The Economics of Exhaustion, the Postan Thesis, and the Agricultural Revolution

GREGORY CLARK

The Postan thesis is that medieval agriculture had low yields because there was insufficient pasture to keep the arable land fertile. This argument (and variants of it) has become an orthodox technological explanation for low preindustrial yields. Yet the thesis, on its face, implies that early cultivators were ignorant, irrational, or completely custom bound. This article develops a revised Postan thesis, in which medieval cultivators knew that pasture restored fertility but were unwilling to employ it. Impatience made this way of increasing yields unattractive because it required large capital investments in the soil nitrogen stock.

Preindustrial Europe was impoverished and thinly populated, and it remained so for a surprisingly long time. As the major economic activity was producing food, the key to the growth of total income, and of income per capita, was increasing agricultural output. Medieval grain yields, for example, were astonishingly low. In many years the yield was only two or three grains for each grain planted. In southern England, in the years before the Black Death, I estimate that the net yield per acre from cultivated land was only equivalent to 4 bushels of wheat, compared with 13 circa 1850.1 The low yields per acre could sustain only a small population, even at the subsistence consumption standards of the preindustrial era.

THE ORTHODOXY

Many historians have theorized about why grain yields stayed low for so long and about what caused them to increase eventually. The most popular theory, the nitrogen theory, posits that the nitrogen input into


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1 Grain yields are translated into bushels of wheat by multiplying barley yields by 0.6 and oat yields by 0.4, their prices relative to wheat. See Clark, "Labour Productivity in English Agriculture," tables 8.2, 8.3.
the grain crops was too small.\textsuperscript{2} The idea is that preindustrial cultivators either did not understand the importance of nitrogen to soil fertility or did not know how to increase its supply.

The Postan thesis on the low grain yields of England before 1349 is based on essentially the same assumptions.\textsuperscript{3} M. M. Postan claimed that population pressure in the thirteenth century led to more and more pasture and woodland being converted into arable land, which reduced the flow of manure (and hence of nitrogen) to each acre of arable. Eric Kerridge's argument that the agricultural revolution occurred in the sixteenth century with the introduction of convertible husbandry (in which land is rotated for long periods between arable and pasture) is also premised on the nitrogen theory.\textsuperscript{4} Nitrogen is likewise the basis for G. P. H. Chorley's claim that it was mainly the introduction of clover that produced an agricultural revolution in the eighteenth century.\textsuperscript{5} Indeed, it does not do too much violence to the facts to state that the nitrogen theory is the conventional wisdom on the cause of the retardation of preindustrial agriculture. The various writers differ mainly in their interpretation of what was required to increase the supply of nitrogen to grain crops.\textsuperscript{6}

The scientific basis for the theory is the Rothamsted and Woburn farm experiments of the nineteenth century, which showed that during continual cultivation of grains nitrogen was the soil nutrient first exhausted. Nitrogen alone added to plots continually sown with grains increased wheat yields by over 7 bushels per acre and barley yields by over 16 bushels at Rothamsted.\textsuperscript{7} These increases were maintained for over 60 years. Land under continual wheat cultivation produced 20 bushels per acre annually as long as nitrogen alone was supplied, and land under barley produced 29 bushels per acre. Additions of a combination of all other major plant nutrients—phosphorus, potassium, magnesium, and sodium—without extra nitrogen increased per-acre yields of wheat at Rothamsted by only 2 bushels and yields of barley by only 7.\textsuperscript{8}

Nitrogen enters the soil from the atmosphere in three ways: (1) by direct deposition, (2) through fixing by free-living bacteria in the soil,
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Nitrogen Flows in Preindustrial Agriculture

Notes: $N$ is the nitrogen stock in the soil, $k$ is the release rate of that stock, and $h$ is the fraction released that is returned to the ground as manure. In the long run, losses of nitrogen must equal gains.

Source: See the text.

and (3) through fixing by symbiotic bacteria on the roots of certain plants. Thus farmers can boost their output by two methods. The first is to limit the nitrogen outflow from the system by returning as much plant material as possible to the soil in the form of manure, thus reducing the nitrogen input required from other sources per unit of output. The second method is to increase the nitrogen inflow by the use of nitrogen-fixing plants. Thus, lack of nitrogen was the most important limitation on yields in preindustrial agriculture (because it most immediately constrained grain yields), and its supply could be increased by growing the appropriate nitrogen-fixing crops.

The Rothamsted experiments suggest that under continual grain cultivation the inflows of nitrogen are about 35 pounds per acre from rainfall and nonsymbiotic fixation. Of that about half is recovered by the grain crop; the rest is lost to leaching or to the atmosphere. The Rothamsted experiments suggest that under continual grain cultivation the inflows of nitrogen are about 35 pounds per acre from rainfall and nonsymbiotic fixation. Of that about half is recovered by the grain crop; the rest is lost to leaching or to the atmosphere. Figure 1 illustrates the nitrogen cycle for preindustrial agriculture.

If the medieval arable was equivalent to Rothamsted soils, medieval cultivators using the traditional wheat-barley-fallow rotation but no

inputs of manure should have been able to achieve a gross yield of over 8 bushels of wheat equivalent per acre. In fact they were achieving a gross yield of only about 6 bushels, some three-quarters of what was possible.\textsuperscript{10} Presumably the shortfall resulted from less careful ground preparation, poorer seed, and more plant disease. But the nitrogen theory proponents would still argue that though the input of nitrogen per unit of output was larger in the preindustrial period, cultivators would have been able to increase yields further had they applied yet more nitrogen. Nitrogen alone should have been able to increase the annual yield of the arable from the 6 bushels achieved to as much as 14 bushels per acre.

How was the nitrogen supply to the arable to be increased? Both Chorley and Eric Jones assume that the only effective way was to introduce clover into the arable rotation.\textsuperscript{11} Clover fixes much more nitrogen than do other leguminous crops, such as beans and peas, found in traditional rotations; under modern conditions it will fix 150 pounds of nitrogen per acre. Assuming that medieval cultivators were able to produce 6 bushels of wheat equivalent per year on arable that was receiving an inflow of 35 pounds of nitrogen per acre, it took them nearly 6 pounds of nitrogen to produce a bushel of wheat. Thus each acre of clover would have fixed enough nitrogen for 25 bushels of wheat, if it could all have been recovered. For Chorley and Jones, therefore, the key component of the agricultural revolution was a technical innovation: the discovery of sown clover. If clover and turnips had replaced the fallow in the traditional rotation of grain-grain-fallow, the yield of the grain crops would have more than doubled.

But there is no reason to believe that clover was essential to improving yields. There are many ways to fix nitrogen, including not cultivating land for a period. Although clover is the most efficient nitrogen fixer, land under natural pasture will also fix large amounts of nitrogen. Because all plant growth depends on nitrogen, many plants have developed that colonize nitrogen-deficient soils, relying on their ability to supply their own nitrogen. Land converted to grass at Rothamsted annually gained about 98 pounds of nitrogen per acre in the topsoil in the first 25 years. This suggests that the nitrogen fixed in grassland is almost three times that fixed in arable.\textsuperscript{12} Pulses such as

\textsuperscript{10} For arable yields see Clark, "Labour Productivity in English Agriculture," p. 215, table 8.2.
\textsuperscript{11} Jones rejected the possibility of increasing fertility by the use of natural pastures. "Ley husbandry may improve soil texture but not soil fertility. since on balance the grazing beasts will take out what they put in." (Jones, "Agriculture and Economic Growth in England," pp. 4–5.) Chorley argued that the cultivation of leguminous crops was "the only variable in the supply side of the nitrogen economy subject to human manipulation at that time." (Chorley, "The Agricultural Revolution," p. 71.)
\textsuperscript{12} This was the nitrogen that accumulated in the top 9 inches of the soil. The same amount of nitrogen accumulated in the next 18 inches. See Wild, "Plant Nutrients," p. 656.
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TABLE 1
CROP NITROGEN-FIXING CAPACITY AND THE OPTIMAL SHARE OF GRAINS

<table>
<thead>
<tr>
<th>Crop</th>
<th>Nitrogen Fixed (lbs./acre)</th>
<th>Optimal Share of Grains (%)</th>
<th>Output per Acre (in bushels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arable</td>
<td>35</td>
<td>—</td>
<td>6.0</td>
</tr>
<tr>
<td>Clover</td>
<td>150</td>
<td>.65</td>
<td>16.2</td>
</tr>
<tr>
<td>Pasture</td>
<td>98</td>
<td>.55</td>
<td>15.0</td>
</tr>
<tr>
<td>Pulses</td>
<td>65</td>
<td>.44</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Notes: Various authors give widely different quotes for the amount of nitrogen fixed by clover. This table shows the average of the rates reported by Cowling, "Biological Nitrogen Fixation," which reflect modern conditions. Output per acre is measured in terms of the equivalent in bushels of wheat.


beans and peas fix less, perhaps 65 pounds of nitrogen per acre. Table 1 summarizes roughly the amount of nitrogen fixed by various land uses.

Even if clover was not available to medieval cultivators, growing peas or beans in the rotation or converting land periodically to grass or wilderness should also have fixed enough nitrogen to substantially increase grain yields. The effects of clover's introduction should have been seen not so much in an increase in the level of grain yields as in a reduction of the area needed for the nitrogen-fixing crop. Suppose, for example, that the maximum output of the grain, with ample nitrogen, were $Q^*$ bushels, but that the arable itself supplied nitrogen sufficient to produce only $I_A$ bushels of wheat. Then each acre of grain would need a supply of $(Q^* - I_A)$ bushels' equivalent of nitrogen from clover, pasture, pulses, or woodland. The more efficient the nitrogen-fixing crop were, the smaller would be the area needing to be devoted to it. But the level of grain yields would not be affected.

Whereas keeping land entirely in arable produced a yield in the medieval period equivalent to only 6 bushels of wheat per acre, an acre of pasture would have fixed enough nitrogen annually to produce about 17 bushels. Any loss of immediate grain yields from the land would have been more than repaid by the higher yields when land was converted back to arable.

One method that uses natural grass to fix nitrogen is switching land on long rotations between pasture and arable. This is the "convertible," "ley," or "up-and-down" husbandry emphasized by Kerridge as the

14 Bruce Campbell has demonstrated that medieval Norfolk estates had higher grain yields than did the rest of England, and that this was associated with the extensive incorporation of legumes into the arable rotation. See Campbell, "Agricultural Progress in Medieval England."
15 I assume that medieval fields had a nitrogen input per year from rainfall and nonsymbiotic fixation of 35 pounds, to produce a yield of 6.1 bushels of wheat equivalent. This implies that 5.7 pounds of nitrogen were required per bushel of wheat.
source of an agricultural revolution beginning in the late sixteenth century. If land long arable is not plowed, it takes some time for natural pasture to establish itself. Yet grass will eventually cover the field, and included in it would be a large percentage of nitrogen-fixing plants, especially if the land were nitrogen deficient.

To see how powerful a boost more pasture would give to output per acre, let us suppose that under medieval conditions the arable sown in grain was capable, if it received enough nitrogen, of producing an annual output of 20 bushels of wheat equivalent per acre. This implies that an additional supply of 82 pounds of nitrogen, enough for 14 bushels of wheat, would be needed for each acre. In general, suppose $I_P$ were the amount of nitrogen (measured in terms of the number of bushels of wheat that nitrogen can produce) fixed each year by the nitrogen-fixing land use. Suppose all of that nitrogen could be transferred without loss to grain production. Then the fraction of land kept in grain, $\alpha$, that maximized total output would be

$$\alpha \cdot (Q^* - I_A) = (1 - \alpha) \cdot I_P$$

$$\Rightarrow \quad \alpha = \frac{I_P}{(Q^* - I_A + I_P)}$$

With clover it would be 65 percent of the land, with natural pasture only 55 percent. Suppose that land kept in pasture, pulses, or clover produced an animal output of value equivalent to 9 bushels of wheat per acre. Then gross output per acre in bushels of wheat equivalent would be

$$\alpha \times 20 + (1 - \alpha) \times 9 = 9 + \alpha \times 11$$

Thus the introduction of clover would allow output to grow to 16 bushels per acre, whereas the use of natural pasture through either the transfer of manure or convertible husbandry would allow an output of 15.0, compared with the actual medieval gross outputs of about 6. Natural pasture, then, would seem to be able to do nearly as much for output per acre as clover. Table 1 illustrates the yields obtainable with each nitrogen-fixing crop.

In practice, transferring the nitrogen from permanent pasture to arable as manure is not very effective. If hay is constantly removed from pasture and supplied to the arable as manure, the pasture will be drained

17 Such land may not produce any natural grass for two years (Large, "Rural Society and Agricultural Change," p. 132). On clay soils it took between one and ten years to establish "acceptable grazing turf" in the 1860s, even though the grass was by then seeded. See Sturgess, "The Agricultural Revolution," p. 112.
18 Pastureland with the lowest inputs of nitrogen developed a cover with the largest percentage of leguminous plants that fix nitrogen. See Hall, The Book of the Rothamsted Experiments, p. 155.
19 As we shall see, this supposition is too optimistic.
of nutrients other than nitrogen: nutrients not required by the grain crops but whose absence limits the growth of grasses. Grassland continually cut at Rothamsted with no manure inputs eventually produced only 0.95 tons per acre, compared with 2.55 tons on land receiving mineral dressings only. On the other hand, rotating land between the two uses both allows the soil nitrogen reserves of the pasture to be used by the grains and other soil nutrients to be used by grass as well as grains. To get the benefit of the nitrogen that pasture fixed in the soil, land had to be switched from one use to the other on a shorter or longer rotation.

THE PROBLEMS OF ORTHODOXY

We have seen that if nitrogen were the constraint on output in medieval agriculture, then cultivators could have released that constraint simply by putting land on long rotations between pasture and arable. Why then was most of the land sown in grain in medieval England, if pasture or even wilderness was potentially so productive? All that was required was a changed allocation of land to different uses to greatly increase yields. Why should farmers have been locked into sowing too much grain if the nitrogen theory is correct?

The Postan thesis holds that population pressure led to increased demand for food grain production and less demand for animal products that are consumed more at higher income levels. The concentration on grains eliminated most of the nitrogen-fixing pasture, thus eventually driving down grain yields. The Postan thesis faces a number of conceptual and empirical problems, however, that make it untenable as a theory of agricultural backwardness. Grain yields did not increase much if at all after the onset of the Black Death in 1349 reduced population pressure. Nor is there any sign of declining yields in the period from 1200 to 1349, as population pressure increased.

This might lead us to believe that the nitrogen-input problem in the medieval period was due not so much to population pressure as to simple ignorance of the benefits of manure generated by pastureland. But medieval cultivators clearly knew the value of manure; for instance, rental agreements would sometimes stipulate that straw was not to be sold from arable land. We can also, without looking too hard, find plenty of evidence of the practice of shifting land between grain and pasture on long rotations. As early as the late thirteenth century arable land was temporarily converted to pasture in such areas as the Weald of Kent and the Breckland of East Anglia. Even in the classical open-field villages

there is evidence of the at least occasional use of such long rotations. In 1310 on the Winchester manor of Rimpton, for example, all the headlands, paths, and other uncultivated parcels of the demesne lying within the open arable fields were converted into plowland, and new headlands and paths seem to have been created out of previously plowed land. The same process seems to have occurred in the late thirteenth century: some plots in the open fields appear from name evidence to have cycled from pasture in the 1260s to arable in the 1280s and back to pasture in 1310. Postan gave an example of 33 acres of arable in a manor in Wiltshire being converted to ox pasture in the early fourteenth century before being plowed again in 1312 or 1314. Dyer found evidence of convertible husbandry in open-field villages in Warwickshire from the late fourteenth century. By the fifteenth century the practice was common enough to be regulated in village by-laws. By the sixteenth century convertible husbandry seems to have become standard practice even in common-field villages. The use of individual strips as pasture was easily accommodated within open-field agriculture. All the cultivator had to do was not sow the plot. It would still be

cites evidence of the use of convertible husbandry in the thirteenth century in Norfolk and in the fourteenth century in Sussex.

23 Ibid., p. 118.

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**Table 2**

WILTSHIRE INQUISITIONS POST MORTEM ANNUAL LAND VALUES (IN PENCE)

<table>
<thead>
<tr>
<th>Period</th>
<th>Arable</th>
<th>Meadow</th>
<th>Pasture</th>
<th>Woodland</th>
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</thead>
<tbody>
<tr>
<td>1240–1299</td>
<td>4.51</td>
<td>18.4</td>
<td>6.5</td>
<td>4.42</td>
</tr>
<tr>
<td></td>
<td>(0.17)</td>
<td>(0.72)</td>
<td>(1.51)</td>
<td>(0.76)</td>
</tr>
<tr>
<td>1300–1349</td>
<td>3.61</td>
<td>20.7</td>
<td>4.90</td>
<td>4.32</td>
</tr>
<tr>
<td></td>
<td>(0.13)</td>
<td>(0.55)</td>
<td>(0.44)</td>
<td>(0.51)</td>
</tr>
<tr>
<td>1350–1375</td>
<td>2.29</td>
<td>17.2</td>
<td>4.36</td>
<td>2.96</td>
</tr>
<tr>
<td></td>
<td>(0.12)</td>
<td>(0.98)</td>
<td>(0.84)</td>
<td>(0.77)</td>
</tr>
</tbody>
</table>

*Notes:* The numbers in parentheses are the standard errors of the estimates. The annual values given in the Inquisitions appear to be the estimated value of the land if rented. It is clear from the text that the difference between pasture and meadow is that meadow is any pasture growing strongly enough to be mowed. Typically the arable land was common, so fallow grazing is not included in the valuation. But where fallow grazing was valued in Wiltshire, in almost all cases the value was a penny per acre. This would imply that we would have to add about 0.4 penny per acre to the average value of the arable to get the value of grazing in the fallow years. The pasture and woodland values are for such land as was not held in common.

*Sources:* Fry, Wiltshire Inquisitiones Post Mortem; and Stokes, Wiltshire Inquisitiones Post Mortem.
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<table>
<thead>
<tr>
<th>County</th>
<th>Arable</th>
<th>Meadow</th>
<th>Pasture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedford</td>
<td>4.34</td>
<td>23.46</td>
<td>8.34</td>
</tr>
<tr>
<td></td>
<td>(64)</td>
<td>(56)</td>
<td>(41)</td>
</tr>
<tr>
<td>Buckingham</td>
<td>4.53</td>
<td>21.73</td>
<td>8.69</td>
</tr>
<tr>
<td></td>
<td>(116)</td>
<td>(97)</td>
<td>(42)</td>
</tr>
<tr>
<td>Hertfordshire</td>
<td>3.50</td>
<td>21.68</td>
<td>8.29</td>
</tr>
<tr>
<td></td>
<td>(81)</td>
<td>(57)</td>
<td>(47)</td>
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<tr>
<td>Huntington</td>
<td>3.93</td>
<td>23.64</td>
<td>9.14</td>
</tr>
<tr>
<td></td>
<td>(29)</td>
<td>(22)</td>
<td>(7)</td>
</tr>
<tr>
<td>Leicester</td>
<td>4.86</td>
<td>19.45</td>
<td>11.61</td>
</tr>
<tr>
<td></td>
<td>(68)</td>
<td>(55)</td>
<td>(9)</td>
</tr>
<tr>
<td>Northampton</td>
<td>5.04</td>
<td>22.55</td>
<td>9.20</td>
</tr>
<tr>
<td></td>
<td>(137)</td>
<td>(96)</td>
<td>(23)</td>
</tr>
<tr>
<td>Nottingham</td>
<td>4.46</td>
<td>20.64</td>
<td>11.12</td>
</tr>
<tr>
<td></td>
<td>(26)</td>
<td>(25)</td>
<td>(8)</td>
</tr>
<tr>
<td>Rutland</td>
<td>5.67</td>
<td>25.12</td>
<td>10.71</td>
</tr>
<tr>
<td></td>
<td>(18)</td>
<td>(17)</td>
<td>(7)</td>
</tr>
</tbody>
</table>

Notes: The figures in parentheses are the number of observations. Fallow grazing on the arable is explicitly valued in only four cases, in which the average value is 1.75 pence, so that 0.7 penny should be added to the arable values for those excluded benefits.


used for common grazing along with the sown land after the harvest, so that other cultivators would not lose from the conversion.  

Thus medieval cultivators must have been aware of the fertility-restoring power of pasture. We cannot, then, explain low yields in preindustrial England on the basis of ignorance. If the standard interpretation of the agricultural revolution in Britain stressing the roles of clover and nitrogen is correct, then the revolution should have occurred long before the introduction of clover, through the mechanism of convertible husbandry.

That it did not becomes even more puzzling when we look at the rental value of different types of land in the Middle Ages. Table 2 shows the annual values for the subperiods 1240–1299, 1300–1349, and 1350–1375, imputed by the Inquisitions Post Mortem to land of different types in Wiltshire.  

Table 3 shows valuations for a variety of midlands

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26 See Thirsk, *English Peasant Farming*, pp. 100–101. It may, however, have been difficult for the owners of such land to graze those pastures without damage to their neighbors, unless they also fenced them.

27 The Inquisition Post Mortem was an assessment of the value of property held by the king as tenant-in-chief when the occupier died. Because the assessed values are so low, it is not clear whether they are the market rental value of the land. But Campbell, in "Arable Productivity in Medieval English Agriculture," and Raftis, in *Assart Data and Land Values*, show that there is a good correlation between the assessed value of the arable and the fertility of the land, or the yield;
counties between 1297 and 1326, according to J. A. Raftis. As both tables show, the assessed value of the land left as pasture or as woods was higher than that of the arable, even though pastureland would often be land too hilly or too poor for use as arable. Yet about 80 percent of cultivated land in the south of England was arable in the years before the Black Death. Why wasn’t arable being converted into the much more valued pasture? Why, indeed, had most of the woodland in England been converted to arable when there was no apparent economic gain to be had from doing so? A viable theory of low medieval yields must answer these questions.

A second problem with the nitrogen orthodoxy is that there is good evidence that substantial grain yield increases were achieved before the widespread use of sown clover in arable rotations. Clover seems to have been used on a substantial fraction of arable land only in the late eighteenth century, yet yields increased substantially before 1750. Direct information on when exactly yields began to rise in England is thin. But Mark Overton has pioneered a method of measuring yields indirectly, using probate inventories. Probate inventory studies have now examined the movement of grain yields in Norfolk, Suffolk, Lincoln, Hertford, Hampshire, and Oxford from the late sixteenth to the early eighteenth century. These studies generally support the idea that significant increases in yields occurred in England in the seventeenth century, well before the area in sown clover was sufficient to account for any yield increases. Indeed, Overton’s study of Norfolk and Suffolk, one of the areas where clover is believed to have first been employed, shows that before 1735 clover was not a substantial part of arable cultivation.

Elsewhere I have tried to estimate grain and meadow yields in England from 1300 to 1850 by using the amount of time it took to harvest an acre of wheat—which depended in part on the yield. How much time was required can be deduced from the relationship between piece rates for harvesting and day rates. For 1250 to 1860 these calculations show a clear upward movement in implied wheat yields in the seventeenth century; most of the yield increase occurred before 1770.

If the nitrogen theory is correct, cultivators must have achieved these earlier yield increases using pasture or pulses to fix nitrogen. But in that case, why didn’t those developments occur even earlier?

The valuations can therefore be expected to be consistently related to the market value of the different land types.

30 Overton, "The Diffusion of Agricultural Innovations."
31 Clark, "Yields per Acre in English Agriculture."
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TABLE 4
ROTHAMSTED BARLEY YIELDS AFTER MANURING TEMPORARILY
(IN BUSHELS PER ACRE)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1852–1861</td>
<td>22.4</td>
<td>30.5</td>
<td>45.0</td>
<td>--</td>
</tr>
<tr>
<td>1862–1871</td>
<td>17.5</td>
<td>24.4</td>
<td>51.5</td>
<td>--</td>
</tr>
<tr>
<td>1872–1881</td>
<td>14.1</td>
<td>18.2</td>
<td>35.1</td>
<td>16.9</td>
</tr>
<tr>
<td>1882–1891</td>
<td>13.7</td>
<td>18.3</td>
<td>28.6</td>
<td>10.3</td>
</tr>
<tr>
<td>1892–1901</td>
<td>11.6</td>
<td>14.9</td>
<td>23.6</td>
<td>8.7</td>
</tr>
<tr>
<td>1902–1911</td>
<td>10.8</td>
<td>18.5</td>
<td>21.3</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Notes: The residual gains are calculated as the third column minus the second (to control for the presence of minerals in the manure). All the yields after 1871 have been adjusted proportionately to remove variations in yields created by weather conditions.

Source: Hall, The Book of the Rothamsted Experiments, p. 73.

A REVISED POSTAN THESIS: NITROGEN AS CAPITAL

The preceding discussion has established that, if we accept the central role of nitrogen in preindustrial soil fertility, at least as early as 1300 cultivators must have been aware of techniques that, if applied, would have increased output per acre in the long run to the levels of 1850. If the barrier to high grain yields in medieval England was not ignorance, it must have been the incentives facing the cultivators, or the institutions that bound them.

One economically relevant feature of the nitrogen fixed by biological means is that it is bound in organic compounds and is not immediately available to plants. These compounds gradually decompose in the soil to release the nitrogen in a form utilizable by plants. The slowness of this process was demonstrated in the Rothamsted and Woburn experiments of the nineteenth century.

In the Hoos field at Rothamsted, one of two plots planted with barley received no manure after 1852; the other received 14 tons of farmyard manure (containing 200 pounds of nitrogen) per acre in each year between 1852 and 1871. If the manure's effects were immediate, yields on the second plot should have dropped immediately to the level of the continually unmanured plot in 1872, when manure was withdrawn. Instead there was a slow decline in yields toward that of the unmanured plot, as is shown in Table 4. Indeed, in 1946 the plot that had received the manure for 20 years still gave a higher yield and had more nitrogen in the soil. This implies that some of the nitrogen in the manure was still not released more than 75 years after being applied to the soil.32 Some

32 Cooke, The Control of Soil Fertility, p. 198. The plot manured from 1852 to 1871 still had more organic material in the soil in 1976, more than 100 years later, than did the never-manured plot (Jenkinson and Rayner, "The Turnover of Soil Organic Matter," p. 299).
of the nitrogen compounds in the manure are more stable than others. Of the 4,000 pounds of nitrogen added to the field between 1852 and 1871, slightly more than half had been released by 1882, when 1,800 pounds remained in the soil. Over the next 64 years (1882 to 1946) a further 740 pounds were released, leaving a soil residue of 1,060 pounds of nitrogen in 1946. In that period the nitrogen was being released at the rate of 10 pounds per year, a release rate of less than 1 percent. Almost half of the nitrogen added was in compounds of this very stable form.

At Woburn, in both the wheat and barley fields, we can compare yields in two plots. One received only mineral compounds continually for 30 years, from 1877 to 1906. The other received 200 pounds of nitrogen in manure for 5 years, and for the next 25 years no manure at all. Table 5 shows the average differences in yields between those plots for five-year intervals. The effects of the organic nitrogen on yields are very clear 25 years after its application. Because the comparison plot received a complete mineral manure throughout, the difference must have been the result of the nitrogen alone. The total nitrogen added in the five years of manure application was enough to produce 315 bushels of wheat.\textsuperscript{33} By 1906, only 150 extra bushels had been produced on the manured plot, suggesting that only 48 percent of the nitrogen had been recovered 25 years after the last application. In the barley plots, similarly, only 57 percent of the nitrogen had been recovered by 1906.

In the wheat field at Rothamsted one plot received no manure of any kind after 1843, whereas another received 14 tons of farmyard manure

\textsuperscript{33} On the plots at Woburn receiving nitrogen in the form of nitrate of soda, it took 2.7 pounds of nitrogen to produce an extra bushel of wheat.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{Period} & \textbf{Mineral Alone} & \textbf{Organic Nitrogen} & \textbf{Residual Gains from Initial Nitrogen Application} & \textbf{Mineral Alone} & \textbf{Organic Nitrogen} & \textbf{Residual Gains from Initial Nitrogen Application} \\
\hline
1877–1881 & 17.2 & 22.9 & — & 22.0 & 35.7 & — \\
1882–1886 & 18.3 & 19.6 & 1.3 & 24.6 & 37.6 & 13.0 \\
1887–1891 & 14.7 & 20.1 & 5.4 & 23.0 & 32.9 & 9.9 \\
1892–1896 & 10.6 & 16.3 & 5.7 & 20.4 & 28.1 & 7.7 \\
1897–1901 & 8.0 & 13.8 & 5.8 & 16.1 & 20.9 & 4.8 \\
1902–1906 & 8.4 & 14.5 & 6.1 & 16.3 & 23.1 & 6.8 \\
\hline
\end{tabular}
\caption{Woburn Grain Yields After Manuring for Five Years (in Bushels per Acre)}
\end{table}

Notes: Between 1877 and 1881 one plot each of wheat and barley received 200 pounds of nitrogen per acre in farmyard manure each year, after which they received no further manure. By mistake, the barley plot received manure in 1888. All the yields have been adjusted proportionately to remove variations created by weather conditions.

Sources: Voelcker, "The Woburn Experimental Farm—III"; and Voelcker, "The Woburn Experimental Station—Field Experiments."
per acre annually, enough extra nitrogen to increase yields per acre by 46 bushels a year, if nitrogen were the limiting factor. If the nitrogen in the manure had been immediately available for plant use, the difference in yields between the two plots should have changed immediately to a new stable level. The actual difference, however, did not attain a constant level until about 20 years later.

Another feature that demonstrates the slow release of biologically fixed nitrogen is the large stock of nitrogen that accumulates in the soil of pastureland as well as of arable receiving organic manure. Over the course of 100 years, the plots in the Rothamsted wheat field receiving 200 pounds of nitrogen in organic manure per acre each year accumulated an equilibrium excess of 3,600 pounds of nitrogen compared with the unmanured arable. If a fraction $k$ of the stock of organic nitrogen in the soil were released every year, the increased stock of nitrogen in the ground $N$ from adding an additional amount $I$ each year would be such that, in the long run,

\[
\frac{dN}{dt} = 0 = I - kN
\]

\[\Rightarrow \quad I = k \cdot N \]

\[\Rightarrow \quad k = \frac{I}{N} = \frac{200}{3600} = .056 \]

If the release rate $k$ were close to 1, we would find little nitrogen accumulation in the manured plots. The large accumulations found suggest a low release rate—a little above 5 percent.

Soil left as wilderness or pasture accumulated about the same excess: 3,600 pounds more nitrogen per acre than unmanured arable. The extra input compared to unmanured arable in this case is only about 45 to 98 pounds of nitrogen per year. Thus the nitrogen fixed directly in the soil by pasture or wilderness has an even slower average release rate than the nitrogen compounds in farmyard manure: 1.25 to 2.7 percent. Organic material eaten by animals has a faster decay rate, because of the action of their digestive systems. Part of the function of animals in agriculture is, in fact, to reduce the nitrogen capital that needs to be held by increasing the flow rates of nitrogen in the system.

The extra accumulations of nitrogen in the manured and pasture soils, converted into grain at the medieval conversion rate, would produce about 600 bushels of wheat per acre before the nitrogen stock were reduced to that of unmanured arable. Thus uncultivated land or pastureland builds up large reserves of fertility that can be tapped over the years if the land is brought into arable cultivation. Permanent pasture at

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Rothamsted converted into arable released enough nitrogen for the first six years to produce wheat crops at modern yield levels without any additions of nitrogen.35

The Rothamsted experiments on rotations demonstrated that even some of the nitrogen residues left in the ground by clover crops were released slowly. This is clear from the records of two plots, on one of which the rotation was roots-barley-fallow-wheat and on the other, roots-barley-beans or clover-wheat. In each case the only input was a mineral manure for the roots, all the crops being removed. For technical reasons, clover could only be grown in some years in the rotation. In the early years beans were grown in the rotation in 1855, 1859, 1863, 1867, and 1871. The wheat crop following the fallow was on the average 3.8 bushels larger than that following beans. Clover crops were grown in 1875, 1883, and 1887. The wheat crops grown after the early clover crops still yielded 0.7 bushel less than the wheat crops following the fallow. It is clear that the clover nitrogen residues in the soil produced no short-term boost in the wheat yields. But by 1907 and 1911, wheat crops following clover yielded 12 bushels more than those following fallow. These observations confirm that much of the nitrogen fixed by clover did not become available till years later.36

To this point I have assumed that the organic nitrogen formed in the soil or found in manure has a constant release rate. But there are at least two problems with this assumption. First, it is clear from the various Rothamsted and Woburn experiments that elements of the organic nitrogen formed by nitrogen-fixing crops have different release rates. In some experiments in the Hoos field in 1930 to 1954, for example, manure was applied in different years of a four-course rotation. Wheat grown immediately after the application of 186 pounds of nitrogen in farmyard manure produced about 10 bushels per acre more than wheat grown four years after the application. But at the response rate to nitrogen found in the comparison plot, this implied that about 15 percent of the nitrogen in the manure was released in the first year and 5 percent in the second.37 Thus, assuming all the nitrogen has one constant release rate $k$ will underestimate the effect of manure on yields in the first few years and overestimate the effect in later years. But if we assume a decay rate of 5 percent for nitrogen in manure and 3 percent for nitrogen in the soil, we will not be too far wrong.

A second complication is that the Rothamsted evidence suggests that the release rate of organic nitrogen is faster when there is more organic matter in the soil.38 This implies, interestingly, that if the nitrogen

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35 Cooke, The Control of Soil Fertility, p. 213.
38 Thus, in the Hoos field, about half of the organic manure nitrogen applied temporarily seemed...
stocks were depleted by long arable cultivation then adding organic nitrogen would initially produce little yield increase; if there were already a lot of organic nitrogen in the ground, further additions would be recycled into yields much more quickly. A decay rate of $k$ implies that if a unit of manure were added to the ground this year the amount released in subsequent years would be $k, k \cdot (1 - k), k \cdot (1 - k)^2, k \cdot (1 - k)^3,$ and so on. But there is an indirect effect as well, because some of the nitrogen in the crops produced each year is recycled within the farm as manure. The straw and some of the grain crops were fed to farm animals, and even some of the produce sold off the farm would return to the agricultural sector in the form of town waste. If a fraction $h$ of the nitrogen applied in manure were recovered by the farm sector, then the release rate for nitrogen added to the system would be $(1 - h) \cdot k,$ though $h$ would typically be small in traditional arable agriculture. Thus, though I use 5 percent as the release rate of organic nitrogen in the following sections, the recycling of organic material on the farm means that the overall release rate would be even lower.

**THE ECONOMICS OF THE NITROGEN CAPITAL**

From at least the seventeenth century, farm leases in England often limited the amount of grassland tenants could plow for arable cultivation; alternatively, leases would stipulate extra rent for each acre of grass plowed and sown. Similarly, farm leases in Scotland in the eighteenth century often limited the amount of outfield tenants could plow, generally confining them to a third or less. Clearly landlords did this because pasture plowed and made arable would initially generate increased profits, but yields would then decline until the land was worth less than pasture. Otherwise there would be no reason for constraining tenants. Tenants have a high rate of time discount: they do not care about benefits accruing after the end of the tenancy, so must be restrained from seeking short-run profits. What I want to argue in parallel with this is that the whole of medieval society had a high rate of discount of future benefits, which led it to plow up permanently almost all the grassland and to sacrifice future yields for current output.
There is no doubting the high medieval rate of discount. Whether we look at the rate of return on holding land or on financial instruments like rent charges or at the rate of price increase of grain in storage, it is clear that medieval rates of return were much higher than modern rates. There is no doubting the high medieval rate of discount. Whether we look at the rate of return on holding land or on financial instruments like rent charges or at the rate of price increase of grain in storage, it is clear that medieval rates of return were much higher than modern rates. Table 6 shows the rates of return on holding land and on rent charges from before 1351 to 1800. Relatively risk-free rates of return in England prior to the Black Death seem to have hovered around 10.5 percent. This fell by 1400 to between 5 and 6 percent, at which level it remained till about 1650. Then there was a further fall to about 4 percent by 1750. A rate of return above 10 percent implies that a benefit received 10 years from now is worth only one-third of one received now, and a benefit 20 years in the future is worth one-seventh of a current benefit.

Why should a high rate of return lead to low yields and explain why land was kept in grains when the rental value of pasture or woodland was higher? If medieval cultivators, like farmers approaching the end of their leases, did not care much about future yields, they would plow up all the grassland to maximize short-run yields. Only those who valued future yields highly would find nitrogen-fixing crops attractive. An agricultural writer in 1808, comparing various possible farm rotations, noted of the one with the most pasture in it that "this course is believed to be very proper for improving an exhausted soil, but neither this nor any other mode of improvement, seems calculated to afford immediate profit, . . . ."

---

**Table 6**

<table>
<thead>
<tr>
<th>Period</th>
<th>Rent Charges (%)</th>
<th>Land or Houses (%)</th>
<th>No.</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-1351</td>
<td>10.6</td>
<td>10.5</td>
<td>146</td>
<td>10</td>
</tr>
<tr>
<td>1351-1400</td>
<td>4.5</td>
<td>9.4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1401-1450</td>
<td>n.a.</td>
<td>5.6</td>
<td>n.a.</td>
<td>17</td>
</tr>
<tr>
<td>1451-1500</td>
<td>4.0</td>
<td>5.0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1501-1550</td>
<td>4.6</td>
<td>7.2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>1551-1600</td>
<td>6.0</td>
<td>5.5</td>
<td>21</td>
<td>6</td>
</tr>
<tr>
<td>1601-1650</td>
<td>6.0</td>
<td>5.4</td>
<td>42</td>
<td>25</td>
</tr>
<tr>
<td>1651-1700</td>
<td>5.3</td>
<td>5.4</td>
<td>65</td>
<td>64</td>
</tr>
<tr>
<td>1701-1750</td>
<td>4.3</td>
<td>4.3</td>
<td>49</td>
<td>126</td>
</tr>
<tr>
<td>1751-1800</td>
<td>4.0</td>
<td>3.6</td>
<td>29</td>
<td>91</td>
</tr>
</tbody>
</table>

*Source: Clark, "The Cost of Capital," table 3 (the pre-1351 observations have been treated slightly differently than in the source).*

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42 The evidence on rates of return for holding land or rent charges is presented in Clark, "The Cost of Capital." The rate of return on storing grain is given in McCloskey and Nash, "Corn at Interest."

43 Batchelor, *General View of the Agriculture of the County of Bedford*, p. 146.
Consider, for example, land permanently divided between arable and pasture. Suppose a piece of land had a nitrogen stock of $N$, so that there were a flow of nitrogen $kN$ available for plant growth. Let the value of output from the land in arable use be $kN$, proportional to the yield.\footnote{This means that we are measuring nitrogen in terms of the amount needed to produce one unit of grain.} Suppose also that the value of the current output from the land in pasture uses were $p \cdot kN$, where $p$ is the price of pasture output relative to arable output. A detailed estimate by Thomas Batchelor in 1808 suggests that in the same rotation the net value of each acre of sown grass was only 47 percent of that of each acre in grain crops. Then $p$ would be about 0.5.\footnote{Batchelor, General View of the Agriculture of the County of Bedford, pp. 84–85, 117–41.} That is, land with a given stock of nitrogen would have less immediate value as pasture than as arable. Suppose, based on the first column of Table 1, that the input of nitrogen in the pasture were enough to produce 18 bushels of wheat annually. If it were used to produce grass, it would have a lower value, equivalent to 9 bushels of wheat per year. If it were converted to arable, the immediate output would be 18 bushels per year. There is an immediate gain from the conversion. But the nitrogen stock declines, because the input through...
rainfall and nonsymbiotic fixation alone on the arable is only 6 bushels' worth of nitrogen per acre. Eventually yields fall to 6 bushels per acre. Figure 2 shows the maximum sustainable output per acre in the long run, compared with the output when the land is converted to arable.

Clearly, some rate of interest by which future yields are discounted would make it worthwhile to switch all pasture to arable. Were medieval cultivators plowing up pasture simply because they faced high interest rates? Suppose they were able to sow grasses, so they could have one grass crop in the arable rotation. When would it be profitable to sow such a crop? The value of the land with a grain crop would be

\[ V_A = kN_A = I_A \]

The value with a pasture crop would be

\[ V_P = p \cdot kN_A + pN \cdot (I_P - kN_A) \]
\[ = p \cdot I_A + pN \cdot (I_P - I_A) \]

The value of the nitrogen fixed, \( pN \), is shown in the Appendix to be

\[ \frac{k}{(r + k)} \]

for land used as arable. Its value depends on the rate of return, as it only becomes available over time to successive arable crops. This implies that the grass crop would be profitable only if

\[ r < k \cdot \left\{ (I_P - I_A) / [(1 - p) \cdot I_A] - 1 \right\} \]

If \( I_P \) equaled 18, \( I_A \) equaled 6, and \( p \) equaled 0.5, for example, the cultivator should not sow grasses if \( r \) were greater than 3\( k \). As I have argued that \( k \) is roughly 5 percent, this implies that constant arable would be optimal if the rate of return were above 15 percent.\(^46\) Medieval rates of return were not this high, but in the medieval period the pasture break would have to be much longer than one year, because it took perhaps two years to establish grasses on old arable. Thus there was a high fixed cost of using pasture, which would make it profitable only if the break were continued for an extended period. Such a fixed cost of switching land to pasture would make it unprofitable to rejuvenate old arable with a pasture break when interest rates approached 7 percent. As the rate of interest fell the share of land kept in pasture would rise, as would the average nitrogen stock of the soil and the average grain and grass yields. At interest rates above 7 percent, which prevailed in

\(^{46}\) There is uncertainty, however, about the appropriate value for the release rate \( k \). The Rothamsted experiments seem to suggest that, in arable depleted of nitrogen, the release rate may be very low.
medieval Europe, the most profitable farming strategy would be to exhaust the arable of its nitrogen reserves by continual grain cropping.

My hypothesis explains the difference in the value of arable and pasture that we find both in the medieval period and later. The value of old arable in medieval England was even less than that of marginal land left as wood or pasture, because the former’s nitrogen stock was depleted. In the long run it would be more valuable as pasture, but in the short term converting arable to pasture would result in a decline in income, because the initial pasture yields would be low due to the low nitrogen stock.

Even if clover or grasses could be sown annually, the extent of their use—and the consequent level of yields from the arable—would depend on the rate of return. The Appendix shows that if land could be switched without cost between pasture and arable, the optimal share of arable would be

$$\alpha = \frac{r + k}{r + 2k} \cdot \left( \frac{I_p}{(I_p - I_A)} - \frac{k}{r + k} \cdot \frac{p}{1 - p} \right)$$

When \( r \) equaled 15 percent, all of the land would be kept in grain, as we have seen. At 10.5 percent, the medieval rate of return, 89 percent of the land would be devoted to grain; at 5 percent, it would fall to 67 percent. For \( r \) as low as 4 percent, the share of grain would be only 61 percent. The average yield of the grain crops would be 10.7 bushels at a rate of return of 4 percent, but only 7.3 bushels at a rate of return of 10.5 percent. This equation would also apply to crops like beans and peas, which fix smaller amounts of nitrogen than pasture or clover, suggesting that the use of those crops would also be highly interest sensitive. Thus, even had sown grasses been available in medieval England, we would expect an increase in grain yields of nearly 50 percent from then till modern times due to declining interest rates alone.

Thus the modified Postan thesis would explain the increase in grain yields before the widespread use of clover in the following way: Medieval cultivators knew that returning arable land to pasture use for a sustained period would restore fertility to the soil. But they found this an economically unattractive proposition, because those gains to fertility took time to realize. The secular decline in rates of return from 1300 to 1750 led to the widespread use of pasture breaks and to substantial grain yield increases by 1750.

THE IMPLICATIONS OF THE REVISED POSTAN THESIS

My alternative explanation for the cause of the agricultural revolution suggests that many of the gains may have stemmed from a decline in the rate of return in agriculture, leading to an increase in the stock of nitrogen farmers kept in the soil. In this story the revolution is more
economic than technological. Is there any way of testing this against other theories of the revolution?

An obvious test is to look at the timing of yield increases in agriculture. My account links them to the rate of return, whereas the technology theory stresses the introduction of clover. A rise in yields (a) before clover was widespread but (b) after the fall of rates of return to modern levels would support the nitrogen capital story of the agricultural revolution. As mentioned earlier, most of the increase in grain yields between 1300 and 1850 appears to have taken place between 1600 and 1750. From 1600 to 1750 rates of return declined from about 6 to 4 percent, so yield increases in that period are not inconsistent with an explanation stressing the rate of return. There seem, however, to have been at best small yield increases between 1300 and 1600, when interest rates fell from more than 10 percent to about 6 percent. But with long pasture breaks, grain yields only become interest sensitive when rates of return fall below a certain threshold level. Above that level, the most profitable farming strategy is always to maximize the arable area.

The modified Postan thesis suggests that, even after farmers understood the role of nitrogen-fixing crops in restoring fertility, they would deplete the fertility of the land if they found themselves in an economic situation equivalent to that of medieval cultivators, in which rates of return were high. Farmers in California’s Central Valley found themselves in just such a position in the late nineteenth century. Rates of return, as revealed by mortgage interest rates, were on the order of 30 percent or more in the late 1850s. They were nearly 20 percent in the 1860s, but fell to about 9 percent by 1900. Central Valley farmers in the 1850s and 1860s followed a strategy echoing that of medieval cultivators: they devoted all of their land to unremitting wheat production, thereby depleting the soil of its nitrogen reserves. There was no attempt in this early period to restore fertility through green fallows; indeed, the model I have outlined here suggests that, given the rates of interest farmers faced, depletion was the optimal strategy.47

Another test of the nitrogen capital theory that should be possible is to look at newly assarted land in the Middle Ages. The newly reclaimed land should have been more fertile initially, until the nitrogen capital was depleted by cultivation. Consequently, rents on newly reclaimed land should have declined over time. Postan claims that this was the case, but gives no evidence.48 A careful test remains to be done.

Whether or not the rise in arable yields in English agriculture was achieved solely by the use of clover or with the additional use of natural pasture, it has implications for the role of capital in increasing income in

47 For more details, see Olmstead and Rhode, "Interest Rates and the Intensification of California Agriculture, 1860–1914." There may have been technical problems that made green fallowing difficult.

Soil Exhaustion and the Postan Thesis

Britain in the period of the Industrial Revolution. For the model of farming technology laid out here implies that the only way of increasing yields in the era before chemical fertilizers (which release nitrogen immediately) was to increase the nitrogen capital in the soil. The nitrogen for each extra unit of yield would require an increase in the nitrogen capital by \( \frac{1}{k} \) units. At a 5 percent rate of return, the marginal capital output ratio would be 7.5 to 1.\(^{49}\)

This would imply enormous "invisible" investments by farmers in the seventeenth to early nineteenth centuries, which would not be captured by conventional growth accounting models of the Industrial Revolution period. The agricultural capital in those models normally includes only machines, animals, and land improvements such as draining, ditching, and enclosing. The measured rate of technical progress in agriculture in those models would consequently be too high. The investments may have been large enough to push up the national net savings rate as well in the same period. Agricultural output in Britain more than doubled from 1650 to 1850, when it was perhaps 20 percent of the value of national output. If much of that rise was due to yield increases created by greater stocks of nitrogen, an increase in capital in agriculture equal to about 75 percent of the GNP in 1850 may have been omitted from traditional accounting exercises for the Industrial Revolution.

Appendix

THE OPTIMAL SHARE OF ARABLE WITH GRASS IN ROTATION

If a farmer chose to rotate land between a nitrogen-fixing crop and grains so that a fraction \( \alpha \) were always pasture, then the total "visible" net output per acre would be

\[
R(\alpha) = \alpha \cdot kN + (1 - \alpha) \cdot p \cdot kN
\]

For the stock of nitrogen in the soil to be stable, the losses from the grain portion of the cultivation cycle would have to equal the gains from the nitrogen-fixing portion. Thus,

\[
\alpha \cdot (I_A - kN) + (1 - \alpha) \cdot (I_P - kN) = 0
\]

\[
\Rightarrow kN = \alpha \cdot I_a + (1 - \alpha) \cdot I_P
\]

To maximize the long-run net output, the farmer would want to choose \( \alpha \) to maximize \( R \). The value of \( \alpha \) that did so would be

\[
\alpha = \left( \frac{1}{2} \right) \left[ \frac{I_P}{I_P - I_A} - \frac{p}{1 - p} \right], \quad \alpha < 1
\]

The optimal share of grains once the soil capital were taken into account can be calculated from the fact that, at the optimal allocation of land to each use, an acre

\(^{49}\) The marginal capital output ratio is measured as \( p_N \), where \( k \) is the rate of release of the nitrogen stock and \( p_N \) is the value of the nitrogen capital (which depends, as we saw, on the rate of return).
devoted to pasture would have to yield a benefit equal to that of one devoted to grain. The full value of land planted in grain would be

$$V_a = kN + p_N \cdot (I_A - kN)$$

where $p_N$ is the value of the nitrogen stock. The value of land as pasture would be

$$V_p = p \cdot kN + p_N \cdot (I_P - kN)$$

The value of a unit of nitrogen in the ground or in manure, $p_N$, would be the discounted present value of the yield increases that nitrogen could produce on the arable. Thus, if the land were always in arable production,

$$p_N = \frac{k}{(1 + r)} + \frac{k(1 - k)}{(1 + r)^2} + \ldots$$

$$= \frac{k}{(r + k)}$$

The value of the nitrogen produced would depend on $\alpha$, because it could only be used for a fraction $\alpha$ of the time to produce grain. It would also depend on the rate of return $r$, because the nitrogen produced would be released over time and would be valued depending on how impatient cultivators were. If land could be rotated between grains and pasture annually, there would be a simple expression for the value of a unit of nitrogen in the soil as a function of $r$. Because land would be growing grain only a fraction $\alpha$ of the time, this would be

$$p_N = \left(\frac{k}{(r + k)}\right) \cdot (\alpha + (1 - \alpha) \cdot p)$$

For $V_a$ to equal $V_p$, we would thus need

$$kN - p \cdot kN = p_N \cdot (I_P - I_A)$$

$$\Rightarrow (1 - p)(\alpha \cdot I_A + (1 - \alpha) \cdot I_P) = (\alpha + (1 - \alpha)p) \cdot \left[\frac{k}{(r + k)}\right](I_P - I_A)$$

$$\Rightarrow \alpha = \frac{r + k}{r + 2k} \cdot \left(\frac{I_P}{(I_P - I_A)} - \frac{k}{r + k} \cdot \frac{p}{1 - p}\right)$$

If $r$ equaled zero, then this formula would reduce to the one given above for maximizing long-run yields. Only if interest rates were zero would farmers maximize long-run output. As $r$ increased and

$$\frac{k}{(r + k)}$$

fell, they would switch more land over to arable. As long as $I_A$ were greater than $p \cdot I_A$ (so that land under continual arable cultivation yielded more than the same land in the first year of pasture use), then at a high enough rate of discount they would devote all of the land to arable. The foregoing simple model shows that yields would be interest sensitive even when farmers were able to employ sown grasses or clover. The model also suggests that a change of relative prices in favor of pasture products would increase grain yields.
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