: Caird J, *English Agriculture* (London, 1852).
1854: British Government, *Agricultural Census* (Sample Returns for 1854) as reproduced in J Thirsk (ed.) *The Agrarian History of England and Wales*, Vol. 6 (Cambridge, 1989), 1042-3.
1871: British Government, *Agricultural Census* (Returns for 1871), as reproduced in M Overton.

Figure 6. English Per Capita Wheat Output, 1700-1840.



It now remains to assess the accuracy of our output series. Since there is no independent output series for wheat before the mid-nineteenth century the best approach is to undertake an indirect test using annual price data. Hence we are going to model the annual market price of wheat. We will first set up the equilibrium equation and then discuss what restrictions we might expect to hold. We will then estimate the equation using our output series and the other relevant variables.

Suppose that domestic and foreign wheat are imperfect substitutes. Then a standard demand function for domestically produced wheat for an individual consumer can be written as follows:

$$q^D_i = q^D_i(wd, wf, p, y)$$

where, wd=domestic wheat price, p=consumer price index, y=individual real income and wf=price of foreign wheat in England. If consumers are identical then we can derive the market demand function simply by summing across all N consumers:

$$Q^D = \sum_{i=1}^{N} q^D_i = Nq^D(wd, wf, p, Y/N)$$

where Q^D=demand for domestic wheat and Y/N=national income per head. Taking the inverse of this demand equation gives us a price equation for domestic wheat:

$$wd = wd(Q^D/N, wf, p, Y/N) \qquad (1)$$

Now let us consider the supply-side for domestic wheat.

$$Q^S = Q^H - X$$

where Q^S=supply of domestic wheat, Q^H=domestic production and X=exports. We have already modelled domestic production, which is basically fixed in any one year:[27]

$$Q^H = Q^H(\text{weather, technology, factor inputs})$$

And the export function can be written:

$$X = X(\text{wd, wf, transport cost, wars...})$$

We do not model imports explicitly because they are imperfect substitutes and therefore enter into the model through foreign wheat prices, wf (although, of course, an import function could be written analogously to the export function). In equilibrium,

$$Q^D = Q^S \qquad (2)$$

Substituting (2) into (1) and rearranging gives an equation for the equilibrium wheat price:

$$wd = wd[(Q^H - X)/N), wf, p, Y/N] \qquad (3)$$

We take a log-linear approximation to this expression, yielding the following equation for estimation:

$$\ln(wd_i) = \alpha_1 + \alpha_2\ln(Q^H - X)_i + \alpha_3\ln(N_i) + \alpha_4\ln(wf_i) + \alpha_5\ln(p_i) + \alpha_6\ln(Y/N_i) + \varepsilon_i \qquad (4)$$

Let us consider what values we would expect the coefficients to take in equation (4). First, the coefficients on foreign wheat prices (wf) and the consumer price index (p) should sum to unity (that is, $\alpha_4 + \alpha_5 = 1$) because prices should be homogeneous of order zero. That is, if *all* prices in the economy doubled (foreign and domestic wheat, as well as other goods) then there should be no effect on the demand for wheat.[28] Second, the coefficients on wheat supply (Q^H - X) and population (N) should have opposite signs but be of equal magnitude (that is, $\alpha_2+\alpha_3=0$). The intuition for this is that if we doubled the supply of wheat and also doubled the population (holding real income per head constant) then there should be no effect on the wheat price.

It is not straightforward to estimate the equation which we have derived because the structure of the English grain trade changed substantially over the eighteenth and nineteenth centuries. This raises several practical issues and here we will highlight two in particular. First, the relevant set of foreign wheat prices changed over time because in c.1765 England went from being a net grain exporter to being a net grain importer. A standard response would be to use a trade-weighted index, with the

[27] There was some flexibility in domestic output owing to the carry-over of grain stocks from one year to the next. However, the volume of grain carried over was only a small proportion of total annual output and this can be safely ignored for our current purposes.

[28] Otherwise consumers would be suffering from ‘money illusion’. For further discussion, see Postel-Vinay G and J-M Robin, ‘Eating, Working and Saving in an Unstable World: Consumers in Nineteenth Century France,’ *Economic History Review*, Vol. 45 (1992).

weights changing over time. But only after 1800 do we have detailed data on wheat imports and exports by country - so it is currently impossible to construct a trade-weighted index.[29] Second, trade was often disturbed by warfare. But the effect of warfare with any particular country differed according to whether England was an importer or exporter of grain. So we would not necessarily expect the parameters of the model to be the same before and after 1765. We have responded to both of these problems by estimating the model on two sub-periods: from 1700 to 1765, and from 1766 to 1825.[30] We choose to end our analysis in 1825 because there were important changes to the Corn Laws in the 1820s which changed the dynamics of the grain trade.[31]

The model for the first period, reported in Table 5 overleaf, provides a good fit and all the variables have the expected sign. The coefficients have the anticipated magnitudes. We tested for a number of non-market trade interventions (for example, wars with various European countries or other trade embargoes) but the only a war with Spain had a significant effect. This is what we would expect because Spain was the primary market for English grain exports in the early eighteenth century, so a war with Spain depressed domestic English prices.

The primary interest of this paper is the performance of Retained Domestic Output - and the model estimated above provides powerful support for our new output series. It would be interesting to compare our new estimates of output directly with the estimates derived by Crafts from the demand-side approach but the two series are not immediately comparable (for example, he models overall agricultural output rather than just wheat). So integrating our new figures with the existing estimates remains a task for the future.

Table 5. The Market for English Wheat, 1700-1765.

Variables Explaining Wheat Price (d/q)	Coefficient	t-statistic
Consumer Price Index (p)	0.40	1.17
Population (N)	0.78	0.90

[29] Ideally, our foreign wheat price index (wf) would be constructed using data on the price of foreign wheat in *England*. This is different to the price of foreign wheat *abroad* because the price in England would be gross of transport costs, home import duties and foreign export duties. In this paper we abstract from the complicated issues transport cost and trade duties, and for simplicity we use the price of foreign wheat abroad. Given the substantial annual fluctuation in foreign wheat prices, this simplification is unlikely to be problematic in terms of generating an accurate estimate of the effect of the foreign wheat price on the domestic wheat price.

[30] The data sources are as follows: wheat prices are for Eton College and the London Gazette; consumer price indices are those of Schumpeter-Gilboy and Rousseau; these series are all taken from Mitchell B R, *Abstract of British Historical Statistics* (Cambridge, 1988). Population is taken from Wrigley E A and R S Schofield, *The Population History of England, 1541-1871: a Reconstruction* (Cambridge, 1981). Real income per head is based on the growth rates given in Crafts N F R, ‘The Industrial Revolution,’ in Floud R and D N McCloskey *The Economic History of Britain since 1700*, Vol. 1, (Cambridge, 1994), 51. It may be preferable to use real wages rather than Crafts’ figures for real income per head (for example, this would allow us to abstract from any changes in the distribution of income). In fact, similar results to those presented here are generated it we use Feinstein’s real wage figures (which also have the advantage of being annual data). We use Crafts’ estimates here because Feinstein’s real wage series does not go back to 1700 and we wanted to maintain comparability of the data sources as far as possible. Foreign wheat prices are proxied by the price of wheat in northern Spain (1700-1765) and Danzig (1766-1825). Prices are taken from the 1826 Parliamentary enquiry into the grain trade (British Parliamentary Papers, 1826-7, Vol. 16).

[31] Notably, it was possible to import and store grain in England without paying import duty - provided that it was placed in a bonded warehouse. This turned England into a storage centre for the European grain trade and meant that grain flows were not necessarily responding to English prices. For a detailed discussion see Barnes D G, *A History of the English Corn Laws* (London, 1930).

Retained Domestic Output (Q^S)	-0.68	-4.31**
Foreign Wheat Price (wf)	0.34	3.60**
Real Income Per Head (Y/N)	-1.81	-2.85**
War with Spain	-0.13	-2.43*
R^2	**0.52**	
Adjusted R^2	**0.48**	
F-statistic	**10.84**	
SE of Equation	**0.18**	
Durbin-Watson	**1.57**	
N	**66**	

Note: ** is significant at the 1 per cent level; * is significant at the 5 per cent level.

The model gives a similarly good fit for the later period, as we see in Table 6 below. Again we find that all the variables have the correct sign and the expected magnitudes. We find that population pressure and domestic output have a smaller effect on domestic prices than in the earlier period. This is consistent with lower consumption per head in the later period (which we found in Figure 6 above). We can also see that the Napoleonic blockade (1806 to 1814) had a significant positive impact on English prices through its effect on imports.

Table 6. The Market for English Wheat, 1766-1825.

Variables Explaining Wheat Price (d/q)	Coefficient	t-statistic
Consumer Price Index (p)	0.98	5.37**
Population (N)	0.51	0.86
Retained Domestic Output (Q^S)	-0.40	-2.40*
Foreign Wheat Price (wf)	0.14	2.05*
Real Income Per Head (Y/N)	-1.21	-0.62
Napoleonic Blockade	0.19	1.98*
R^2	**0.77**	
Adjusted R^2	**0.75**	
F-statistic	**29.81**	
SE of Equation	**0.19**	
Durbin-Watson	**1.77**	
N	**59**	

Note: ** is significant at the 1 per cent level; * is significant at the 5 per cent level.

V. Conclusions. Our analysis of wheat production in the Industrial Revolution has a number of implications for our estimates agricultural productivity and national income.

The literature on English agricultural development has suffered from the absence of a quantitative model encompassing the wide range of factor and technology inputs employed in agricultural production. There have been many estimates of yields or land inputs or the returns to new technologies - but none of these estimates has had to be consistent with any of the other estimates because each investigation has examined only one factor. This paper integrates the available data on many aspects of wheat production and considers the historical ebb and flow of all these factors in a rigorous way.

Contrary to the traditional analysis, we have found that crop rotation, fertiliser and seed drilling were primary determinants of wheat yields. There was also an important effect from fluctuations in the quantity of marginal land in production. Our analysis emphasises the fact that yields can go down as well as up - because the yield is a choice variable which farmers optimise in response to economic conditions (produced by factors such as war and population pressure). Hence the unexpected decline in yields after 1770 and the recovery following the Napoleonic Wars.

The implications of our research for the literature on national income are two-fold. First, we have generated new annual series for wheat yields and output; these offer an alternative series to the output estimates based on demand equations. The new series suggest that weather shocks have caused us to underestimate output in 1700 and overestimate output in 1860; the rise in wheat yields was only 50 to 70 percent of the apparent increase based on the raw yield data. Second, the new output series enables us to estimate price and income elasticities directly, rather than imposing elasticities on a priori grounds. This will enable us also to revise our output estimates based on demand equations, so that in the future we can furnish compromise estimates which are more trustworthy. Either way, the new estimates for wheat output should feed into new estimates of national income during the Industrial Revolution and prompt us to revise downwards our estimates of economic growth.

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