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# *"WHERE THERE'S MUCK, THERE'S BRASS"* *THE MARKET FOR MANURE IN THE INDUSTRIAL REVOLUTION*

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## Abstract

Between 1700 and 1850, English grain yields were substantially higher than those attained in other countries. It is widely believed that yields were constrained by the availability of nitrogen, and that supplies of nitrogen were effectively limited to animal dung produced on the farm. This paper presents the first systematic analysis of *off-farm* sources of nitrogen, such as urban and industrial waste. We show that the use of off-farm nitrogen was both widespread and intensive by 1700, contrary to the received wisdom. We further argue that there was only modest growth in the use of off-farm nitrogen up to 1850. We explain this pattern of use of off-farm nitrogen by supply and demand factors. We use a new method of estimation to show that the overall impact was to raise wheat yields by a constant 20 per cent throughout the period.



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# “Where There’s Muck, There’s Brass” The Market for Manure in the Industrial Revolution

by

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# "WHERE THERE'S MUCK, THERE'S BRASS"
# THE MARKET FOR MANURE IN THE INDUSTRIAL REVOLUTION[1]

## I. Introduction

The performance of English agriculture during the Industrial Revolution was spectacular by international standards and it has been highlighted as one of the key factors permitting an early release of labour to industry. But it is also widely accepted that agricultural output in England - as elsewhere - was limited by the availability of soil nitrogen.[2]

The farmers' first response to the scarcity of nitrogen was to recycle as much as possible on the farm. This technique was perfected in the eighteenth century by the take-up of root crops and the emphasis on mixed farming, with its associated increase in animal dung per arable acre. The farmers' second response was to bring nitrogen onto the farm from other locations, such as urban and industrial centres. Overton recently commented that: 'From the sixteenth century onwards agricultural writers enthused about the possible sources of additional manure: seaweed, putrifying fish, silt, crushed bones, rags, malt dust, ashes and soot were all advocated.'[3] Given the rate of urbanisation and industrialisation between 1700 and 1850, we might well ask to what extent there was an increase in the use of these manures and what might have been the effect on output. But Overton concludes that:

'There is no way of knowing the extent to which these more esoteric substances were used, although it is likely to have been minimal except where a farm had good access to water transport.'[4]

This echoes the sentiments of other researchers in English agriculture.[5] O'Brien, in particular, argues that the high ratio of animals to arable acreage in England was the bedrock of her success – precisely because off-farm sources of nitrogen were so scarce before 1850. But this assessment is too pessimistic - both with respect to the state of our knowledge, and the use of off-farm nitrogen. In this paper we present the first detailed assessment of off-farm manure in English agriculture, by quantifying the use of 21 varieties. We consider how many people were using each type of manure; how much they were using; and the total effect on wheat yields. Our analysis starts from the farm survey undertaken by Arthur Young in the late 1760s, covering 299 farms in 185 villages throughout England.[6] We supplement this information with Royal Society survey data from 1665, and with the

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1 An English proverb meaning that agriculture flourishes when lots of dung is used to fertilise the land. For early usage, see Bohn H G, *A Handbook of Proverbs* (London, 1855), 564. This research was funded by the Economic and Social Research Council, the Fulbright Commission and Nuffield College, Oxford, under its Prize Research Fellowship Programme. The paper was completed whilst I was a visitor at the Harvard economics department. I am grateful to James Foreman-Peck, Oliver Grant, Jane Humphries, Avner Offer and - especially - Lucy White for helpful comments. I would also like to thank seminar participants at the London School of Economics and Oxford. Any remaining errors are entirely my own responsibility.

2 Overton M, *Agricultural Revolution in England* (Cambridge, 1996), 107. Similar arguments are presented in, for example: Chorley G P H, 'The Agricultural Revolution in Northern Europe, 1750-1880: Nitrogen, Legumes and Crop Productivity,' *Economic History Review*, vol. 35 (1981), 71-93; Shiel R S, 'Improving Soil Productivity in the Pre-fertilizer Era,' in Campbell B M S and M Overton (eds.) *Land, Labour and Livestock* (Manchester, 1991), 51-77.

3 Overton M, *Agricultural Revolution in England* (Cambridge, 1996), 109.

4 Overton M, *Agricultural Revolution in England* (Cambridge, 1996), 109.

5 O'Brien P K, 'Path Dependency, or why Britain became an Industrialized and Urbanized Economy long before France,' *Economic History Review*, vol. 49 (1996), 222; Woodward D, 'An Essay on Manures,' in Chartres J A and D Hey (eds.) *English Rural Society, 1500-1800* (Cambridge, 1990), 276.

6 The survey was undertaken by a gentleman farmer and writer called Arthur Young on a personal tour of England and Wales. His surveys were published in *A Six Weeks' Tour through the Southern Counties of England* (London, 1766); *A Six Months' Tour through the Northern Counties of England* (London, 1768);

experiments reported in *the Journal of the Royal Agricultural Society of England* in the 1840s. We show that by 1770 there were local, regional and even international markets for manure; and we can explain the pattern of manure use by supply and demand. We estimate that off-farm manure raised yields by a steady 20 per cent throughout the period 1700 to 1840.

In order to gauge the historical impact of off-farm manure we must consider two issues. First, we need to measure how many units of each type of manure were employed. Second, we must establish the effect of each unit on grain yields. Hence we begin in section II by quantifying the input of each type of manure - both the *extent* and the *intensity* of usage. We show that it was normal by 1770 for farmers to use large amounts of off-farm manure; and the quantities applied were similar in 1665, 1770 and 1840. In section III we measure the responsiveness of yields to each type of manure. This is difficult due to the small number of observations; so we use a novel technique based on the idea that a rational farmer would not spend more on manure than he was recouping in terms of higher yields. Wherever possible, we demonstrate the similarity of these results to other estimates of manure effectiveness. In Section IV we extend our analysis by considering the factors which determined the level of manure use in England, and how they changed over time. We explicitly model the demand and supply of manure and show that progress was constrained by the supply-side. In Section V we combine the quantity and responsiveness data and thereby estimate the overall contribution of off-farm manure to wheat yields in 1700, 1770 and 1840. Section VI concludes.

## II. The Extent and Intensity of Manure Use

Let us begin by defining more precisely what we mean by the term 'manure'. We normally think of manure as referring to animal dung but in fact a much wider range of substances are can also be classed as 'manure'. The preceding quote by Overton gives examples such as malt dust, ashes, seaweed and bones. Essentially, a manure is any substance which increases the fertility of the soil, but it is useful to divide these substances into two broad categories: nitrogenous fertilizers and alkalis.

First, there are the nitrogenous fertilizers. These products furnish the three main chemical elements required for healthy plant growth (nitrogen, potassium and phosphorus) but particularly nitrogen. Growing plants use more nitrogen than any other chemical element, so nitrogen is usually in shortest supply and farmers rectify this problem by applying fertilizers which are rich in that chemical element. Before 1850 all nitrogenous fertilizers were organic substances such as malt dust and ashes. Second, there are the alkalis – chalk, lime and marl. These are used to adjust the acid balance of the soil. Plants cannot be cultivated successfully unless the acid balance of the soil is kept close to neutral. This is particularly true of the most valuable crop (wheat); and the new fodder crop (the turnip) which was substantially raising arable output in the eighteenth century.

It may seem surprising to categorise alkalis as manures, but in fact this was the standard usage of the eighteenth and nineteenth centuries. For example, Arthur Young referred to marl as 'the prince of manures.' Moreover, this inclusive definition of manure can still be found in the Oxford English Dictionary. To make our historical analysis more complete in this paper, we consider both

and *The Farmers' Tour of the Eastern Counties of England* (London, 1769). They are hereafter referred to as the *Southern*, *Northern* and *Eastern Tours* respectively. Arthur Young and his data have managed to generate an entire literature of their own which is too vast to discuss here - 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.

types of manure (fertilizer and alkali). We will see that alkalis were actually the most popular type of manure.

Young recorded information on the take-up of 21 types of off-farm manure, which included all the most common types. We begin by examining how extensively each type of manure was employed. It is clear from Table 1 below that the systematic use of off-farm manure was extremely common in 1770. In fact, 62 per cent of villages in our data set used at least one off-farm manure (be it alkali or nitrogen). Moreover, those villages which employed off-farm soil dressings typically used more than one, with the mean number being 1.9 manures. If we break down the figures more precisely then we find that 32 per cent of villages used an off-farm nitrogenous fertilizer (which is perhaps more central to the historical issue of nitrogen availability). So it was normal by 1770 to use a variety of nitrogenous and alkali manures produced off the farm.

It is generally accepted that all the manures listed in Table 1 below were also used widely in the 1840s (although we do not have detailed survey data revealing the exact popularity of each type). But it is worth emphasising the fact that these manures were also in common use as early as 1665. An agricultural survey undertaken by the Royal Society devoted great attention to the use of off-farm manure and found that the use of several types was reported in most localities.[7] It should be stressed that only 11 returns from the 1665 survey have survived, covering only five counties. If we had returns for *all* counties then the extent of off-farm manure use would obviously be much larger than that captured in Table 1.

Let us consider the use of mineral manures in 1770 in more detail. The alkali minerals - chalk, lime and marl - form the most popular group of manures in Table 1. Lime alone was used in 33 per cent of all villages and the total use of alkalis covered well over half of the villages in the sample. This is what we would expect, given the importance of soil pH and the occurrence of acidic soils in the UK. The other minerals – salt and sea sand - served a less important purpose than the alkalis, and were consequently less popular. Salt was added to the soil because it contained sodium. Plants do not need sodium to grow; but sodium replaces potassium in chemical compounds and thereby liberates the potassium which occurs naturally in the soil. Through this liberation of potassium, salt can have a very marked short term effect on yields - although the overall impact is limited by the stock of potassium in the soil. Sand could be applied to change the soil structure, thereby improving the drainage of clay soils and making them easier to work.[8] Sea sand therefore had a double effect, both improving the soil structure and providing sodium from salt.[9]

**Table 1. The Extent of Fertilizer Use in England, *c*. 1770.**

| Fertilizer | Mineral or Organic | 1770 Frequency (% of villages) | 1770 Frequency (No. Villages) | Definitely Used in 1665 |
|---|---|---|---|---|
| Lime | M | 33 | 61 | Y |
| Yard dung | O | 18 | 33 | Y |

[7] The detailed returns for this survey are not available in printed form but have been extensively transcribed and discussed in Lennard R V, 'English Agriculture under Charles II: the Evidence of the Royal Society's Enquiries,' *Economic History Review*, vol. 4 (1932), 23-45. The survey was instigated by the Royal Society shortly before the plague struck London; the meetings of the Society were suspended during the plague and most of the questionnaires seem either never to have been completed or to have gone astray.

[8] Improving the soil structure was also a side-benefit of marling, although the primary purpose of marl was to reduce acidity.

[9] Lockhart J A R and A J L Wiseman, *Introduction to Crop Husbandry* (London, 1966), 102.

| | | | | |
|---|---|---|---|---|
| Paring and burning | O | 16 | 30 | Y |
| Chalk | M | 11 | 20 | Y |
| Marl | M | 10 | 19 | Y |
| Ashes | O | 7 | 13 | Y |
| Soot | O | 4 | 8 | Y |
| Malt dust | O | 4 | 7 | |
| Pigeon dung | O | 3 | 6 | Y |
| Oil cake | O | 2 | 3 | |
| Peat ashes | O | 2 | 3 | |
| Compost | O | 1 | 2 | Y |
| Hooves | O | 1 | 2 | |
| Peat | O | 1 | 2 | |
| Rags | O | 1 | 2 | Y |
| Rape dust | O | 1 | 2 | |
| Salt | M | 1 | 2 | Y |
| Seaweed | O | 1 | 2 | Y |
| Soap ashes | O | 1 | 2 | Y |
| Rabbit dung | O | 0.5 | 1 | |
| Sea sand | M | 0.5 | 1 | Y |

Let us turn to the organic manures, each of which represented a unique bundle of inputs. The primary attribute of *all* organic manures was nitrogen, and some types of fertilizer were highly prized because they were particularly nitrogen-rich (for example, oil cake and rape dust contained respectively 5 and 15 per cent nitrogen by weight). Organic fertilizers also had varying amounts of secondary attributes which increased their value to some extent. Notably, phosphorus and potassium were important chemical elements and they could be secured in the form of fertilizers such as bone dust and seaweed. The final attribute of organic fertilizers was humus (fibrous organic matter) which increased the resilience of the soil, enabling moisture and nitrogen to be retained through the growing season. Fertilizers such as yard dung and oil cake were important sources of humus.

**Table 2. The Intensity of Fertilizer Use in England, 1665, 1770 and 1840.**

| Fertilizer | 1770 Mean Quantity Used (St Deviation) | 1770 No. Obs. | 1665 Mean Quantity Used (St Deviation) | 1665 No. Obs. | 1840 Typical Quantity Used (St Deviation) |
|---|---|---|---|---|---|
| Ashes | 63.20 bushels (63.68 bushels) | 5 | | | |
| Bones | | | | | 15.00 bushels |
| Chalk | 40.00 tons (24.00 tons) | 18 | 64.8 tons | 1 | |
| Compost | 50.00 loads (0.00 loads) | 2 | | | |
| Hooves | 64.00 bushels | 1 | | | |
| Lime | 3.12 tons | 56 | 5.29 tons | 6 | 6.38 tons |

| | | | | | |
|---|---|---|---|---|---|
| | (2.52 tons) | | (1.44 tons) | | |
| Malt dust | 32.50 bushels (5.28 bushels) | 4 | | | 80.00 bushels |
| Yard dung | 16.45 tons (8.88 tons) | 11 | 30.95 tons (12.61 tons) | 5 | 11.68 tons |
| Marl | 82.47 tons (70.00 tons) | 17 | 160.84 tons (128.79 tons) | 5 | 150.00 tons |
| Oil cake | 0.46 tons (0.18 tons) | 2 | | | 0.50 tons |
| Peat | 10.00 bushels | 1 | | | |
| Pigeon dung | 26.00 bushels (8.00 bushels) | 4 | | | |
| Rags | 0.40 tons | 1 | | | |
| Rape dust | 28.00 bushels | 1 | | | 12.00 bushels |
| Salt | 0.34 tons | 1 | 0.07 tons | 1 | 0.15 tons |
| Sea sand | | | 13.66 tons (10.24 tons) | 2 | |
| Soap ashes | 96.00 bushels | 1 | | | |
| Soot | 27.00 bushels (9.36 bushels) | 2 | | | 32.00 bushels |

*Sources:* **1665** – all the data are derived from the agricultural survey of the Royal Society, as reported in Lennard R V, 'English Agriculture under Charles II: the Evidence of the Royal Society's Enquiries,' *Economic History Review*, vol. 4 (1932), 23-45. Where necessary, we have assumed that one quarter of lime weighed 672lb, following Way J T, 'On the Influence of Lime on the Absorptive Properties of Soils,' *Journal of the Royal Agricultural Society,* vol. 15 (1854), 495.

**1770** – all the data are derived from Arthur Young's *Tours.* The tonnage estimate for yard dung is based on the assumption that 1 cartload of dung weighs 1 ton – see Heathcote W, 'Experiments on Manures,' *Journal of the Royal Agricultural Society,* vol. 5 (1845), 277.

**1840** – Bones: Clowes F, 'Experiments on Manures,' *Journal of the Royal Agricultural Society of England,* vol. 4 (1843), 283-5; Sim W, 'Experiments with Manures,' *Journal of the Royal Agricultural Society of England,* vol. 1 (1840), 418. Note that the volume of bones varied according to how finely they were ground down. The figures in the table refer to bone *dust* - if the bones were ground down to pieces the size of a walnut then up to 90 bushels per acre might be required. See Billyse E, 'On the Application of Bones to Grass Lands,' *Journal of the Royal Agricultural Society of England,* vol. 2 (1841), 91.

*Lime:* Caird J, *English Agriculture, 1850-51* (2nd edition, New York, 1967), 303; Sybray J, 'On the Use of Lime,' *Journal of the Royal Agricultural Society of England,* vol. 3 (1843), 429.

*Malt dust, Yard dung and Oil Cake:* Clowes F, 'Experiments on Manures,' *Journal of the Royal Agricultural Society of England,* vol. 4 (1843), 280-5. This assumes 4 bushels of malt dust per sack. For yard dung see also Caird J, *English Agriculture, 1850-51* (2nd edition, New York, 1967), 270, 292, 424.

*Marl:* Linton W, 'An Account of the Transposition and Admixture of Soils,' *Journal of the Royal Agricultural Society of England,* vol. 2 (1841), 68.

Rape dust, Salt and Soot: Hannam J, 'Experiments with Salt and Other Manures upon Oats, Barley and Wheat,' *Journal of the Royal Agricultural Society of England*, vol. 5 (1845), 267-75.

The total volume of manure employed (i.e. the size of the market) is a function of both its popularity and the quantity applied. Having considered the extent of the market, let us now consider the intensity of use in 1770. Where possible, we make explicit comparison with the practices of 1665 and 1840. This is an interesting issue because the 'Age of High Farming' (1840s) could be considered a guide to best practice using traditional methods. Agricultural technique in 1840 was strongly influenced by scientific knowledge, whereas agricultural technique in 1665 and 1770 was based primarily on experience. It is therefore important to see whether farmers in 1665 and 1770 employed similar practices to those of 1840 in spite of their greater scientific ignorance.

The data in Table 2 above show that the average practices in 1665 and 1770 were remarkably close to the best practices of 1840.[10]

The results in Table 2 are actually what we would expect, given the way the fertilizer market operated (as we discuss in detail below). The data show that farmers in 1665 and 1770 were making best use of the resources which they possessed, and the quantities of off-farm manure which they employed would have had a measurable effect on yields. For example, we can put the use of yard dung in 1770 in the context of the Rothamsted farm experiments. Plot 2B of the Rothamsted experiment has been growing wheat *perpetually* since 1843 on the same acre of land. It currently shows no sign of soil exhaustion and it is dressed with only 14 tons of yard dung each year.[11] By comparison, the average dose of yard dung in 1770 was 16.5 tons. The volumes of lime, chalk and marl employed are similarly staggering and required large inputs of labour and capital. Soil dressings were clearly an important component of agricultural costs in 1665, 1770 and 1840 - and in the next section we draw out the implications of this fact for agricultural output.

## III. The Impact of Manure on Yields

Modern data show that the beneficial impact of manure is substantial.[12] But we cannot simply estimate the effect of manure in 1770 from modern controlled experiments because there have been a number of important changes since the eighteenth century. For example, the quality of manure has changed; and earlier farmers used different varieties of wheat and different cultivation methods. However, it is also difficult to assess the impact of manure using data from 1770. The number of farmers in the Young data set using a particular type of manure is often very small, so it is difficult to get a precise statistical estimate of the manure effect. Moreover, yields vary greatly due to soil type, weather and cultivation techniques - so trying to isolate the effect of manure is difficult without controlled experiments. We therefore take a new approach to estimating the effect of soil dressings.

Farmers were fully aware of the fact that muck was brass - and they would never pay more for a load of muck than they could recoup in terms of brass.[13] In the language of modern economics,

10 Personal correspondence with Michael Limb of the Royal Agricultural College, Cirencester, also suggests that these figures would be typical of England in the mid-twentieth century (before the widespread use of chemical fertilizers and herbicides).

11 Rothamsted Crop Research Centre, *Annual Report for 1968* (London, 1968).

12 Lockhart J A R and A J L Wiseman, *Introduction to crop Husbandry* (London, 1966).

13 Farmers were experienced in valuing muck, as evidenced by the fact that dung heaps were commonly one of the items valued in probate inventories. For example, see Wilshere J, *Ratby Probate Inventories, 1621-1844* (Leicester, 1984), 6, 9, 10 and 23; and *Evington Probate Inventories, 1557-1819* (Leicester, 1982), 15, 32. Dung heap valuations are generally to be found in May probates because that was just before spring muck spreading, when the heap (and hence its value) was at its greatest. In the examples given above, four out of

a rational farmer with perfect information would never spend more on manure than he would receive in increased revenues. So if we divide the cost of manure per acre by the unit value of output (such as the price of a bushel of wheat), then we can infer how many extra bushels of wheat must have been generated by using that manure. For convenience we will call this the 'value method' of estimation.

In fact, this calculation gives a *lower bound* on the effect of the manure for two reasons. First, a profit-maximising farmer will keep adding units of manure until the marginal revenue of an extra unit equals the marginal cost of an extra unit. So if the marginal revenue of manure is falling (which is the standard assumption) then this implies that the *total revenue* from the manure exceeds the *total cost*. Whether total cost is a good guide to total revenue depends on the rate at which marginal revenue is falling. We show below that the marginal revenue of nitrogenous fertilizer is constant over most of its range - so total cost should be a good guide to total revenue. Second, we have not taken into account the cost of transporting and spreading nitrogenous fertilizer. Typically the historical sources give only the 'factory gate' price for fertilizer (that is, excluding transport cost) and we have used those figures in our calculations. Young reveals that the cost of transport raised the cost of salt to the farmer by 13 per cent, and this is a plausible figure for most types of fertilizer. The exceptions to this rule are the alkalis, chalk, lime, and marl. For these three manures, transport constituted between 64 per cent and 99 per cent of the total cost of the manure. Therefore all the historical sources give the 'delivered price' rather than the factory gate price (which would have been a fairly meaningless piece of information). This helps us to minimise the problem of under-estimation and it will help us to interpret our findings more clearly below.

Following the strategy outlined above, we used the following formula to calculate the effect each manure used on each farm:

$$\text{Percentage increase in yield} = \frac{\text{Total cost of manure (per acre)}}{\text{Total revenue (per acre)} - \text{Total cost of manure (per acre)}}$$

It was standard practice to spread manure on the wheat crop, which was the primary output. Hence where the life of the manure was only one year, we have assumed that it was placed on the wheat crop. Where the life of the manure was greater than one year, we have calculated the (discounted) revenues generated by one acre of land - taking into account the crop rotation which would have been implemented over the lifetime of the manure. We assume a discount rate of 6 per cent; this seems reasonable in the light of Allen's evidence that the rate of interest on low-risk mortgages was 4.25 per cent in this period.[14] The results are not sensitive to the choice of interest rate. The results are presented in Table 3 below (all based on data from Young).

These results are very encouraging. The manures are ordered broadly as we would expect. Rape dust and oil cake were exceptionally effective. They were extremely rich fertilizers (in terms of both nitrogen and potassium) and nowadays they would be considered much too valuable to use as fertilizer - a more common use would be animal feed for fattening cattle. The middle of the rankings

seven observations occur in May, with one each in March and April. I am indebted to David Stead for these references.

14 Allen R C, "The Price of Freehold Land and the Interest Rate in the Seventeenth and Eighteenth Centuries," *Economic History Review*, vol. 41 (1988), 33-50.

is dominated by the alkalis (chalk, lime and marl), with an impact on yields of 10 or 20 per cent. The less effective fertilizers were the urban and industrial waste products which furnished only nitrogen, such as soot, ashes and rags. They contained only low levels of chemical nutrients and added little in terms of humus or soil structure.

We can verify the magnitude of some of our estimates using two other techniques. First, the simplest approach is to compare the mean yields of land with and without manure. This is not ideal because the number of people in the data set using each type of manure is quite low and the variance of yields across the sample is quite high (so it is unlikely that the mean yields will be statistically different between the groups of adopters and non-adopters). We tested all the manures which had more than ten adopters and here we report the results for those which had mean yields which were significantly different for adopters and non-adopters. Second, we can use regression techniques to control for extraneous variation and thereby produce cleaner estimates of the manure effects.[15] So in Tables 4 and 5 below we present the results of all three tests (difference of two means, regression and the value method outlined above) so that we can compare all the estimates. It is clear that the value method introduced in this paper gives comparable results to the other methods.

**Table 3. The Response of Wheat Yields to Fertilizers, *c*. 1770.**

| Fertilizer | Average Cost of Fertilizer (d/acre) | No. Obs. | Average Revenue (d/acre) | Average Life of Fertilizer (years) | Implied Average Increase in Yields (%)[16] |
|---|---|---|---|---|---|
| Rape dust | 560 | 1 | 1438 | 1 | 63.8 |
| Oil cake | 563 | 2 | 1570 | 1 | 55.9 |
| Yard dung | 298 | 3 | 1515 | 1 | 24.5 |
| Pigeon dung | 372 | 2 | 1930 | 1 | 23.9 |
| Chalk | 1623 | 4 | 12014 | 19 | 21.0 |
| Salt | 260 | 1 | 1570 | 1 | 19.8 |
| Malt dust | 208 | 3 | 1290 | 1 | 19.2 |
| Pare & burn | 219 | 16 | 1672 | 1 | 15.1 |
| Peat | 208 | 1 | 1682 | 1 | 14.1 |
| Lime | 468 | 4 | 6827 | 6 | 11.3 |
| Soot | 149 | 4 | 1543 | 1 | 10.7 |
| Marl | 748 | 9 | 9212 | 17 | 9.1 |
| Soap ashes | 288 | 1 | 4657 | 4 | 6.6 |
| Ashes | 76 | 2 | 1593 | 1 | 5.0 |

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

[16] Note that the column 6 is not computed directly from columns 2 and 4. Instead, we have calculated the implied increase for each farm and subsequently averaged across farms. Hence column 6 may not be exactly equal to [column 2 / (column 4 - column 2)] when there is more than one farm.

| | | | | | |
|---|---|---|---|---|---|
| Hooves | 72 | 1 | 2203 | 2 | 3.4 |
| Rags | 84 | 1 | 4783 | 4 | 1.8 |

**Table 4. Alternative Estimates of the Effect of Marl on Wheat Yields**

| Marl Effect by Diff 2 Means (%) | Marl Effect by Regression (%) | Marl Effect by Value (%) |
|---|---|---|
| 17** | 24** | 9 |

Note: ** denotes a significant difference at the 1 per cent level.

In the case of paring and burning, the results are more clear-cut if we consider the effect on different quality grades of land. In Table 5 below we present results for Grade 2 land (good arable) and Grade 3 land (average arable). Paring and burning does not take place on the best quality land (Grade 1) and we have no observations for poor quality land (Grade 4).[17] The results for Grade 3 land are very similar for all the estimation techniques, but there is a big discrepancy on Grade 2 land. However, it is not obvious which estimation technique is generating the anomalous result. In Table 5 the effect of paring and burning on Grade 2 land appears to be negative, according to both the regression results and the difference of two means. There are two possible explanations for this result. First, it could be the case that farmers are irrational and they reduce their yields by paring and burning land; this seems unlikely. Second, it could be a selection effect. If farmers only pare and burn particularly low-quality Grade 2 land then it would appear to have a negative effect on yields (but the low yields would actually be caused by the poor quality of the soil, rather than paring and burning). Of course, the value method can never predict a negative effect from using manure because the cost of the manure is always positive (so a rational farmer would never use it unless the return was also positive).

**Table 5. Alternative Estimates of Paring and Burning Effect on Wheat Yields**

| Land Grade | Pare and Burn Effect by Diff 2 Means (%) | Pare and Burn Effect by Regression (%) | Pare and Burn Effect by Value (%) |
|---|---|---|---|
| 2 | -17* | -10 | 17 |
| 3 | 9* | 8 | 13 |

Note: * is significant at the 5% level.

We have now outlined the extent and intensity of manure use in 1770 and quantified the impact of each manure on wheat yields. In the next section we draw together these strands by examining the operation of the manure market.

## V. The Demand and Supply of Manure

In this section we explain the extent and intensity of manure use with reference to demand and supply factors. We will see that both sides of the market have some unusual features which mean

[17] For a detailed discussion of land quality and the Ministry of Agriculture grading system, see *Agricultural Land Classification: Agricultural Land Service Technical Report No. 11*, Ministry of Agriculture, Food and Fisheries (London, 1966).

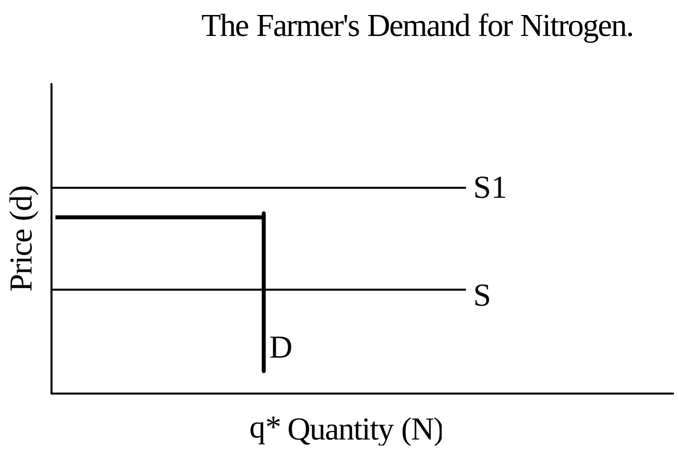
that the *extent* of the market is determined primarily by supply considerations, whereas the *intensity* is determined primarily by demand considerations. We begin our analysis by looking at the individual farmer's demand for nitrogenous fertilizer; we extend our analysis to the supply-side; and then we consider how the market clears. We concentrate on the market for nitrogenous fertilizer - but where appropriate we contrast the market for nitrogenous fertilizer with that for alkali. Having formulated both a demand function and a supply function, we will estimate a simple econometric model of the nitrogenous fertilizer market.

First, let us consider the market for different types of nitrogenous fertilizer. We start from the obvious fact that the value of nitrogenous fertilizer derives from its nitrogen content. In fact, we noted in the previous section that the value of the nitrogen is equal to the increase in crop revenue which it produces. This simple fact generates a precise pricing structure for different types of fertilizer based on nitrogen content. If peat contains twice as much nitrogen as soot per unit of volume, then the unit price of peat must be twice as high as the unit price of soot. In this way, the prices of all the nitrogenous fertilizers are fixed in relation to one another (although the *level* of prices is determined by other factors, as we shall see). A similar effect has been noted and quantified with regard to the pricing structure of heating fuel in European economies from the medieval period onwards.[18] This demand structure is a useful property because we can henceforth concentrate on the market for nitrogen - and we can largely ignore the particular form in which it appears (peat, soot, etc).

Second, let us consider the demand curve for nitrogen. We know from scientific evidence that wheat yields respond linearly to nitrogen inputs until nitrogen reaches its optimal quantity, at which point the response drops rapidly to zero (or can even become negative).[19] This produces a demand curve for nitrogen (D) with a rather unusual shape, as shown in Figure 1 below. The farmer's marginal revenue from nitrogen is constant over most of the range and then drops rapidly to zero. If the farmer is also a price-taker in the nitrogen market (which is a reasonable assumption) then he faces a perfectly elastic supply curve at the market price. If the supply curve lies above the marginal revenue curve (S1) then the farmer consumes zero nitrogen; if the supply curve lies below the marginal revenue curve (S) then the farmer consumes the optimal amount of nitrogen (q*).

The model presented in Figure 1 suggests that the farmer effectively faces an all-or-nothing decision - to use the optimal amount of nitrogen or none at all. Recall from Table 2 above that between 1665, 1770 and 1840 there was no substantial change in the quantity of fertilizer used per acre. This is what we would expect in the light of Figure 1 because variations in the market price determine only whether or not a farmer uses nitrogen. Once a farmer has decided to use nitrogen then he will use q* irrespective of the price. So we would expect to see a change in fertilizer intensity only in the unlikely event that there was a change in q* between 1665, 1770 and 1840. Let us now consider in detail what determines q*.

**Figure 1. The Farmer's Demand for Nitrogen.**




[18] Allen R C, 'Th ... World War,' *University of E...*

[19] Shiel R S, 'Imp ... (eds.) *Land, Labour and Li...*

The primary determinant of q* is the type of crop in cultivation: grain crops (such as wheat) have a very high demand for nitrogen per acre but fodder crops (such as clover) have a much lower demand. In the eighteenth and early nineteenth centuries most nitrogen was expended on the wheat crop because it was by far the most important crop in the farmer's balance sheet - hence in this paper we have been considering the use of nitrogen on wheat crops. If all farmers used nitrogen on their wheat crop then the optimal quantity (q*) would have been similar across farms and over time - a hypothesis borne out by casual inspection of the data. The coefficient of variation for the quantity per acre of each type of nitrogenous fertilizer was low - typically around 0.3. The limited variation in q* which we do observe is due to factors such as soil type, climate and seed variety. For example, it is optimal to use more nitrogen on sandy soil because the sand has lower nitrogen reserves; and it is optimal to use more nitrogen on higher-yielding varieties of wheat because they require more nitrogen to attain their maximum yield.[20] Since there were no systematic changes in these variables between 1665, 1770 and 1840, there was no marked increase in fertilizer intensity.

The low variation in nitrogenous fertilizers (0.3) stands in sharp contrast to the high variation in alkali manures (chalk, lime, marl). For alkalis the coefficient of variation of quantity per acre was typically around 0.8. The greater variation in alkali use arises from two factors – high variation in the *level* of soil acidity and high variation in the *responsiveness* of the soil to alkali. First, there is substantial natural variation in the level of acidity across soil types. Soils which are inherently more acidic require more alkali to achieve a balanced pH. This is compounded by that fact that the pH scale is logarithmic rather than linear. So reducing soil acidity from pH 5 to pH 6 takes substantially more alkali than a move from pH6 to pH7. Second, it is inherently more difficult to change the acidity of some soils than others (this is determined by the 'buffer capacity' of particular soils). This problem is overcome simply by adding more alkali per acre. These two factors mean that there is much greater variation in the intensity of alkali use than nitrogenous fertilizer use.

So far we have considered two aspects of the demand for nitrogenous fertilizers. First, we argued that the price of each type of fertilizer was simply a reflection of the amount of nitrogen which it contained. Second, we argued that no matter which fertilizer was employed, the farmer would apply enough of it to reach the optimum nitrogen level q*. If we combine these two facts then we generate an unexpected prediction. Whichever nitrogenous fertilizer is employed, the farmer will spend the same amount of money per acre on fertilizer. Continuing our previous example, suppose that the farmer has access to soot and peat. On any acre of wheat land the farmer would apply twice as much soot as peat (because soot contains only half the amount of nitrogen as peat and the farmer wants to reach q* on each acre of wheat land). But we noted that the unit cost of each fertilizer must reflect the nitrogen content - so the price of soot will be only half the price of peat. This means that the total expenditure on fertilizer will be the same in each case (whether the farmer uses soot *or* peat).

[20] Gooding M J and W P Davies, *Wheat Production and Utilization* (Wallingford, 1997).

This prediction is borne out by a casual inspection of the data. In Table 3 above we computed the value of each type of fertilizer used per acre. Most of the fertilizers are clustered between 150d and 300d per acre. There are a few outliers above and below, but given the extremely small sample size we certainly could not rule out the hypothesis that they are all drawn from the same population. (Recall also that there will be some variation in optimal nitrogen input q* owing to factors such as soil type and seed variety). We will undertake a stronger test below when we explicitly model the fertilizer market.

Let us now consider the supply-side, which also has some unusual features. We suggested above that each farmer was a price-taker in the market - he faced a perfectly elastic supply curve so that he could purchase an infinite amount at the market price, but nothing below the market price. Now let us consider the supply curve for the industry. Most nitrogenous fertilizers were produced as urban and industrial waste, as shown in Table 6 below.

The fact that most nitrogenous fertilizers were waste products has an important implication - the market supply curve was very (perhaps perfectly) inelastic. For example, some of the costs of heating fuel could be recouped by the sale of soot and ashes as low-value fertilizers. But it is rather implausible to suggest that factories and individuals would substantially increase their consumption of fuel in response to a rise in the price of soot and ashes. Similarly, yard dung was produced by stabled horses which were used in trades such as road transport or mining; but it seems unlikely that mining companies would increase the number of stabled horses in response to an increase in the price of yard dung.

Of course, in principle the *supply* of nitrogenous fertilizer could be elastic even if the *production* of fertilizer was perfectly inelastic. This could occur if it was not worthwhile to trade all the fertilizer at low prices. In fact, this scenario is implausible for several reasons and we also have direct evidence that all available waste products were traded. First, the general picture of the early modern economy suggests that there were many marginalised members of society who were underemployed; these people were likely to find it worthwhile to scavenge for industrial waste in order to re-sell it. Second, many industrial waste products (such as stable dung) simply *had* to be removed. If the firm did not sell the waste product then it would have had to pay someone to remove it (i.e. the firm would have been willing to accept a negative price for the waste product). For these two reasons it seems almost certain that all nitrogenous waste was recycled in the early modern economy.[21]

**Table 6. Fertilizers Used in *c*. 1770, Grouped by Origin.**

| 1. Fertilizers from the Primary Sector[22] | 2. Fertilizers from Town and Industry | If 2 is Urban or Industrial Waste |
|---|---|---|
| Chalk | Ashes | U/I |
| Compost | Bones | I |
| Lime | Hooves | I |
| Marl | Malt dust | I |

[21] One might wonder whether this argument still holds if the supplier of the fertilizer were a local monopolist (such as a coal mine producing stable dung as a by-product). In the appendix we show that it would almost always be optimal for a monopolist to supply the whole quantity of fertilizer available.

[22] In some cases these fertilizers could be produced on the farm, but they were commonly bought from outsiders.

| | | |
|---|---|---|
| Paring & burning | Oil cake | I |
| Peat | Peat ashes | U |
| Pigeon dung | Rags | U |
| Rabbit dung | Rape dust | I |
| Salt | Soot | U/I |
| Sea sand | Soap ashes | I |
| Seaweed | Yard dung | U/I |

The direct evidence from the Royal Society survey of 1665 supports the idea that all the available waste products were collected for use as fertilizer.[23] Around Bristol they used 'coal-ashes, soap-ashes and woollen rags'; in Yorkshire the farmers used pigeon dung 'when we can get it'. In Dorset 'all sorts of dung' were used, including:

'shovellings of streets and highways, with straw or weeds rotted amongst it.'

Similarly, in Gloucestershire they used 'dung of all sorts,' including:

'shovellings of streets, courts, ponds, ditches, or any other good earth with straw, weeds, or muck rotted among it.'

We have now established that the supply of nitrogenous fertilizer was inelastic and that all supplies were traded. Now let us consider how the market for fertilizer cleared, given the unusual nature of demand and perfectly inelastic supply.

Nitrogenous fertilizers were produced and traded mainly in towns; typically the farmers then shipped the fertilizer back to their farms by horse and cart. The transport cost was low for most types of fertilizer (compared to its value) but the existence of transport costs created a cost gradient for farmers. The farms which were situated further out of town had to bear a higher cost of transport (even though they paid the same factory gate price for the fertilizer) and this made fertilizers a less attractive proposition. This was compounded by the fact that farmers who were more distant from the town also had to bear a higher transport cost to bring their wheat to market - so they placed a lower value on the extra output which fertilizers provided. The town produced a fixed amount of each type of fertilizer. The closest farmers then found it worthwhile to use fertilizer at the market price and they consumed the optimal amount of fertilizer q*. Farmers further afield also found it worthwhile to use fertilizer and the total quantity demanded rose as we moved away from the town. This continued until the total quantity demanded met the total quantity supplied (which was perfectly inelastic). The equilibrium market price was set at such a level that, given the prevailing transport cost, it was just worthwhile for the last (marginal) farmer to purchase the last units of fertilizer.[24]

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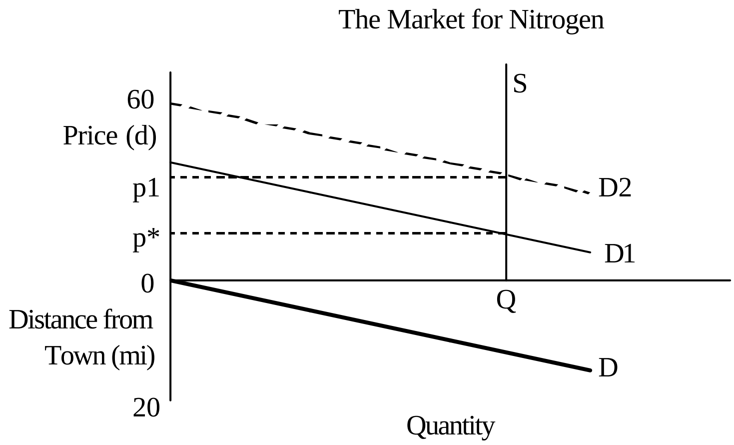
23 The following evidence is taken from Lennard R V, 'English Agriculture under Charles II: the Evidence of the Royal Society's Enquiries,' *Economic History Review*, vol. 4 (1932), 33.

24 This argument holds as long as fertilizer was not in 'free disposal' – that is, as long as a market price above zero was required to clear the market. Otherwise there would be excess supply and the equilibrium quantity would depend on demand conditions. We argued above that suppliers had incentives to trade all the available fertilizer; but how can we be sure that the quantity available for supply was not greater than the quantity which could be consumed? There are at least three reasons to suppose that fertilizer was never in free disposal. First, even very local farmers would demand a considerable amount of fertilizer. For example, there would be approximately 2000 acres of agricultural land within even a one mile radius of any particular source of fertilizer. Second, the suppliers of fertilizer could rely on demand from farmers situated much further than one mile from the fertilizer source – because transport costs were quite low and farmers generally found it economic to transport fertilizer considerable distances (such as 10 or 20 miles - see Table 9 below). Third,

This situation is reflected in Figure 2 below. The demand curve for each farmer is perfectly elastic; total demand increases as we move further from the town because the number of farmers rises (D); total supply is perfectly inelastic (S); the market price p* equates supply and total demand (D1).

**Figure 2. The Market for Nitrogen.**




This model has some interesting implications. First, in equilibrium the marginal farmer set the marginal cost of fertilizer (i.e. the price) equal to the marginal benefit, and it was just worthwhile for him to buy the fertilizer. This means that in Figure 1 above, the supply curve for the marginal farmer crossed the demand curve right on the kink. We noted in Section III above that the value method under-estimates the effect of fertilizer to the extent that some part of the marginal revenue curve lies above the market price. But for the marginal farmer the marginal revenue curve is flat at exactly the market price - so there is no under-estimate at all.[25] Of course, there is some under-estimation for the other (intra-marginal) farmers because they are situated closer to the town – so they pay the same market price for fertilizer but bear a lower transport cost. (In Figure 1 above, the supply curve is situated at S - below the kink in their demand curve – so the farmers are earning a consumer surplus equal to that part of the box described by D which lies above S). However, we can quantify the degree of under-estimation (consumer surplus) for the intra-marginal farmers. Suppose that the transport cost of the marginal farmer were ten per cent of the value of the fertilizer. Farmers situated next to the source of fertilizer would therefore earn a rent equal to ten per cent of the value of fertilizer. (In Figure 1 above, the box above S would be equal to ten per cent of entire box described by D). If transport costs were linear, then we can see that the average farmer would bear a transport cost equal to five per cent of the value of the fertilizer. Hence on average, the value method would under-estimate the effect of fertilizer by around five per cent. This is a very minor error.

Second, consider what happens in the model when the cost of transport falls. We know that in equilibrium the supply of fertilizers is fixed. So a fall in transport cost makes it worthwhile for

Young never mentioned fertilizer being in free disposal – despite the fact that he noted when other goods were in free disposal (such as firewood).

25 In fact, we still have a slight under-estimate because we have excluded transport cost. However, this is a shortcoming of the data rather than the model (and therefore in principle we could correct for this effect).

farmers further afield to purchase fertilizer - but there can be no increase in supply. It has also become worthwhile for those farmers who already purchase the fertilizer to pay a higher price because the cost of transport has fallen - and so the demand curve shifts from D to D1 in Figure 2 above. The price of fertilizer is bid up (p* to p1) until it is once again just worthwhile for the farmer who was previously marginal to purchase the same quantity of fertilizer as he was purchasing before the fall in transport costs. Since the marginal farmer always has lower transport cost than farmers further afield, he will always out-bid them. The net result is that everyone is purchasing the same quantities of nitrogenous fertilizer as before but the market price is *higher*. This is due to that fact that quoted price excludes transport cost and the supply curve is perfectly inelastic.

By contrast, a fall in transport cost results in a *lower* market price for lime, chalk and marl. This is because the market price quoted for these fertilizers includes the transport cost (it is the delivered price rather than the factory gate price, as discussed above). Therefore a reduction in transport cost is effectively an increase in supply rather than an increase in demand: this induces a fall in the market price.

Table 7 below shows that the cost of transport fell substantially over time in both nominal and real terms. In fact, this probably gives an *under-estimate* because it does not take into account the diffusion of wagons in the agricultural sector. Wagons were just beginning to diffuse in the 1760s and made long hauls - especially on roads - considerably cheaper.[26]

**Table 7. The Cost of Transport, 1770-1840.**

| | 1770 Mean Price | No. Obs. | 1840 Mean Price | No. Obs. | Price Change (%) |
|---|---|---|---|---|---|
| Carting (d/ton-mile) | 2.2 | 24 | 1.7 | 1 | **-23** |
| Canal Carriage (d/ton-mile) | | | 1.2 | 1 | |
| Sea Carriage (d/ton-mile) | 0.2 | 1 | 0.1 | 6 | **-50** |
| Railway Carriage (d/ton-mile) | n/a | N/a | 2.2 | 1 | **n/a** |

*Sources:* **1770** – from Young. The carting cost per ton-mile is calculated on the assumption that a three-horse cart draws a 2 ton load 15 miles per day. The average distance to the wheat market was 7.4 miles and I have assumed that the farmer would travel to and from market in one day - turnpikes only charged once if the farmer went to market and returned on the same day. See Pawson E, *Transport and Economy: the Turnpike Roads of Eighteenth Century England* (London, 1977), 202. The average daily distance for a wagon team in New England in this period was only 10 miles - see Rothenberg W, 'The Market and Massachusetts Farmers, 1750-1855,' *Journal of Economic History*, vol. 41 (1981), 299. **1840** - The cost of canal and railway carriage are taken from Hawke G R, *Railways and Economic Growth in England and Wales, 1840-1870* (Oxford, 1970), 85-6. Railway carriage was particularly expensive for fertilizer because fertilizer travelled toll-free on roads and canals – see Albert W, *The Turnpike Road System in England, 1663-1840* (Cambridge, 1972). Canal carriage for goods which paid tolls was around 2.5d/ton-mile. The cost of carting is based on the data in Linton W, *ibid.,* 69. I assume that a three-horse cart will draw a 2 ton load 30 miles in one day. This is the figure for an average horse given in Spooner W, 'On the Management of Farm Horses,' *Journal of the Royal Agricultural Society of England*, vol. 8

26 Gerhold D, 'Packhorses and Wheeled Vehicles in England, 1550-1800,' *Journal of Transport History*, vol. 14 (1993), 1-27.

(1848), 251. Rankine J, gives 36 miles per day in *Useful Rules and Tables for Engineering* (London, 1847), 251. The increase in daily mileage between the 1760s and 1840s can be explained by improvements in horse-breeding and road-building (notably the advent of macadamised roads in the 1820s). The cost of coastal shipping is taken from the Parliamentary Papers 1826-7, vol. 16 (Reports on the Corn Trade); it refers to almost exactly the same routes discussed by Young (both the south coast of England and the England-Holland crossing). This is important because the rate per mile falls as the mileage increases (due to the fixed cost of loading).

Our model thus provides a clear prediction regarding the evolution of manure prices over time. The decline in transport cost should lead to a price *increase* for nitrogenous fertilizers (factory gate prices) but a price *decrease* for other types of manure (delivered prices). This is exactly what we find in Table 8 below.

**Table 8. Fertilizer Prices, 1770-1840.**

| Fertilizer | 1770 Mean Price | No. Obs. | 1840 Mean Price | No. Obs. | Change in Price (%) |
|---|---|---|---|---|---|
| Marl (d/ton, including carting) | 16 | 15 | 8 | 1 | -50 |
| Salt (d/ton) | 780 | 1 | 720 | 1 | -8 |
| Soot (d/bushel) | 6 | 4 | 6 | 1 | 0 |
| Oil cake (d/ton) | 1245 | 3 | 1440 | 1 | 16 |
| Rape dust (d/bushel) | 20 | 1 | 31 | 2 | 55 |
| Dung (d/ton) | 19 | 15 | 38 | 2 | 100 |
| Bone dust (d/bushel) | 3.5 | 1 | 36 | 3 | 1029 |

*Sources:* **1770 –** Young. **1840 –** as in Table 2 above.

This result turns on its head the usual argument about transport cost and the use of off-farm nitrogenous fertilizer. The quote from Overton in the introduction articulates the commonly-held view that transport cost prevented the widespread use of off-farm fertilizer. But the model and evidence presented here suggest that the price of the fertilizer simply adjusted in order to clear the market (thus absorbing any transport cost effect). Therefore the fall in transport cost between 1770 and 1840 would have had no effect on the extent of the fertilizer market and we would expect to see an active market in 1770 (and earlier). The available evidence supports this hypothesis. If we consider first the case of land carriage, then we find that in 1770 fertilizers were generally transported further than wheat, as shown in Table 9 below.[27]

The available evidence also suggests that there was no increase over time in the distances which fertilizer was transported by land. The Royal Society survey reveals that in 1665 sea sand was typically transported 10 or 12 miles inland from the sea.[28]

[27] The difference is not significant because the variance is very large - some farmers had to go great distances to market, and others only a few miles.

[28] Lennard R V, 'English Agriculture under Charles II: the Evidence of the Royal Society's Enquiries,' *Economic History Review*, vol. 4 (1932), 34.

**Table 9. Road Distances to Market for Fertilizers and Wheat, *c*. 1770 (miles).**

| Distance to Market | Fertilizer (Whole Sample) | Wheat (Whole Sample) | Fertilizer (Paired Sample) | Wheat (Paired Sample) |
|---|---|---|---|---|
| Distance (mi) | 9.30 | 7.44 | 11.42 | 10.20 |
| St Dev (mi) | 7.98 | 4.73 | 9.07 | 8.70 |
| N | 27 | 47 | 5 | 5 |

Manure was transported even greater distances by canal. Arthur Young gives the example of Stillingfleet in Yorkshire, where farmers brought manure by canal from York (7 miles away) and Hull (40 miles away).[29] Canals were relatively cheap for three reasons. First, much more manure could be transported for a given number of men and horses. Second, bulk purchases of manure often came at relatively low prices. Thirdly, it was usually laid down in the canal licence that manure was allowed toll free passage (so the transport of manure was effectively subsidised by other traffic, which had to pay for the expensive capital investment).[30]

Ships were similarly cost-effective. The evidence in Table 7 above suggests that the cost of ship carriage was only one-tenth the cost of land carriage. Arthur Young gives three instances of farmers using oil cake, two in Norfolk and one in Kent. He noted explicitly that the Norfolk farmers imported their oil cake from the Netherlands by ship,[31] and it seems likely that the Kentish farm (which was situated on the coast) did likewise. We also have four other cases of soil dressings travelling by ship. Three of these involve shipping Kentish chalk from the Thames Estuary to Billericay, Colchester and the Isle of Wight. Chalk was an ideal material to be transported by ship because it was very bulky and needed to be used in large quantities to have a significant effect on soil pH. The final case of ship transportation is at Gilbury (Hampshire) where the farmer imported manure from Portsmouth and Southampton (both around 15 miles along the coast).

It now remains to test our model of the nitrogenous fertilizer market on the detailed data from Young. Using the insights from our model, we should be able to explain the pattern of fertilizer expenditure per acre. Given that the supply is fixed, we expect fertilizer expenditure per acre to be determined on the demand side. Demand can vary in two ways. First, the optimal amount of nitrogen can vary (q*). So low quality soils such as sand will induce higher expenditure. Second, farmers might be willing to pay more or less for the same amount of fertilizer (in Figure 1 above, p* could move up or down). In particular, an increase in the price of wheat will induce farmers to bid up the price of fertilizer (because each unit of fertilizer is worth more to the farmer) and this will result in more fertilizer expenditure per acre. A fall in the cost of transport will similarly cause farmers to raise their valuation of fertilizer and result in higher fertilizer expenditure per acre, as discussed above.

These effects are captured in Table 10 below. In Regression 1, expenditure rises significantly in response to higher wheat prices and sandy soil. We cannot test directly for the effect of transport costs because we do not have sufficiently detailed information, but in Regression 2 we use oat prices to proxy for transport costs. (In the Young data set the correlation between oat prices and the daily hire price for a horse and cart is 0.6, significant at the 5 per cent level). We do indeed find in Regression 2 that lower oat prices result in higher fertilizer expenditures per acre. The

[29] Young A, *Eastern Tour.*
[30] Phillips, *The Inland Navigations of Great Britain* (London, 1836).
[31] Young A, *Eastern Tour.*

transport cost effect is not statistically significant, but this is scarcely surprising given the quality of the data and the small sample size.[32]

**Table 10. Explaining Fertilizer Expenditure, *c*.1770 (d/acre)**

| Explanatory Variable | Regression1: Coefficient (SE) | Regression 2: Coefficient (SE) |
|---|---|---|
| Wheat Price | 9.88* (4.9) | 13.36* (6.6) |
| Sandy Soil | 110.47** (46.7) | 123.40** (50.0) |
| Oat Price | | -10.68 (13.3) |
| $R^2$ | 0.36 | 0.39 |
| Adjusted $R^2$ | 0.27 | 0.25 |
| F-statistic | 3.95 | 2.78 |
| SE Equation | 85.58 | 86.71 |
| N | 17 | 17 |

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

In this section we have shown that the *intensity* of nitrogenous fertilizer use was determined by demand factors such as the price of output and soil type. But the *extent* of fertilizer use was determined by the supply side. By 1770 there was an established market for many fertilizers at the local, regional and even international levels. Cities such as Liverpool and London created nitrogen-rich waste products that were recycled by an efficient local fertilizer market. Until the advent of artificial fertilizers in the 1850s, the total supply of nitrogenous fertilizer was simply a function of the waste generated by urbanisation and industrialisation. We will use this insight in the next section when we estimate the overall impact of manure in 1700, 1770 and 1840.

## V. The Impact of Off-farm Manure, 1700 to 1840

The final step in our analysis is to estimate the historical impact of manure on English wheat yields and see how the impact changed over time. We have already documented the proportion of villages using each type of manure in 1770; and we have estimated the yield effect of each type of manure where it was employed. So to gauge to the overall impact, we simply need to multiply the proportion of villages using the manure by the effect on yields. This gives us an estimate of the total yield effect of off-farm manure in 1770. Of course, this is only a very rough guide to the overall effect - our purpose is simply to establish the likely orders of magnitude.[33] The results are presented in Table 11 below.

[32] In principle, we could further utilise the coefficient on wheat price to infer the effect of nitrogen on wheat yields. However, we choose not pursue that strategy here because the result is very sensitive to the value of the coefficient, which is estimated rather inaccurately in such a simple model.

[33] In principle, we could refine our estimating procedure. Instead of weighting the individual fertilizer effects by the proportion of villages adopting each fertilizer, we could weight by the proportion of total wheat output produced in each village (village acreage multiplied by the village yield, divided by the output of all villages in

**Table 11. Impact of Soil Dressings on Average Wheat Yields, 1700 to 1840**

| Fertilizer | 1770 Effect on Wheat Yield (% increase) | 1770 Extent of Fertilizer Use (% of villages) | 1770 Total Effect (% increase in national yields) | Est. 1700 Effect (% increase in national yields) | Est. 1840 Effect (% increase in national yields) |
|---|---|---|---|---|---|
| Yard dung | 24.5 | 18 | 4.4 | 4.6 | 5.0 |
| Lime | 11.3 | 33 | 3.7 | 3.7 | 3.7 |
| Pare & burn | 15.1 | 16 | 2.4 | 2.4 | 2.4 |
| Chalk | 21.0 | 11 | 2.3 | 2.3 | 2.3 |
| Oil cake | 55.9 | 2 | 1.1 | 1.0 | 2.0 |
| Marl | 9.1 | 10 | 0.9 | 0.9 | 0.9 |
| Malt dust | 19.2 | 4 | 0.8 | 0.7 | 1.4 |
| Pigeon dung | 23.9 | 3 | 0.7 | 0.6 | 0.7 |
| Rape dust | 63.9 | 1 | 0.6 | 0.5 | 1.1 |
| Soot | 10.7 | 4 | 0.4 | 0.4 | 0.8 |
| Ashes | 5.0 | 7 | 0.4 | 0.3 | 0.6 |
| Salt | 19.8 | 1 | 0.2 | 0.2 | 0.2 |
| Soap ashes | 6.6 | 1 | 0.1 | 0.1 | 0.1 |
| Peat | 14.1 | 1 | 0.1 | 0.1 | 0.1 |
| Hooves | 3.4 | 1 | 0.0 | 0.0 | 0.1 |
| Rags | 1.8 | 1 | 0.0 | 0.0 | 0.0 |
| **Overall Effect** | | | **18.1** | **16.9** | **21.4** |

It would be useful to gauge the contribution of manure to the increase in wheat yields which occurred over the whole Industrial Revolution period, say 1700 to 1840. At first sight, this appears to be difficult because the data for 1700 and 1840 are not as detailed as those for 1770. We know from direct evidence that the intensity of manure use was similar in 1665, 1770 and 1840 (as we would expect, given the nature of demand). But there are no data on the extent of manure use in 1700 and 1840 because there are no farm surveys comparable to that of Arthur Young. However, we showed in the previous section that the extent of off-farm nitrogenous fertilizer use was determined solely by the supply side (because the supply curve was perfectly inelastic and therefore demand shocks had no effect on the equilibrium quantity). We can therefore estimate the extent of fertilizer use by estimating the increase in waste products generated by the urban and industrial sectors – and we do not need farm level information.

We must take account of two conflicting factors when we estimate the change in the extent of off-farm fertilizer use between 1770 and the earlier and later years. First, there was an increase in the supply of fertilizer over time owing to population growth and industrialisation. In the context of

the sample). We do not pursue that strategy here because it is not clear that it would produce estimates which are any more accurate.

the model that we developed above, the increase in supply put downward pressure on fertilizer prices and raised the probability that villages further away from the town would find it economic to purchase fertilizer. But second, there was an increase in the wheat acreage over time owing to the increase in arable acreage and changes in crop rotation. This raised the demand for fertilizer in the villages close to the town - which put upward pressure on prices and so reduced the probability that villages further out would find it economic to purchase fertilizer. We need to quantify both of these effects in order to gauge the impact of increasing fertilizer use on *average* wheat yields.

The data on wheat acreage are taken from the standard sources and estimated to increase from 2.2 million acres (1700) to 2.4 million acres (1770) and to 3.2 million acres (1840).[34] We estimate the increase in the supply of fertilizer between 1700 and 1840 based on the following assumptions. We suggest that the supply of yard dung rose in proportion to the national draft animal stock (0.85 million animals in 1700; to 0.93 million in 1770; and 1.39 million in 1840). We suggest that the supply of urban and industrial by-products rose in proportion to the population (an index of 1 in 1700; 1.27 in 1770; and 2.96 in 1840).[35] We suggest that the use of alkalis and other mineral manures increased in line with wheat acreage between 1700 and 1840.[36]

The manure estimates for 1700 and 1840 are presented in Table 11 above. It is clear that manure was making a significant positive contribution to average wheat yields even by 1700 – but there was very little *increase* in the effect of manure on average wheat yields. This is because the substantial increase in nitrogenous fertilizer supplies was barely keeping pace with the increase in wheat acreage. This is especially true of yard dung, which was quantitatively the most important waste product but increased at a slow rate. So during the Industrial Revolution, manure was having a positive effect on *total output* by helping to maintain yields in the face of a rising wheat acreage. But there was little effect in terms of pushing up average wheat yields above their 1700 levels. Manure was adding 17 per cent to yields in 1700 (about 3.4 bushels per acre) and a similar amount in 1840.

## VI. Conclusion

In this paper we have brought a great deal of new data to bear on the issue of off-farm manure in the period 1700 to 1840. We have used the data to clarify three main issues. First, we have provided a detailed quantitative description of manure use in 1770, both in terms of the extent and the intensity of use. Second, we have explained the pattern of use in 1770 with reference to the biological effects of nitrogenous fertilizer and the economic incentives to apply it. Third, we have formed preliminary estimates of the impact on grain yields of manure between 1700 and 1840. The main conclusions are as follows.

There was an active and sophisticated market for manure by 1770: most villages used off-farm manure, and typically more than one variety. The primary off-farm manures were alkalis (in the form of chalk, lime or marl) and this was followed in popularity by animal dung (mainly from cattle

[34] For a detailed discussion, see Brunt L, 'Estimating Wheat Production in the Industrial Revolution,' *Oxford University Discussion Papers in Economic History*, no. 29 (June, 1999).

[35] Schofield R S, 'British Population Change, 1700-1871,' in Floud R and D N McCloskey (eds.) *The Economic History of Britain since 1700*, vol. 1 (Cambridge, 1994), 60-95.

[36] It seems unlikely that falling transport costs would lead to a large increase in alkali use because the requirement to correct soil acidity was fairly constant over time. The demand for some primary sector fertilizers may even have fallen over time - notably salt, which was effective only whilst there were unexploited stocks of potassium in the soil (as discussed above).

and horses). We have also shown that - despite the lack of formal scientific knowledge - farmers in 1665 and 1770 used manure rationally and in a similar fashion to the farmers of 1840.

The impact of off-farm nitrogenous fertilizers on wheat output was limited only by their availability, which mostly arose as industrial and urban waste. Even so, by 1770 manure was pushing up wheat yields by 17 per cent. The growth in industrialisation and urbanisation between 1700 and 1840 led to a gradual increase in the supply of nitrogenous fertilizers which just slightly exceeded the increase in wheat acreage. The evidence on manure use before 1665 is even thinner than the evidence presented in this paper, but the outlines of story are probably very similar. In the long run, the acreage of wheat is likely to have grown at a similar rate to the production of waste products – because the growth of both variables was driven by the growth in population. The contribution of off-farm manure to English wheat yields was therefore probably fairly constant at 15 to 20 per cent of wheat yields.

## Appendix. The Monopolist's Decision to Supply Nitrogenous Fertilizer

Remember that the primary objective of the firm is to produce a good (for example, coal). The firm also produces fertilizer (for example, yard dung), but only as a by-product of its production process. Now suppose that the firm has a local monopoly in the production of the by-product (yard dung).[37] Here we are concerned only with the firm's decision to supply the by-product as a local monopolist. In Figure 3 below we show the standard situation for a monopolist with linear demand. The average revenue (demand) curve (AR) intersects the x-axis at q, and the marginal revenue curve (MR) intersects the x-axis halfway between the origin and q (i.e. at q/2).

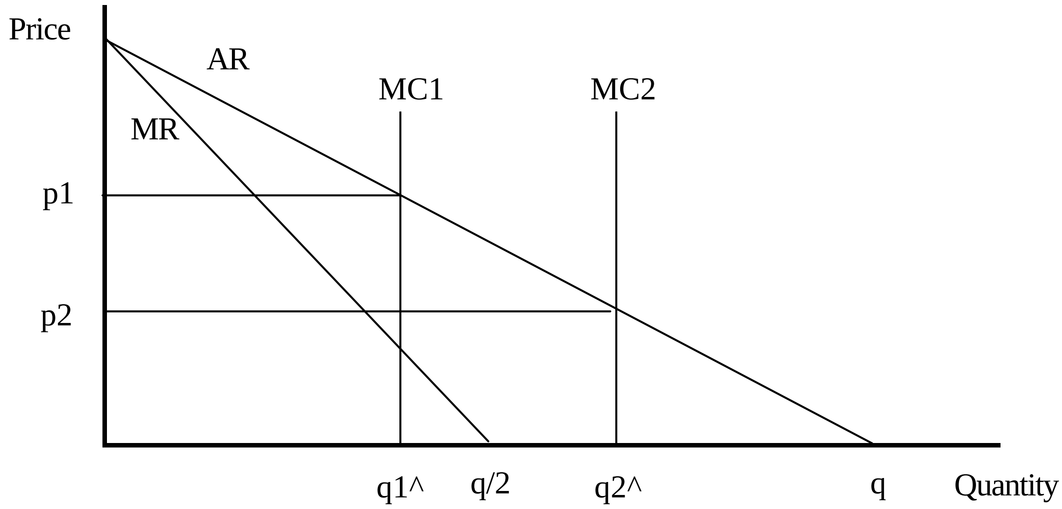
The monopolist will choose his sales of fertilizer by setting marginal revenue equal to marginal cost (MC).[38] However, in this case the marginal cost curve has an unusual shape. At the current level of output of the primary good (coal), the firm will already produce a certain quantity of by-product (q^). The marginal cost of supplying the by-product to the fertilizer market will be zero up to q^ (remember that the firm is selling the fertilizer at the factory gate, so it does not face any transport cost). But above q^ the cost of producing the by-product will be large because it necessitates producing more of the primary good (coal).[39] So the marginal cost curve for fertilizer (the by-product) is kinked: the marginal cost is zero up to the current level of output q^, and rises sharply thereafter.

**Figure 3. The Monopolist's Decision to Supply Nitrogenous Fertilizer.**

[37] Note that this does *not* imply that the firm is also a local monopolist in the production of the primary good. For example, Durham coal may be sold onto national or international markets which are very competitive; but we can still imagine that the coal mine might hold a local monopoly over the supply of yard dung.

[38] Of course, the output of fertilizer is already determined by the output of the primary product – so the monopolist is choosing only the level of *sales* of fertilizer, not the level of output.

[39] We are assuming that the firm is producing the profit-maximising quantity of the primary good. So producing more of the primary good would, by definition, lead to a reduction in profits from the primary good. Hence it would be expensive to produce more than q^ of the by-product.




The question then arises, under what conditions will the monopolist want to supply less of the by-product than is currently available (i.e. less than q^)? First, suppose in Figure 3 above that the firm faces the marginal cost curve MC1. Then q1^ lies to the *left* of q/2 (the point where the marginal revenue curve intersects the x-axis); and so the monopolist will sell all of the available fertilizer (q1^). At that quantity, the price will be set at p1 to ensure that the quantity demanded equals the quantity supplied. Second, suppose in Figure 3 above that the firm faces the marginal cost curve MC2. Then q2^ lies to the *right* of q/2 (the point where the marginal revenue curve intersects the x-axis). So the monopolist will again set marginal cost equal to marginal revenue (i.e. zero) and sell quantity q/2 at price p2. This strategy maximises profit for the monopolist but leaves some fertilizer unsold (to be exact, q2^ minus q/2).

We are interested in whether the monopolist will always want to sell all his stocks of fertilizer waste. We can now frame our question much more precisely. Can we be sure that q/2 will always be greater than q^ if the monopolist were to set a price of zero? Putting some plausible values into this model shows that the answer to the question is almost certainly affirmative. That is, the monopolist would *always* want to sell *all* the fertilizer which he produces. We can show this as follows.

Suppose that a farmer was willing to spend 200d per acre on fertilizer (this is a typical value taken from Table 3 above). Suppose that the fertilizer weighed a ton and the farmer then transported the fertilizer 10 miles (the average distance from Table 9 above) at a cost of 2.2d per ton/mile (the average cost from Table 7 above).[40] So the total on-farm cost of the fertilizer is 222d, and we can take this as being the typical value of the fertilizer to *all* farmers.[41] Now suppose that the monopolist set the price to zero. Since all farmers value the fertilizer at 222d and they only have to bear the transport cost (2.2d per ton/mile), then they would be willing to transport the fertilizer 100 miles! Within a 100 mile radius of the fertilizer source, there are likely to be 31416 acres of farm land and

[40] In fact, nitrogenous fertilizers were commonly used at about the rate of 0.4 tons per acre, as shown in Table 1. So our allowance for transport cost is quite generous. A few of the nitrogenous fertilizers (notably yard dung) were used in greater quantities.

[41] In our model, the reason that farmers further afield do not buy fertilizer is that they have to pay a higher transport cost. For example, farmers 11 miles out would have to pay 24.2d in transport cost and the total on-farm fertilizer cost would then be 224.2d – which would exceed their valuation of 222d. Hence the farmers 11 miles out do not purchase fertilizer at the going price, even though the fertilizer has the same overall value to them as to the farmers closer to the town.

hence 3142 acres of wheat land.[42] If one ton of fertilizer were spread on each acre of wheat, then the total quantity demanded at a price of zero (i.e. q) would be 3142 tons. Hence q/2 would be 1571 tons. If the amount of by-product generated by the monopolist (q^) were less than 1571 tons per annum, then the optimal strategy for the monopolist would be to sell all of the by-product. Given the scale of industrial operations in 1770, it is hard to believe that many (if any) firms with a local monopoly were producing more than 1571 tons of fertilizer by-product per annum.[43]

In fact, the case is even more clear-cut than our analysis has suggested so far. First, most firms were producing a by-product which simply *had* to be removed (such as stable dung). If the firm had not sold the by-product as fertilizer then they would have had to pay a removal cost. So the firm would actually be willing to accept a price lower than zero for its units of fertilizer by-product up to q^. This would obviously increase still further the distance which farmers would have been willing to travel to pick up the fertilizer. Second, if the price were low enough (such as zero) then farmers would obviously have found it economic to spread fertilizer on crops other than wheat. So the acreage to be covered with fertilizer within a 100 mile radius would probably have been at least 15708 (i.e. all arable land) and the quantity demanded (q) would therefore have risen to 15708 tons. Then q/2 (7854 tons per annum) would clearly have exceeded the capacity of any monopoly producer (q^) to meet the quantity demanded.

In the light of this analysis, it seems certain that firms were not holding back supplies of fertilizer in order to push up the price. Hence we can safely assume that all fertilizer was traded (almost certainly for a positive price). And we can therefore further assume that supply was very inelastic because the monopolist would have been operating on the inelastic section of his marginal cost curve.

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[42] The number of acres of farm land in a 100 mile radius of the fertilizer source would be approximately (100*100*3.1416). In line with our previous argument, we assume that fertilizer was spread on wheat land only. If half of the land in the locality were pasture; and if only 20 per cent of arable land were under wheat; then 31416 acres of farm land would include 3142 acres of wheat.

[43] A pit pony would have produced something less than 15 tons of dung per annum. So a mine employing 100 pit ponies would still have produced only 1500 tons of by-product per annum.

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