The Nitrogen Hypothesis and the English Agricultural Revolution:

A Biological Analysis

By

Robert C. Allen

Nuffield College

New Road
Oxford OX1 1NF
U.K.

bob.allen@nuffield.oxford.ac.uk

2004

Between 1300 and 1800, the average yield of wheat rose from about 12 bushels per acre to about 20 bushels. The yield of peas and beans grew similarly, while barley and oats realized even greater increases. Explaining these improvements is a long standing problem that has been tackled in many ways. A recent approach has been the statistical analysis of micro data drawn from probate inventories, Arthur Young's tours, and similar survey material. While much has been learned from these investigations, they have not established the causes of rising yields in the agricultural revolution.

Another approach is needed. This paper explores what science has to offer. Since the great days of Liebig, Lawes, and Gilbert, agronomists have studied the growth of plants to improve their yields. Nitrogen plays a pivotal role in this research. Economic historians have appreciated the importance of the knowledge acquired and have often alluded to the importance of nitrogen in ways we will discuss. Some historical work has utilized formal, scientific models of nitrogen. Chorley (1981), for instance, used a nitrogen-based analysis to explain the rise in continental cereal yields between 1770 and 1880, Shiel (1991) discussed the nitrogen cycle and applied it to some aspects of English agriculture, and Clark (1992) analyzed convertible husbandry in terms of soil nitrogen as a kind of capital. This essay takes the analysis of nitrogen a step further and asks if it can explain the rise in grain yields during the Agricultural Revolution.

Plant growth requires water and nutrients--notably, nitrogen, potassium, and phosphorous. Plants use them in roughly fixed proportions, which means that there is usually a shortfall of one, which then limits production. In early modern agriculture, that was nitrogen: More nitrogen meant more plant growth, while increased provision of potassium and phosphorous had little effect. Only in modern times, when the heavy application of artificial fertilizers has remedied the nitrogen deficit, has it become important to provide grains with other nutrients as well. Nitrogen does not explain all of the growth in early modern yield, but it explains a great deal, and, at the same time, defines the contribution of other improvements in farming.

The analysis of nitrogen is particularly helpful in understanding the import of livestock and land management. Many historians have emphasized the role of animals in explaining both the low yields of the middle ages and the increases between 1300 and 1800. Indeed, the most common explanation of rising yields is "mixed husbandry," that is, the combination of corn and livestock into a unified system. "The spread of integrated mixed husbandry has now been marked out as the core element of Europe's agrarian transformation since the middle ages." (O'Brien 1996, p. 222). Usually, the emphasis in this explanation is on dung. More animals meant more manure, and more manure meant higher corn yields. The high productivity of the nineteenth century is explained in this way–"agricultural development depended upon the accumulation of ever increasing numbers of animals per unit of cultivated land" (O'Brien 1996, p. 222)–as is the low productivity of the middle ages. "Dung was the only real fertilizer...The main restriction on the use of manure depended on the sufficiency of animals." Before the Black Death, population growth meant a continual conversion of arable to pasture, and that threatened "the viability of arable cultivation itself." (Postan 1971, pp. 63-4.) In this view, arable and pasture formed a positive feed-back system with nitrogen at its centre: Manure contains nitrogen, so more animals meant more nitrogen and higher yields. But was medieval agriculture really held back by an insufficiency of animals and did more animals cause the agricultural revolution?

A second explanation of rising productivity is convertible (or up-and-down) husbandry. In this system, land was alternated between grass and arable at regular intervals. Since cattle were pastured on the grass, this sounds like a special case of the manure argument, but, in fact, the logic is different since natural deposition (rather than grazing) accounts for the increase in nitrogen in the grass. Kerridge (1967, pp. 181, 194) has emphasized the importance of up-and-down husbandry particularly in the period 1560-1660. Broad (1980), however, has noted that the system had fallen out of favour by 1800. Are there reasons why convertible husbandry might have made an important contribution to productivity growth in the sixteenth century, but a lesser contribution in 1800? The analysis of nitrogen provides some insight.

Legume cultivation is a third technique that may have raised yields, and it is one where nitrogen played a leading role. Peas and beans replaced barley and oats as the spring crop in many open fields villages in the early modern period. Clover was introduced as a field crop in the seventeenth century and by the eighteenth it was integrated into the famous Norfolk rotation (turnips-barley-clover-wheat). The barley and wheat produced beer and bread for people, while the turnips and clover fed sheep and cattle. On soils like the Cottswolds, sainfoin meadows were sown. A common feature of all these crops was that they fixed nitrogen and, thereby, increased soil fertility. Chorley (1981) has emphasized their importance for the rise in yields in continental Europe between 1770 and 1880, but the case has not been investigated for early modern England. That is an objective of this essay.

This essay is prompted by modern studies of the growth of cereals that show yields to be highly responsive to nitrogen fertilizer. Figure 1 is a widely cited (e.g. Wild 1998, p. 681) example of two yield response curves derived from German experimental data (Becker and Aufhammer 1982, p. 53). The curves make several important points. First, the more nitrogen applied to a hectare, the greater the yield of grain. Second, the response to nitrogen was approximately linear over a wide range of application until the curves flatten out as diminishing returns set in.[1] Third, the yield curve shifted upwards between 1949-52 and 1978-81. The rise was attributed to better farming methods, improved seeds, and greater nitrogen residues from the heavier fertilizing of the preceding crop. Nitrogen was important, but it was not the whole story. There was a role for better ploughs, seed drills, improved working for the soil, drainage, new seed varieties, and so forth.

Figure 1 emphasizes that we can divide the causes of higher cereal yields into two types–those that increased free nitrogen and those that raised the efficiency with which nitrogen was used. We will apply that breakdown in this paper to dissect the sources of rising grain yields. Figure 2 summarizes the method.[2] The figure plots the yield of grain on the vertical axis and free nitrogen on the horizontal. Point A shows the yield in 1300 and point B in 1800. The line OY_{1300} is the medieval yield response curve, while OY_{1800} is its counterpart at the beginning of the nineteenth century. These curves are straight lines through the origins since yield was proportional to free nitrogen, as will be explained. The 1800 yield response curves is higher than the 1300 curve since improvements in farming methods between those dates increased the take-up of nitrogen, and that was one cause of

[1]Diminishing returns to nitrogen arise when plant growth is so vigorous that it uses up all of the potassium and phosphorous in the soil, and those elements set the limits to growth.

[2]The decomposition depends on whether the data are analyzed with the 1300 or the 1800 yield response curves. The latter corresponds to asking how much yields would have dropped if farmers using 1800 techniques and equipment had been forced to give up legume cultivation, convertible husbandry, or whatever. This backward decomposition will assign a greater importance to nitrogen than a 1300 forward projection since the 1800 yield response curve is steeper than the 1300 curve.

progress. A second was the increased availability of nitrogen from more animals, convertible husbandry, legume cultivation, and so forth. The upward slope of OY_{1300} means that their use would have raised yields without any improvement in the efficiency of nitrogen utilization. Why are yields at point B in1800 greater than at point A in 1300? Increasing the nitrogen from N_{1300} to N_{1800} would have raised yields from Y_{1300} to Y^*_{1800}. Improved farming methods would have increased the efficiency with which nitrogen was utilized (as represented by the rotation in the response curve) and that would have raised the yield from Y^*_{1800} to Y_{1800}. The overall increase in yield can, thus, be decomposed into two parts: that due to increased nitrogen availability (Y^*_{1800} - Y_{1300}) and that due to other improvements in farming methods that raised the efficiency with which nitrogen was used (Y_{1800} - Y^*_{1800}).

The response of cereal yields to nitrogen

There are two steps in analyzing the agricultural revolution in terms of nitrogen: the first is establishing how crop yields respond to soil nitrogen; the second is determining changes in soil nitrogen over the early modern period. I begin with the first.

Thousands of experiments have been done to measure the response of grain yields to varying applications of manure and fertilizers. These experiments show that there is a linear relationship between yield and nitrogen at low levels of nitrogen application. In this situation, applications of phosphorous or potassium cause little increase in yield. However, once the application of nitrogen has pushed yields to such a high level that it is no longer the nutrient limiting growth, then the application of further nitrogen ceases to raise yields, while the addition of potassium or phosphorous, as the case may be, leads to higher yields. The usual formulation of these results is to say that yield is directly proportional to free nitrogen in the soil so long as nitrogen is the nutrient limiting output[3]:

$$Y = mN \qquad (1)$$

where Y is yield and N is nitrogen. The yield response coefficient m is the only parameter to estimate, and it is both the average and the marginal product of nitrogen. Y and N must be measured in the same units–kilograms per hectare and hundred weights (cwt) per acre are the most common in the technical literature. To anticipate future discussion, N is “free” nitrogen (in water soluble form) and includes ammonium and nitrates from artificial fertilizers, residual nitrates from previous crops, and the “mineralized” nitrogen released every year as organic matter in the soil decomposes.

The yield response coefficient m can be measured in several ways. One is the slope of an experimentally derived graph of yield as a function of nitrogen applied as fertilizer.[4]

---

[3]Shiel (1991, p. 58) summarizes the scientific literature with a graph that shows an almost linear relationship between nitrogen and yield until nitrogen ceases to be the limiting nutrient at which point response falls to zero and even becomes negative at very high levels. Forecasting models of agricultural nitrogen requirements assume that yield is directly proportional to free nitrogen in the soil (e.g. Stanford 1973, Remy and Viaux 1982, Tinker and Widdowson 1982).

[4]These graphs (e.g. Figure 1) usually have positive intercepts, which are attributed to unmeasured mineralized nitrogen and nitrogen residues from cultivation in previous years.

This method has been widely used with twentieth century data. Russell and Watson (1938, p. 284) reviewed many studies and found that "there is obviously no rigid rule, but it appears to be generally true that when barley is grown in rotation" the application of ammonium sulphate fertilizer produces "an average increase of 13 or 14 lb. of grain...per lb. of nitrogen supplied." In the definitive review of 7,828 pre-World War II experiments in Britain, Ireland, Scandinavia and Germany, Crowther and Yates (1941, p.81) reported that the application of 0.25 cwt. of nitrogen per acre raised wheat yields by 3.8 cwt, barley yields by 4.1 and oat yields by 3.6. Dividing the yield response by the increase in nitrogen gives response rates of 15.2, 16.4, and 14.4.

More recent studies indicate that the marginal product has risen since World War II. Many German studies summarized by Becker and Aufhammer (1982, pp. 53) show the marginal product to be 16 - 17 in the linear range.[5] Needham (1982, p. 133) concluded that there were "considerable variations between sites and year" in the response of yield to increases in fertilizer applied with "a median value of 16 - 18 kg of grain per kg of N" before diminishing returns set in. More dramatically, Tinker and Widdowson (1982, p. 167) have argued that English yields can be successfully predicted assuming that marginal product of nitrogen is 35-40. With the productivity of nitrogen rising in the twentieth century, we must wonder whether it was also rising between the middle ages and the nineteenth century.

Some insight into the response of yield to nitrogen comes from decomposing it into the product of ratios:

$$Y = N\,Ugb \qquad (2)$$

U is the take-up ratio, which is the fraction of the nitrogen absorbed by the plant. g is the quantity of dry matter (stem, leaves, and grain) relative to the nitrogen absorbed by the plant, and b is the ratio of grain to dry matter.[6]

Soil scientists have measured these ratios and investigated their stability under varying agricultural practices. The nitrogen required by the plant for a unit of grain (g) has been extensively analyzed. Russell and Watson (1938, p.285) conclude "for each pound of nitrogen assimilated by barley roots under good conditions of growth about 80 or 85 lb. of dry matter is, under ordinary circumstances, produced in the plant." This stability reflects the protein content of the plant and its distribution among grain, leaves, stems, and roots.

In the usual interpretation, the experimental relationship between yield and fertilizer shows the marginal product of nitrogen, and this is assumed to be the average product (as in equation 1) that would have been measured had the mineralized and residual nitrogen been included in the analysis. These sources of nitrogen are explicitly modeled in this paper, so equation 1 is the appropriate specification for the relationship between free nitrogen and yield.

[5]When nitrogen is increased on the lower curve from 0 to 70 kg/ha, the yield rises from 2800 to 4000 kg/ha implying a slope of 17.1 = (4000-2800)/(70-0). On the upper curve, an increase in N from 0 to 130 kg/ha increased yield from 4800 to 7000 kg/ha giving a slope of 16.2.

[6]Models like this are used by plant scientists to analyze yields and forecast fertilizer requirements, e.g. Stanford (1973) and Remy and Viaux (1982).

As for b, Russell and Watson (1938, p. 273) report that "there is considerable uniformity about the ratios of grain to total produce." It varied between .40 and .48 in all experiments at Rothamsted and Wooburn over 70 years.

The least stable ratio was U, the fraction of nitrogen absorbed by the plant. In the Hoosfield barley experiments at Rothamsted, take-up rates were typically 30-40%, while they were in excess of 60% at the Stackyard Field experiments in Woodburn. In both cases, there was considerable temporal variation. Interestingly, both sets of experiments went through "crises" between 1910 and 1930 in which yields dropped dramatically. The declines are attributed to reductions in U, which fell as low as 13% (Russell and Watson 1938, p. 286, Johnston and Poulton 1976, Part 2, p.59). This is even lower than that typical of medieval agriculture, as we will see.

Dividing equation 2 by N expresses the productivity of nitrogen in terms of the ratios that determine it. We can calculate the marginal response of yield to nitrogen using typical nineteenth century values of (.45 for the take-up fraction, 82.5 for the grain produced by a unit of nitrogen, and .44 for the proportion of grain in the dry matter). With those values, the yield response to nitrogen was:

$$Y/N = Ugb = .45 * 82.5 * .44 = 16.335 \qquad (3)$$

This value is close to the values found by Crowther and Yates. Very different values are implied by different take-up rates. 20%, near the low end of observed values, implies a nitrogen response coefficient of just over 7, while complete take-up implies a value of 36, which is like those observed today. The rise in the response coefficient measures the contribution of modern cultivation practices that have increased the efficiency with which nitrogen is used.

We do not have data to measure take-up rates or nitrogen response coefficients during the early modern period. We can only infer them by dividing the yield of grain by the free nitrogen in the soil (equation 1). We have considerable evidence about historical grain yields but not measurements of soil nitrogen. They must be inferred from models of the nitrogen cycle, to which we turn.

Scientific Analysis of Nitrogen[7]

Soil scientists draw a sharp distinction between two forms in which nitrogen is present in soils–organic (also known as immobilized) nitrogen and mineralized (or free) nitrogen. The former includes undecomposed organic matter. One of its distinguishing features is that the nitrogen is combined in chemicals that are not water soluble, so it cannot be absorbed by the roots of plants. Mineralized nitrogen, on the other hand, is in the form of either ammonium or nitrate ions and is water soluble. Plants can absorb nitrogen in its mineralized form, and one path to higher crop yields is to increase the supply of mineralized nitrogen.

The principal source of ammonium and nitrates in early modern agriculture was the mineralization of organic nitrogen. "The term 'nitrogen mineralization' is commonly used to

---

[7]Shiel (1991), Foth (1984, pp.295-305) and Wild (1988, pp. 652-79) give introductions to the biology and mathematics of nitrogen.

describe the conversion of organically bound nitrogen, mainly as amine groups but not exclusively so, into inorganic forms such as ammonium or nitrate." (Wild 1988, p. 609) This was a natural process in which 1-3% of the stock of organic nitrogen in the soil was converted each year. More mineralized nitrogen, therefore, depended on a larger stock of organic nitrogen to decompose.

The stock of organic nitrogen increases if additions exceed reductions from one year to the next. Since the reductions are mineralization and are a constant fraction of the stock, its evolution is governed by a difference[8] equation:

$$N_t = N_{t-1} + A_t - rN_{t-1} \qquad (4)$$

where N_t is the stock of organic nitrogen at time t, A_t represents additions to the stock, and the mineralized nitrogen (at rate r) is rN_{t-1}.

If the additions to the stock A increase and remain constant at the higher rate indefinitely, the stock of nitrogen will rise. As it rises, the amount that is lost through mineralization each year also rises since that loss is a constant fraction of the stock. Once these losses have risen to equal the annual additions, the stock has reached an equilibrium (N^e_t) and will remain indefinitely at that level. Consequently, $N^e_t = N^e_{t-1}$ and substitution in equation 1 implies:

$$rN^e_t = A_t \qquad (5)$$

This equation can be used as written to calculate the flow of mineralized nitrogen from a specified stock–in equilibrium the flow equals the additions--or to calculate the mineralization rate

$$r = A_t/N^e_t \qquad (6)$$

or to compute the equilibrium stock implied by a unending stream of additions at a constant rate:

$$N^e_t = A_t/r \qquad (7)$$

Equations 4-7 comprise the simplest exponential model. "In general, these simple exponential models give reasonably satisfactory representations of reality over the 10 to 100 year period," (Wild 1988, p. 605) which is the relevant time frame for understanding the agricultural revolution.

The long term experiments at Rothamsted provide support for the exponential model and data that are indispensable for calibrating it. The Broadbalk wheat and Hoosfield barley experiments are two of the most famous. Plots have been planted ever year since 1852 with wheat[9] and barley. Each experiment had a control that was not manured or fertilized and

[8]In the scientific literature, the relationship is usually expressed with the differential equation dN/dt = A - rN. The difference equation used here is equivalent.

[9]The wheat experiment actually began in 1843 but the fertilizer regimes were not consistent enough for analysis. 1852 marked the beginning of the long term experiments.

experimental plots receiving either farmyard manure or varying doses of artificial fertilizers. Yields fell on the plots that were not fertilized, but the decline was gradual. This was evidence of a stock of fertility in the soil that was being slowly depreciated. After about half a century, the yields stabilized. The slowness of this process suggested that the deterioration of the stock was a slow process.

The first step in applying the model is defining and measuring the stock of soil nitrogen. The first measurements were taken by Lawes and Gilbert in the nineteenth century, and their work has defined the basic approach. Samples are taken to a depth of nine inches (23 centimetres). This depth was chosen since the roots of cereals did not penetrate below that level nor did ploughing raise soil up from a greater depth. So Lawes and Gilbert reasoned that the soil chemistry relevant to plant growth was confined to the top nine inches.

The measurements of the nonmanured plots at Broadbalk and Hoosfield indicate that the nitrogen content of the soil has declined from about .12% in the midnineteenth century to about .10% today with most of the fall taking place by 1900 (Jenkinson and Johnston 1976, p. 92). At the same time, wheat and barley yields declined and then stabilized, and that is fundamental support for the nitrogen model.

To relate these results to the nitrogen model, soil composition must be expressed as nitrogen. A typical assumption is that the top nine inches (23 centimetres) of a one hectare plot contain 2.91 million kilograms of earth (Jenkinson 1976, p. 104). If the nitrogen content is .1%, the stock of nitrogen is then 2910 kilograms per hectares and so forth for other percentages. These values are measures of N_t in the nitrogen model.

The second step in applying the model is determining the mineralization rate. Jenkinson (1966) and Jenkinson and Johnston (1976) integrated the differential equation corresponding to equation 4 and fit the resulting equation to time series data for experimental plots at Rothamsted. They concluded that the equilibrium stock of nitrogen was about 3000 kg/ha, which was essentially the value reached by the end of the nineteenth century (and maintained since) in the plots that were never fertilized in both Hoosfield and Broadbalk. Mineralization rates were in the range of 1-3% implying the mineralization of 30 to 90 kg of nitrogen per hectare per annum. Jenkinson (1976) and Jenkinson and Johnson (1976) have attempted to narrow the range by summing all the additions to fixed nitrogen (which equal mineralization in equilibrium). One calculation reached a value of 34 kg/ha, while another gave 36 kg. These values are consistent with a mineralization rate of 1.14%, which is at the low end of the estimated range. The 34 kg/ha was reckoned to include "2 kg in seed, 5 kg in rain, plus a hypothetical value for dry fixation of atmospheric ammonia , set at 10 kg." The remaining 17 kg. came from biological fixation by blue-green algae as well as by bacteria like Azobacter and Clostridium.[10] As the word "hypothetical" suggests, many components of the calculation are speculative, so there remains suspicion that some of the material has been missed, but these analyses remain the best attempts to measure the nitrogen balance in wheat and barley production.

After considerable experimentation with the model, I use a mineralization rate of 1.5%, which implies annual additions of 45 kg/ha to the stock of nitrogen. 45 kg/ha slightly

---

See Hall (1919, p.31).

[10]Jenkinson and Johnston (1976, p. 96). Cf. Jenkinson (1976, p. 107) where the corresponding figure for plot 3 in the Broadbalk wheat experiment is worked out to be 36 kg/ha. Jenkinson (1966) is an earlier attempt at fitting these models.

exceeds the nitrogen balance figures of 34-36 kg/ha thus allowing for some missed nitrogen.

One feature of the simulation approach of this paper is that all endogenous variables are simulated. Parameter values cannot be estimated arbitrarily and independently. Requiring all of the simulated values to conform to empirical measurements limits the range of possible values. For instance, when legume cultivation is simulated with this model using a 2% mineralization rate (rather than a 1.5% rate), the equilibrium level of nitrogen fixed by the beans is implausibly high in view of their yield. Not only are low mineralization rates consistent with the calculated nitrogen balances, however imperfect they may be, but they imply closer agreement with the values of other variables than do higher mineralization rates. To make sure this procedure does not prejudice the results, the analysis of this paper has been redone with a range of mineralization rates. The main historical conclusions are unaffected.

Medieval Agriculture

At first glance, the Broadbalk continuous cropping experiment looks like a model for the middle ages: a wheat yield of 12 bushels per acre was about the medieval average, and the absence of manuring tallies with Postan's (1972, pp. 45-80) description of thirteenth century farming. However, the differences look equally great: the land was fallow for one year in three in the medieval system–which should have bumped up medieval yields–while the Rothamsted experimenters were using nineteenth century seed varieties and farm equipment, which should have been to their advantage. So adjustments have to be made to apply the Rothamsted data to the middle ages. The changes relate to rotations, spring grains, nitrogen carry-over, and manuring.

Medieval farmers did not grow cereals continuously but interspersed their cultivation with summer fallow. Medieval agriculture is analyzed here as a three field system in which the land rotated between fallow, wheat, and spring grain (barley and oats). Medieval practice was not homogeneous, but most of the variants produced similar results. The main exception in England was northeastern Norfolk where higher yields were reported. These will be discussed later, for they illustrate some of the themes of the early modern period.

While different crops were usually grown in the spring and winter fields, the analysis of this paper follows Chorley (1981) and does not develop separate models for each grain. The yields of the spring grains were often greater than those of wheat when measured in bushels per acre, but the bushels of the spring grains were also lighter: barley was conventionally rated at 50 lbs per bushels, while oats was 40 in contrast to the 60 lbs per bushel of wheat. When production is reduced to weight, the differences shrink, and I will use the same assumptions for productivity and nitrogen response for the spring grains as for wheat. This is consistent with the Crowther and Yates (1941, p.81) survey, previously discussed, which shows similar response to nitrogen fertilizer in wheat, barley, and oats. The scientific literature measures production by weight and does not draw sharp distinctions between the cereals.

Fallow was an important difference between medieval cultivation and the continuous cropping experiments. Fallow performed three functions in medieval agriculture. One was to remove the weeds by pasturing animals on the bare field. The second was to receive the manure from those animals–a role to be considered shortly. The third was to accumulate mineralized nitrogen for the benefit of crops in subsequent years. Each year 1.5% of the stock of organic nitrogen was mineralized whatever was grown on the land. If the land was left fallow, these nitrates, in addition to those in manure applied to the fallow, were potentially available for the succeeding wheat crop.

Stress, however, needs to be put on 'potential'. Nitrates are water soluble, and their availability to the wheat depended on the winter rain. Heavy rains washed away the nitrates. Experiments at Rothamsted showed that "the increased crop after fallow is almost wholly dependent on the retention in the soil of the nitrates thus formed in the summer. Should a wet autumn and early winter succeed, the nitrates are washed so far down in the subsoil as to be out of reach of the crop, which then shows a very small return for the previous summer fallowing." (Hall 1919, p. 223). Hall divided late nineteenth century data into two equal sized groups–those following heavy rain and those following light rain. Wheat yields following a fallow and a wet winter were scarcely greater than yields in the continuous cropping experiment. The heavy rains, thus, leached out all of the nitrogen fixed during the fallow year. On the other hand, the yields following the fallow were about 900 kg per hectare greater if the autumn rains were light. This increment in yields required all of the nitrogen fixed during the fallow, so losses over the winter were inconsequential. My models of agriculture track residual nitrogen from one course to the next making allowance for the probability that heavy rains leached the nitrates from the surface soil. Following Halls (1919, p. 223), complete loss is presumed to occur half the time with no loss occurring the other half.[11] On average, half the residual free nitrogen is lost each year, and half is carried forward. Given the linearity of the model, the expected yield depends on the expected carry-over, so I have simulated nitrogen stocks on the assumption of a 50% carry-over of residual nitrogen from one year to the next.

Manure is the final new element in a model of three field farming. When livestock graze on pasture or eat meadow hay, their manure is a net addition of nitrogen to the arable. The rub is that the magnitudes are small. Most of the manure from stock grazing on pastures was deposited on those pastures and never reached the arable. Chorley (1981, p. 79) estimated that at most one kilogram of nitrogen was added to each hectare of arable. Even meadow hay, which was fed to animals in barns where the manure could be collected, resulted in only a minor addition: On the generous assumption that the ratio of meadow to arable was 1:4, only about 4 kg of nitrogen were in the manure that was added to the arable each year.[12] These figures are small compared to the 45 kg of nitrogen fixed from the atmosphere.

The other source of nitrogen in manure is the products of the arable–the oats eaten by the horses for instance and the wheat chaff in which they were bedded. There is an upper bound on how much nitrogen this contains–it is limited to the nitrogen in the crops eaten on the farm and the straw used in the barns. More animals can raise that limit only if the fraction of grain fed to them is increased. Campbell's figures imply that 15% of the spring corn was used as fodder in the high middle ages.[13] Perhaps in the eighteenth century, all of

---

[11]Shiel (1991, 59-60) deals with this question by treating the mineralized nitrogen as a separate stock that becomes available to plants at the rate of 40% per year. This treatment also parallels my treatment of clover in the Norfolk rotation model.

[12]Further assumptions include a hay yield of 2000 kg per hectare, a nitrogen content of 1.33% in the hay, and a 50% loss of manure. (Chorley 1981, p. 79).

[13]Campbell (2000, p. 392) indicates that one third of the oats and none of the barley and dredge were used as fodder. Applying these proportions to the estimates of net production (and assuming a bushel of oats weighed 40 lbs and barley 50 lbs) implies that fodder amounted to 15% of the spring corn.

the spring corn was being fed to animals, and that was surely the upper limit to the practical.

A second way to increase the nitrogen flow to the arable was by increasing the efficiency with which manure was managed. There were limits there as well for two reasons: First, it was difficult to collect all of the manure dropped by the livestock for obvious reasons. Second, the nitrogen in the manure was easy to lose since it dissipated naturally and rapidly. Manure's stench, for instance, is ammonia escaping into the atmosphere, and those losses are of consequence. Furthermore, half of the nitrogen excreted by animals is in urine, which easily seeps away if not collected in the litter. The solid excrement contains water soluble nitrates which are also at risk (Foth, 1984, pp. 345-9). Chorley's (1981) assumption that half of the nitrogen consumed by livestock was returned to the arable does not seem too high under these circumstances. It is buttressed by Foth's (1984, p. 299) claim that "if the [legume] crop is cut for hay and fed on the farm, about 50 percent of the nitrogen taken from the air by legume bacteria can be returned to the soil, if special care is exercised in handling the manure to prevent loss."

Despite the losses, the manure that reached the soil did raise yields both immediately and in the long term. The immediate boost came from the ammonium and nitrates in the manure. They were water soluble and were thus available to growing plants. On the other hand, some nitrogen was in organic residues like straw or lignin that increased the stock of organic nitrogen and thus raised fertility in the long run without having an immediate impact (Hopkins 1910, p. 541, Foth 1984, p. 346). In the calculations of this paper, I assume that two thirds of the nitrogen was immediately available while one third increased the nitrogen stock.

These considerations specify the nitrogen flows in the three field system. The evolution of the stock of organic nitrogen was governed by additions and decomposition. The former included the various forms of atmospheric fixation, the nitrogen in the seed, and one third of the nitrogen in the manure applied to the land. Some of that manure came from grazing in the pasture and hay from the meadow, while the rest came from the spring grain, chaff, and stubble supplied to the livestock. Mineralization was the only reduction in organic nitrogen, and equilibrium occurred when the stock reached the size where mineralization equaled additions. Since only two thirds of the arable was cultivated, the free nitrogen per cropped hectare was greater than under continuous cultivation.

The stock of organic nitrogen was not immediately usable by plants. It promoted growth only through its decomposition since only mineralized nitrogen was water soluble and available to the plants. The mineralized nitrogen (in the form of ammonium and nitrates) available on any plot equaled the amount mineralized on that plot in that year plus any carry-over from the previous year's cultivation. Carry over depended on the amount of winter rain and what was left after cultivation the previous year. If the land was fallow, the residue equaled the nitrogen produced by mineralization on the fallow plus two thirds of the nitrogen in the manure, which is treated here as being applied to the fallow. If the land grew cereals, the residue equaled the residue bequeathed by the preceding year's activity, plus that created by mineralization, minus the nitrogen taken up by the growing plants.

These relationships can be programmed, so that the dynamics and equilibrium of the nitrogen economy can be simulated. The equations are shown in Appendix I.

Calibrating the Yield Equation

The nitrogen accumulation model can be used to calibrate the yield equation for medieval conditions and determining the corresponding equilibrium stock of fixed nitrogen. These were done jointly. Not only does yield depend on the stock of nitrogen, but there is also feedback from yield to the nitrogen stock since spring grain was feed to livestock and their manure applied to the arable. The latter effect, however, is small (as previously noted), so it plays no important role in the calibration.

To calibrate the model, it was simulated over 400 years with a starting value of the nitrogen stock of 3000 kg/ha. The yield response coefficient m was calculated from Ugb as in equations 2 and 3. g and b were assumed to equal 82.5 and .45, and the take-up ratio U, which is bounded by zero and one, was searched to find the value that produced a long run wheat yield of 11.6 bushels per acre. As a check, the model was then resimulated using the equilibrium nitrogen stock from the first simulation as the starting value. This second simulation showed stability in all values over the 400 year simulation period thus confirming that an equilibrium had been found.

This simulation of the medieval economy showed that the equilibrium stock of nitrogen was 3272 kg/ha and the yields of wheat and barley were 11.6 bu/acre and 13.0 bu/acre, respectively. The barley yield is close to that implied by Campbell's figures, which is reassuring since parameters were not chosen to ensure that value. The take-up rate was 23% and the yield response coefficient was 8.349, so the medieval yield equation was:

$$Y = 8.349*N \qquad (9)$$

The take-up rate and the yield response coefficient are lower than those for the nineteenth century, and the increase is indicative of the improvements in farming methods (over and above those that raised soil nitrogen) between 1300 and 1800. The stock of organic nitrogen in the soil was not much above the three ton equilibrium of the continuous cropping experiment.

Medieval Productivity: Too few animals?

In the introduction, I identified three hypotheses about yields that involved arguments about nitrogen. The first was that medieval agriculture suffered from a deficiency of animals with the result that inadequate manure was applied to the arable (Postan 1972, pp. 45-80) . Campbell's estimate that only 15% of the spring grain was fed to livestock is evidence in favour of this view. However, our model of medieval agriculture points to a different conclusion.

Like scientifically-based models of nitrogen in agriculture, the one developed here does not focus on the number of animals but instead on the degree of nitrogen recycling. The reason is simple: Unless the animals are associated with some process that brings additional nitrogen onto the farm, there was an upper limit to what they could have done and that was to recycle all of the nitrogen in the cereals grown on the farm. This would have been achieved if they had eaten all of the grain, and the manure was returned to the fields. The feasible change was an increase from 15% (the share of spring grain fed to animals c. 1300) to 100%. The impact of this change can be easily simulated, and the impact turns out to be small–the equilibrium stock of organic nitrogen only rises trivially from 3272 kg/ha to 3322 kg/ha. In consequence, the mean yield of grain would have risen by only 0.4 bushels per acre. This was negligible. Two general conclusions follow: (1) Inadequate livestock depositing meager amounts of manure on the arable were not the cause of low medieval yields. (2) Only by bringing in substantial quantities of feed from off the farm could livestock manure be increased enough to make much impact on cereal yields.

Early Modern Revolution: Peas and Beans

Crop yields increased in England during the early modern period. There were contemporaneous changes in cropping and land use. The innovations varied from district to district, but they all had one thing in common, and that was the capacity to raise the stock of organic nitrogen in the soil. I will analyze three of the most important techniques–the cultivation of peas and beans, the Norfolk rotation, and convertible husbandry.

I begin with peas and beans. Their cultivation was limited in most of England during the middle ages. Norfolk was the exception. According to Campbell (2000, p. 240), 14% of its demesne land was planted with legumes in 1250-1325. In England as a whole, the corresponding proportion was only 7%. This changed in the fifteenth century. By 1400-49, almost 20% of the demesne in England was planted with legumes. The new pattern was first glimpsed by Hoskins (1950, 1951) in his study of Leicestershire inventories.[14] Open field farmers in that county were growing a whole field of peas in the sixteenth and seventeenth century, and the practice had begun in the fifteenth. Parkinson's (1808, 1811) survey data for Huntingdon and Rutland c. 1800 show bean or pea growing to have been well night universal in villages where the soil was heavy and unsuited for turnips and clover.

The cultivation of peas and beans are strong candidates for raising yields since they fix atmospheric nitrogen through infection of their roots by Rhizobium bacteria. The benefits are controversial, however. Foth (1984, p. 299), for instance, contends that the nitrogen in the roots and stubble equals the free nitrogen absorbed from the soil, while the nitrogen fixed from the atmosphere equals the nitrogen in the stems, leaves, and seeds. The fixed nitrogen, therefore, benefits the soil only if the legumes are eaten by animals and their manure returned to the land.[15]

The success of legume cultivation in raising the stock of organic nitrogen may have depended on a second feature of their growth: They were sponges for free nitrogen in the soil, absorbing it and converting it to organic nitrogen, which was left in the land.[16] This is born out be experiments on crop rotations at Rothamsted where it was found that "bare fallow proves a better preparation for wheat than does the bean crop, after which in all cases the wheat crop is somewhat diminished....In other words, the bean crop, which is pulled, not cut, does not leave behind any great amount of nitrogen gathered from the atmosphere–not sufficient to compensate for the absence of the summer tillage that the bare fallow receives."

---

[14]Campbell (2000, pp. 276-85) shows the fifteenth century leadership of the midlands in introducing legumes as field crops.

[15]Chorley (1981, p. 75-6), however, has disputed this. He claims that root formation has been undermeasured. A complete measurement, in his view, would be so large that it must include nitrogen fixed from the atmosphere. This critique, however, applies more to clover than to peas and beans

[16]This is the burden of Foth's observation about the nitrogen in the roots of legumes. Chorley (1981, p. 78) makes the same point. See also his sources: Allison (1973, p. 463) and Löhnis (1926, pp. 253ff). The latter, for instance, observes that only "two-thirds or three-quarters of the 100 or 150 pounds nitrogen per acre harvested in a leguminous crop has come from the air." The rest of the harvested crop and the nitrogen in the roots and stubble comes from nitrates assimilated from the soil and converted to organic nitrogen.

(Hall 1919, p.201) Measurement of the impact of particularly large bean harvests on succeeding wheat crops showed large reductions in wheat yield compared to wheat succeeding fallow. "These results can only be interpreted by supposing that the large bean crop, so far from obtaining all the nitrogen it required from the atmosphere, drew extensively upon the resources in the soil, consequently, instead of enriching the land like the clover crop it actually left it poorer than it was before." (Hall 1919, p. 202)

To explore the impact of beans on yields, I have replaced spring corn with beans in the model of medieval agriculture and then simulated yields. Adding beans requires that their nitrogen economy be modeled, and I have taken a conservative course in this regard. I have followed Foth and allowed no role for atmospheric fixation beyond the nitrogen recycled to the arable by feeding beans to livestock. However, I have allowed beans to raise the stock of organic nitrogen by assimilating all free nitrogen in the soil. Assimilation was estimated as the difference between available free nitrogen and the nitrogen removed in seeds, stems, and leaves. The resulting bean residues contained about 47 kg/ha of organic nitrogen in equilibrium, which is above Chorley's (1981, p. 75) estimate of 30 kg/ha but within the range implied by the data he cites.

The introduction of this much additional nitrogen into the agricultural system had a profound impact on the stock of organic nitrogen and on cereal yields. Figure 3 plots the simulated stock of organic nitrogen for the medieval three field system and the early modern system including beans as the spring crop. The "years" are notional and show what would have happened had the beans been introduced suddenly in 1550. Both simulations begin with the stock of nitrogen set at its medieval equilibrium (3272 kg/ha). The medieval simulation continues steadily at that level. With the addition of beans, nitrogen stocks rise steadily toward a value of about 5500 kg/ha in the mid-eighteenth century. One of the important features of the simulation is the long time it took for legume cultivation to raise soil stocks to their new equilibrium. This is a fundamental reason that the agricultural revolution took close two hundred years to accomplish.

Figure 4 contrasts simulated wheat yields in the two farming systems. The medieval open field system shows wheat yields steady at 11.6 bushels per acre–a continuation of the medieval pattern. The introduction of beans as a field crop had two effects on yields. The immediate impact was a reduction in cereal yields by about 1.5 bushels per acre. The reason for this drop is that beans absorbed residual nitrates in the soil and converted them into organic nitrogen. These nitrates would have otherwise been available to the wheat, so wheat yields dropped initially.[17] The economic incentive to introduce peas and beans as field crops was not their immediate impact on the other cereals, but lay elsewhere as we will see.

In the long term, however, the cultivation of beans benefitted the wheat. As the stock of organic nitrogen in the soil rose, so did the flow of mineralized nitrogen. As a result, when legumes replaced spring corn in the three field system, there was a rising trend in wheat yields, which rose to a new equilibrium of 16.4 bushels. Between 1300 and 1800, the yield of wheat increased from 11.6 bushels per acre to 20. The cultivation of peas and beans as field crops raised soil nitrogen enough to increase yields from 11.6 to 16, while greater animal numbers accounted for the extra 0.4 bushel of the increase. Thus, legume cultivation accounted for 52% of the increase in crop yields and greater livestock numbers may explain another 5% of the rise. Together these changes (in the districts where they occurred) explain

---

[17]This is the solution to Farmer's (1983, pp. 346-7) puzzle as to why legumes were sown before the fallow rather than before the wheat. Cf. Campbell (2000, p. 230).

57% of the rise in wheat yields in early modern England. The remainder is due to other changes in method. These will be discussed later.

The simulations make a further important point about the agricultural revolution–it was slow. As with the stock of soil nitrogen, the transition to the new equilibrium level of yields took a century and a half. The agricultural revolution was bound to be a drawn out business given the low mineralization rate of organic nitrogen. Labeling any half century as the "agricultural revolution" is bound to be misleading.

Early Modern Revolution: Clover and Turnips

The Norfolk rotation (turnips-barley-clover-wheat) is perhaps the most famous innovation of the Agricultural Revolution. Clover and turnips were introduced into England from the Netherlands in the late sixteenth century (Chambers and Mingay 1966, pp. 56-60). Probate inventories show that the fraction of farmers in East Anglia growing clover increased from 10% to 17% between 1680 and 1710, while the proportion growing turnips rose from 10% to over 50% during the same period (Overton 1977, pp. 325-6). It was only in the eighteenth century that clover and turnips were routinely combined with wheat and barley to form the classic four course rotation. This diffusion of these changes occurred later than peas and beans, and this implies a later rise in yields.

To assess the impact of the Norfolk rotation on corn yields, the nitrogen flows must be established, so that clover and turnips can be added to the medieval model. Turnips raise few issues since the plant absorbed little nitrogen, and much of that was returned to the soil in organic form.[18] Clover, on the other hand, was highly nitrogenous. It fixed nitrogen from the air and absorbed free nitrogen from the earth. Following Chorley (1981, pp. 75-6), the former was estimated as 2.5% of the roots and stubble, which were taken to equal three quarters of the weight of clover. This is a conventional but arbitrary assumption, as Chorley has noted, that underestimates the organic nitrogen amassed by the clover. In particular, the assimilation of nitrates from the soil must also be included, and that component equaled the available mineralized nitrogen not required for hay production. This represented an addition to roots and stubble that increased organic nitrogen. The implied equilibrium rate of nitrogen residue formation is 54 kg/ha, which is slightly over half of Chorley's (1981, pp. 76, 78) estimate of 100 kg/ha. The difference arises because I assume that clover yields were only two tons per acre, while he makes them four.

An important way in which clover differs from beans is in the timing of the availability of nitrogen for plant growth. Experiments at Rothamsted showed that beans absorbed all of the free nitrogen in the soil with the result that wheat following beans yielded less than wheat following fallow. In contrast, wheat following clover yielded more than wheat following fallow. In the case of clover, two opposing effects were at work. On the one hand, clover, like beans, assimilated free nitrogen from the soil. "Although undoubtedly the clover takes up a good deal of its nitrogen as nitrate, this would seem to be derived from accumulations within the soil" rather than fixation from the atmosphere (Lawes and Gilbert, 1895, p. 253). On the other hand, white clover "tissues, which have high N content, rapidly

---

[18]Foth (1984, p. 291) indicates that turnips have a root yield of about 10 tons per hectare containing 45 kg of nitrogen. I have reduced these to 8 tons and 36 kilograms. The nitrogen was assimilated from free nitrogen in the soil. I assume that the turnips were eaten off by sheep, and half of the roots were left in the ground.

break down on death to release N into the soil." (Harris 1987, p. 254) The second effect dominates the first. In the modeling here, this outcome is represented by assuming that 40% of the nitrogen in clover was available to the wheat in the following year. (The implied increase in yields is consistent with the Rothamsted experiments on clover.) The remaining 60% increased the stock of organic nitrogen and contributed to the long run rise in yields.

To investigate the historical impact of the Norfolk rotation on soil nitrogen and crop yields, the model can be simulated with an initial stock of organic nitrogen of 3272 kg/ha–the equilibrium stock in the medieval three field system. On the assumption that the Norfolk rotation was introduced in 1650 (perhaps too early a date), Figures 3 and 4 show the trajectories of soil nitrogen and the yield of wheat. Nitrogen stocks rose substantially but leveled out at a lower level than with peas and beans.

In broad outline, the simulated yield of wheat was like that when beans were cultivated, but there were some important differences in detail. First, the immediate impact of clover cultivation was to increase wheat yields rather than to depress them for reasons just discussed. Second, clover cultivation was as successful as bean cultivation in pushing up yields in the long term despite the lower equilibrium stock of nitrogen. The release of nitrogen by clover in the year following cultivation made up for the smaller annual flow of mineralized nitrogen from the smaller stock. Third, the yield trajectory with the Norfolk rotation began its ascent at a later date than the bean trajectory in view of the later adoption of clover. Since the length of time it took to accomplish the rise in yields was of similar length, the increases in wheat yields continued through the eighteenth century rather than being accomplished at its beginning when beans and peas were the bases of advanced.

Early Modern Revolution: Convertible Husbandry

Convertible husbandry was a third innovation of the early modern period. In this system, land was alternated between arable and pasture. Only a small fraction of the land was arable at one time. It was used to grow corn for a decade or two after which it was put down to grass for decades before being ploughed up again. The long pasture ley raised corn yields by increasing the stock of organic nitrogen in the soil.

The success of convertible husbandry is based on a biological fact–the equilibrium stock of nitrogen in grassland is about 7275 kg/ha. As a result, if land that has been 'worn out' by growing corn (and hence has a low stock of nitrogen) is put down to grass and left for 150 years, its nitrogen stock will rise to 7275. Figure 5 plots nitrogen levels for various pastures as a function of their age and shows this convergence to the higher nitrogen equilibrium.

While this relationship is well established, the underlying biology remains mysterious. To balance mineralization, additions to the stock of nitrogen must have equaled 109 kg/ha per year.[19] This nitrogen did not come from grazing cattle on the pasture since their manure merely returned nitrogen to the soil from where it came. One possible source is grasses like clover that are legumes and fix nitrogen, but nitrogen levels rise even when pastures contain grasses without root nodules (Cooke 1967, p. 207). Richardson (1938, pp. 112-5) pointed out that the increase in nitrogen was not due to the regeneration of the existing soil but rather to the creation of a new layer of soil above the old as the roots of grass

[19]This is typical for pastures. See Crush (1987, pp. 192-4).

died and decomposed. This new soil was high in organic nitrogen.

Whatever the explanation, the high level of organic nitrogen in land that lay under grass for a century or two created the possibility of nitrogen mining. Yields were high when grass was ploughed up and planted with corn. As the stock of nitrogen was driven down to the equilibrium level of the arable system, yields fell. Eventually, it no longer paid to take out the nitrogen as corn, and the land was laid back again to grass.

Figures 3 and 4 show these patterns for a hypothetical plot of land. The nitrogen stock is initially at a high value (7275 kg/ha) in Figure 3 and falls as the land is cultivated. This simulation assumes a medieval three field system so the equilibrium nitrogen stock is 3272 kg/ha as in our earlier analysis of that system. Figure 4 shows the evolution of wheat yields. They start off at about 25 bushels per acre–2.2 times the level obtainable by conventional medieval farming--and fall to the medieval level after two centuries. There was a long period, therefore, when ploughing up old grass land could generate yields much above those attained by the generality of farmers in the fourteenth century.

The gains were particularly marked under medieval conditions when nitrogen stocks were particularly low. The yield of wheat was initially 25 bushels per acre when old pasture was ploughed up. This yield was 2.2 times the level obtainable by conventional medieval farming (11.6 bushels/acre). The wheat yield converged downward toward that level as nitrogen stocks were depleted, but the drop was slow. Even after fifty years, the wheat yield was 18.4 bushels per acre–59% above the equilibrium value and almost at the 1800 average.

If parallel calculations are undertaken for conditions in 1800–i.e. assuming beans are grown as the spring crop, stocking rates are higher, and the take-up ratio has been raised to 30%–the gains from convertible husbandry are cut in half. These improvements push up wheat yields when old pasture is broken up. Initially the yield is about 29 bushels per acre–43% above the new equilibrium level of 20.3 bushels to which yields converge. After 50 years, the wheat yield falls to 25.9 bushels–28% above the equilibrium. Under 1800 conditions, the advantages of convertible husbandry–43% on the initially yield and 28% after half a century–are much less than those for the medieval calculations–120% and 59%. Improvements in arable farming between 1500 and 1800 slashed the relative advantage of convertible husbandry.[20]

This finding sheds light on two important features of early modern agriculture. The first is the similarity in crop yields across natural districts. Grain yields in those parts of Leicestershire and Northamptonshire where convertible husbandry was practiced at the beginning of the nineteenth century were not radically higher than those in places specializing in corn production. The latter were using modern rotations of one sort or another, and they eliminated much of the advantage of convertible husbandry.

The second issue is the rise and decline of convertible husbandry. Broad (1980) pointed out that many of the parishes in the midlands that Kerridge had cited as examples of convertible husbandry in the seventeenth century had given the practice up and were following a purely pastoral husbandry by 1800. Why would such a highly productive technique be abandoned? The answer is that its productivity advantage had been seriously eroded. In the sixteenth century, convertible husbandry meant that land which was intrinsically well suited for grazing was also exceptionally productive in raising corn.

[20]The simulated advantage of convertible husbandry is sensitive to the mineralization rate used. Higher mineralization rates reduce the advantage of convertible systems, while lower rates increase them.

'Exceptional' in this case is with respect to arable regions whose cultivation had not yet been revolutionized by legume cultivation. Consequently, some of the high quality pasture was allocated to corn growing via convertible husbandry. However, as legume cultivation spread in the arable districts, their productivity rose and arable cultivation was reduced on land that was intrinsically better suited to pasture.

From technology to economics

I have identified some of the technologies (legume cultivation and convertible husbandry) that raised corn yields in the early modern period. The next questions are: How and when were they invented? Why were they adopted in the sixteenth and seventeenth centuries? Why not earlier or later? My answers depend on the profits of livestock production, which were transformed after the Black Death. The population fall in 1348/9 played a critical role by changing the relative values of labour and land and by shifting the structure of demand from corn to livestock products. These changes created a strong incentive to increase the production of animal products, and that need was the main reason for adopting the techniques that ultimately raised corn yields.

Consider peas and beans first. There are two reasons why increasing corn yields could not have been the incentive to plant the spring field with legumes. First, the immediate impact of growing these crops was negative in as much as they absorbed free nitrogen from the earth and cut cereal yields by 1.5 bushels per acre. Second, no one realized in 1500 that the cultivation of beans or peas for two centuries would double corn yields. Indeed, the gains were so gradual that no one probably realized what had happened in 1700. In that sense, the yield increases were not only inadvertent, they were unconscious.

Peas and beans were very good animal feed, however, and that was the reason for their adoption. "Their appeal lay as a source of fodder to support the growing numbers of animals now being stocked, for whose meat and dairy produce there was a steadily strengthening demand." (Campbell 2000, p. 256.) Peas and beans were much richer in protein than cereals. Barley and oats are 8 -10% protein, while beans are 25-30% (Bland 1971, pp. 131,298-300). According to Fussell (1966, p. 55), the dairy farmer "was told that if milk was wanted for cheese he must give plenty of flesh forming food e.g., peas and beans and water, and other 'carbonaceous' feed."

The incentives were more varied in so far as clover cultivation was concerned. On the one hand, the long term benefit for corn yields was not apparent in advance and so could not have motivated the decision. On the other hand, clover cultivation had an immediate, positive impact on corn yields. The initial increase was small but it began to grow immediately. So higher corn yields were one reason to grow clover. The greater incentive, however, was the value of the hay. On the modest assumption that clover gave two loads of hay per acre, the clover was worth over £9 pounds as against the value of the extra wheat and barley attributable to the Norfolk rotation, which was £3.5.[21] Livestock provided a much greater incentive to grow clover than did corn.

Convertible husbandry should also be seen in the context of growing livestock output

[21]These calculations assume that five bushels of wheat were worth £0.41 per bushel, five bushels of barley @ £0.238, while hay was worth £4.558333 per load. These are the 1815 prices used to aggregate farm production in Allen (1994, p. 102).

rather than as an innovation primarily oriented to corn, but the matter is complex and has been extensively debated. Kerridge (1967) is a great champion of 'up and down' husbandry as a technique aimed at raising corn production in the early modern period. Clark (1992) has argued that medieval farmers knew all about the contribution that convertible husbandry could make to corn yields, but chose not to practice it because the cost of capital was so high.

These factors may have played a role, but they were far from the whole story. In much of England c. 1300, convertible husbandry was not practiced since there was not enough grassland to plough up. (It is, after all, ploughing up old grass that makes the money rather than putting worn out arable down to pasture.) With the drop in the population in 1348/9, the incentives to produce livestock products increased, and much land was laid down to permanent pasture between 1350 and 1375 (Campbell 2000, p. 400). By 1500, the nitrogen level of this grass was high enough to give high corn yields if it was ploughed up. Peas and beans were just coming into use and had not yet raised the nitrogen levels of purely arable systems. Until that happened–i.e. for the period 1500-1650–convertible husbandry was the most efficient way to grow corn and was in vogue. Thereafter its productivity advantage waned, and its use declined.

Non-Nitrogen Causes of the Rise in Yields

Increases in soil nitrogen explain much of the rise in corn yield between 1500 and 1800 but were not the whole story. Where convertible husbandry was practiced, enough nitrogen was released to push yields up to 1800 levels. However, in purely arable districts, the wide spread cultivation of peas, beans, and clover accounted for only about half of the yield increase that occurred between the late middle ages and the nineteenth century. I will briefly discuss some of other changes in farming that were occurring to ask whether they could have accounted for the rise in yields.

1. One candidate is improved seed varieties. Plott (1677, p. 151), for instance, described how seventeenth century farmers carefully selected seed from high yielding plants. This seed was propagated and then sold. In this way, higher yielding varieties were brought into general cultivation. Indeed, better seeds have often gone hand-in-hand with increases in soil nitrogen. The Green Revolution is a case in point. The introduction of high yield rice in south Asia was accompanied by increases in fertilizer applications; indeed, the improved rice was required to use the nitrogen effectively since increased fertilization caused vigorous stem growth–and then lodging–with the traditional varieties. Could the same have been true of early modern England? In discussing the limits to the application of manure to wheat in the eighteenth century, Young (1770, Vol. I, p. 362) remarked that it was "so apt to lodge if the land is very rich."

The experience of eastern Norfolk in the high middle ages is suggestive in this regard. Some farmers there reaped yields like those generally attained in the eighteenth century–on the order of 20 bushels per acre for wheat. As Campbell's (2000, pp. 295, 327-9) work has shown, this region was the one in which legumes were extensively cultivated, so nitrogen levels were already elevated. Norfolk farming was also remarkable for the very high seed rates used. The county's high yields were not due to high yield-seed ratios but rather to dense sowing. Perhaps this is what Norfolk farmers had to do in order to offset the tendency of their wheat to lodge if doused with nitrogen? Dense sowing meant exceptional competition among the wheat plants for nitrogen in the ground. Dense sowing raised the overall take-up rate without any plant getting too much nitrogen. One of the striking differences between medieval and eighteenth century seed was the ability of the latter to generate higher yield-seed ratios. These new varieties cut costs by saving seed. They may not, however, have raised yields since dense sowing allowed farmers to take advantage of high nitrogen levels with varieties that had a tendency to lodge.

2. Improved water supply is often required to get the greatest benefit from improved seed and higher nitrogen inputs. In the English case, improvements in water supply meant better drainage rather than irrigation, and better drainage is a second candidate for raising yields. Subsurface, hollow drainage were introduced onto heavy clays in the midlands and eastern Anglia in the eighteenth century. Statistical studies indicate that it was responsible for a considerable rise in yields, especially for barley and oats whose yields did rise substantially in this period.

3. Applying lime to farm land was a third technique that increased yields. Lime increases the mineralization rate and, thereby, increases the release of free nitrogen from the stock. More free nitrogen pushes up the yield. The gain is transitory, however. The equilibrium stock of nitrogen drops as the mineralization rate increases (equation 7), and the yield boost from liming persists only until the new equilibrium is reached. During the transition, the yield gain falls as the new equilibrium is approached. After it is reached, the annual release of free nitrogen is limited to the annual additions, which are unchanged by liming. Lime was not a source of yield gain that would last.

4. Nitrogen take-up can be increased by eliminating competing plants, and that can be done by more extensive weeding, folding animals on fallows, and more extensive or better executed ploughing. These techniques can also increase nitrogen take-up by improving soil structure to allow fuller root development and penetration. Greater labour intensity and seed drills, better ploughs, and improved implements are a fourth set of techniques that could have raised yields in the early modern period. Farm implements were certainly improved in this period. There has been considerable discussion as to the course of labour inputs, but the matter is not resolved. The importance of more intensive cultivation in raising yields warrants more investigation.

<u>Nitrogen and the Agricultural Revolution</u>

The models developed here provide answers to three major questions about the Agricultural Revolution.

The first key question is why it happened. Nitrogen can explain a lot of the yield gain during the Agricultural Revolution, but not all of it. Convertible husbandry alone was enough to push corn yields from medieval to early nineteenth century levels, and nitrogen was responsible for that gain. In regions dedicated to corn growing, the cultivation of legumes explains about half of the yield increase during the early modern period. The manure from livestock made only a small contribution to soil nitrogen. Low medieval yields were not due to a deficiency of manure nor were high eighteenth century yields due to its abundance. Livestock, however, were crucial to the yield increases. It was not their dung that mattered, however, but what they ate, for the legumes fed to them increased nitrogen stocks that ultimately benefitted the corn.

The second questions is when it happened. Historians have been trying to pin the revolution down to a half century some time between 1500 and 1800. But which? Was it during the parliamentary enclosures? the last half of the seventeenth century? 1590-1660? The important point of the simulations reported here is that the Agricultural Revolution took several centuries. 150 - 200 years is the time frame for the stock of soil nitrogen to move from one equilibrium to another, so that is the time frame for yields to rise from medieval to eighteenth century levels. That time frame sets a lower bound for the time need to accomplish the Agricultural Revolution, but actual time was larger. Some regions began raising their soil nitrogen earlier than others because the appropriate techniques became available at different times. In addition, a county might have started with one (e.g. convertible husbandry) and shifted to another (e.g. peas and beans), so that the regional picture was even more drawn out. National progress was slower still since it was the sum of the nonsynchronized regional histories. The Agricultural Revolution was consequently a gradual, long term development, and any attempt to narrow the time frame to a crucial half century is bound to be misleading.

The third question is the role of open fields and enclosures in raising productivity. Open fields posed no serious obstacle to rises in crop yields. The cultivation of peas and beans was widespread in the open fields, and that was the decisive innovation in many places. Clover and sainfoin were introduced in many open field villages. The main contribution of enclosure was in laying land down to grass in 1350-75. (When this land was ploughed up a century and a half later, it was the basis of Kerridge's agricultural revolution.) Enclosure and depopulation was an important way in which this conversion to pasture took place, but it was not the only way. In open field villages where more grass was desirable, strips in the fields were transformed into grass leys, so that livestock production could be expanded. These villages also practiced a form of convertible husbandry. Moreover, the open fields posed no barriers to many of the techniques like better ploughs or more intensive cultivation that increased the take-up of nitrogen. Since open field villages could and did adopt the fertility-enhancing techniques of the early modern period, comparisons of crop yields between open and enclosed villages c. 1800 find only small differences in average yields.

Appendix I

The Nitrogen Stock Model

The following equations describe the nitrogen accumulation process for a notional farm of one hectare of arable. The three field system is practiced, so one third of a hectare is fallow, one third is planted with wheat, and one third with spring corn or beans. Meadow and pasture are also presumed to belong to the farm. This model is used to simulate medieval agriculture, the cultivation of beans and peas, and convertible husbandry.

To model the Norfolk rotation, this model was altered, so that the arable was divided into four courses including turnips and clover. Equations describing the production of manure from feeding clover and turnips, free nitrogen on the clover and turnip fields, and residual nitrogen from the cultivation of clover and turnips were included. These equations were pattern on those shown here. Clover (like beans here) was assumed to absorb all free nitrogen in the soil, but (unlike beans) it was assumed that 40% of that nitrogen was released in the following year. The remaining 60% increased the stock of fixed nitrogen as in this model.

Variables:
B_t = stock of nitrogen (kg/ha) in year t
C_t = nitrogen mineralized per hectare per year in year t
D_t = yield of wheat (kg/ha)
E_t = yield of spring corn (kg/ha)
F_t = yield of beans (kg/ha)
G_t = addition to nitrogen on the one ha farm from wheat chaff (kg)
H_t = addition to nitrogen on the one ha farm from manure from feeding spring corn (kg)
I_t = addition to nitrogen on the one ha farm from manure from feeding beans (kg)
J_t = addition to the nitrogen stock on the one hectare farm from seed sown (kg)
K_t = addition to the nitrogen stock on the one hectare farm from manure (kg)
L_t = addition to the nitrogen stock on the one hectare farm from legume residues (kg)
M_t = free nitrogen on the fallow at year's end (kg)
N_t = free nitrogen on the wheat field at year's end(kg)
O_t = free nitrogen on the spring corn field at year's end(kg)
P_t = nitrogen brought to the one ha arable farm from meadow and pasture (kg)
Q_t = wheat yield (bushels per acre)
R_t = spring corn yield (bushels per acre)
S_t = bean yield (bushels per acre)

Equations

1. Nitrogen stock evolution

$$B_t = B_{t-1} - C_{t-1} + J_{t-1} + K_{t-1} + L_{t-1} + 45$$

The stock in one year equals its value in the previous year minus mineralization plus additions from seed, manure, and legume residues, plus natural deposition estimated at 45 kg/ha=.015*3000 (the mineralization rate multiplied by the equilibrium stock in continuous cultivation)

2. Mineralization

$C_t = .015*B_t$

Mineralization each year equals the mineralization rate multiplied by the stock of nitrogen.

4. Wheat yield equation

$D_t = 8.349*(C_t + .5*M_{t-1}/(1/3) + (2/3)*(G_{t-1} + H_{t-1} + I_{t-1} + P_t)/(1/3))$

Wheat yield equals the yield response coefficient (here 8.349, the medieval value) multiplied by the free nitrogen on one hectare of planted land. Free nitrogen includes mineralization (C_t), free nitrogen from the previous year's fallow ($.5*M_{t-1}/(1/3)$), and free nitrogen from manure and chaff, $(2/3)*(G_{t-1} + H_{t-1} + I_{t-1} + P_t)/(1/3)$. In the calculation of free nitrogen from the previous year's fallow, .5 is the probability that the nitrogen will not be washed away by winter rain and division by one third, which is the share of the fallow as well as wheat, expresses the nitrogen per hectare of land planted with wheat. In the calculation of nitrogen from manure and chaff, multiplication by 2/3 means that two-thirds of the nitrogen is free and immediately available and division by 1/3 expresses the nitrogen per hectare of planted wheat.

5. Spring corn and bean yields

$E_t = 8.349*(C_t + .5*N_{t-1}/(1/3) + (2/3)*(G_{t-1} + H_{t-1} + I_{t-1} + P_t)/(1/3))$
$F_t = 8.349*(C_t + .5*N_{t-1}/(1/3) + (2/3)*(G_{t-1} + H_{t-1} + I_{t-1} + P_t)/(1/3))$

Like the wheat equation exception that free nitrogen on the wheat field replaces free nitrogen on the fallow.

6. Nitrogen in the wheat chaff

$G_t = .5*D_t *(.55/.45)*.0036*(1/3)$

.5 is the proportion of the nitrogen that is collected and applied to the land, D_t is the wheat produced per hectare, (.55/.45) is the ratio of stems and leaves to wheat, .0036 is the nitrogen content of stems and leaves, and (1/3) is the hectares planted with wheat.

7. Nitrogen in the spring corn returned to the farm

$H_t = .5*(E_t*.02*(1/3)*FEED + E_t *(.55/.45)*.0036*(1/3))$

.5 is the proportion of the nitrogen that was collected and applied to the land. There are two sources of nitrogen represented by the two terms. Nitrogen in the grain that was fed to animals and returned to the land in their manure is represented by $E_t*.02*(1/3)*FEED$. In this expression E_t is the yield of corn, .02 is its nitrogen content, 1/3 is the hectarage planted with spring corn, and FEED is the fraction of spring corn fed to the animals. The second term $E_t *(.55/.45)*.0036*(1/3)$ is nitrogen in stems and stalks and is interpreted as in the wheat chaff equation.

8. Nitrogen in the beans returned to the farm

$I_t = .5*(F_t*.02*(1/3) + F_t *(2)*.0036*(1/3))$

This equation parallels that for spring corn except that it is assumed that all beans are fed to animals on the farm and the ratio of steams and leaves to grain was 2 rather than .55/.45.

9. Nitrogen in the seed

$J_t = .02*(169.875*(1/3) + 169.875*(1/3))$

.02 is the nitrogen content of seed, 169.875 kg/ha (2.5 bushels per acre) is the seed rate, 1/3 ha is the area planted with wheat or spring grain. When beans were grown as the spring crop, the seed of 203.85 (3 bushels per acre) was used for that course.

10. Increase in nitrogen stock from manure

$K_t = (1/3)*(G_t + H_t + I_t + P_t)$

One third of the nitrogen in manure and barnyard litter (from wheat chaff, spring corn, beans) and from pastures and meadow hay increases the stock of soil nitrogen. The remaining two-thirds provide an immediate increase in free nitrogen, subject to losses (equations 4 and 5).

11. Increases in the stock of nitrogen from legume residues

$L_t = .5*N_{t-1} + (1/3)*(C_t - .0225*F_t - .0036*F_t*2)$

Legumes are assumed to absorb all free nitrogen, so their residues equal that total less the nitrogen in their grain, stems, and leaves of the beans. $.5*N_{t-1}$ is the free nitrogen on the wheat field at the end of the previous year multiplied by .5, which is the probability that that nitrogen will not be leached away by heavy rain. C_t is the free nitrogen produced by mineralization on a hectare, and $.0225*F_t$ is the nitrogen taken up in the grain, and $.0036*F_t*2$ is the nitrogen in the seeds and stems on the assumption that their mass was twice that of the grain. The coefficient (1/3) is the hectares of beans on the farm.

12. Free nitrogen on the fallow at year's end

$M_t = (1/3)* C_t + .5*O_{t-1}$

Free nitrogen on the fallow equals the hectares of fallow (1/3) multiplied by the nitrogen mineralized per hectare plus the probability that residual nitrogen will not be leached away multiplied by free nitrogen on the spring corn fallow in the previous year. In this case, spring corn definitely does not include beans since their free nitrogen is converted into legume residues that increase the stock of fixed nitrogen (equation 11).

13. Free nitrogen on the wheat field at year's end

$N_t = .5*M_{t-1} + (1/3)*(C_t - .0225*D_t - .0036*D_t*(.55/.45))$

The term $.5*M_{t-1}$ represents the expected carry-over of nitrogen from the fallow. The remaining term equals naturally deposited nitrogen minus nitrogen taken up in the grain, leaves, and stems of the wheat.

14. Free nitrogen on the spring corn field (not including beans) at year's end

$O_t = .5*N_{t-1} + (1/3)*(C_t - .0225*E_t - .0036*E_t*(.55/.45))$

The term $.5*N_{t-1}$ represents the expected carry-over of nitrogen from the wheat. The remaining term equals naturally deposited nitrogen minus nitrogen taken up in the grain, leaves, and stems of the wheat.

15. Nitrogen in manure from meadow hay and pasture

$P_t = .25*2000*(Q_{t-1}/20)*.0133*.5 + 2$

The first term is manure derived from feeding hay to the animals. .25 equals the hectares of meadow attached to the one hectare of arable. The yield of hay is calculated as $2000*(Q_{t-1}/20)$. This expression means that the yield of hay increased in line with other yields: The hay yield equaled 2000 kg/ha when the yield of wheat was 20 bushels per acre, and the hay yield varied in proportion to the wheat yield. .0133 is the nitrogen content of hay, and .5 is the fraction of nitrogen in the manure that was applied to the arable. The second term, 2, is Chorley's estimate of nitrogen in manure that was collected from the gazing of animals on pasture and applied to the arable.

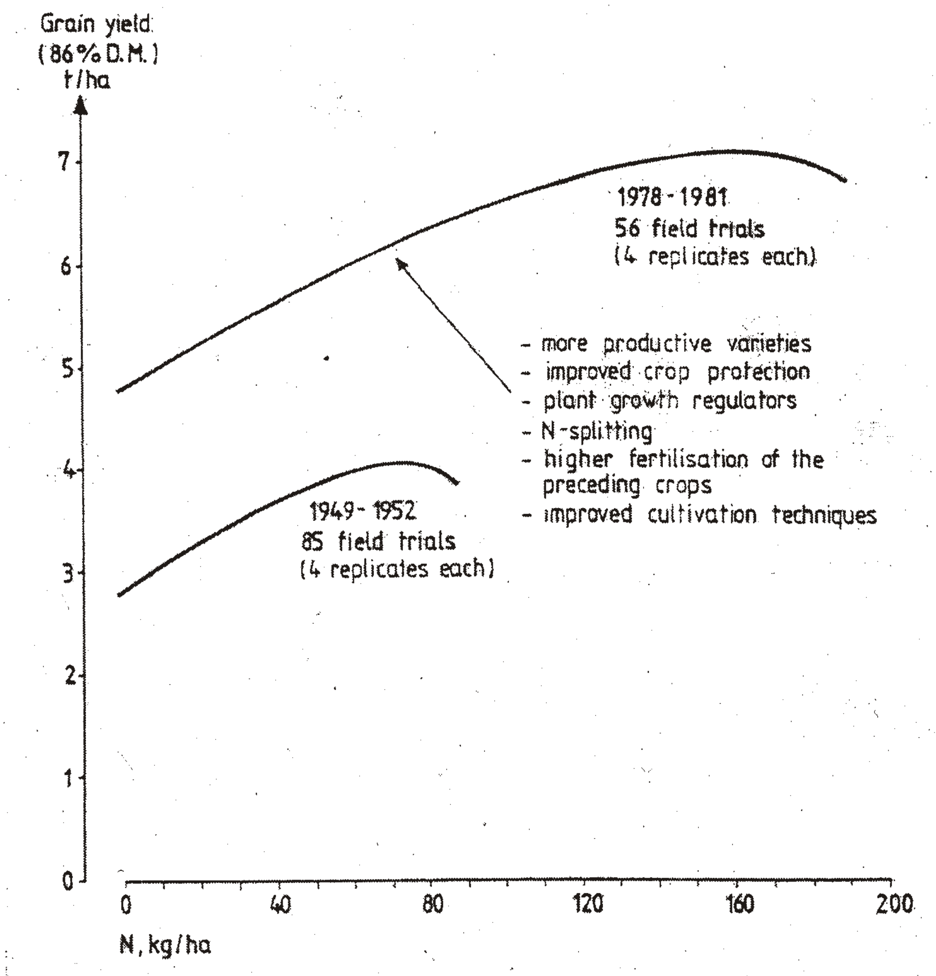
16. Yields of corn in bushels per acre

$Q_t = (((D_t/.454)/60)*.4$
$R_t = (((E_t/.454)/50)*.4$
$S_t = (((F_t/.454)/60)*.4$

These are the yields per acre of wheat, spring corn, and beans. Kilograms per pound is .454, and acres per hectare is .4. Wheat and beans are presumed to weight 60 pounds per bushel, while spring grain, here modeled on barley, is presumed to weight 50 pounds per bushel.

Figure 1

The Response of Wheat Yields to Nitrogen, German Data



Source: Becker and Aufhammer (1982, p. 53)

Figure 2

Decomposing the Change in Grain Yield

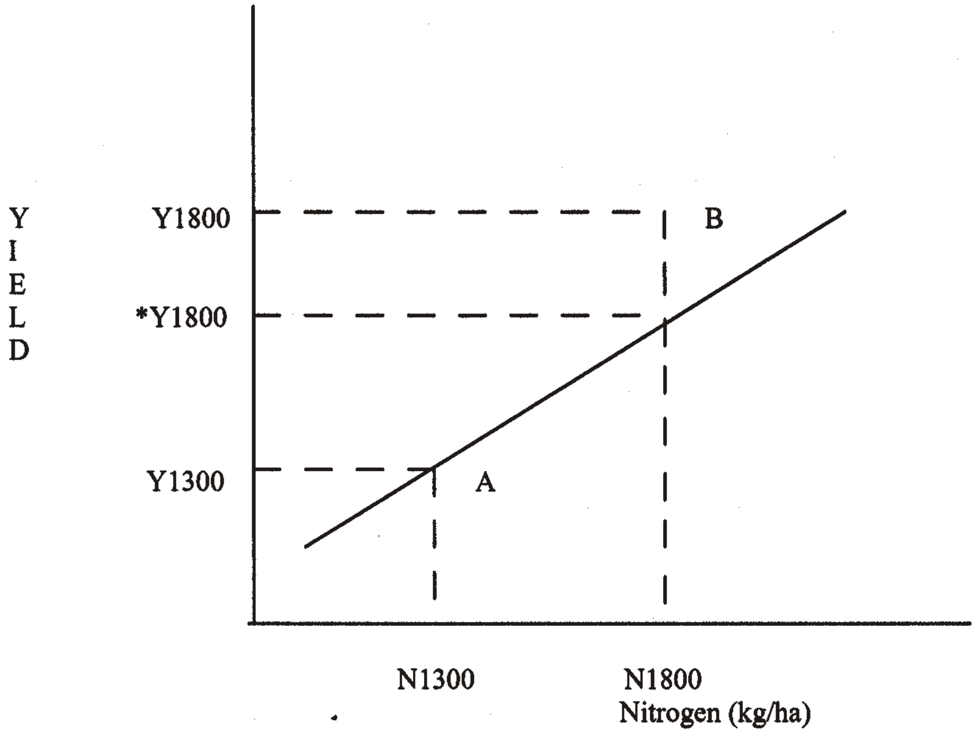


Figure 3

Simulated Stocks of Nitrogen (kg/ha)

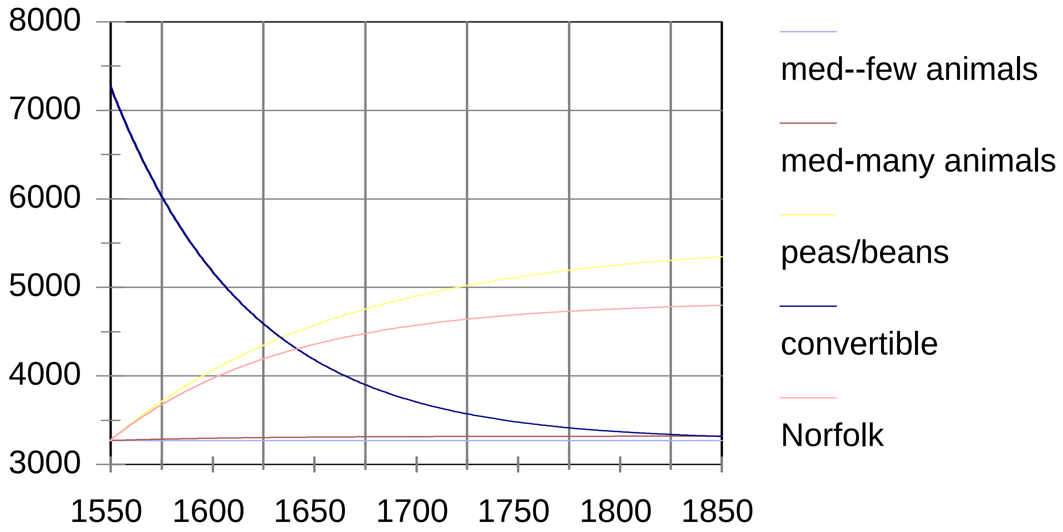


Figure 4

Simulated Yield of Wheat (bushels/acre)

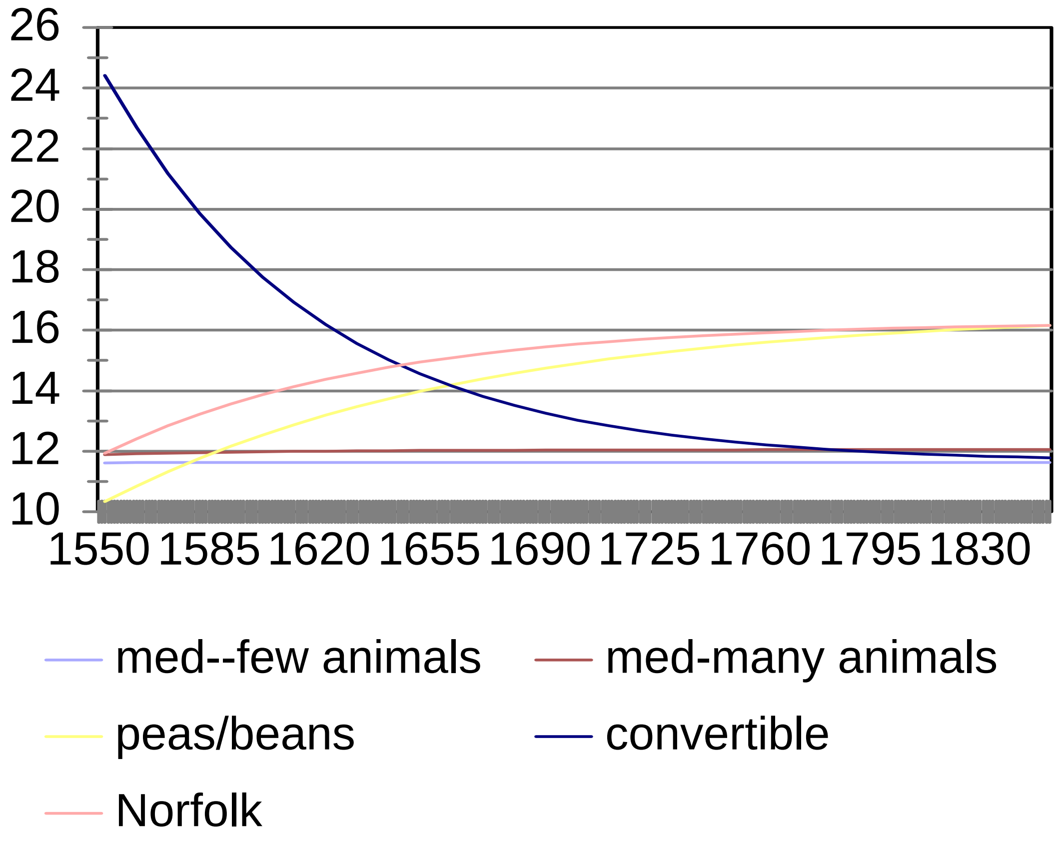
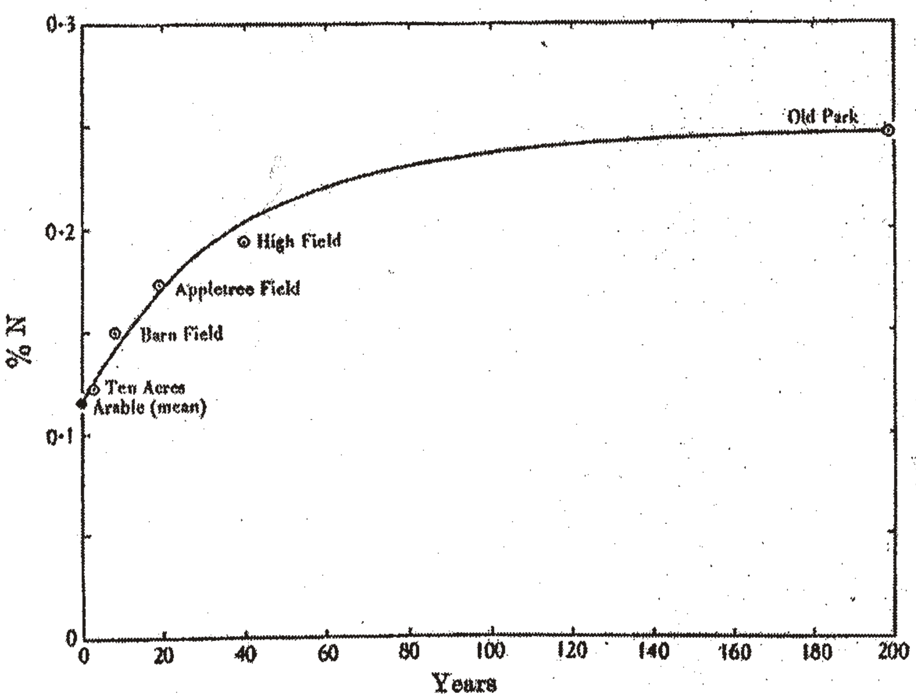


Figure 5

Nitrogen Stock (percentage) in Pastures



Source: Richardson (1938, p. 109)

References

Allen, Robert C. (1992). Enclosure and the Yeoman: The Agricultural Development of the South Midlands, 1450-1850, Oxford, Clarendon Press.

Allen, Robert C. (1994). "Agriculture during the Industrial Revolution," in R. Floud and D.N. McCloskey, eds., The Economic History of Britain since 1700, Vol. 1: 1700-1860, Cambridge, Cambridge University Press, 2nd edition.

Allison, F.E.(1973). Soil Organic Matter and Its Role in Crop Production, Amsterdam, Elsevier Scientific Publishing Company.

Becker, F.A. and Aufhammer, W. (1982). "Nitrogen Fertilisation and Methods of Predicting the N Requirements of Winter Wheat in the Federal Republic of Germany," Proceedings of the Fertiliser Society, No. 211, pp. 33-66.

Bland, Brian F. (1971). Crop Production: Cereals and Legumes, London, Academic Press.

Broad, J.F.P. (1980). "Alternate Husbandry and Permanent Pasture in the Midlands, 1650-1800," Agricultural History Review, Vol. 28, pp. 77-89.

Campbell, Bruce M.S. (2000). English Seigniorial Agriculture, 1250-1450, Cambridge, Cambridge University Press.

Chorley, P. (1981). "The Agricultural Revolution in Northern Europe, 1750-1880: Nitrogen, Legumes, and Crop Productivity," Economic History Review, 2nd series, Vol. XXXIV, pp. 71-93.

Clark, Greg (1992). "The Economics of Exhaustion, the Postan Thesis, and the Agricultural Revolution," Journal of Economic History, Vol. 52, pp. 81-84.

Cooke, G.W. (1967). The Control of Soil Fertility, London, Crosby Lockwood & Son.

Crush, J. R. (1987). "Nitrogen Fixation," in M.J. Baker and W.M. Williams, eds., White Clover, Wallingford, Oxon, C.A.B. International, pp. 185-201.

Farmer, D.L. (1977). "Grain Yields on Westminster Manors, 1270-1410," Canadian Journal of History, Vol. 18, pp. 331-47.

Foth, Henry D. (1984). Fundamentals of Soil Science, New York, John Wiley & Sons, seventh edition.

Fussell, G.E. (1966). The English Dairy Farmer, 1500-1900, London, Frank Cass & Co. Ltd.

Hall, Sir A.D. (1919). The Book of the Rothamsted Experiments, revised by E.J. Russell, London, John Murray, second edition.

Harris, W. (1987). “Population Dynamics and Competition,” in M.J. Baker and W.M. Williams, eds., White Clover, Wallingford, Oxon, C.A.B. International, pp. 203-97.

Havinden, M.A. (1961). "Agricultural Progress in Open Field Oxfordshire," Agricultural History Review, Vol. 9.

Hopkins, Cyril G. (1910). Soil Fertility and Permanent Agriculture, Boston, Ginn and Company.

Hoskins, W.G. (1950b). "The Leicestershire Farmer in the Sixteenth Century," in W.G. Hoskins, ed., Essays in Leicestershire History, Liverpool, pp. 123-183.

Hoskins, W.G. (1951). "The Leicestershire Farmer in the Seventeenth Century," in W.G. Hoskins, ed., Provincial England, London, Macmillan & Co Ltd, 1963, pp. 149-169.

Jenkinson, D.S. (1966). “The Turnover of Organic Matter in Soil,” in The Use of Isotopes in Soil Organic Matter Studies, Oxford, Pergamon Press, pp. 187-207.

Jenkinson, D.S. (1976). “The Nitrogen Economy of the Broadbalk Experiments: I. Nitrogen Balance in the Experiments,” Rothamsted Report for 1976, Part 2, pp. 103-9.

Jenkinson, D.S. Johnston, A.E. (1976). “Soil Organic Matter in the Hoosfield Continuous Barley Experiments,” Rothamsted Report for 1976, Part 2, pp. 87-101.

Kerridge, E. (1967). The Agricultural Revolution, London, Allen & Unwin.

Lawes, Sir John Bennet, and Gilbert, Sir J. Henry (1895). The Rothamsted Experiments, Edinburgh and London, William Blackwood and Sons.

Löhnis, F. (1926). “Nitrogen Availability of Green Manures,” Soil Science, Vol. 22, pp. 253-89.

Mingay, G.E. (1984). "The East Midlands," in Joan Thirsk, ed., The Agrarian History of England and Wales, 1640-1750: Regional Farming Systems, Vol. V, Part I, pp. 89-128.

Needham, P. (1982). “The Role of Nitrogen in Wheat Production: Response, Interaction and Prediction of Nitrogen Requirements in the UK,” Proceedings of the Fertiliser Society, No. 211, pp. 125-47.

Overton, Mark (1996). The Agricultural Revolution in England, Cambridge, Cambridge University Press.

Parkinson, R. (1808). A General View of the Agriculture of the County of Rutland, London.

Parkinson, R. (1811). A General View of the Agriculture of the County of Huntingdon, London.

Postan, M.M. (1972). The Medieval Economy and Society, Harmondsworth, Penguin Books

Ltd.

Richardson, H.L. (1938). "The Nitrogen Cycle in Grassland Soils: With Especial Reference to the Rothamsted Park Grass Experiment," Journal of Agricultural Science, Vol. 28, pp. 73-121.

Remy, J.C. and Viaux, I.T.C.F. (1982). "The Use of Nitrogen Fertilisers in Intensive Wheat Growing in France," Proceedings of the Fertiliser Society, No. 211, pp. 67-92.

Shiel, Robert S. (1991). "Improving Soil Productivity in the Pre-Fertilizer Era," in Bruce M.S. Campbell and Mark Overton, eds., Land, Labour, and Livestock: Historical Studies in European Agricultural Productivity, Manchester, Manchester University Press, pp. 51-77.

Stanford, George (1973). "Rationale for Optimum Nitrogen Fertilization in Corn Production," Journal of Environmental Quality, Vol. 2, pp. 159-66.

Tinker, P.B. and Widdowson, F.V. (1982). "Maximising Wheat Yields and Some Causes of Yield Variation," Proceedings of the Fertiliser Society, No. 211, pp. 149-84.

Wild, Alan (1998). Russell's Soil Conditions and Plant Growth, Harlow, Longman Scientific & Technical, eleventh edition.

Yelling, J.A. (1977). Common Field and Enclosure in England, 1450-1850, Hamden, Connecticut, Archon Books.

Young, Arthur (1770). The Farmer's Guide in Hiring and Stocking Farms, London, W. Strahan.