UNIVERSITY OF OXFORD

Discussion Papers in
Economic and Social History

Number 32, September 1999

AN ARBITRAGE MODEL OF CROP ROTATION IN 18TH CENTURY ENGLAND

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Abstract

The Industrial Revolution in England was characterised by early and rapid labour release from agriculture to industry. This was facilitated by rising levels of labour productivity in agriculture which permitted labour to be released without excessive upward pressure on food prices. New technology played a central role in raising agricultural productivity but the importance of particular innovations remains controversial. In this paper we develop an arbitrage model of crop rotation which enables us to estimate the impact of crop rotation on wheat yields, requiring only the yields and prices of crops to be known. We apply this technique to eighteenth century English agriculture to assess the importance of two new crops in raising the yield of wheat (the primary agricultural output). Contrary to the received wisdom, we show that turnips substantially pushed up wheat yields but clover pushed down wheat yields. We confirm this result by comparing our estimates to both experimental data and production function estimates. Further detailed analysis facilitated by the new model enables us to explain this surprising result in terms of management practices pursued by farmers.

An Arbitrage Model of Crop Rotation in 18th Century England*

by

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* This research was undertaken as part of my doctorate, which was funded by the Economic and Social Research Council, the Fulbright Commission and Nuffield College, Oxford. The paper was completed whilst I was a visitor at the Harvard economics department. I am grateful to James Foreman-Peck, Oliver Grant, Avner Offer and – especially – Lucy White for helpful comments. I would also like to thank seminar participants at the Nuffield econometrics seminar; and the 1999 Cliometrics Society Conference in Oxford, Ohio. Any remaining errors are entirely my own responsibility.

AN ARBITRAGE MODEL OF CROP ROTATION

1. Introduction

The defining feature of the Industrial Revolution in England was the transfer of labour resources from agriculture to industry, which occurred exceptionally early by international standards.[1] But England had to remain virtually self-sufficient in food production during the eighteenth century because very few exportable surpluses were being generated by other European countries.[2] The adoption of new technology was a crucial factor which permitted England to attain a high level of agricultural labour productivity - which in turn facilitated labour release.[3] The number and range of innovations coming into general use in the eighteenth century has prompted commentators to dub it the period of the 'Agricultural Revolution'.[4] There were new animal breeds (the Shire horse and the dairy short- horn cow); new crops (turnips and clover); new machines (seed drills and threshers); and new hand tools (the cradle scythe). The first problem faced by economic historians is to quantify the impact of each of these innovations in order to explain the increase in output and productivity which enabled England to feed its growing population. The second stage is to identify why England adopted those particular technologies so much earlier than her continental rivals, who suffered much lower levels of agricultural productivity.

Assessing the benefits of each innovation is a difficult task because the production process in traditional agricultural systems is very complex and the available data are sketchy. Moreover, the qualitative evidence is a hindrance as much as a help: there were very committed enthusiasts for each of the innovations, and in consequence each of them has been declared to be of far greater importance than any of the others.[5] Distinguishing between the real and bogus benefits of each technology requires micro-level data. The only source which provides such detailed material is the farm data set compiled by Arthur Young on his tour of England in the 1760s, and the analysis presented in this paper relies largely on Young's survey.[6]

In this paper we quantify the importance of new crops (turnips and clover) to the increase in English productivity. The principles of crop rotation were well-known in the eighteenth century, although the mechanism in operation was not fully understood.[7] We now know that the availability of nitrogen is usually the factor which determines the yield of grain crops in organic farming systems. Grain crops (wheat, barley, oats) reduce the stock of nitrogen in the soil and in order to maintain yields it is necessary to put nitrogen back into the soil by cultivating break crops. The traditional break crops were either forage crops (peas or beans) or bare fallow (weeds).[8] In the early eighteenth century two new break crops came into general use in English agriculture - turnips and clover. In biological terms, turnips and clover are simply technologically superior to peas and beans as break crops. In particular, clover is leguminous - which is to say that it fixes nitrogen into the soil directly from the

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[1] Crafts, N. F. R., *British Economic Growth during the Industrial Revolution* (Oxford, 1985).

[2] Wrigley, E. A., *People, Cities and Wealth* (Oxford, 1987).

[3] Overton, M., *Agricultural Revolution in England* (Cambridge, 1996).

[4] The phrase originated with Lord Ernle in his book *English Farming Past and Present* (London, 1912).

[5] Kerridge, E., 'Arthur Young and William Marshall,' *History Studies*, vol. 1 (1968), 43-53.

[6] 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, 1768); *A Six Months' Tour through the Eastern Counties of England* (London, 1769).

[7] Shiel, R. S., 'Improving Soil Fertility in the Pre-fertiliser Era,' in Campbell, B. M. S. and M. Overton (eds.) *Land, Labour and Livestock* (Manchester, 1991), 51-77.

[8] Lockhart, J. A. R. and A. J. L. Wiseman, *Introduction to Crop Husbandry* (Oxford, 1966).

atmosphere through bacteria harboured by the root system. Hence turnips and clover enrich the soil more effectively than peas and beans and we should see an increase in subsequent grain yields. A second effect could also be felt in the pastoral sector. Turnips and clover provided more forage per unit of arable land, so more animals could be kept on the farm and revenue raised through meat production.[9]

In order to measure the impact of turnips and clover on arable farm productivity we need to quantify two effects. First, we must measure the effectiveness of each crop in raising grain yields. Second, we must measure the take-up of turnips and clover. This paper is concerned with only the first of these goals - quantifying the impact of turnips and clover on grain yields. We have already addressed the second (adoption) issue elsewhere.[10]

The fundamental difficulty in estimating the benefits of crop rotation is to specify an accurate production function for the sample of farms. In particular, it is imperative to control fully for the effect of environmental variables. For example, farms on good quality land usually grow a higher percentage of grain crops and also have higher yields. If we try to build a causal model based on this crude correlation then it appears in a cross-section that growing more grain crops *raises* the yield. Of course, this is completely wrong and we have been misled by our failure to take explicit account of the quality of the land. This type of missing variable bias is a serious issue in agricultural economics because there is generally no independent measure of land quality available.

However, it is sometimes possible to employ economic logic as a substitute for direct evidence. In Section II we develop an arbitrage model of crop rotation from a standard profit maximisation model of farmer behaviour. We show that it is possible to estimate the effect of crop rotation using only data on yields and prices, which is commonly available. In Section III we operationalise the model and show that turnips had a large positive effect on English wheat yields but that clover had a negative effect. (Henceforth we refer to these yield effects as externalities). We show that these results are consistent with those derived from a traditional production function approach for the same sample of farms, and also with data from experimental farms. In Section IV we further test and extend the analysis. We show that farmers responded rationally to variations in relative prices (both across England and over time), given the externalities produced by turnips and clover. We then calculate the benefits of crop rotation on each individual farm and use regression techniques to establish when the externalities were most positive or negative. We show that management techniques were extremely important and very intensive fodder production was responsible for the adverse effect of clover on wheat yields. This is consistent with qualitative evidence regarding the production processes of eighteenth century agriculture. Section V concludes.

2. An Arbitrage Model of Crop Rotation

We assume that farmers maximise the discounted sum of expected future profits by choosing the amount of land to devote to growing each crop in each period of time. In order to simplify the exposition here, we take the case where the farmer can choose between just two crops, wheat W and beans B. Of course, the results easily generalise to the case where other crops are grown which affect the yield of wheat (turnips, clover, oats and so on). We allow for the possibility that the farmer faces a binding land constraint L (that is, he cannot rent as much land as he would like at the market rent r). Thus the representative farmer's problem is:

$$\max_{W_t, B_t} \Sigma^{\infty}_{t=0} (1+\delta)^{-t} E[\pi_t] \qquad (1)$$

[9] Overton, M., 'The Determinants of Crop Yields in Early Modern England,' in Campbell, B. M. S. and M. Overton (eds.) *Land, Labour and Livestock* (Manchester, 1991), 284-322.

[10] The take-up of turnips and clover at the national level is surveyed in Brunt, L., 'Estimating English Wheat Production in the Industrial Revolution,' *Oxford University Discussion Papers in Economic and Social History*, no. 29 (June 1999).

subject to: $W_t + B_t \leq L \ \forall t: t=0,1,...,t,..$ (2)

where W_t is the amount of land devoted to wheat and B_t the amount of land devoted to beans at time t; and L is the land constraint (which is the same in all periods). The farmer discounts profits at rate δ, where expected profits at time t are given by:

$$\pi_t = P^W{}_t.Q^W{}_t + P^B{}_t.Q^B{}_t - r(W_t + B_t) - c(K^W{}_t + K^B{}_t) \qquad (3)$$

where $Q^W{}_t$ and $Q^B{}_t$ are wheat and bean output respectively in period t; and $P^W{}_t$ and $P^B{}_t$ are expected prices for wheat and beans respectively in period t. The rental cost of land is r; other factors used in wheat and bean production in period t are $K^W{}_t$ and $K^B{}_t$ respectively, and their cost is c. In order to simplify things, let us assume that prices, rent and other costs are all expected to be constant over time: $E[P^W{}_t]=P^W$, etc. The production function for beans is conventional and is given by:

$$Q^B{}_t = g(B_t, K^B) \qquad (4)$$

The production function for wheat has the special feature that the quantity of wheat produced today depends not only on current inputs of wheat land and other factors, but also on how much land was devoted to growing beans in the past. This reflects the fact that beans change the fertility of the soil through their impact on physical characteristics such as the levels of nitrogen and humus.

$$Q^W{}_t = h(W_t, B_{t-1},...B_0, K^W) \qquad (5)$$

We will also assume that the farmer is in a steady state, in that he expects to grow the same fractions of each crop over time (rather than exhausting the soil by growing only wheat and then leaving the land, for example). This will considerably simplify the notation by allowing us to drop the time subscript. We let the farmer choose only the steady state values of land devoted to wheat W and beans B.

$$Q^W = f(W, B, K^W) \qquad (6)$$

Setting up the Lagrangean for the farmer's problem and differentiating to give the first order conditions yields:

$$\underset{W, B, KW, KB}{\text{Max}}\ L = \Sigma^{\infty}{}_{t=0}\,(1+\delta)^{-t}\,[P^W.f(W, B, K^W) + P^B.g(B, K^B) - c(K^W+K^B) - r(W+B) - \lambda(L-W-B)] \qquad (7)$$

$$\frac{\partial L}{\partial W} = \Sigma^{\infty}{}_{t=0}(1+\delta)^{-t}[P^W.f_W - (r+\lambda)] = 0 \quad \rightarrow \quad [P^W.f_W - (r+\lambda)] = 0 \qquad (8)$$

$$\frac{\partial L}{\partial B} = \Sigma^{\infty}{}_{t=0}\,(1+\delta)^{-t}.[P^W.f_B + P^B.g_B - (r+\lambda)] = 0 \quad \rightarrow \quad [P^W.f_B + P^B.g_B - (r+\lambda)] = 0 \qquad (9)$$

$$\frac{\partial L}{\partial K^W} = \Sigma^{\infty}{}_{t=0}(1+\delta)^{-t}[P^W.f_{KW} - c] = 0 \qquad (10)$$

$$\frac{\partial L}{\partial K^B} = \Sigma^{\infty}{}_{t=0}(1+\delta)^{-t}[P^W.f_{KB} - c] = 0 \qquad (11)$$

$$\frac{\partial L}{\partial \lambda} = L-W-B = 0 \text{ or } \lambda = 0 \text{ with complementary slackness.} \qquad (12)$$

where subscript W denotes the partial derivative with respect to wheat land; subscript B the partial derivative with respect to growing beans; and subscript KW the partial derivative with respect to other inputs into wheat; etc. We assume that the production functions are well-behaved so that these first order conditions define a maximum.

Equations (10) and (11) define the optimal level of other inputs K^W and K^B given the crop rotation, and equation (12) sets the shadow cost of land to ensure that the land constraint is satisfied; these equations will play no further role in the analysis. For our purposes, the interesting first-order conditions are those that relate to crop rotation: (8) and (9). We can interpret these equations as follows. Equation (8) says that the marginal revenue product of growing wheat must equal the rental cost of land plus its shadow cost (λ); otherwise it would be better to take land out of production. The expression (9) for beans contains an extra term: the revenue from beans *plus the value of the resulting future increase in wheat yields,* must equal the rental cost of land plus its shadow cost. This impact of beans on wheat yield is the value we are seeking to isolate in this paper.

The direct approach to estimating the impact of beans would be to use the first order conditions derived above - equate the marginal return of each crop with the cost of land. We could then easily isolate the externality using data on the yields and prices of each crop. In fact, this proves to be quite difficult because we do not know the shadow cost of land (λ) and there are four reasons to believe that the shadow cost was quite high. First, the farmer could not easily increase the amount of land on his farm: he would have to negotiate additional rent contracts and it might be difficult to find a piece of land locally which complemented his existing holding, in terms of position and quality and so on. Second, farmers in the eighteenth century commonly rented land on long year leases. The eighteenth century saw a prolonged period of unanticipated increases in agricultural prices owing to wars and population growth. This meant that the level of rents lagged considerably behind the economic value of land and resulted in a high shadow price.[11] Third, the rental value of land does not include various taxes (such as the land tax and tithe), so it does not reflect the cost of land to the farmer. In principle we could control for taxes, but in practice the land tax and tithe were both levied in an archaic fashion and we would need data specific to each place and time.[12] Fourth, casual inspection of the data shows that the revenues generated by each crop (even the least valuable crop) were considerably in excess of the rent; this bears out the notion that the shadow cost of land was high.

Fortunately, we can manipulate the first-order conditions to eliminate the cost of land ($r+\lambda$). Rearranging, we have:

$$P^W{}_t.f_W = (r+\lambda) \qquad (13)$$

$$P^W f_B + P^B g_B = (r+\lambda) \qquad (14)$$

[11] Turner, M. E., Beckett, J. V. and B. Afton, *Agricultural Rent in England, 1690-1914* (Cambridge, 1997).

[12] The value of land was assessed and the tax was then levied as a proportion of the assessed value, rather than the current market value. But different places were assessed at different times and there were long lags between assessments (about 50 years) so that assessed values bore little or no resemblance to market values. Moreover, the assessed value was influenced by factors such as whether the owner was a Catholic (which tended to result in a high tax assessment). Hence to calculate the amount of tax actually levied we would need to locate specific archival records, rather than making an estimate based on the market rent. For a detailed discussion see Ginter, D., *A Measure of Wealth: the Land Tax in Historical Analysis* (London, 1992).

Equating these expressions and again rearranging:

$$P^W f_B = P^W{}_t . f_W - P^B g_B \qquad (15)$$

Thus the marginal impact of beans on wheat revenue is given simply as the difference between bean and wheat revenue. The equation has an obvious interpretation: if growing beans generates less revenue than growing wheat, then beans must make up the difference by increasing future wheat revenue. Otherwise the farmer would be better off switching land out of bean production and into wheat production.

The model of profit maximisation which we are using in this paper is completely standard.[13] The only innovation is then to eliminate the cost of land by setting up the arbitrage equations between crops. However, a number of points may seem rather opaque to the uninitiated and it is worth drawing them out more clearly.

First, think of the marginal impact of beans (equation 15 above) as simply the derivative of the wheat revenue function with respect to the acreage of beans. It may seem worrying that no physical inputs appear in this equation - for example, manure. After all, the impact of beans on the wheat yield (and hence wheat revenue) will certainly depend on how much manure is used. It is true that if a different quantity of manure were used, then the effect of beans on wheat revenue would be different. But it is nonetheless true that *given the quantity of manure currently used*, the effect of beans is correctly isolated in our equation (15). Just because the productivity of beans would be different under alternative circumstances does not mean that we have measured it incorrectly under the circumstances which currently pertain.[14]

Second, it may seem strange that labour and capital do not appear in the arbitrage equation (15). Surely the farmer would equate marginal *profits* from the two crops rather than *revenues*? One might think that if the production costs of two crops were different (if labour and capital requirements were different for the two crops) then the farmer would not equate profits by equating revenues. But it must be the case that – given the current labour and capital inputs – all the crops generate the same revenue per acre. Otherwise the farmer could make more profit by switching land from one crop to another *holding all other inputs constant*. Since we have postulated that the farmer is profit maximising, it must be the case the he is equating marginal revenues from all the crops.[15]

Third, it is important to note that we could make analogous arguments regarding inputs of labour or capital. The profit maximising farmer is also arbitraging crop revenues per worker and crop revenues per unit of capital. For example, the marginal revenue per worker in bean production must be the same as the marginal revenue per worker in wheat production, otherwise the farmer could profitably reallocate his workers. Therefore we could rework the analysis of this paper in terms of revenues per worker or per unit of capital - and the answers would be *exactly the same*. We choose to concentrate on revenue per acre simply because the

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[13] A text book exposition can be found in Varian, H. R., *Intermediate Microeconomics* (2nd edition, London, 1990), 327.

[14] Let us frame the argument in terms of a firm producing widgets. We can calculate the marginal effect of labour on the output of widgets (i.e. labour productivity). You may then point out that if we added more machines then the marginal productivity would change. You may be correct – but it still does not imply that our current estimate of the marginal productivity is wrong!

[15] In fact, we do not need such a strong assumption as profit maximisation to motivate our model. Suppose that the farmer was employing too much labour for social reasons (for example, he was under a moral obligation to employ all the workers in the village). Hence he was not maximising profit because he was bearing an inflated wage bill. Even then the farmer would want to equate the revenues generated by each crop: otherwise he could make himself better off by changing his crop rotation to increase his revenues.

yield of each crop (which we use to calculate the revenue of each crop) is invariably recorded per acre in historical sources (rather than per worker or per unit of capital).

Finally, suppose that each farm has a different production function, as well as facing different prices (for output, rent, shadow cost of land, etc). Nevertheless, provided that each farmer is profit-maximising given his own particular functions and parameters, the above arbitrage equation (15) should hold for each farm. So if we knew all the elements of the right-hand side of the equation then we would have an exact value for the contribution of beans to wheat revenue given on the left-hand side. We could then estimate the likely effects of changes in crop rotation on each particular farm. Data on crop prices are readily available. So all we need to operationalise the model is data on the marginal product of land in each crop (that is, the marginal yield). In fact, this requirement for marginal yield data raises a slight problem. Although data on crop yields are readily available, they actually represent the *average* product of land in production rather than the *marginal* product. We therefore need to argue either that average and marginal yields are the same, or at least that they are functions of one another in a predictable way. However, this is a common problem in empirical economics and the normal solution is simply to assume that average and marginal yields are equal. We follow this approach in this paper. We thus have an approximation to the impact of growing beans on wheat output, as follows:

Impact of beans on all future wheat revenue on farm *i* = wheat revenue - bean revenue

Naturally, it is important to test our model in order to verify the plausibility and accuracy of the predictions. There are two obvious yardsticks against which we can compare our model. First, we can simulate the variations in crop rotation which occurred on experimental farms (such as Rothamsted) and see whether the model and the field experiments give similar results. Second, we can compare our results to production function estimates of crop rotation effects. We will begin with a comparison to the production function estimates by Brunt.[16] This has the advantage that we can use exactly the same set of farms for the two estimates and thereby eliminate any noise which might contaminate the results.

The production function estimates take the following form:

Farm *i* wheat yield =

$$\Sigma_i \alpha X_i + (W/L + Ba/W + T/W + B/W + O/W + P/W + C/W + F/W) + \varepsilon_i$$

where W, Ba, O, P, B, T, C and F are the acreages of wheat, barley, oats, peas, beans, turnips, clover and fallow respectively; and X_i are other variables unrelated to crop rotation (weather, soil type, technology, etc). In order to compare the results from the arbitrage model with the regression results, we now consider the following thought experiment. Increase the bean acreage in order that the bean to wheat ratio goes up from its initial value B/W to (B/W)+1. The resulting increase in wheat yield should be the coefficient on B/W in the regression model, ceteris paribus. The problem with performing this thought experiment is that it violates the land constraint on the size of the farm: in order to increase the bean acreage and keep everything else equal, we would have to increase the size of the farm. So now consider cutting the acreage of all the other crops by an equal proportion (so as to keep their ratios constant) in order to allow the bean/wheat ratio to increase by one. This is the counterfactual which we are going to calculate for the arbitrage model.[17]

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

[17] It should be noted that this induces a second effect in the regression model - cutting the percentage of wheat to accommodate changes in bean acreage will have a positive effect on wheat yields in addition to the effect of beans themselves. We add this effect to the regression coefficient when we compare the two models below.

The current yield is given by:

$$\text{Wheat yield before change} = \frac{f(W, Ba, O, P, B, T, C, F)}{W}$$

We can calculate the new wheat yield (after changing the crop rotation) using a first-order Taylor series expansion. The principle is that the new wheat output will be approximately equal to: the old wheat output; less the reduction in wheat output due to planting less wheat land; plus the increase in wheat yield due to growing more beans; less the reduction in wheat yield due to growing less of the other crops (with their associated externalities). The reduction in wheat output due to a change in wheat land is obviously approximately the wheat yield times the change in wheat area. Similarly, the increase in wheat output due to growing more beans will be approximately the marginal impact of beans on wheat output (f_B) times the change in bean acreage. The cut in wheat output due to growing fewer peas will be the impact of peas on wheat output (f_P) times the reduction in pea acreage, and so on. Thus we have:

$$\text{New wheat yield} = \frac{\text{New wheat output}}{\text{New wheat land area}}$$

$$\approx \frac{f(W, Ba, O, P, B, T, C, F) + \Delta W f_W + \Delta Ba f_{Ba} + \Delta O f_O + \Delta P f_P + \Delta B f_B + \Delta T f_T + \Delta C f_C + \Delta F f_F}{W + \Delta W}$$

where the ΔW denotes change in area of wheat land, etc.

So the change in the wheat yield implied by the arbitrage model is given by the difference between the wheat yield before changing crop areas and the estimated wheat yield after changing crop areas. In other words,

Farm *i* externality by arbitrage method = Actual wheat yield - New wheat yield

where the new wheat yield is calculated from the Taylor series expansion. In the next section we compare results from the arbitrage model with regression estimates and experimental data.

3. Estimating the Effects of Crop Rotation

We operationalise our model using the data drawn from a survey of 400 farms visited by Arthur Young in England in the 1760s. The data set is exceptionally detailed and high quality, as evidenced by its widespread use amongst other researchers.[18] One of the advantages of the Young data set it that it has already been used to estimate a production function for wheat - including the effects of crop externalities - so we can make a direct comparison with the results derived in this paper for the same sample of farms. To estimate the model we need three pieces of information. First, we need to know the crop rotation on each farm; second, we need the yield of each crop in cultivation; and third, we need the market price of each crop in each locality.

The crop rotation is detailed for each of several hundred farms. Young recorded data on the eight major field crops then in cultivation (wheat, barley, oats, peas, beans, turnips, clover and bare fallow).[19]

[18] For example, Clark, G., 'Productivity Growth without Technical Change in European Agriculture before 1850,' *Journal of Economic History*, vol. 47 (1987), 419-32; 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. 58 (1988), 93-116.

[19] Not all farms produced all eight crops. The minimum number is three and the maximum is eight; the median is four.

The yield data is not specific to each farm but instead to each village (which normally contained two or three farms). Hence we may have a distortion in our calculations to the extent that the yields on a particular farm diverged from the village average. However, any discrepancy is likely to be small for three reasons. First, environmental conditions and husbandry practices were generally very similar within each village, which resulted in similar yields.[20] Second, Young took careful note of farmers who were doing something different to other farmers in the village (better or worse) and he used them as examples to be praised or pilloried as necessary. So if Young was content to record an average yield for several farms in a village then it is because their yields were not substantially different. Third, in cases where farm-specific yield data is available we have used it in preference to the village level data.

The final piece of information required is the local output price data for each crop. Young recorded village output prices only for turnips, so we need to find an alternative source for the other crops. The standard source for local agricultural prices in the eighteenth century is the London Gazette.[21] We use the 1770 and 1775 London Gazette price series for wheat, barley, oats and beans.[22] And following Allen, we assume that peas and beans sold for the same price.[23] For clover, we assume that the price was 360d per ton everywhere, which is the median price found in the scattered references in Young. For fallow, there is no direct price data available because it was not a traded product, so instead we simply estimate the fodder output of fallow to be 300d per acre. This is a plausible figure given that the fodder output of turnips was around 500d per acre, and it is certain that turnips produced a significantly higher value of fodder per acre than did fallow. Calculating the externalities for each farm yields the results in Table 1 below.

These initial results are encouraging. We expect grain crops to enter negatively into the rotation and Table 1 shows that growing barley reduces the wheat yield by 1.9 bushels and oats reduce the wheat yield by 0.9 bushels. (The mean wheat yield for our sample is 23 bushels per acre). These values are in the range which we would expect and they also show that the adverse effect of oats is less severe, which is consistent with general evidence that oats are a less exhausting crop.[24]

The traditional break crops in 1770 were fallow, peas and beans. The existing historical and scientific literature argues that peas and beans had a high value as fodder but only a small effect on wheat yields. This is because peas and beans do not put nitrogen back into the soil directly, they simply recycle it and allow the soil time to recover from a grain

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[20] Consultation of the Ministry of Agriculture Land Classification Sheets for each village shows that land quality was fairly homogeneous within each village. This is supported by the fact that crop rotations were extremely similar on all the farms within each village – whereas we would expect farmers to have chosen different crop rotations if the climate or soil conditions varied significantly across the village.

[21] Parliament collected weekly prices for the four main market towns in each county. It then averaged the four prices for each county and published the results by county in the London Gazette. The disaggregated data have been lost, so we have perforce applied the average county price to the outputs of each farm.

[22] Since Young completed his tour between 1766 and 1769, it is not clear which price period would be the most appropriate. Moreover, farmers presumably optimised on the basis of the prices *expected* to pertain in the following year, rather than those which actually pertained. In fact, the argument is mute because the price data only begin in 1770. Hence we use the average annual price (for each county) for 1770. We tested the sensitivity of our results by repeating the exercise using prices for 1775, as discussed in the text.

[23] Allen, R. C., 'The Consequences of Parliamentary Enclosure for Productivity in English Agriculture,' *Economic Journal*, vol. 92 (1982), 937-53.

[24] Lockhart, J. A. R. and A. J. L. Wiseman, *Introduction to Crop Husbandry* (London, 1966).

crop (for example, through the natural action of nitrogenizing soil bacteria).[25] In line with the received wisdom, our results suggest that peas and beans had only a modest effect on yields (positive in the case of peas and negative in the case of beans).

Table 1. The Effect on Wheat Yields of Cultivating Other Crops, c. 1770 (in bu/acre).

Externality From:	Mean Effect at 1770 Prices	SE	Mean Effect at 1775 Prices	SE	N
Barley	-1.87	0.25	-2.19	0.28	129
Oats	-0.89	0.29	0.23	0.27	138
Peas	1.03	0.45	0.76	0.42	59
Beans	-1.69	0.50	-1.72	0.53	40
Turnips	7.28	0.48	6.99	0.49	84
Clover	-1.11	0.50	-1.36	0.52	51
Fallow	9.97	0.28	9.69	0.28	136

By contrast, we find that fallow had a very substantial positive effect. We would intuitively expect fallow to have a large effect. In primitive agricultural systems (such as mediaeval England) it was common to fallow a field every second or third year, despite the high value of forgone production. Fallowing must therefore have been very effective in raising subsequent yields to make it economic. But on the other hand, the price data for fallow is the least satisfactory and the benefit of fallowing may be over-estimated due to an under-estimate of the fodder value of fallow. We analyse the case of fallow in more detail below in conjunction with the regression model.

The most interesting results from Table 1 are the estimated effects of the new break crops, turnips and clover. It is widely believed that nitrogen was the factor limiting wheat yields before the advent of artificial nitrogenous fertilisers in the 1850s.[26] The traditional view is that turnips and clover boosted wheat yields by returning more nitrogen to the soil, and that clover was particularly effective because it is leguminous.[27] Our results show that turnips did indeed have a substantial positive effect on wheat yields. But the effect of clover has been greatly over-estimated and it was typically *negative*. A recent production function analysis has also suggested that clover reduced wheat yields, probably owing to the intensive way in which it was managed.[28] The results from the arbitrage model clearly support this new hypothesis about clover.

The coefficients from the arbitrage model and the production function are reported together in Table 2 below. It is clear that the arbitrage and regression approaches give very similar estimates. It should be pointed out that the congruence of the estimates is not driven by methodology or data. Although the two calculations are based on the same set of farms, the only data which appear in both calculations are the yield of wheat and the crop acreages. Whereas the production function is based on physical characteristics of the farm (soil type, climate, technology) the arbitrage model is based on economic variables (yields and prices).

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[25] Shiel, R. S., 'Improving Soil Productivity in the Pre-fertiliser Era,' in B. M. S. Campbell and M. Overton (eds.) *Land, Labour and Livestock* (Manchester, 1991), 51-77.
[26] Chorley, G. P. H., 'The Agricultural Revolution in Northern Europe, 1750-1880; Nitrogen, Legumes and Crop Productivity,' *Economic History Review*, vol. 34 (1981), 71-93.
[27] Overton, M., 'The Determinants of Crop Yields in Early Modern England,' in B. M. S. Campbell and M. Overton (eds.) *Land, Labour and Livestock* (Manchester, 1991), 284-322.
[28] Brunt, L., 'Nature or Nurture? Explaining English Wheat Yields in the Industrial Revolution,' *Oxford University Discussion Papers in Economic and Social History*, no. 19 (October 1997).

Table 2. The Effect on Wheat Yields of Cultivating Other Crops, c.1770 (on Grade 3 Land only in bu/acre).[29]

Externality From:	Regression Model	Arbitrage Model	SE	N
Barley	-1.68	-2.57	0.30	82
Oats	-1.32	-0.54	0.28	102
Peas	1.67	0.27	0.53	44
Beans	2.88	-1.25	0.59	30
Turnips	4.69	6.13	0.43	62
Clover	-0.18	-0.42	0.56	36
Fallow	1.72	9.42	0.30	97

The main discrepancy between the two methods of estimation arises in the case of fallow. We noted above that the effect of fallow is likely to have been over-estimated in the arbitrage model, owing to the possible under-estimation of the value of fodder. There is another reason why the effect of fallow may be over-estimated in the arbitrage model.

There may be a 'dumb farmer' effect in operation. Fallow was an inferior technology in 1770. Although it was economic to fallow each field occasionally, fallowing frequently was certainly not an optimal use of resources.[30] Hence it is likely that farmers who often fallowed their land were less competent managers (that is, 'dumb'). Dumb farmers might also produce low wheat yields for entirely independent reasons - such as not choosing the best seed corn, or sowing at the wrong time. In a cross-section of farms, this would create a negative correlation between the proportion of fallow and the wheat yield. Larger areas of fallow land would be pushing up wheat yields; but at the same time, the increasing incompetence of the farmer would be pushing down wheat yields. The estimated effect of fallow might still be positive in regression, but the effect would be *under*-estimated.

By contrast, the dumb farmer effect would cause an *over*-estimate in the arbitrage model. We assume that the farmer is maximising profits by earning the same revenue from each crop at the margin. Differences in crop revenues therefore measure the size of the externality. But it may be the case the dumb farmers were earning less from the marginal field of fallow than they were earning from a marginal field of wheat (or some other crop). Since the externality is effectively calculated as a residual, over-estimating the return to a field of fallow would lead us to over-estimate the positive externality. So the correct estimate of the fallow externality probably lies somewhere between the arbitrage and regression estimates.

Another useful test of the arbitrage estimates is to simulate a variety of crop rotations and compare them to both the regression estimates and experimental data, as shown in Table 3 below.

For several reasons, we would not expect to find a perfect match between the arbitrage model and the experimental data. Notably, the level of yields is likely to be higher on experimental farms owing to a higher level of inputs (which will be reflected in factors such as closer monitoring of the crop and greater timeliness of ploughing and sowing). However, the experimental data should give us some idea of the level of yields expected and the yield variation between crop rotations.

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[29] In the regression model, the effect of crop rotation is estimated on land of grade 3 quality only (as defined by the Ministry of Agriculture). So to make a proper comparison of the two techniques, we compare the regression and arbitrage estimates of crop externalities on land of grade 3 quality only.

[30] Since fallowing is the best form of weed control in organic systems, all farmers fallowed their land occasionally. This remained true in England until the advent of herbicides in the post-war period. See Ministry of Agriculture, *A Century of Agricultural Statistics* (London, 1968).

Table 3. Wheat Yields under alternative Crop Rotations (bu/acre).

Rotation:	Continuous Wheat	Wheat-Fallow	Wheat-Turnips-Barley-Fallow
Arbitrage Model[31]	14	22	24
Rothamsted[32]	12	18	29
Waite[33]	11	21	28
Regression Model	8	18	25

The regression estimates are closer than the arbitrage estimates to the experimental data, and the levels also seem more plausible for the regression estimates (that is, they lie *below* the experimental data). The arbitrage estimates are being pushed up by the very positive effect of fallow. It is also noticeable that the divergence of both models from the experimental data is more marked for the continuous wheat case. This is to be expected because we are using the models to predict a long way out of sample (no one in the data set cultivates anything like 100 per cent wheat), so we are forced to apply estimates based on marginal changes to large changes. Even allowing for these caveats, both the regression and arbitrage models furnish estimates which are similar to the experimental data.

4. Testing and Extending our Results

Given the surprising results on turnips and clover, it is important to undertake further analysis to verify our findings. Our argument is essentially that the fodder output of clover was greater than that of turnips; but the effect on wheat yields was negative for clover whilst being strongly positive for turnips. Hence the farmer faced a trade-off when choosing which fodder crop to cultivate. This is intuitively obvious after a moment's reflection - if clover had been better at producing *both* fodder and nitrogen, then clover would have been a superior technology and displaced turnips completely from the rotation. If our argument is correct then we would expect to see farmers switching between clover and turnips in response to variations in the price of beef and wheat. Clover produces more fodder but depresses wheat yields - so farmers would switch to clover when the price of beef was high relative to the price of wheat. Turnips produce higher wheat yields but less fodder - so farmers would switch to turnips when the price of wheat was high relative to beef. It is generally accepted that flexibility was one of the major benefits of 'mixed farming' (that is, producing both arable and pastoral outputs). Relative prices fluctuated very substantially year-on-year as a result of supply shocks (primarily caused by weather) and demand shocks (caused by wars and import restrictions). But responding to shocks was difficult because it was very costly and time-consuming to switch land resources between pastoral and arable production. Instead, the farmer could respond by changing his fodder crop - he could reduce wheat output

[31] To permit a fair comparison between different rotations we used the same sample of farms for all three simulations. This restricted our sample to 41 farms because all the farms had to be cultivating wheat, turnips, barley and fallow (in order for us to be able to calculate all the relevant externalities).

[32] The Rothamsted Experimental Station in England is the oldest experimental farm in the world, founded in 1838. The data presented here is taken from the long term rotation experiments reported in Hall, A., *The Book of the Rothamsted Experiments* (London, 1905).

[33] The Waite Experimental Station in Australia was founded in 1925 and reflects drier climatic conditions. The data presented here are taken from Grace, P. and J. M. Oades, 'Long Term Field Trials in Australia,' in Leigh, R. A. and A. E. Johnson (eds.) *Long Term Experiments in Agricultural and Ecological Sciences* (Wallingford, 1994), 53-82. Wheat-Turnips-Barley-Fallow was not reported for Waites, so instead we give the figures for Wheat-Barley-Peas.

and raise meat output simply by planting clover in his rotation instead of turnips. This could be achieved very rapidly and was basically a costless substitution.

We can show that farmers in England responded rationally in this way both across the country and over time. First we consider the planting response of the farmers in the Young data set to local variations in relative output prices. In Table 4 below, we regress the ratio of clover acreage to turnip acreage on the ratio of the beef price to the wheat price. The response is very clear, with the expected sign.[34]

Table 4. Variations in Output Prices and the Choice of Fodder Crop, c.1770.

Variable Explaining Clover-Turnip Acreage Ratio	Coefficient (SE)
Beef-Wheat Price Ratio	36.70** (10.77)
N	72
R^2	0.14
Adjusted R^2	0.13
F-statistic	11.62

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

Secondly, we can show that farmers also responded rationally over time. From 1870 the British government took an annual agricultural census. We can relate changes in the national acreages of clover and turnips to changes in national average prices of beef and wheat. The results in Table 5 below are very similar to the cross-sectional results for 1770 (we have added a time trend to control for changes in capital or technology). The lag structure is interesting because it suggests that farmers responded more to prices pertaining several years' previously than to last year's price. This seems reasonable given the high variance of agricultural prices and adaptive expectations – farmers could be more sure that price changes were 'permanent' after a few years.

Another advantage of the arbitrage approach is that it enables us to calculate an externality for each individual farm. We can then seek to explain the variation in the size of the externality itself, with reference to detailed agricultural management practices. This is a good test of the estimated externalities and it also reveals additional information about the usefulness of different crops and cultivation techniques. In principle, we could undertake a similar exercise using regression techniques in a production function format, by using interaction terms to pinpoint when the externalities were large or small. In practice, it is impossible to get accurate estimates using a production function because the number of observations is generally too small relative to the number of explanatory variables (which rises sharply when interaction terms are added).[35]

[34] In this regression we use only farms which were growing at least some turnips and some clover. Other farms were probably at a corner solution and could not be expected to respond smoothly to changes in relative prices.

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

Table 5. Changes in Output Prices and the Choice of Fodder Crop, 1870-1888.

Variable Explaining Clover-Turnip Acreage Ratio	Coefficient (SE)	Coefficient (SE)
Time	-0.05* (0.02)	-0.05** (0.01)
Beef-Wheat Price Ratio (mean of last 5 years)	24.25** (5.64)	
Beef-Wheat Price Ratio (lagged 1 year)		4.23* (1.36)
Beef-Wheat Price Ratio (lagged 2 years)		5.15** (1.37)
Beef-Wheat Price Ratio (lagged 3 years)		6.75** (1.58)
Beef-Wheat Price Ratio (lagged 4 years)		4.98** (1.36)
Beef-Wheat Price Ratio (lagged 5 years)		2.88 (1.50)
N	14	14
R^2	0.86	0.94
Adjusted R^2	0.84	0.89
F-statistic	34.75	19.27
DW	1.73	1.88

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

We have analysed the externalities of all the field crops reported above. As we would expect, they generally depend on factors such as soil conditions and cultivation practices. Here we report the analysis only of turnips and clover, which are the most historically interesting crops. The other results are reported in the Appendix to this paper.

Cultivating turnips is generally thought to have raised wheat yields in three ways, and each of these factors appear significantly in the turnip regression in Table 6 below.

Table 6. Explaining Variations in the Turnip Externality, c.1770 (in wheat bu/acre).

	Coefficient (SE)
Grade 2 Land Dummy	11.95** (1.20)
Sandy Soil Dummy	2.13* (1.02)
No. of Ploughings before Turnip Sowing	1.76** (0.66)
Seed Drill Dummy	5.21* (2.05)
Turnips Drawing Dummy	4.52** (1.66)
Turnips Carried to Barn Dummy	-5.04** (1.73)
N	73
R^2	0.64
Adjusted R^2	0.61
F-statistic	19.50

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

First, turnips added organic matter (humus) to the soil, which was particularly valuable in areas with sandy soil such as Norfolk. This is captured by the Sandy Soil Dummy, which raised the externality by two bushels per acre (almost ten per cent of average wheat yields).

Second, turnips were a method of weed control. The seed-bed was prepared very carefully for turnips in order to eliminate as many weeds as possible (turnips are otherwise over-run by weeds and there is a very small crop). The turnips were then planted in rows (either by hand or by drill) and this allowed the farmer to hoe out more weeds in the spring. Both of these activities cleaned the soil in preparation for the following wheat crop, which would have higher yields due to reduced weed competition for nutrients. Table 6 shows that ploughing more times before sowing the turnip crop resulted in a larger externality on wheat, which is consistent with the traditional story. We do not find any effect from hoeing itself, but we do find a substantial effect from drilling seed (which should have made hoeing more effective).

Third, turnips recycled nitrogen more effectively in the form of manure. But the quantity and effectiveness of manure was affected by management practices, and these are again captured in Table 6. The turnips grow half above ground and half below. The farmer then had a choice. If labour was cheap then he could use labourers to pull up (draw) the turnips so that the whole root was eaten by the farm animals; but if labour was expensive then the farmer could leave the turnips in the ground and let the animals eat only the top half. If the farmer had the turnips drawn then he had another choice - either he could let the turnips be eaten in the field, or he could have them moved to the barn for stall feeding. As we would expect, the regression shows a positive effect from drawing turnips because more of the crop is recycled through the animal. But the regression also shows a negative effect if the turnips are taken to the barn for stall feeding. This is because the manure (and hence the nitrogen) is removed from the field. In principle, the manure was returned to the field in the spring during muck spreading. But in fact, experimental evidence shows that more than half of the nitrogen is lost from stored manure even under ideal storage conditions.[36] Hence the positive externality of turnips is much reduced in the case where turnips were carried to the barn.

We can undertake a similar exercise with the clover externality. We argued above that the surprising negative effect of clover was due to the removal of clover (and hence nitrogen) from the field. We can show that this resulted from two particular management choices.

The clover started to grow in the spring and early summer. The farmer then faced his first choice - whether to let the animals graze the clover in the field (like a normal meadow) or to mow the clover and feed it to the animals in the yard. Of course, clover tended to reappear soon after consumption as manure. So the advantage of feeding in the field was that manure was generated in the field (rather than in the farm yard). The disadvantage of feeding in the field was that the animals would not graze the field as effectively as a man might mow it, so the total fodder output would be reduced. The farmer had to weigh up these two effects and make his best response on the basis of the relative prices of manure and fodder (when fodder was at a premium, mow the field; when manure was at a premium, graze the field). Towards the end of the growing season the clover was invariably allowed to grow long and then cut for hay for winter feeding. The farmer then faced his second choice – whether to feed the clover to the animals in the field or remove it to the barn. This presented the farmer with the same advantages and disadvantages as early summer mowing (more dung in the field versus more fodder in the yard).

We can quantify the effects of these management decisions on soil fertility. The econometric results in Table 7 below clearly demonstrate the adverse impact on soil fertility of removing the manure by early mowing and taking clover hay to the farm yard. The

[36] Voelcker, J., 'Manures,' in *Encyclopaedia Britannica*, vol. 17 (Cambridge, 1910), 610-18. This is because nitrogen compounds are volatile and break down under atmospheric conditions - so the nitrogen literally vanishes back into the atmosphere.

increased nitrogen losses caused by those two techniques have a serious negative impact on the clover externality.

Table 7. Explaining Variations in the Clover Externality, c.1770 (in wheat bu/acre).

	Coefficient (SE)
Clover Hay Taken To Barn Dummy	-6.34** (1.04)
Early Summer Mowing Dummy	-2.05* (0.84)
N	44
R^2	0.48
Adjusted R^2	0.45
F-statistic	18.67

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

These results have an important implication: the effect of clover on wheat yields *could have been positive* if different management strategies had been pursued. The mean effect of cultivating clover in our sample was to *reduce* wheat yields by 1.37 bushels per acre. But 20 per cent of those farmers took their clover hay to the yard; and 45 per cent of them mowed the clover in the early summer. If all the farmers had stopped these management practices then the clover externality on wheat would have risen (on average) by 2.18 bushels per acre. So cultivating clover would then have *increased* wheat yields on average by 0.81 bushels per acre. Our analysis therefore supports the conventional wisdom in the sense that clover *could have* pushed up wheat yields in the eighteenth century. But we show that in fact clover *pushed down* wheat yields purely as a result of the management strategies actually pursued. A substantial minority of farmers were choosing to depress their soil fertility in order to generate more animal fodder. This may well have been an optimal strategy, given the relative prices which they faced.

5. Conclusions

In this paper we have formulated an arbitrage model of crop rotation which offers a new method of estimating the effect of crop externalities on wheat yields. Estimating the effects of crop rotation is very important in both historical and development economics, where the agricultural sector is large and crop rotation is the primary source of soil fertility. The arbitrage method has two important advantages over the traditional production function approach.

First, the arbitrage method relies on different data series to the production function (yields and prices rather than physical inputs) and these data series are much more commonly available. This means that the arbitrage method can be used as an independent check on the production function estimates; and it can often be estimated for periods and places where there is insufficient data for a production function analysis, such as medieval England. Moreover, regression estimates of agricultural production functions typically suffer from severe missing variable bias due to an inability to control for natural soil fertility; this problem is entirely absent with the arbitrage model.

Second, the arbitrage model allows us to estimate the yield effect of each crop in the rotation on each individual farm. This is theoretically attractive because we can treat each farm as an individual population rather than an observation drawn from a single population (which is the assumption underlying regression estimates of production functions). This is important if we have reason to believe that farms in the data set have access to different technology, for example. It is empirically attractive to isolate the externality effect on each farm because we can then analyse the variation in the externality much more precisely (with reference to environment and management, and so on).

We have applied the arbitrage model to a data set of English farms from 1770, for which it is also possible to estimate a production function. The arbitrage model gives very similar results to the production function. It reinforces the claim that the effects of turnips and clover on wheat yields during the Industrial Revolution have been estimated inaccurately. Turnips had a very positive effect on wheat yields - but clover had a negative effect. This unexpected result if supported by an analysis linking the variation of cropping patterns (clover versus turnips) and output prices (beef versus wheat). When beef prices were high relative to wheat, farmers sacrificed wheat yields to raise their beef output by switching from turnips to clover. This was true in 1770 and in the late nineteenth century.

Further examination of the externalities reveals that they varied dramatically in response to management practices. Farmers could increase their output of fodder by sacrificing the fertility effect of turnips and clover. In particular, there was a strong adverse yield effect from removing turnips and clover from the field in order to stall-feed animals. Whereas the fertility effect of clover could have positive (in line with conventional wisdom), it was negative overall due to stall feeding. This improves our understanding of the agricultural techniques employed in the eighteenth century and will lead us to revise our understanding of productivity change during the Industrial Revolution.

Appendix. Modelling Crop Externalities

Modelling the turnip and clover externalities was relatively straightforward and generated historically important results. But it is more difficult to model the externalities of the other crops. This is for two reasons. First, we have very little scientific information to guide us in model building. Since modern farmers have access to powerful artificial fertilisers, they are not very interested in rotating crops in order to raise the fertility of the soil. Therefore there has been very little research carried out to ascertain under what conditions the externality from (say) peas is likely to be large or small. Second, Young was very interested to discover the best cultivation techniques for the new crops such as turnips and clover. But he was less interested in the cultivation techniques employed on the standard field crops, such as peas and beans. Consequently, Young recorded less information about the standard crops and we are left with fewer explanatory variables at our disposal with to explain the variation in externalities.

Table 8. Explaining Variations in the Bean and Pea Externality, c.1770 (bu/acre)

Explanatory Variable	Beans (SE)	Beans (SE)	Peas (SE)	Peas (SE)
Clay (dummy)	-3.58** (1.05)	-3.60** (1.08)		-0.03 (1.27)
Sand (dummy)	-3.45** (1.15)	-3.44** (1.17)	3.87** (1.07)	4.07** (1.09)
Lime (dummy)	6.12** (1.02)	6.15** (1.08)	2.13** (0.77)	2.30* (0.96)
Drill (dummy)	3.53* (1.42)	3.53* (1.44)		2.79 (2.15)
Grade 1 or 2 Land (dummy)		0.08 (0.96)	4.18** (0.91)	4.39** (1.07)
N	37	37	55	55
R^2	0.56	0.56	0.41	0.43
Adjusted R^2	0.51	0.49	0.37	0.37
F-statistic	10.19	7.90	11.71	7.35

Note: * is significant at the five per cent level and ** is significant at the one per cent level.

The clearest results are generated for beans and peas. Beans and peas are similar in the sense that they are both leguminous pulses and they both benefit from liming of the soil. But nonetheless they flourish under slightly different conditions. Beans grow best in heavier clay soils, whereas peas grow best in lighter sandy soils.[37] Also beans can be sown in rows and benefit from seed drilling, whereas peas were never drilled. We have information on all these variables in the Young data set and they feature significantly in the contrasting regressions in Tables 8 above.

We get similar results with fallow, in Table 9 below. This time we find that the externality is larger on sand and clay soils and on Grade 4 land (poor quality). Casual evidence suggests that more fallowing occurs on lower quality land; we have now shown that this is because lower quality land derives greater benefit from fallowing.

The results from the oats and barley regressions are the most complex to explain. First, let us consider the use of lime. Liming reduces the oats and barley yields because they prefer acidic soil. The farmer nonetheless applies lime to his land because it benefits his other crops. This *reduction* in oats and barley yields has a *positive* effect on the *externalities* of oats and barley. This is because the lower-yielding oats and barley offered less competition for the limited stock of nutrients sought by the wheat plants, so wheat yields would be higher. The positive effect of liming on the barley externality in Table 10 below is therefore understandable. The negative effect on the oat externality is rather surprising.

Table 9. Explaining Variations in the Fallow Externality, c. 1770 (bu/acre).

Explanatory Variables	Fallow (SE)	Fallow (SE)
Clay (dummy)	1.91** (0.58)	1.96** (0.58)
Sand (dummy)	2.00** (0.75)	2.04** (0.75)
Drill (dummy)		3.22 (2.91)
Grade 4 Land (dummy)	2.80* (1.10)	2.83** (1.09)
N	131	131
R^2	0.15	0.16
Adjusted R^2	0.13	0.13
F-statistic	7.45	5.90

Note: * is significant at the five per cent level and ** is significant at the one per cent level.

The effect of barley ploughing operates via a similar mechanism (i.e. more ploughing produces a better barley crop and drains more nutrients away from the subsequent wheat crop). Hence barley ploughing has a negative effect on wheat yields. Remember that barley is a more exhausting crop than oats, so it is not surprising that the effect of ploughing can be seen in the barley externality but not the oat externality.[38] The barley externality is also significantly more positive on higher grade land, which is again what we would expect.

[37] Lockhart, J. A. R. and A. J. L. Wiseman, *Introduction to Crop Husbandry* (Oxford, 1966), 126-9.
[38] Lockhart, J. A. R. and A. J. L. Wiseman, *Introduction to Crop Husbandry* (Oxford, 1966), 122.

Table 10. Explaining Variations in the Barley and Oats Externality, c.1770 (bu/acre).

Explanatory Variables	Barley (SE)	Barley (SE)	Oats (SE)	Oats (SE)
Sand (dummy)		-1.15 (0.67)	2.77** (0.72)	2.75** (0.72)
Lime (dummy)	2.21** (0.57)	2.76** (0.56)	-1.34* (0.61)	-1.41* (0.61)
Drill (dummy)	6.58** (2.52)	6.71** (2.36)		-3.25 (3.28)
Grade 1 or 2 Land (dummy)	2.01** (0.64)	2.20** (0.60)		
Barley Ploughings	-1.08** (0.26)	-1.45** (0.26)		
N	94	92	132	132
R^2	0.29	0.39	0.12	0.12
Adjusted R^2	0.26	0.35	0.10	0.10
F-statistic	9.02	10.85	8.43	5.95

Note: * is significant at the five per cent level and ** is significant at the one per cent level.

These results are of considerably less historical interest than the turnip and clover results. Nonetheless, it is a useful exercise to examine the characteristics of all the crop externalities, and it reinforces our overall confidence in the reliability of the arbitrage model.

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