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NATURE OR NURTURE? EXPLAINING ENGLISH WHEAT YIELDS IN THE AGRICULTURAL REVOLUTION

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EXPLAINING ENGLISH WHEAT YIELDS IN THE AGRICULTURAL REVOLUTION [1]

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Abstract

We estimate a model of wheat yields for eighteenth century England using village-level data. This is an entirely new approach to quantifying progress during the Agricultural Revolution and enables us to consider both environmental and technological inputs. We find that climate was a crucial factor but soil quality was much less important, thus throwing doubt on traditional explanations for England's high productivity. Traditional technologies such as drainage were effective in raising yields, but the technological innovations of the eighteenth century were much more effective. We find that turnips and seed drills were by far the most important innovations, contrary to the received wisdom.

Nature or Nurture? Explaining English Wheat Yields in the Agricultural Revolution.

I. Introduction.

Economic historians have devoted a great deal of effort to measuring and comparing wheat yields across European countries during the Industrial Revolution.[2] The attraction of grain yields as a historical source is threefold. First, there is good yield data available for most countries and periods - it is plentiful, ubiquitous and relatively unambiguous. Second, yields are a useful measure of productivity. Although yields are only a *partial* measure of productivity, agricultural production is so intimately bound up with land inputs that the productitivity of land is probably the most useful single indicator of agricultural productivity.[3] Third, international comparisons of yield data for the eighteenth and nineteenth centuries reveal marked productivity differences between European countries. These productivity levels are consistent with other evidence regarding the relative development of European countries.[4]

Despite the extensive literature, there has been virtually no attempt to model the determination of wheat yields in the Industrial Revolution. Such a model is crucial to any serious analysis of the variations and fluctuations in wheat yields. First, a model allows us to assess the relative importance natural and acquired advantages in wheat production. This bears heavily on the O'Brien and Keyder thesis that the productivity differential between Britain and France was primarily a function of Britain's natural resource endowments.[5] Second, a full model of wheat production enables us to estimate the effect of different agricultural innovations in raising productivity. There was a stream of innovations coming into use after 1700 but there have been virtually no attempts to quantify their impact on productivity and output.

In this paper we concentrate on the determination of wheat yields in England during the Agricultural Revolution. In Section II we estimate a model of wheat yields which encompasses both environmental factors (soil and climate) and technical factors (fertilisers, machinery, crop rotation). This enables us to isolate the impact of different techniques on yields. In Section III we use our model to examine some counterfactual hypotheses and explain the England-France yield gap. Section IV concludes.

II. Modelling English Wheat Yields.

Modelling wheat crops has been a popular occupation for plant biologists since the 1960s, owing mainly to its commercial application. In particular, the CERES model has been successfully adapted to predict yields in most wheat-growing areas around the world.[6] The standard technique is to take periodic data on a range of environmental variables (rainfall, temperature, daylength, sunlight, soil type) and all of the artificial variables (fertiliser, seed

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[2] The seminal work was undertaken by B H Slicher van Bath in *The Agrarian History of Western Europe, A.D. 500-1850* (London, 1963). The less important grains - rye, barley and oats - have also received considerable attention.

[3] Turner M, 'Agricultural Productivity in England in the Eighteenth Century: Evidence from Crop Yields,' Economic History Review, Vol. 35 (1992), 489-510.

[4] Wrigley E A, *People, Cities and Wealth: the Transformation of Traditional Society* (Oxford, 1987).

[5] O'Brien P K and C Keyder, *Economic Growth in Britain and France, 1780-1914: Two Paths to the Twentieth Century* (Chichester, 1978).

[6] Ritchie J T, 'Validation of the CERES-Wheat Model in Diverse Environments,' in Day W and R K Atkin, *Wheat Growth and Modelling* (NATO ASI series. Series A, Life Science. Bristol, 1984), 293.

variety, cultivation techniques) and estimate a model of wheat yields as a function of all these inputs. This is precisely the approach that we take in this paper.

A model of wheat yields is akin to a production function. The basic difference is that the inputs in a wheat model are described much more precisely and hence measured much more accurately. For example, land inputs represent bundles of soil and climate which are normally assumed to be homogeneous; but in agriculture the variations in climate and soil quality are fundamentally important in determining output, so we need to describe the land inputs much more carefully. Also in a wheat model the inputs are not necessarily broken down into units of capital and units of labour; instead they are represented as units of services which combine both factors (such as ploughing or draining). This is mainly because we are interested in exactly how the optimal bundles of labour and capital change in response to variations in the type of the land inputs. If we consider a cross-section of farms (as we do in this paper) then variations in the capital-labour bundles across the sample are more important in raising output than variations in the total quantity of labour and capital employed.

The data on wheat yields and artificial inputs is taken from the information gathered by Arthur Young on his tours of England in the late 1760s.[7] Young recorded the average yield of wheat harvested in a normal year in each village which he visited (amounting to around 200 villages). For each village he also recorded information on many other aspects of agricultural production and technique. For example, he noted which types of manure and machinery were used; which crop rotations were used on various farms in the village; the soil and drainage conditions; the distribution of farmland between arable and pastoral; the type and number of animals kept. In all, Young compiled data on around 400 variables for each village that he visited.

The complementary data on environmental variables has been taken from several sources. We have used two sources of information on soil type. Young himself gave a brief description of the soil in each village (sandy, loamy, clay, chalky, etc). We coded this data using dummy variables. We have also used modern land classification data.[8] All farmland in the UK is graded on the basis of its inherent suitability for agriculture (soil type, relief, stoniness, hilliness, etc). Grade 1 land is the best and Grade 5 the worst: there is virtually no economic exploitation of Grade 5 land, and most Grade 4 land is rough hill pasture. Hence most of our sample occupies Grade 3 land or better. We have similarly been able to use modern weather data.[9] Since Young recorded the normal yield in an average year, we do not need to use weather data specific to the year in which he visited each village. This is extremely useful because year-specific regional weather data do not exist for the late eighteenth century. So instead we have used weather data recorded at 55 weather stations in the years 1930-60: this has the advantage that all the data are comparable, accurate and reliable. It might be objected that the climate has changed between 1770 and 1960 (which may or may not be true). However, this will only affect our results in the unlikely event that the climate has changed differently in different regions of the UK (the effect of any uniform climate change will simply

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[7] Young A, *A Six Weeks' Tour through the Southern Counties of England* (London, 1766); *A Six Months' Tour through the Northern Counties of England* (London, 1767); *A Six Months' Tour through the Eastern Counties of England* (London, 1769). Arthur Young is a well-known (but controversial) historical source. I do not intend to discuss his merits in this paper - see Allen R C and C O'Grada, 'On the Road again with Arthur Young: English, Irish and French Agriculture during the Industrial Revolution,' *Journal of Economic History*, Vol. 48 (1988), 93-116. The dataset compiled by Young is far more exhaustive that any other dataset for the period before 1850 (at least). There is no other dataset known to the author which would enable us to esimate the kind of detailed model used in this paper.

[8] Ministry of Agriculture, Fisheries and Food, *Land Classification* (London, 1955).

[9] Meteorological Office, *Tables of Temperature, Relative Humidity, Precipitation and Sunshine for the World: Part III - Europe and the Azores* (London, 1972).

drop out in the constant term of a regression). We are therefore content that modern weather data is pertinent and useful.

On the basis of this data we estimated a cross-section regression model using a general-to-simple approach. The initial specification was very full because we wanted to test a large number of hypotheses, so for the sake of clarity we have reported only the finalised model in Table 1 below. Other versions of the model are reported in the Appendix and they are referred to in the text where they are particularly enlightening. In line with the CERES model of wheat yields we expected weather variables to enter into the model as follows:

W1: Rainfall is a crucial determinant of wheat yields from spring onwards.
W2: Temperature has an important effect on yield (mainly through water availability).
W3: Climatic factors become more critical around harvest time (the crop then has less time to recover from any adverse shock).
W4: Higher altitude tends to increase exposure to severe weather and reduce yields.

We also wanted to test the following historical hypotheses:

H1: Soil quality was a primary determinant of the variation in wheat yields.
H2: Hollow drainage substantially raised yields in areas with poor natural drainage.
H3: Turnips added humus to sandy soils - without which wheat cultivation would have been impossible on the poorest soils.
H4: Liming and marling substantially raised yields by correcting soil acidity.
H5: Crop rotation was an important determinant of yields (more frequent grain cropping *lowered* yields but more frequent fallow cropping *raised* yields).
H6: The quantity of manure produced was more strongly influenced by the production techniques employed than by the gross amount of fodder available.
H7: Clover fixes atmospheric nitrogen directly into the soil and created higher yields.
H8: Mixed arable-pastoral farms created more manure and hence higher grain yields.
H9: Higher volumes of seed resulted in higher yields.
H10: Ploughing more often raised yields through weed suppression.
H11: Large farms did not have higher yields.
H12: The use of drill husbandry and horse-hoeing raised yields through weed suppression.

The finalised model is reproduced in Table 1 below. We preferred to err on the side of caution when rejecting hypotheses, so we generally removed variables only if they were not significant at the ten per cent level.

Table 1. A Model of English Wheat Yields, c.1770.

Variables Explaining WHEAT YIELD	Coefficient	t-statistic	Mean Yield Effect (bu)
July-August Rainfall	-0.069	-1.86	-8.8
July-August Temperature Change[10]	12.740	3.78**	-2.9
July-August Rainy Days Change	-2.988	-2.85**	1.2
Spring Rainfall in Poor Drainage Areas	-0.026	-1.79	-3.4
Clay Soil Dummy	2.863	2.26*	2.9
Sandy Soil Dummy	4.687	2.21*	4.7
Grade 1 & 2 Land Dummy	-6.296	-2.41*	-6.3
Grade 3 Land Dummy	-3.239	-0.28	-3.2
Proportion of Wheat (Grade 3 Land)	-17.034	-0.63	-3.3
Barley/Wheat Ratio (Grade 3 Land)	-2.287	-0.96	-2.5
Oats/Wheat Ratio (Grade 3 Land)	-2.012	-1.02	-1.8
Peas/Wheat Ratio (Grade 3 Land)	0.991	0.35	0.4
Beans/Wheat Ratio (Grade 3 Land)	2.208	0.94	0.3
Fallow/Wheat Ratio (Grade 3 Land)	0.968	0.48	0.6
Clover/Wheat Ratio (Grade 3 Land)	-0.773	-0.52	-0.5
Turnips/Wheat Ratio (Grade 3 Land)	3.359	1.40	1.8
Lifted Turnips/Wheat Ratio (Grade 3 Land)	2.084	0.82	0.4
Liming	2.811	2.18*	2.8
Marling	5.661	3.41**	5.7
Paring and Burning Dummy (Grade 3 Land)	1.934	1.15	1.9
Sandy Soil with Turnip Cultivation Dummy	-5.638	-1.70	-5.6
Drill Husbandry Dummy	4.978	1.73	5.0
Horse Hoeing Dummy	4.174	1.12	4.1
R^2	**0.52**		
Adjusted R^2	**0.35**		
SE of the Equation	**4.44**		
F-statistic	**2.99**		
N	**87**		

Note: Crop rotation variables and the Grade 3 Land Dummy are not significant due to multicollinearity, but an F-test shows that they are jointly very significant. The size of the coefficient is not biased by multicollinearity. The variables marked ** are significant at the 1 per cent level; * are significant at the 5 per cent level.

Let us begin by discussing the role of climate (W1-W4). By far the most important climatic factor determining the wheat yield in Western Europe is rainfall because the grain yield is susceptible to rainfall fluctuations *throughout* the growth cycle. But the relationship between rainfall and yield is complicated - we are not only concerned with the quantity of rainfall but also how it is distributed over short periods. Our model suggests that three phases of the growth cycle are particularly sensitive to rainfall. The first period is spring (April to June) when the wheat plants are developing; the second period is early summer (July) when the grains are 'filling' (that is, becoming mature and plump); and the third period is late summer (August) when the grain is harvested.

The *quantity* of rainfall was important in all three periods. Excessive spring rainfall can reduce yields by waterlogging the soil and thus interrupting the flow of oxygen to the roots. It can also promote the spread of fungal plant diseases such as 'rust', for which there was no cure in the eighteenth century. The model shows that this was a particular problem in areas with poor drainage. In a normal year the mean Spring Rainfall in Poor Drainage Areas was 135 millimetres, which reduced the local wheat yield by 3.4 bushels. Excessive rainfall in July and

[10] This is the difference between the average daily maximum temperature in July and August.

August can damage the wheat plants and make harvesting very difficult; moreover, wet grain cannot be put into storage because it will soon start sprouting. Hence the abysmal harvest of 1811 (estimated at 40 per cent below normal) was very wet and '...one half of the corn was exposed for three weeks to rains and storms, much of which was badly sprouted.'[11] The mean July-August Rainfall across England is 128 millimetres, which reduced the mean wheat yield by a massive 8.8 bushels.

[11] Taken from the *Farmer's Magazine*, quoted in Jones E L, *Seasons and Prices* (Chichester, 1964), 159.

The *distribution* of rainfall is important in July and August. In July it is important to have sufficient moisture to allow proper grain filling. This does not mean that high rainfall is beneficial - rather, it is useful to have light rain on a large number of days. By contrast, in August the weather should be as dry as possible. However, in the UK there is a strong correlation between July and August precipitation (ie places which are wet in July also tend to be wet in August), so in effect there is a trade-off between July and August weather. Ideally there would be (light) rainy days in July but none in August - so July-August Rainy Days Change would be large and negative. In fact, the mean July-August Rainy Days Change is only -0.34 and the mean wheat yield is therefore 1.2 bushels higher.

The role of temperature in determining wheat yields is more straightforward. For most of the lifecycle of the wheat plant there is no relationship between temperature and the future grain yield of the plant - temperature only affects the date at which the wheat plant reaches maturity. (This is leaving aside periods of extreme weather which are atypical of Britain). But once the wheat plant has matured and started to produce grain then the temperature becomes important. Vos has shown that reducing the temperature from 22 degrees Celsius to 16 degrees Celsius would prolong the period of grain filling by 20 days (50 per cent) and lead to an increase in yield of 25 per cent.[12] In Britain most of the grain filling occurs in July, so lower July temperatures are highly desirable (since everywhere in Britain has average July temperatures above 16 degrees Celsius). By contrast, when the period of grain filling has ended high temperatures are extremely useful in drying out the crop to avoid sprouting and other damage. Hence a hot August is very beneficial. Unfortunately, July and August temperatures are highly correlated across Britain and we again see a trade-off between July and August weather - we would like a cool July to improve grain filling but a hot August to improve the harvest. Hence we are really interested in the July-August Temperature Change: and with a mean Change of -0.24 the mean wheat yield is reduced by 2.9 bushels. The poor harvest of 1808 had all the ingredients of a poor summer suggested by our model. A contemporary noted:

‘The crops more deficient than last year. The hot days in the early part of July did great injury to the wheat, and they were followed by a great deal of wet and stormy weather, from that time until the getting in of the harvest.’[13]

Our model is therefore consistent with the CERES model with regard to the impact of weather (W1-W4). Rainfall is indeed a crucial determinant of wheat yields from spring onwards; temperature has an important effect on yields (mainly through water availability); and climatic factors become more critical around harvest time. The effect of altitute (W4) also had the expected sign but had little explanatory power (see Model 5 in the Appendix).

We will now consider the historical hypotheses in the light of the model. Soil quality has a significant but modest impact on yields (H1). Hence the yields on Grade 3 land are on average 1 bushel lower than on Grade 1 or 2 land (taking into account the average effect of crop rotation). Moreover, clay and sandy soils are noticeably better than other types. In terms of soil structure clay and sand are at two ends of the spectrum - clay is compact and heavy because the soil particles are tiny, whereas sand is loose and light because the particles are very large. Clay soils have a number of benefits. They are capable of retaining moisture, humus and

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[12] Vos J, ‘Aspects of Modelling Post-floral Growth of Wheat and Calculations of the Effects of Temperature and Radiation,’ in Day W and R K Atkin, *Wheat Growth and Modelling* (NATO ASI series. Series A, Life Science. Bristol, 1984), 144.

[13] Quoted in Jones E L, *Seasons and Prices* (Chichester, 1964), 158.

chemical compounds in a kind of ‘nutrient sink’which is difficult to destroy. Clay soil also tends to be more alkaline than other types of soil, which may have been useful when farmers had a continuing problem of the soil becoming too acidic (we will discuss this further below). Hence the wheat yield was 2.9 bushels higher on clay soils. By contrast, sandy soils tend to be of low quality and it is therefore surprising that they have higher yields. This could be for two reasons. It may be the case that we have controlled for most aspects of land quality in the Grade 3 Land Dummy - and sandy soils are actually better for cultivation than other soil types *holding everything else constant*. Alternatively, sandy soils are easily exhausted because they contain few nutrients and little humus - but they are consequently easy to regenerate (they have a lower ‘buffer capacity’). For example, to reduce soil acidity from pH6 to pH7 on an acre of land would take around 0.75 tons of limestone on a sandy soil but 3 tons on a clay soil.[14] So it may simply be the case that farmers could afford to keep sandy soils in a relatively good condition.

Our results show that the impact of hollow drainage was large (H2). Hollow draining involved digging trenches across a field and filling the bottom of the trench with a material which permitted the free flow of water (such as stones or clay pipes), before refilling the trenches with earth. This was an expensive technique for removing excess water but the drains normally lasted a long time and the benefits could be felt for 50 years or more. Young noted whether or not a village needed hollow-draining - and whether or not draining had been undertaken. There was no significant reduction in areas which *had* been hollow-drained. But in Poor Drainage Areas (that is, where drainage was required but not completed) the mean reduction in wheat yield due to spring rainfall was 3.5 bushels (14 per cent). This result fits closely with modern experimental data, as Table 2 below demonstrates.[15] Winter wheat is particularly susceptible to waterlogging in April, May and June (which corresponds to our definition of ‘Spring’), when a three-day period of waterlogging reduces yields by 10-20 per cent.

Table 2. Percentage Reduction in Winter Wheat Yields due to Waterlogging.

No. Days	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3	-	-	5	10	20	20	-	-	-	-	-	-
7	5	5	15	25	40	50	-	-	-	-	-	-
15	15	20	50	70	100	100	20	-	-	20	20	20

The technique of growing turnips on very sandy soils to add humus and enable a wheat crop to be taken is well-known in the literature (H3) - mainly because it was pioneered on the reclaimed soils of East Anglia by the great improvers such as Coke of Holcomb. We find that wheat yields were 5.6 bushels (23 per cent) lower on sandy soils where turnips were cultivated. This is consistent with the notion that this was very marginal land where wheat cultivation would have been otherwise impossible. This type of cultivation was undertaken by seven villages in our sample: three of these were in East Anglia (Aylsham, Earlham and Hadleigh); one in Fenton, Northumberland (where arable agriculture was similar to East Anglia in many

[14] Donahue R L, R W Miller and J C Shickluna, *Soils: An Introduction to Soils and Plant Growth*, (London, 1977), 256.

[15] Data taken from Trafford B D, ‘Field Drainage,’ *Journal of the Royal Agricultural Society of England*, Vol. 131 (1970), 148-9.

ways); and three in the West Midlands (Stone, Shenstone and Aston). Our model thus appears to have successfully captured this particular feature of the Agricultural Revolution.

Let us turn to the question of liming and marling (H4). Most soil is naturally acidic and it becomes more acidic when crops are cultivated. This is because many alkaline compounds are broken down when chemicals are removed from the soil to furnish nitrogen, phosphorus and potassium for healthy plant growth. Although most crops prefer a slightly acidic soil, their tolerance of acidity is quite low and in the face of continued cultivation the soil naturally becomes too acidic for them.[16] Turnips are particularly averse to acidic soils, so the issue of acidity became even more important with the diffusion of turnips during the eighteenth century. The most common way to correct soil acidity was to add either lime or marl to the soil. These are both forms of calcium carbonate (which is alkaline) which occur naturally in different regions of England; after simple preparation they can be spread on the acidic farmland and mixed in with a plough. Marling was particularly popular after 1750 because the cost of labour was relatively low and marling is very labour-intensive.[17] The positive effect of marling and liming is generally thought to have been large, and indeed Young called marl 'the Prince of Manures'.[18] Our model suggests that liming increased output by 2.8 bushels (12 per cent) and marling increased yields by 5.7 bushels (24 per cent). We tried testing for the effect of other types of manure - such as ashes and pigeon dung - but the number of adopters of each type was too small to give any reliable results. By contrast, 48 per cent of our sample used lime and 17 per cent used marl.[19]

We wanted to test for the effect of crop rotation (H5). Growing more fallow crops and fewer grain crops ought to improve the fertility of the soil by increasing the stock of nitrogen. Of course, the effect on wheat yields will be larger when the proportion of wheat in the crop rotation is smaller - because the stock of nitrogen *per wheat plant* is higher when their are fewer wheat plants. Hence our explanatory variable is turnip-wheat ratio, fallow-wheat ratio, etc.[20] We found that the effects of crop rotation only became apparent when the crop ratios were interacted with Land Grade Dummies. That is, we estimated the effect of variations in crop rotation on Grade 1 Land; and then on Grade 2 Land independently; etc. This is the correct method of modelling if crop rotation has a different effect on different grades of land - which seems to be borne out by the data. We found that crop rotation was important only on Grade 3 Land, probably because manipulating the nitrogen cycle is more critical on land which is less naturally fertile.[21] Since the vast majority of agricultural land is Grade 3, the impact of

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[16] Donahue R L, R W Miller and J C Shickluna, *Soils: An Introduction to Soils and Plant Growth*, (London, 1977).

[17] Dodgshon R A, 'Land Improvement in Scottish Farming: Marl and Lime in Roxburghshire and Berwickshire in the Eighteenth Century,' *Agricultural History Review*, Vol. 26 (1978), 2.

[18] In the eighteenth century the word 'manure' had the same meaning as 'fertiliser'. See Young A, *The Farmer's Kalender* (London, 1770).

[19] Brunt L, 'Where there's Muck, there's Money: the Market for Manure in the Agricultural Revolution,' mimeo. (Oxford, 1996).

[20] In fact, we have data on the distribution of land between crops on each *farm* rather than each village - so we aggregated the acreage for each crop and then calculated the crop ratios accordingly. This implicitly assumes that the farms for which we have detailed data are representative of the village as a whole. This seems to be a good assumption: if there are several farms in a particular village then we find that they have very similar crop rotations. This is not surprising, since they tend to face similar weather and soil conditions.

[21] However, we cannot rule out the possibility that crop rotation was also important on other grades of land. We may have failed to get a significant result due to a lack of sample size - whereas we have 54 villages on Grade 3 land we have only 24 villages on Grade 2 land, 8 villages on Grade 1 land and 4 villages on Grade 4 land. Remember that estimating the effect of crop rotation involves the estimation of 9 additional variables.

crop rotation is widespread in any case. The following points are worth noting about these results.

As expected, cultivating grain crops (wheat, barley and oats) reduces the wheat yield. By contrast, fallow crops (such as beans, peas and bare fallow) all have a positive impact on wheat yields. Given the crop rotations employed by our sample, the overall impact was to reduce wheat yields on Grade 3 Land by 4.2 bushels (17 per cent). The role of turnips and clover is particularly interesting because they were only just coming into general use in the eighteenth century and it has been widely argued that they significantly boosted productivity.

Turnips have a much stronger impact than other fallow crops - and their impact is nearly twice as large if they are ‘lifted’. Turnips can either be lifted out of the soil or eaten off in the field (which is to say that the animals are simply herded into the field and left to eat only the top part of the turnip which is showing above the ground). The disadvantage of harvesting is that it is labour-intensive, especially if the turnips are then carried to the farmyard for stall-feeding; but the advantage is that twice as much of the turnip is eaten. In our model the variable Lifted Turnips/Wheat Ratio acts *in addition* to the Turnip/Wheat Ratio. This captures accurately the extra benefit of lifting turnips. It also bears out the argument that the volume of manure was strongly influenced by processing techniques, not just the amount of fodder which is notionally available (H6).

The impact of clover is more surprising (H7). In addition to creating fodder (and hence manure) clover fixes nitrogen directly into the soil and this should increase wheat yields. This effect should be particularly marked because it was normal for wheat to follow clover immediately in the crop rotation - so there should be no nitrogen losses due to extraneous factors. The quantity of nitrogen available should also have been boosted by the fact that it was normal to grow clover in a field for several years before returning it to wheat production. Theoretical calculations suggest that clover should substantially increase the output of a mixed farm.[22] In fact, clover has a small *negative* impact on wheat yields. This is surprising, but is borne out by other analyses using completely different techniques.[23] The most likely explanation for this is that clover was harvested and used as hay for winter fodder. But the dung which was thus created during the winter may have been stored very badly and most of the nitrogen lost back into the atmosphere - we know that even under ideal conditions it is normal to lose 50 per cent of the nitrogen content of stored manure.[24] So making clover hay could lead to a net *reduction* in the amount of nitrogen available for grain crops (and hence lower yields).

The eighteenth century is said to have seen a move towards more mixed farms (ie farms containing both arable and livestock in substantial proportions); the new root crops which replaced bare fallow were used to feed animals and the resulting dung was used to fertilise the arable crops (H8).[25] Some researchers have even suggested that in England:

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[22] Shiel R S, ‘Improving Soil Productivity in the Pre-Fertiliser Era,’ in Campbell B M S and M Overton (eds), *Land, Labour and Livestock: Historical Studies in European Agricultural Productivity* (Manchester, 1991).

[23] Brunt L, ‘Water into Wine: new Methods of Aggregating Farm Outputs and New Insights into Rising Crop Yields during the Agricultural Revolution,’ *Oxford University Discussion Paper in Economic and Social History*, No. 2 (Oxford, 1995).

[24] Voelker J A, ‘Manures,’ *Encyclopaedia Britannica* (London, 1913).

[25] Shiel R S, ‘Improving Soil Productivity in the Pre-Fertiliser Era,’ in Campbell B M S and M Overton (eds), *Land, Labour and Livestock: Historical Studies in European Agricultural Productivity* (Manchester, 1991).

‘...the availability of organic fertiliser [dung] exercised a decisive influence on the level of physical yields achieved in the cultivation of cereal, potatoes and other crops.’[26]

We tested for this effect directly by estimating the amount of dung produced in the village (as a function of the horses, oxen, cattle and sheep available) and then entering this variable into our model of wheat yields. We also tested indirectly for the effect of mixed farming by just entering the arable-pastoral ratio as an explanatory variable. In neither case could we find any effect on wheat yields from mixed farming. In general, we do not find it surprising that there is no simple relationship between mixed farming and higher yields: we showed above that the quantity of manure produced from a given quantity of fodder depends strongly on the techniques employed (H6). Moreover, although the evidence presented here suggests that mixed farming offered few benefits for arable yields, this does not mean that mixed farming was unimportant in raising total agricultural output. The move to mixed farming may well have increased meat output because it permitted more intensive animal husbandry. We are simply arguing here that mixed farming had no detectable effect on wheat yields.

It seems reasonable to expect higher volumes of seed sown to result in higher yields (H9). But in fact the sign on seed volume was *negative* and statistically insignificant. There are three possible explanations for this. First, it may be the case that there were variations in the variety and/or quality of seed employed - so farmers using low-quality seed may have used more seed and still obtained lower yields. If this hypothesis were true then we might expect to see a marked regional pattern because all farmers buying their seed from the same source would face the same problem. However, regional dummies did not improve the fit and therefore this seems to be an unlikely explanation (although it is the subject of on-going research). Second, some areas may have been more prone to weeds than others. One (partial) solution to the weed problem was to sow more seed and try to choke out some of the weeds. This could cause the apparent correlation of plentiful seed and low yields. Third, there is some evidence that it was possible to use *too much seed*. The growth of wheat plants was constrained by the quantity of nutrients available (especially nitrogen). If seed was sown intensively and a high proportion germinated then the wheat plants were effectively competing with each other for nutrients; all of the plants might continue to grow until the nutrients were exhausted and then all the plants would give a very poor yield. A later farmer noted that:

“...I find it imperative to sow thin, say 3 to 4 pecks per acre, or the crop would be mostly straw.”[27]

We would normally expect more ploughings to raise the yield of a grain crop (H10). This would explain why more valuable crops received more ploughings: 4 for wheat; 3 for barley; 2 for turnips; and 1 for oats, peas and beans.[28] In fact, the sign on the number of wheat ploughings was perverse and insignificant. There are two possible explanations for this. First, plough design varied enormously across the country and it may be the case that less effective ploughs induced more cultivations but lower yields. We tested for this in several ways - for example, using a dummy variable to reflect whether or not wheel ploughs were being used. Although the evidence cannot be conclusive (because we do not have a perfect measure of plough effectiveness) we think that it is unlikely that variations in plough-type are driving this

[26] O’Brien P K and C Keyder, *Economic Growth in Britain and France, 1780-1914: Two Paths to the Twentieth Century* (Chichester, 1978), 137.

[27] Mechi I J, ‘Experiments in Thin Sowing,’ *Journal of the Royal Agricultural Society of England*, Vol. 7 (1846), 537-539.

[28] All data taken from Young’s *Tours*, using only those places for which we have *all* the data (so that it is based on a constant and uniform sample).

result. Second, it is certainly true that some soils require more ploughing than others but still give lower yields. We tried inter-acting plough type and soil type without success - but it is possible that this aspect of soil type has been captured only imperfectly in our soil variables.

The issue of wheat yields and farm size has featured prominently in the literature on enclosure (H11). The agricultural improvers of the eighteenth century (notably Arthur Young) were adamant that the creation of large farms through enclosure led to higher efficiency. But they also maintained that large farms employed relatively more labour than small farms (so the efficiency gains can not have been due to cost-cutting). In order for these claims to be compatible it would have to be the case that yields were higher on large farms. On the basis of a casual examination of the Arthur Young dataset, Allen has argued that yields were not higher on large farms - so the benefits of enclosure must have been felt through labour-cutting.[29] We tested whether or not yields were higher on large farms taking into account the impact of all the other factors (soil, etc). Model 4 in the Appendix shows that wheat yields were definitely higher on large farms - typically the wheat yield was higher on a farm of 250 acres by 0.5 bushels per acre (2 per cent).

Whilst this finding on farm size has some interesting implications for the enclosure debate, we should be wary of drawing any conclusions about economies of scale more generally. It is not obvious why there should be economies of scale in wheat production. It is likely that large farms found it more economic to make capital investments which covered large geographical areas. Most notably, drainage projects suffered from a free-rider problem which inhibited installation and maintenance in areas where the ownership of land was divided. But this effect should already be captured directly by the drainage variable. Moreover, there could be other explanations for the apparent correlation between farm size and wheat yields. In particular, it could be the case that good farmers have higher yields and over time they migrate towards larger farms. This would not be a true economy of scale, merely an unmeasured input (the superior skill of the farmer). Further work needs to be done on this in order to reach a definitive answer.

The final hypothesis to be tested was that drill husbandry and horse-hoeing raised yields (H12). Drilling seed into the ground instead of sowing it broadcast allowed farmers to control weeds much more effectively. Before the invention of herbicides in the twentieth century weeds were very problematic because they were impossible to eradicate on a permanent basis (they reproduced rapidly and often ran deep into the soil). The detrimental effect on yields arose from the fact that weeds competed very effectively for the limited amounts of nitrogen which were available for plant growth. The traditional method was to sow seeds broadcast and wait until the spring (when the wheat plants were just shooting) and then harrow-out any weeds which had started to grow.[30] But harrowing was not very effective because many weeds survived and many others had yet to start growing.[31] By contrast, drilled seed was planted in straight rows and it was then possible to weed between the rows with a hoe and attack the weeds much more effectively and much later in the season. Hoeing could either be done by hand or with a horse-

[29] Allen R C, *Enclosure and the Yoeman* (Oxford, 1992), 202.

[30] A harrow is like a large rake: it has a framework of spikes which dig vertically into the ground. When the harrow is dragged over the crop the wheat shoots (which grow vertically) are left largely unscathed but the weeds (which are larger and often grow horizontally) are ripped out.

[31] Brenchley W E, 'Weeds on Arable Land and their Suppression,' *Journal of the Royal Agricultural Society of England*, Vol. 85 (1924), 14-37.

hoe.[32] The model shows that both seed-drilling and horse-hoeing were important innovations, raising yields by 5 bushels and 4 bushels respectively.

Overall our model suggests that traditional characterisations of the Agricultural Revolution have focused on the wrong techniques when trying to explain increases in productivity. Contrary to popular belief the move to mixed farming contributed little to arable production; the introduction of clover was not associated with higher wheat yields; and there is no evidence that more frequent ploughing had a positive impact.

There were only two eighteenth-century innovations which had a substantial impact on yields. First, there is the turnip - the only innovation which features both in our model and in the received wisdom. Turnips appear to have been used effectively on sandy soils to add humus and facilitate wheat cultivation on very marginal land. They also appear to have made a positive contribution to the stock of manure available on the farm (particularly when they were harvested). Second, our model shows that the other really important technological innovation in the eighteenth century was seed-drilling - a technique which has generally been dismissed in the literature as unworkable and uneconomic. In fact, evidence presented in the next Section suggests that the diffusion of drilling was a primary factor pushing up yields between 1750 and 1850.

The two other techniques which had an important impact on wheat yields in the Agricultural Revolution were not at all novel. First, adding alkali by liming or marling had been known for many years but became more economic - and hence more popular - in the late eighteenth century.[33] The striking effect of liming and marling would come as no surprise to a modern arable farmer, for whom the first task is correct soil acidity. Even other forms of fertilisation (for example, adding nitrogen) are a secondary concern. Second, hollow drainage was not especially new - it was just very expensive. The low price of labour may well have been responsible for the rising popularity of drainage in the late eighteenth century. The massive increase in drainage schemes in the nineteenth century (after cheap tile piping had been invented) was another important reason for the increase in yields.

Having established the role of climate, soil and technology in raising English wheat yields we can now explore more fully the implications of this new information. In the next Section we undertake some counterfactual simulations to test the sensitivity of wheat yields to changes in environment and technology.

III. The Agricultural Revolution in Different States of Nature.

We begin this Section by testing the sensitivity of our model to changes in the values of different variables - in particular we compare the power of natural factors (climate and soil quality) and technological factors (crop rotation, seed drills and so on). We would expect the weather to be the single most important factor determining wheat yields in the eighteenth century - even in England, which had the most advanced agricultural system in the world. The climate counterfactuals in Table 3 (C1 and C2) do indeed demonstrate the dominant role of climate in determining yields.

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[32] The celebrated proponent of horse-hoeing is, of course, Jethro Tull in *Horse-Hoeing Husbandry* (London, 1733).

[33] Mathew W M, 'Marling in British Agriculture: a Case of Partial Identity,' *Agricultural History Review*, Vol. 41 (1993), 104.

Table 3. Counterfactual English Wheat Yields, c.1770.

Wheat Yield (bu/acre)	Mean Yield (N=114)	Standard Deviation	% Change from Actual Mean Yield
Sample	24.08		
Predicted by Model	24.08	3.97	
C1: Poor Climate[34]	10.25	3.95	-57
C2: Good Climate[35]	37.87	3.95	+57
C3: Poor Soil[36]	22.23	3.92	-8
C4: Good Soil[37]	27.95	3.73	+16
C5: Low Technology[38]	17.35	6.48	-30
C6: High Technology[39]	36.46	4.08	+51

The magnitude of the climate effect (±57 per cent) immediately raises the issue of international comparative advantage in wheat production. Since there are important climatic differences between European countries we might suspect that the exceptionally high English yields were partly a function of a benign climate. It is difficult to reach any firm conclusions without specifying detailed yield models for other countries, but the prima facie evidence suggests that climate was indeed significant in pushing up English yields. For example, the average values taken by French and English weather variables would give England a climatic advantage of up to 3 bushels per acre.[40] It must be stressed that this is a very approximate estimate and should be considered as an upper bound. In particular, by using the English model with French data we are assuming that the French could not adapt their agriculture to local climatic conditions. We know that this is actually false - for example, it was normal to grow rye in wet mountainous areas where wheat yields would have been very poor.

The soil-quality counterfactuals show that variations in the natural fertility of the soil had only a modest impact on wheat yields (C3 and C4). Reducing soil quality to Grade 3 would have reduced the average yield by only 8 per cent, whereas levelling soil quality up to Grade 1 would have raised average yields by 16 per cent. This is simply because the vast majority of villages (62 per cent) have Grade 3 Land; only 9 per cent have Grade 1 Land and 24 per cent have

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[34] Assuming: July-August rainfall at the sample maximum everywhere; the difference between July and August temperature at its sample minimum everywhere; the difference between July and August rainy days at its sample maximum everywhere.

[35] Assuming: the opposite of poor climate - see the previous note.

[36] Assuming: everyone has Grade 3 soil and an average crop rotation. No one has clay or sandy soil.

[37] Assuming: everyone has Grades 1 or 2 soil which is also sandy.

[38] Assuming: no drainage; a modern crop rotation of 33 per cent wheat, 33 per cent barley and 33 per cent fallow; no seed drills; no liming; no marling; and no wheat cultivation on sandy soils where turnips were grown.

[39] Assuming: drainage wherever necessary; a traditional crop rotation comprising 25 per cent wheat, 25 per cent barley, 25 per cent beans and 25 per cent lifted turnips; drills and horse-hoes used everywhere.

[40] The average harvest rainfall was 128mm in England and 119mm in France; the average July-August Temperature Change was -0.24 in England and -0.25 in France; and the average July-August Rainy Days Change in England was -0.34 in England and 0.86 in France.

Grade 2 Land. This casts serious doubt on the O'Brien and Keyder argument that Britain's natural endowment was largely responsible for its higher productivity. They argue that:

'Furthermore, the quality of land available to British farmers was hectare for hectare definitely superior to the quality of French farmland....[So] differences in the quantity and quality of land account for most of the gap in the productivity of labour employed in British and French agriculture...'[41]

Young estimated that French yields were around 17.5 bushels in 1789.[42] So the difference between actual French yields (17.5 bushels) and British yields assuming low-quality land (22.23 bushels) was over 20 per cent. Moreover, this clearly under-estimates the difference because it takes no account of the fact that a great deal French of wheat cultivation took place on high-quality land: a fair comparison ought to adjust French yields downwards to impose uniformly poor quality land in both countries.

The influence of man-made factors (which we have loosely termed 'technology') was far greater than soil quality (C5 and C6). The high-technology counterfactual shows that yields could have been 51 per cent higher than those actually observed by Arthur Young. We can decompose this increase to find the potential for each technique to raise output after 1770. Such a decomposition shows that seed drilling and horse-hoeing were the most important by far (70 per cent of the postulated increase); this is due to the high potential for adoption (from 8 per cent to 100 per cent) and also the massive effect on yields (9 bushels per acre). Adopting the Norfolk four-course crop rotation was second in importance, raising yields by 13 per cent. Other innovations were tiny by comparision, such as harvesting turnips (4 per cent) and under-drainage (2 per cent). These estimates of the returns to various technologies may seem surpising - in particular, the prominence of seed-drills in our model runs contrary to the received wisdom of technological change in the Agricultural Revolution. But in fact, the adoption of seed drills rose steadily after 1810 and became widespread during the 'Age of High Farming' (1840s). By 1870 the rate of adoption was 50 per cent - which would have raised the mean yield from 23 to 27 bushels. This is close to the actual 1870 yield of around 28 bushels.

IV. Conclusions.

The model presented in this paper substantially improves our understanding of wheat production in the eighteenth century. For the first time it draws together all the environmental and technological factors which determine the output of wheat and estimates their impact simultaneously. The model offers important new insights into both the level and growth of English wheat yields during the Industrial Revolution.

English yields were substantially higher than those achieved in other European countries during the Industrial Revolution. Our counterfactuals show that climate had the largest influence on yields and gave English farmers an advantage of up to 3 bushels per acre; soil quality may also given England an advantage of up to 2 bushels. But the English productivity advantage in 1770 was around 6 bushels per acre, so even soil quality and climate combined are insufficient to explain England's lead. It should also be stressed that the estimated impact of climate and soil quality are based on rather generous assumptions in favour of France.

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[41] O'Brien P K and C Keyder, *Economic Growth in Britain and France, 1780-1914: Two Paths to the Twentieth Century* (Chichester, 1978), 112-113.

[42] Allen R C and C O'Grada, 'On the Road again with Arthur Young: English, Irish and French Agriculture during the Industrial Revolution,' *Journal of Economic History*, Vol. 48 (1988), 93-116.

There is clearly a substantial role for technology in explaining the international productivity differential. This is scarcely surprising given the superior levels of English investment in agriculture.[43] Unfortunately, it is difficult to be very precise because detailed data for other countries is very scarce (for example, we have no idea how commonly drainage was undertaken or seed drills used). A realistic lower bound for the impact of technology is 2 bushels per acre (10 per cent) and it was probably at least as important as the environmental variables.

Technological improvement and increased investment also explain the growth in English yields over time. Our model shows that turnips, drilling and marling were most effective in raising yields. Turnips diffused rapidly after 1700 and were already fully diffused by 1770 (there was virtually no increase in the proportion of turnips in the crop rotation between 1770 and 1870).[44] By contrast, drilling only became important after 1815 and thereafter became steadily more important until around 1880.[45] There is much less information available on the extent of marling. In contrast to turnips and drilling, marling was a very old technology known in medieval times and there was no diffusion occuring during the Agricultural Revolution (though changes in relative prices may have made it slightly more or less popular after 1700). Thus drilling and turnips were probably the primary causes of increasing wheat yields after 1700.

These findings seem to be at odds with the received wisdom, which places great emphasis on clover and dismisses drilling as useless (or worse). Two points need to be emphasised. First, the improvements in drilling technique in the nineteenth century made drilling more efficient - but they did not necessarily make it more effective. So the result of drilling improvements could have been simply to reduce the cost rather than increase the effect on yields. This would explain why we find a marked drilling effect in 1770 but diffusion was nonetheless rather limited. Second, clover may have increased total output through its effect on meat production, and so it diffused greatly after 1770 (especially when the price of meat rose relative to the price of wheat). But the effect of clover on wheat yields may still have been adverse, as suggested by our model. In that sense our findings do not contradict the received wisdom, they merely describe the mechanisms at work much more explicitly.

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[43] Hickey D, ‘Innovation and Obstacles to Growth in the Agriculture of Early Modern France: the Example of Dauphiné,’ *French Historical Studies*, Vol. 25 (1985), 208-30.

[44] Ministry of Agriculture, Fisheries and Food, *A Century of Agricultural Statistics* (London, 1968).

[45] Walton J R, ‘Mechanisation in Agriculture: 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).

V. Appendix.

Table 5. Alternative Models of English Wheat Yields, c.1770.

Variables Explaining **WHEAT YIELD**	**MODEL 1** Coefficient (t-statistic)	**MODEL 2** Coefficient (t-statistic)	**MODEL 3** Coefficient (t-statistic)	**MODEL 4** Coefficient (t-statistic)	**MODEL 5** Coefficient (t-statistic)
July-August Rainfall	-0.069 (-1.86)	-0.072 (-1.88)	-0.090 (-2.60*)	-0.087 (-2.40*)	-0.0618 (-1.67)
July-August Temperature Change[46]	12.740 (3.78**)	12.283 (3.51**)	9.949 (3.35**)	12.789 (3.96**)	11.762 (3.44**)
July-August Rainy Days Change	-2.988 (-2.85**)	-3.025 (-2.84**)	-3.382 (-3.37**)	-3.560 (-3.45**)	-3.047 (-2.92**)
Spring Rainfall in Poor Drainage Areas	-0.026 (-1.79)	-0.023 (-1.53)	-0.023 (-1.62)	-0.023 (-1.64)	-0.026 (-1.84)
Altitude					-0.018 (-1.40)
Clay Soil Dummy	2.863 (2.26*)	2.727 (2.09*)	2.542 (2.17*)	3.188 (2.61*)	2.451 (1.90)
Sandy Soil Dummy	4.687 (2.21*)	5.058 (2.26*)	4.686 (2.36*)	4.867 (2.39*)	3.947 (1.82)
Grade 1 Land Dummy		-6.226 (-1.94)			
Grade 2 Land Dummy		-5.879 (-2.14*)			
Grade 1 & 2 Land Dummy	-6.296 (-2.41*)		-6.431 (-2.44*)	-7.048 (-2.79**)	-6.812 (-2.60*)
Grade 3 Land Dummy	-3.239 (-0.28)	-3.243 (-0.28)	-7.624 (-3.02**)	-2.057 (-0.19)	-1.285 (-0.11)
Proportion of Wheat (Grade 3 Land)	-17.034 (-0.63)	-16.414 (-0.59)		-18.604 (-0.71)	-24.386 (-0.89)
Barley/Wheat Ratio (Grade 3 Land)	-2.287 (-0.96)	-2.200 (-0.91)		-2.333 (-1.02)	-2.270 (-0.96)
Oats/Wheat Ratio (Grade 3 Land)	-2.012 (-1.02)	-1.984 (-1.00)		-2.058 (-1.09)	-2.156 (-1.10)
Peas/Wheat Ratio (Grade 3 Land)	0.991 (0.35)	0.906 (0.32)		-1.347 (0.47)	0.674 (0.24)
Beans/Wheat Ratio (Grade 3 Land)	2.208 (0.94)	2.204 (0.93)		1.525 (0.67)	1.693 (0.72)
Fallow/Wheat Ratio (Grade 3 Land)	0.968 (0.48)	0.927 (0.45)		0.720 (0.37)	1.169 (0.58)
Clover/Wheat Ratio (Grade 3 Land)	-0.773 (-0.52)	-0.711 (-0.47)		-0.705 (-0.50)	-1.027 (-0.69)
Turnips/Wheat Ratio (Grade 3 Land)	3.359 (1.40)	3.360 (1.38)		2.619 (1.13)	3.162 (1.32)
Lifted Turnips/Wheat Ratio (Grade 3 Land)	2.084 (0.82)	2.042 (0.80)		2.597 (1.07)	1.748 (0.69)
Liming Dummy	2.811 (2.18*)	2.893 (2.21*)	2.083 (1.70)	3.045 (2.46*)	2.745 (2.15*)
Marling Dummy	5.661 (3.41**)	5.659 (3.19**)	5.636 (3.67**)	6.404 (3.95**)	5.577 (3.38**)
Paring and Burning		-2.403			

[46] This is the difference between the average daily maximum temperature in July and August.

(Grade 2 Land)		(0.63)			
Paring and Burning (Grade 3 Land)	1.934 (1.15)	1.792 (1.05)	1.697 (1.09)	1.658 (1.03)	1.907 (1.15)
Sandy Soil with Turnip Cultivation Dummy	-5.638 (-1.70)	-6.226 (-1.75)	-5.183 (-1.88)	-7.289 (-2.25*)	-5.140 (-1.55)
Drill Husbandry Dummy	4.978 (1.73)	4.977 (1.68)	4.980 (1.78)	5.321 (1.92)	5.493 (1.90)
Horse-Hoeing Dummy	4.174 (1.12)	4.055 (1.08)	3.973 (1.11)	4.392 (1.23)	3.077 (0.82)
Arable Acreage				0.002 (2.54*)	
R^2	0.52	0.52	0.43	0.57	0.54
Adjusted R^2	0.35	0.33	0.33	0.40	0.36
SE of the Equation	4.45	4.50	4.53	4.27	4.41
F-statistic	2.99	2.69	3.93	3.38	2.99
N	87	87	87	87	87

Note: Those marked ** are significant at the 1 per cent level; * are significant at the 5 per cent level.

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