

Did Soil Fertility Decline in Medieval English Farms? Evidence from Cuxham, Oxfordshire, 1320–1340*

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Abstract

It has been suggested that during the century before the Black Death the fertility of the soil on English farms was declining, leading to decreased food production and increased mortality. We here estimate nutrient balances for a manorial demesne, to determine whether the nutrient status of the soil was declining. We calculate the losses of nitrogen, phosphorus and potassium in the produce during 1320–1340, using information from the demesne accounts. The main inputs of phosphorus and potassium would be from weathering of rock; these would probably have been enough to balance the losses of potassium but not of phosphorus. Potential inputs and non-produce losses of nitrogen are so large that we cannot say whether the demesne was in balance for nitrogen. The paper thus points to phosphorus as the key element likely to have led to falling soil fertility at this time.¹

IT is widely accepted that the population of England rose steeply during the century and a half after 1086. From about 1250 until the Black Death in 1348–9 the population was probably higher than it had ever been before, and higher than it would be again until the seventeenth or eighteenth centuries.² This high population placed special demands on agriculture. More than forty years ago Postan put forward the view that during the thirteenth century and the first half of the fourteenth century agricultural production was declining, human mortality was increasing due to

food shortage, so the human population was already declining before the Black Death; and that these changes had a major impact on economic activity. The primary cause of the decline in farm productivity, he proposed, was declining soil fertility. Farmers 'had been cultivating old land for too long'.³ In earlier times, if yields per acre from existing farmland declined additional land could be brought into cultivation; but by the fourteenth century scarcely any reserves of suitable unused land remained.

These views of Postan have provoked much debate, which continues today.⁴ The debate concerns the evidence on farm yields, on human population changes, and on levels of economic activity; it also concerns the interpretation to be put on this evidence. What has been missing is evidence on whether the fertility of the

* E I N wishes to thank Dr P Glennie for pointing out especially interesting features of the early fourteenth century in agricultural history, and Professor C Dyer for initiating this collaboration by recommending the writings of Harvey on Cuxham. We are both very grateful to Merton College, Oxford, for keeping safely the accounts upon which this paper is based, and for allowing one of us (PDH) to study them in detail. We thank Professor B M S Campbell, Professor C Dyer and two anonymous referees for helpful comments on earlier versions of this paper.

¹ Meanings of words, as used in this paper. Village: a nucleated settlement; vill: a settlement, nucleated or dispersed, with all attached lands; demesne = manorial demesne: the home farm, the lands tilled for the lord himself, as against those in the hands of permanent local tenants; manor: a single administrative unit of a landed estate, that usually, as at Cuxham, contained the manorial demesne and also lands held by local tenants.

² C Dyer, *Standards of Living in the Later Middle Ages*, 1989; R M Smith, 'Demographic developments in rural England, 1300–48: a survey', in B M S Campbell, ed., *Before the Black Death*, Manchester, 1991, pp 25–77; P J Fowler, *The Farming of Prehistoric Britain*, 1981.

³ M M Postan, *Essays in Medieval Agriculture and General Problems of the Medieval Economy*, 1973, pp 3–27 and 150–85, and *The Medieval Economy and Society*, 1972.

⁴ Dyer, *Standards of Living*; B F Harvey, 'Introduction: the "crisis" of the early fourteenth century', in Campbell, *Black Death*, pp 1–24; Smith, 'Demographic developments', pp 25–74; K Biddick, 'Agrarian productivity on the estates of the Bishopric of Winchester in the early thirteenth century: a managerial perspective', in B M S Campbell and M Overton, eds, *Land, Labour and Livestock*, Manchester, 1991, pp 95–123.

soil in English farms was in fact declining during this period. It is this question that we address here. There are other possible causes of decline in crop yields. One is climate change: there is evidence that average temperatures were declining from about 1250 to 1450. Another possibility is that cultivation practices became less effective, for example due to shortage of labour.⁵ So it is important to have direct evidence on whether soil fertility did decline.

I

Several sorts of change in soil can reduce its fertility: top-soil can be eroded away by wind or rain; or the amount of organic matter in the soil can decrease, resulting in less ability to hold water and nutrients, and in a less favourable structure for root growth. Here, however, we concentrate on nutrient balance. Plants require various chemical elements, and many of these have to be obtained from the soil, for example nitrogen, phosphorus and potassium. (However, leguminous plants, such as beans and peas, can obtain nitrogen from the air with the aid of bacteria in root nodules.) Without these nutrient elements plants cannot grow at all; if the supply of an essential element is insufficient, crop growth, and hence seed production, will be reduced.⁶ When crops and animals are removed some of these nutrients are removed in them; the nutrients can also be lost from soil in other ways, for example dissolved in rainwater that flows into rivers. If these losses are not made good by inputs to the soil, then year by year the nutrient status of the soil will decline, and it is

almost inevitable that this will, sooner or later, reduce the growth of crop plants and of plants grown as food for animals. In this paper we present evidence on whether, on one fourteenth-century demesne, the losses of three essential elements, nitrogen (N), phosphorus (P) and potassium (K), were balanced by inputs. These three elements are among the six that plants have to obtain in relatively large amounts from soil.⁷ They have been chosen because they are the three that have most commonly limited crop production on English farms during the twentieth century, unless artificial fertilizers have been added. Other essential elements can be deficient locally, but none is a widespread cause of low crop yields in twentieth-century Britain.

The chemical forms of nitrogen, phosphorus and potassium in soil are often classed as 'available' to plants and 'non-available', though in fact there is a range of availabilities. Some N, P and K is in soluble inorganic forms, which plant roots can take up quickly, ie within days or weeks. The other principal form of N is in organic matter. The turnover of organic matter in British arable soil commonly has a time-scale of decades, so organic N would become available to plants on this time-scale. Phosphorus in soil is in a variety of inorganic compounds, which can convert from one to another, but some only very slowly. It also occurs in organic matter. Potassium also has a variety of inorganic forms, but little in organic matter. Therefore, if inputs of these three elements failed to balance losses, the stores in the soil could be expected to continue to supply the plants over a period of some decades, though at a gradually declining rate. In addition, P and K (though not N) occur in the fine mineral (rock) material that forms the basis of soil. This P and K is usually ignored by ecologists studying nutrient cycling. However, it can be slowly

⁵ H H Lamb, *Climate, History and the Modern World*, 2nd ed, 1995, ch 11; D Postles, 'Cleaning the medieval arable', *AHR*, 37, 1989, pp 130-43; B M S Campbell, 'Land, labour, livestock and productivity trends in English seignorial agriculture, 1208-1450', in Campbell and Overton, *Land, Labour and Livestock*, pp 144-82.

⁶ The biological functions of individual elements are described in text-books of plant physiology, for example, L Taiz and E Zeiger, *Plant Physiology*, Benjamin Cummings, Redwood City, 1991.

⁷ The other three are sulphur, calcium and magnesium.

released by weathering (ie breakdown) of the mineral material, a process which can continue for thousands of years. As we shall show, this could play an important part in the long-term P and K balances of medieval farms.⁸

There has been some previous discussion of the importance of soil nutrients in medieval farming. Cooter surveyed the difficulties of maintaining crop yields long-term in the medieval open-field system. He concluded that 'At best, open-field husbandry offered a means for sustaining a mediocre level of productivity at the price of a judiciously slow depletion of the nutrient reserves of the arable's hinterlands'.⁹ He was right to draw attention to the nutrient status of the 'hinterland'. If the fertility of the arable can be maintained only at the price of a decline in the fertility of associated meadowland, rough pasture and woodland, then the system as a whole is not sustainable long-term. Cooter's paper was, however, confined to generalities and lacked any firm historical evidence on nutrient balances. In his reply to Cooter, Loomis concentrated on nitrogen, presenting figures to show that the various inputs of nitrogen to a hypothetical medieval farm could be enough to balance the amount removed in grain.¹⁰ His figures were 'best guesses' rather than firmly rooted. He did not ask whether any other essential element might become depleted over a long time.

Shiel discussed in some detail the role of nitrogen in pre-fertilizer agriculture.¹¹ He was, however, more interested in the forms of nitrogen in soil and their interconversion than in the input/output balance. He makes an important statement about

phosphorus and potassium, that before the mid-nineteenth century their 'soil supplies would have tended to decrease slowly with time'. If this is correct, it must have had a crucial role in limiting crop productivity on land that had been farmed for centuries. Unfortunately, Shiel gives no evidence to back up this statement. In this paper we present evidence on whether the statement is correct.

Shiel stated that 'production of arable crops was ultimately limited by the amount of manure available', and other writers on agricultural history have placed great emphasis on the supply of manure.¹² Manure was recognized as a valuable commodity by the fourteenth century. Walter of Henley in the thirteenth century gave instructions for its storage and application. At Cuxham in the fourteenth century people were paid to cart and spread it.¹³ However, the precise function of manure was not then understood. The animals do not create the nutrient elements in their faeces and urine: their excreta are merely a processed version of what they ate. Manure can benefit plants in two ways. If it is deposited in the same area where the animals ate, it can provide mineral nutrients in forms more readily and more rapidly available to plants than from decomposing plant materials. Viewed over the long term, however, the animal does not increase the nutrients in the soil, and may even reduce them, since dissolved nitrogen compounds can be readily lost from urine patches, by leaching and as ammonia gas.¹⁴ Secondly, animals can act as transporters of nutrients. The time taken for the food eaten by a horse, cow or sheep to pass through it and

⁸ For more information on nutrients in soils and their availability to plants see A Wild, *Soil Conditions and Plant Growth*, Harlow, 1988.

⁹ W S Cooter, 'Ecological dimensions of medieval agrarian systems', *AH*, 52, 1978, pp 458-77.

¹⁰ R S Loomis, 'Ecological dimensions of medieval agrarian systems: an ecologist responds', *AH*, 52, 1978, pp 478-83.

¹¹ R S Shiel, 'Improving soil productivity in the pre-fertiliser era', in Campbell and Overton, *Land, Labour and Livestock*, pp 51-77.

¹² B H Slicher van Bath, *The Agrarian History of Western Europe, AD 500-1850*, 1959; G E Fussell, *Farming Techniques from Prehistoric to Modern Times*, 1966; Postan, *Medieval Economy*; Shiel, 'Improving soil productivity'.

¹³ Walter of Henley, *Le Dite de Hesebondrie*, c 1230; P D A Harvey, *A Medieval Oxfordshire Village, Cuxham 1240 to 1400*, 1965.

¹⁴ D R Lockyer and D C Whitehead, 'Volatilization of ammonia from cattle urine', *Soil Biology and Biochemistry*, 22, 1990, pp 1137-42; J C Ryden, P R Ball and E A Garwood, 'Nitrate leaching from grassland', *Nature*, 311, 1984, pp 50-53.

the remains to emerge as excreta is between one and several days.¹⁵ Therefore, if animals are moved every twenty-four hours or more frequently, the excreta they deposit in one place will contain materials eaten elsewhere. Cattle and sheep eat mainly during daylight, but deposit urine and faeces about equally by day and night.¹⁶ Therefore, the medieval system of allowing animals to graze on pasture or 'waste' by day and folding them on arable fields at night was an effective way of transferring nutrients from the pasture to the arable. This nutrient transport has important implications for the nutrient balance of the arable and the pasture if they are considered separately. But for the system to be truly sustainable, the nutrient balance of both arable and pasture must be maintained. Therefore, we have here considered the whole demesne as the unit for nutrient balance calculations. We are not denying the importance of nutrient movement within the farm, and the contribution of manure to that; indeed, we are assuming that some movement of nutrients from pasture and meadow to arable did occur. But we are drawing particular attention to the importance of the whole farm being in balance for essential nutrients, because if it is not then no amount of nutrient movement within the farm will prevent long-term decline in soil fertility.

II

This paper presents evidence on the balance of nitrogen, phosphorus and potassium in the manorial demesne of Cuxham, Oxfordshire, in the period 1320 to 1340.

The three-field, open-field system was in operation. This demesne was chosen, firstly, because detailed accounts were kept for the years 1288 to 1359 and many of these have survived. One of us has made a detailed study of these accounts, and has published complete, edited accounts for some years, as well as tabulated data from accounts of all available years.¹⁷ We here make use of these sources, and also other, unpublished information extracted from the accounts.

The period 1320–1340 was chosen to provide two decades shortly before the Black Death, but avoiding 1313–1319, when crop yields were unusually low because of unfavourable weather.¹⁸ An advantage of this period is that the areas sown to each crop are reported in the accounts in measured acres, whereas before 1318 only customary acres, of uncertain size, were reported. Another favourable feature is that throughout the period the farm was in the charge of one reeve, Robert Oldman. The accuracy of the accounts was substantially the responsibility of the reeve, although they were audited each year. Robert Oldman was the reeve from 1311 until he died in March 1349, soon after the Black Death arrived in Cuxham. This long service until death implies confidence by the landlord, Merton College, in his competence and honesty. During this twenty-year period the accounts for four years are missing, and two others are seriously damaged and so illegible in parts. We therefore base our calculations on the accounts for the fourteen years 1320–23, 1327–29, 1331–34, 1336, 1338, 1339. The account year runs from July to July, and so includes a harvest and records of what happened to the produce of that harvest. Each twelve-month period will be referred to by its starting year, ie the year of the harvest.

¹⁵ A C I Warner, 'Rate of passage of digesta through the gut of mammals and birds', *Nutrition Abstracts and Reviews Series B*, 51, 1981, pp 789–820.

¹⁶ D C Church, *The Ruminant Animal*, Prentice Hall, Englewood Cliffs, 1988; M E Castle, A S Foot and R J Halley, 'Some observations on the behaviour of dairy cattle with particular reference to grazing', *J Dairy Research*, 17, 1950, pp 215–30; W A Hardison, H L Fisher, G C Graf and N R Thompson, 'Some observations on the behaviour of grazing lactating cows', *J Dairy Science*, 39, 1956, pp 1735–41.

¹⁷ Harvey, *Medieval Village*; P D A Harvey, *Manorial Records of Cuxham, Oxfordshire*, HMSO, 1976.

¹⁸ Lamb, *Climate*, p 195.

TABLE 1
Areas of land in Cuxham in 1320-40

Land areas	Acres	Hectares
Whole vill	604	245
Arable land	458	185
of which demesne arable	269	109
Meadows	50	20
Pasture land	37	15
Adjoining manorial buildings	17	7
Remainder*	42	17

* Land associated with church, rectory and tenants' houses, plus roads and verges.

TABLE 2
Area sown to each crop, and yield (including tithe)

Crop	Area sown (acres)	Mean yield per year ^a	
		bushels per acre	tons per hectare
Wheat	88.8	17.3	1.02
Oats	52.9	14.0	0.55
Barley	5.3	21.5	1.09
Dredge ^b	19.1	16.1	0.73
Peas	10.4	11.8	0.73
Beans ^c	0.4		
Vetch ^c	1.4		

^a For basis of bushel/weight conversion, see text.

^b Mixture of oats and barley.

^c No seed yield was reported for beans and vetch in most years. Most of the seed for sowing them was imported.

Cuxham lies twelve miles south-east of Oxford, on rolling lowlands a few miles from the edge of the Chilterns. A detailed description of the village and its farmland between 1240 and 1400, based on contemporary records, has been published previously.¹⁹ The whole vill belonged to Merton College, Oxford, from 1271 onwards. However, accounts are available only for the manorial demesne, so it is to this that our calculations apply. The first detailed map of Cuxham is dated 1767. Merton College had remained the owner, and the three-field system was still in operation. After allowing for some changes in land use that had taken place it is possible to use this map, along with earlier manorial surveys, as a basis for determining areas within the vill. Table 1 provides a summary. The arable was divided into three fields of approximately equal size, each of which was part demesne, part glebe and part tenant land. The demesne arable was 59 per cent of the total arable area. The area of meadow plus grazing land was less than a quarter of the total arable land. There was no woodland within the vill.

The customary three-field rotation was practised: fallow, autumn-sown wheat, spring-sown crops. Table 2 shows the mean area sown to each crop in this period; Table 10 shows the same data expressed as

percentages. In the spring-sown field cereals predominated, with more than half the area occupied by oats. Table 2 also shows the mean yields per sown acre. As was usual, the accounts record the harvest yields after deduction of the tithe. For the figures in Table 2, the reported yields have been divided by 0.9 to give the true amount harvested, including the tithe; all yields referred to in this paper have been calculated in that way.

Cuxham was primarily a grain-producing demesne, and the area of pasture and hay meadow was relatively small. However, some animals were kept; some were grazed on the fallow, or were fed oats and crop legumes. Hay was brought in from other places. Exports of animal produce were relatively modest: the only animal products exported from the demesne in large quantities were doves, eggs and cheese. There was some production of calves and piglets, but the number of cows present was never more than thirteen and sows never more than two. Sheep were also bred; the number of adult sheep varied considerably from year to year, up to 113 during this period. Chickens and doves were numerous, but geese and ducks few. Horses and oxen were

¹⁹ Harvey, *Medieval Village*.

kept for draught purposes, but were bought in, not bred on the farm.²⁰

III

The main aim of this paper is to determine the amounts of nitrogen (N), phosphorus (P) and potassium (K) leaving the demesne per year, and whether this is likely to have been balanced by inputs. The demesne here comprises not only the fields that were growing crops in a given year, but also the fallow field, plus the part of the pastureland and meadowland which fed demesne animals. Transfer of nutrients between these areas within the demesne is not calculated. What we need to know is what left the demesne (here called exports). If we can calculate the weight of crop grain, the number of animals and the weight of animal produce (cheese, eggs, wool) that left the demesne, then the amount of nitrogen, phosphorus and potassium exported can be estimated, using information on their concentration in twentieth-century plants and animals.

The following are classed as exports: produce sold; produce sent to Merton College; the tithe; produce 'delivered' to other villages; 'gifts' (often bribes) to visiting important people; and produce recorded as 'taken not paid for' or simply as 'theft'. Classed as remaining in the demesne are: seed sown; grain fed to farm animals and to visiting horses; and animals that died of disease ('murrain'). An implied assumption here is that all the N, P and K in food eaten by demesne animals found its way, via their excreta, back on to the demesne land (arable, pasture or meadowland), apart from any nutrients in their bodies or their cheese, eggs, wool when they were exported. The carcasses of animals that died of disease were not eaten by people, but presumably rotted, buried or

unburied, leading to return of nutrients. However, their bones would take many years to decompose; these contain substantial amounts of phosphorus, which would recycle only slowly.

Not included in these two lists is produce given to people in the village, and used to prepare meals for them or for visitors. Most of the nutrients in their food would reach their excreta, and the question is how much of this found its way back to the demesne fields. Much of it would have been put into middens, along with other domestic rubbish. It is likely that some of this was spread on the open fields. Apart from that, people working all day in the fields presumably relieved themselves there. The houses of the village were mostly close to the stream, which flowed on down to the pasture and meadow areas; it would be surprising if some nutrients from human excreta did not reach the fields this way. On the other hand, it seems unlikely that all the nutrients in the food were returned to the demesne fields. Of the food given to workers as payment, some may have been sold by them outside the village. Some of their excrement probably ended up fertilizing the vegetables and fruit growing near their houses. So two alternative calculations are presented, one assuming that all the nutrients in produce given to people within the village were recycled back to the demesne lands, the other assuming that none of them was; the true value must lie somewhere in between. In contrast, nutrients in the tithe are assumed all to leave the farm; the rector was not resident in the village, and most of the tithe was presumably sold.

The accounts were audited each year, and alterations were sometimes made. Some of these indicate amounts of produce which the reeve had not accounted for. These cannot be allotted to export or non-export and have been ignored in the calculations. The amounts involved were a small

²⁰ Details of the numbers of animals are given in appendix vi of Harvey, *Manorial Records*.

TABLE 3
Fate of grain (grown on the demesne and imported), expressed as a percentage of the total for each crop species*

Crop	Remained in demesne	To people in village	Exported from demesne
Wheat	13.9	13.1	73.0
Oats	78.3	3.9	17.8
Barley	16.2	35.7	48.1
Dredge	27.4	36.8	35.8
Peas	30.8	52.2	17.0
Beans	66.2	20.0	13.8
Vetch	98.0	0.0	2.0

* For further explanation of the three categories, see text.

proportion of the total; for the cereals it was less than 1 per cent.

In the calculations all the straw from crops is assumed to remain in the demesne. There are occasional references in the accounts to sale of straw, but these would total insignificant amounts. If straw was used for thatching in the village during this period, that could have taken some straw out of circulation for a long time. But nearly all the straw produced was used as fodder, as bedding for animals (which was later returned to the fields as farmyard manure), or was left in the fields to be eaten or to rot.

There were some imports to the demesne: seed was sometimes bought, animals were bought, wool was received. These are used to calculate net exports of each commodity (export - import). Hay was also brought from other places (but never exported); the effect of this on the nutrient balance will be considered later. Firewood, too, was sometimes brought in from other places, and this may have contributed a nutrient input if the ash was spread on the fields. No marling occurred at Cuxham during this period.

Table 3 shows what percentage of each crop fell into each of the three use categories. Some of the wheat, barley and dredge was made into malt. The subsequent uses

of this malt were recorded in the accounts, so the end uses have been allocated to the original cereals. As might be expected, the uses differed greatly between crops. Much of the wheat was sold. In contrast, most of the oats was fed to animals. Almost all the vetch seed was retained for sowing. Presumably vegetative parts of the vetch were used for animal fodder. Peas and dredge were mixed together as food for local people.

Our calculations require information on the concentration of nutrients in seeds. This has been determined in mg per g dry weight, and we therefore need to convert the amounts of seed, reported by the accounts in volume units (quarters and bushels), into weights. By 1340 units of volume and weight had not been standardized throughout England. Following the detailed review by Connor,²¹ we assume that the weight of wheat in one bushel was 64 troy pounds, which is 23.9 kg. The weight: volume ratio of other cereals is different from wheat. Campbell *et al* give it for wheat:barley:oats about 1300 as 1:0.86:0.75 (ie the volume holding 1 kg of wheat could hold 0.86 kg of barley or 0.75 kg of oats). This calculation is based on the carrying capacity of carts. Campbell *et al* give the ratios from 1791 statutes as 1:0.86:0.67. The modern ratios are 1:0.90:0.68.²² We have used 1:0.86:0.67. Dredge is assumed to be intermediate between barley and oats. Peas, beans and vetch are taken as 1.05, on the basis of modern weights of beans. So the weights in kg per bushel are: wheat 23.9; barley 20.5; oats 16.0; dredge 18.3; peas, beans and vetch 25.1. The amounts of grain in the different categories, calculated in this way, are shown in Table 4. In the exports, wheat far exceeds all the other

²¹ R D Connor, *The Weights and Measures of England*, HMSO, 1987.

²² B M S Campbell, J A Galloway, D Keene and M Murphy, *A Medieval Capital and its Grain Supply*, Historical Geography Research Series no 30, 1993, p 41; I Moore, ed, *Primrose McConnell's Agricultural Notebook*, 16th ed, 1976; J A Watson and J A More, *Agriculture*, Edinburgh, 1949.

TABLE 4

Amount of grain imported to demesne; fate of grain (imported and grown on demesne); and net export from demesne (export - import): all expressed as air-dry weight (metric tons per year)

Crop	Import	Fate of grain			Net export
		Remained in demesne	To people in village	Exported from demesne	
Wheat	0.93	5.52	5.20	29.02	28.10
Oats	1.34	11.45	0.58	2.60	1.26
Barley	0.11	0.39	0.86	1.15	1.04
Dredge	0.0	1.45	1.95	1.90	1.90
Peas	0.17	0.89	1.50	0.49	0.32
Beans	0.15	0.15	0.05	0.03	-0.12
Vetch	0.08	0.09	0.0	<0.01	-0.08

crops combined. There was a net import of beans and vetch, since seed brought in exceeded exports.

Nutrient concentrations of seeds have been taken from published measurements on crops grown on unfertilized soil in Britain, in the twentieth or late nineteenth centuries. Many of the crops were grown at Rothamsted, Hertfordshire, or one of its associated farms. Often the same crop had been grown continuously in the field for some years. It might be more realistic to use data for wheat grown after fallow, and for other cereals second year after fallow. But where these growing conditions have been compared with continuously cropped unfertilized plots, the nutrient concentrations in the seeds have generally differed little. The values used are given in Table 5. There is little difference among the cereals in concentration of any of the nutrients elements, but the legumes are higher in N and K.

These concentrations are per g oven-dry weight. The weights of grain in Table 4 are air-dry weight, so for calculating nutrient contents they have been multiplied by 0.85, to allow for the normal water content of air-dry seed, about 15 per cent. Use of figures in Tables 4 and 5 then allows calculation of the nutrients in the plant

produce exported and given to people in the village (Table 7).

The accounts also provide figures for the number of animals that were born on the demesne and that died there, and the numbers imported and exported. Horses and sheep have not been included in the calculations: horses were not bred on the demesne; some lambs were born, but their numbers approximately equalled the number of lambs and sheep that died of murrain. The number of sheep increased greatly during the period, mainly due to a large purchase in 1336, but their nutrient content clearly did not end up in the soil. Table 6 provides information on the other animals. A 'customary render' of 81 chickens was received from tenants each year at Martinmas and Christmas; this exceeded the number sold and sent to Oxford, so the demesne was a net importer of chickens. The only large numbers of exports were doves, eggs and cheeses. Cheeses were of three sizes, which we have assumed to be the standard 2 lb, 4 lb and 6 lb. Weights of fleeces are given in the accounts. For conversion to kg we have used modern lb. In fact the *libra mercatoria* may have been used at Cuxham, but this differs only slightly.

The nutrient concentrations assumed in

TABLE 5

Nutrient concentrations (mg per g) in plant and animal produce, assumed for calculations*

Product	Nitrogen	Phosphorus	Potassium
Wheat, oats	18	3.6	4.8
Barley	14	3.1	5.2
Dredge ^a	16	3.35	5.0
Beans	43	4.0	10.0
Peas, vetch ^a	40	4.0	10.0
Hay	18	1.4	14.0
Firewood		0.11	1.7
Cattle, pigs, geese, chickens, ducks, doves	23	6.0	1.6
Eggs	20	2.2	1.3
Cheese	40	5.0	1.2
Wool	90	1.0	1.0

* Concentrations in seeds, hay and wood are per g dry weight, in animals and animal produce per g fresh weight.

^a Dredge was taken as the mean of oats and barley. No published values were found for vetch, so it was assumed to have the same concentrations as peas.

Sources: Grain: E J Russell and J A Voelcker, *Fifty Years of Field Experiments at Woburn Experimental Station*, 1936; J B Lawes and J H Gilbert, *The Rothamsted Experiments*, Edinburgh, 1895; A E Johnston, 'The plant nutrients in crops grown on Broadbalk', *Rothamsted Annual Report* [hereafter RAR] for 1968, pt 2, 1969, pp 50-62; A E Johnston and P R Poulton, 'Yields on the Exhaustion Land, 1852-1975', *RAR* for 1976, pt 2, 1977, pp 53-83; G V Dyke, B J George, A E Johnston, P R Poulton and A D Todd, 'The Broadbalk wheat experiment 1968-78: yields and plant nutrients', *RAR* for 1982, pt 2, 1983, pp 5-44; D S Powlson, G Pruden, A E Johnston and D S Jenkinson, 'The nitrogen cycle in the Broadbalk wheat experiment', *J Agric Sci*, 107, 1986, pp 591-609; F V Widdowson, A Penny and M V Hewitt, 'Results from the Woburn Reference Experiment', *RAR* for 1981, pt 2, 1982, pp 5-21; J I Sprent and A M Bradford, 'Nitrogen fixation in field beans as affected by population density, shading and soil moisture', *J Agric Sci*, 88, 1977, pp 303-10; D J Greenwood *et al*, 'Comparison of the effect of fertilizers on the yield, potassium, phosphate and nitrogen content and quality of 22 different vegetable and agricultural crops', *J Agric Sci*, 95, 1980, pp 441-85.

Hay: A B Stewart and W Holmes, 'Some effects of heavy dressings of nitrogen on the mineral composition of grassland herbage', *Jnl Science of Food and Agriculture*, 4, 1953, pp 401-408; B Thomas, W B Holmes and J L Clapperton, 'A study of meadow hays from the Cockle Park experiment', *Empire Jnl Experimental Agriculture*, 23, 1955, pp 102-8; R G Warren and A E Johnston, 'The Park Grass Experiment', *RAR* for 1963, 1964, pp 240-62; A Penny, F V Widdowson and R J B Williams, 'An experiment measuring effects of fertilizers on yield and N, P and K contents of grass', *J Agric Sci*, 95, 1980, pp 575-82.

Firewood: D E Reichle, *Dynamic Properties of Forest Ecosystems*, 1981, p 647.

Animals and animal produce: J B Lawes and J H Gilbert, 'Experimental enquiry into the composition of some of the animals fed and slaughtered as human food', *Phil Trans Royal Soc*, 149, 1859, pp 493-680; Lawes and Gilbert, *The Rothamsted Experiments*; W S Spector, ed, *Handbook of Biological Data*, Saunders, Philadelphia, 1956; D T Crisp, 'Input and output of minerals for an area of Pennine moorland', *J Applied Ecol*, 3, 1966, pp 327-48; P H Williams and R J Haynes, 'Balance sheet of phosphorus, sulphur and potassium in a long-term grazed pasture', *Fertilizer Research*, 31, 1992, pp 51-60; E A LeFebvre, 'Measuring energy metabolism in *Columba livia*', *The Auk*, 81, 1964, pp 403-16; A L Romanoff and A J Romanoff, *The Avian Egg*, Wiley, New York, 1949; S K Kon, *Milk and Milk Products in Human Nutrition*, FAO, Rome, 1972; H Tiessen, ed, *Phosphorus in the Global Environment*, Chichester, 1995, pp 9, 45; A A Paul and D A T Southgate, *The Composition of Foods*, HMSO, 1978.

animals and their produce are given in Table 5. We have assumed the same concentration in all animals, based on published data for cattle, pigs, sheep, poultry and pigeons. There is no certainty about the weight of farm animals at this period. The weights we have assumed for cattle and pigs (Table 6) are based mainly on sixteenth- to eighteenth-century reports. The weights for birds and eggs are based on the low end of the range in the twentieth century. Using figures in Tables 5 and 6 then allows calculation of the total nitro-

gen, phosphorus and potassium in animals and their produce, given in Table 7.

IV

The aim of this paper so far has been to produce the figures on the bottom line of Table 7. On that line there are two figures for each element; the actual total loss per year of that element from the demesne, due to export plus use by people, lay somewhere between those two figures. Table 7 shows that wheat played a pre-

TABLE 6
Data on animals and animal produce

Animal	Number per year		Assumed weight ^b (kg per individual)
	Net export ^a	To people in village	
Adult cattle	1.2	0	200
Calves	4.8	0	50
Adult pigs	2.1	2.2	40
Piglets	1.4	0.2	10
Geese	11.1	5.1	5
Chickens	-18.1	31.9	2
Ducks	2.8	1.1	2
Doves	603.6	94.5	0.3
Eggs	282.4	37.3	0.06
	Total weight per year		
Cheese (kg/yr)	235.7	55.6	
Wool (kg/yr)	22.8	0	

^a Net export: export from demesne - import to demesne.

^b Sources: G E Fussell, *Farming Techniques from Prehistoric to Modern Times*, 1966; G Clark, 'Labour productivity in English agriculture, 1300-1860', in B M S Campbell and M Overton, eds, *Land, Labour and Livestock*, Manchester, 1991, p 217; J A S Watson and J A More, *Agriculture*, Edinburgh, 1949; H-J Rothe and W Nachtingall, 'Pigeon flight in a wind tunnel', *Jnl Comparative Physiology B*, 157, 1987, pp 91-109. Young are assumed 1/4 of adult weight, based on the ratio in modern cattle and pigs.

TABLE 7
Nutrient content (kg per year) of produce exported from the demesne and received by people in the village

Product	Nitrogen		Phosphorus		Potassium	
	Export ^a	Export + ^b people	Export ^a	Export + ^b people	Export ^a	Export + ^b people
Wheat	429.9	509.4	86.0	101.9	114.6	135.8
Other cereals	57.5	103.0	12.0	21.6	17.8	32.2
Legumes	3.9	56.6	0.4	5.7	1.0	14.2
Animals	18.1	22.9	4.7	6.0	1.3	1.6
Eggs + wool + cheese	11.8	14.1	1.2	1.5	0.3	0.4
Total	521.1	705.9	104.4	136.6	135.1	184.2

^a Export means net export from demesne.

^b Export + people means net export plus received by people in village.

dominant role in determining these totals. This might be expected, since wheat occupied the largest area each year (Table 2), and a large percentage of its yield was exported (Table 3). These numbers on the bottom line of Table 7 may not mean much to the reader at this moment; the key question, which we shall now try to answer, is whether these annual losses are likely to have been balanced by inputs to

the farm. We consider nitrogen first (Table 8).

One source of nutrient input to the farm was hay brought in from other villages: the nutrients in the hay, passing through the animals that ate it, would reach the farm soil in their excreta. The accounts record purchase of hay in all but two of the years of our period. The price paid is given, but unfortunately not the quantity of hay

TABLE 8
Estimated nitrogen inputs, for comparison with losses

Losses and inputs	kg/ha/yr	Whole demesne (kg/yr)
Losses in produce		521-706
Inputs		
(a) Based on information from accounts		
Hay bought		110
N fixation by crop legumes	19.6	97
Total (a)		207
(b) Additional N fixation, based on twentieth-century rates*		
Legumes in pasture and meadow	5	105
Legume weeds in cropland and fallow	?	?
Cyanobacteria in cropland and fallow	3+	327+
Free-living bacteria in soil (whole demesne)	2+	273+
Total (b)		705+
Grand total inputs		912+

* The inputs per hectare are set at the bottom end of the likely range.

Sources: Losses in produce, Table 7. Inputs (a), see text. Inputs (b), D W Cowling, 'Biological nitrogen fixation and grassland production in the United Kingdom', *Phil Trans Royal Soc*, 296, 1982, pp 397-404; P Newbould, 'Biological nitrogen fixation in upland and marginal areas of the U.K.', *Phil Trans Royal Soc*, 296, 1982, pp 405-17; J F Witty, P J Keay, P J Frogatt and P J Dart, 'Algal nitrogen fixation on temperate arable fields', *Plant and Soil*, 52, 1979, pp 151-64; K E Giller and J M Day, 'Nitrogen fixation in the rhizosphere: significance in natural and agricultural systems', in A H Fitter, ed, *Ecological Interactions in Soil*, 1985, pp 127-47.

bought. We have therefore estimated the quantity from the mean price paid at Cuxham during 1320-40, and the mean price paid per load between 1307 and 1343 at other places in southern England, tabulated by Rogers.²³ In 1336 and 1338 no payment for hay at Cuxham is recorded in the accounts, yet in 1336 the accounts report that oats were provided to feed horses carrying hay from Holywell to Cuxham. Therefore, rather than assuming the amount of hay bought in 1336 and 1338 was zero, we have used the mean of the other twelve years. The mean amount paid was 19.84s. Rogers reports price per load at eight places (one of them twice), ranging from 1s 8d to 4s 5d, averaging 2.91s per load. A load was traditionally 18 cwt (0.9 tons) of air-dry hay.²⁴ Hence the mean amount of hay bought per year is estimated at 6.1 tons. The nitrogen concentration in the hay is taken as 18 mg/g, from measurements on the unfertilized long-term hay

plots at Rothamsted; similar concentrations have been reported elsewhere. So the nitrogen input in hay is estimated at 110 kg/year.

Imported firewood could not have provided a nitrogen input, because during burning all the nitrogen in wood is lost as gases.

Rain-water contains dissolved nitrogen compounds. We have decided, however, not to count this as an input to Cuxham. The source of the nitrogen in rain is mainly dissolved ammonia and nitrogen oxide gases. Nowadays some of this comes from industrial sources, but in 1320-40 ammonia would have come mainly from animals' urine, and nitrogen oxides from soil by the action of some bacteria. So Cuxham would be receiving this nitrogen from other farmland in England, and as a first approximation the gains in rainfall would balance the losses from Cuxham in these gases. Hence we do not consider it to be a net gain. For the same reason, we have not made any allowance for loss of nitrogen as ammonia or N-oxides from animal excreta.

²³ J E T Rogers, *A History of Agriculture and Prices in England*, vol 1, 1866, p 404.

²⁴ Rogers, *Agriculture and Prices*; Connor, *Weights and Measures*.

The main opportunity for gain of nitrogen is by nitrogen fixation. This means conversion of nitrogen gas from the air into other compounds. Plants and animals cannot do this, but some bacteria can: bacteria in nodules on the roots of leguminous plants, some bacteria living free in soil, and some cyanobacteria ('blue-green algae') which live on the soil surface. The leguminous crops grown at Cuxham were beans, peas and vetch, and we know the area sown with each (Table 2). One way to estimate their N fixation would be to assume that their fixation rate per acre was the same as has been found in the same species in the twentieth century. However, modern legume crops, under more favourable conditions, grow substantially more than in the Middle Ages, and hence may fix more N. To allow for this, we have used the seed production as a measure of growth. We have assumed that the ratio N fixed:weight of seed produced was the same at Cuxham as in modern legume crops. We have found data on this ratio from two experiments, one in Denmark, one in Canada.²⁵ The ratio was similar at the two sites and for beans and peas; it averaged 41.5 kg N fixed/ton seed, and we have applied this for all three legume crops. This gives 97.2 kg N fixed per year; this is 19.6 kg N per hectare of legume per year, which is substantially lower than rates reported for modern beans and peas.

These two inputs, hay and crop legumes, provide an annual input large enough to balance only about one-third of the losses (Table 8). Section (b) of the table provides figures for the other likely inputs by N fixation. The pastureland and haymeadows at Cuxham were shared between the demesne and the manorial tenants. In the absence of any firm evidence on how

the use was divided, we have assumed that the demesne obtained 59 per cent of the produce, since it had 59 per cent of the arable area. The figures taken for input per hectare in section (b) are all chosen to be 'pessimistic' – at the bottom end of the range measured by modern methods; the true inputs in section (b) could easily have been two or three times as high as the figures given. We have put no figure for N from legume weeds, since there is no information on how abundant these were. In spite of this caution, the total inputs of 912 kg/year cover the losses of 521–706 with a comfortable margin to spare. This suggests that the nitrogen content of the soil on the farm was not decreasing year by year. However, there is another likely loss not yet mentioned, leaching – in other words nitrogen compounds dissolved in water percolating through the soil and ultimately into rivers.

Rates of nitrogen loss by leaching from unfertilized arable fields have unfortunately rarely been measured. Probably the most thorough measurements were on a barley field in Sweden, whose leaching loss averaged 5 kg N/ha/yr. Loss from the long-term wheat field at Rothamsted was estimated in the nineteenth century to average 12 kg/ha/yr. The true value may well have been lower. But on the other hand, loss from fallow could be higher: soil at Rothamsted kept bare long-term lost in one year of measurement 25 kg N/ha/yr.²⁶

However, nutrients leached from the fields were not necessarily a net loss to Cuxham. Two streams entered Cuxham parish, carrying dissolved nutrients from other villis. One of them flowed through the village and between the arable fields, where it no doubt received further nutrients, then through the pastureland and on to the meadow area, where it joined the

²⁵ E S Jensen, 'Symbiotic N₂ fixation in pea and field bean estimated by ¹⁵N fertilizer dilution in field experiments', *Plant and Soil*, 92, 1986, pp 3–13; R J Rennie and S Dubetz, 'Nitrogen-15-determined nitrogen fixation in field-grown chickpea, lentil, fababean and field pea', *Agronomy Jnl*, 78, 1986, pp 654–60.

²⁶ K Paustian *et al*, 'Carbon and nitrogen budgets of four agro-ecosystems', *J Applied Ecol*, 27, 1990, pp 60–84; D S Jenkinson, 'The nitrogen economy of the Broadbalk Experiments', *Rothamsted Annual Report for 1976*, pt 2, 1977, pp 103–109.

TABLE 9
 Summary of phosphorus and potassium balances

Balances	Phosphorus	Potassium
Losses in produce (kg/yr)	104.4–136.6	135.1–184.2
Input in hay bought (kg/yr)	8.5	85.4
Deficit (losses – input in hay) (kg/yr)	95.9–128.1	49.6–98.8
Deficit per hectare of whole demesne (kg/ha/yr)	0.70–0.94	0.36–0.72
Release by weathering of rock material (kg/ha/yr)	0.05–0.5	0.5–20

Sources: Losses in produce, Table 7. Input in hay: 6.1 tons/yr (see text) $\times$ nutrient concentrations in Table 5. Rates of P release by weathering: E I Newman, 'Phosphorus inputs to terrestrial ecosystems', *J Ecol*, 83, 1995, pp 713–26; T E Crews *et al.*, 'Changes in soil phosphorus fractions and ecosystem dynamics across a long chronosequence in Hawaii', *Ecology*, 76, 1995, pp 1407–24. Rates of K release by weathering: S M Colman and D P Dethier, *Rates of Chemical Weathering of Rocks and Minerals*, 1986, pp 468–550; G E Likens, F H Bormann, R S Pierce, J S Eaton and N M Johnson, *Biogeochemistry of a Forested Ecosystem*, Springer, New York, 1977; G S Henderson, W T Swank, J B Waide and C C Grier, 'Nutrient budgets of Appalachian and Cascade region watersheds: a comparison', *Forest Science*, 24, 1978, pp 385–97; E K Miller, J D Blum and A J Friedland, 'Determination of soil exchangeable cation losses and weathering rates using Sr isotopes', *Nature*, 362, 1993, pp 438–41.

other stream and finally left the parish. The meadows were probably flooded in winter, so some of the nutrients would have been retained, and returned through the hay and the animals that ate it to the arable soil. So the net loss of nitrogen from the demesne by leaching is very uncertain. If we take 10 kg/ha/yr as the average for the cropland and fallow, the loss would total 1090 kg/yr for the whole area. Leaching loss from the grassland would be small. Combined with the losses in produce (Table 8) this would give total losses of about 1600–1800 kg/yr. This could be balanced by inputs if those in section (b) of the table totalled about 1500 (plus 200 from section (a)): in other words about twice as much as assumed in the table. This is by no means impossible: the inputs per hectare given in the table are definitely at the bottom end of a wide possible range. However, the nitrogen balance includes large uncertainties, and the overall conclusion must be that nitrogen inputs may or may not have balanced losses.

The balances of phosphorus (P) and potassium (K) are summarized in Table 9. Hay brought in made a substantial contribution towards balancing the losses of K, but only a minor contribution for P. This is because (as shown in Table 5) hay con-

tains ten times as much K as P, whereas cereal seeds, the main export from the farm, are only slightly higher in K than P. Table 9 shows 'deficits' for P and K, the losses so far not balanced by inputs; as a result of its low input in hay, P has a greater deficit than K.

In the air there are no gases containing P or K, so there is no source of these elements analogous to nitrogen fixation. The two possible sources are in rain and in release by weathering from the finely divided rock material in the soil. The P and K in rain, like the N, must have come mainly from other parts of England. Seawater contains K, but Cuxham is too far from the sea for this to be a significant source. Major sources of P and K in the rain falling on Cuxham are likely to have been fine dust from soil and dead plants, smoke, pollen.²⁷ Therefore, as for N, we assume that input of P and K to Cuxham in rain approximately balanced losses. The main potential net input is thus weathering of rock material. Rates of weathering are difficult to measure, and data are scanty. Most of the estimates for phosphorus have

²⁷ E K Berner and R A Berner, *The Global Water Cycle*, Prentice-Hall, Englewood Cliffs, 1987; E I Newman, 'Phosphorus inputs to terrestrial ecosystems', *J Ecol*, 83, 1995, pp 713–26.

given rates from 0.05–0.5 kg P/ha/yr. A rate of 1 kg/ha/yr has been reported from New Zealand, but from material freshly ground up by a glacier, a situation not found in England for more than 10,000 years.²⁸ If these figures are representative, the P input by weathering would probably be too slow to balance the calculated P deficit of 0.70–0.94 kg P/ha/yr.

Table 9 contains no figure for gain of P in firewood or for loss by leaching. P is not a mobile element in soil. P losses from unfertilized fields by leaching have rarely been measured, but figures from North America suggest that they will usually be about 0.2 kg/ha/yr or less.²⁹ Any net loss of P by leaching will reinforce our conclusion that losses often exceeded inputs; but the leaching loss is unlikely to alter fundamentally the balance shown in Table 9.

It is not possible to determine from the accounts the amount of firewood imported. The concentration of P in branches and trunks of typical British trees is very low, compared with hay or seeds (Table 5), so the amount imported in firewood would be low. To obtain a very approximate figure, suppose that the amount of firewood used at Cuxham per person per year was similar to present-day use in sub-tropical Third World countries with much agricultural land. Figures given for such countries by a United Nations handbook³⁰ range from about 100–600 kg/person/yr. To err on the high side, suppose that in Cuxham the average firewood use for the whole population of the village³¹ was 1000 kg/person/yr; if this contained 0.11 g P per kg (Table 5), none was lost during burning, and the ash was spread evenly

over the whole parish area, this would provide only 0.05 kg P/ha/yr, too little to contribute significantly to the P balance (Table 9). Clearly this is a very uncertain estimate; among other things, it ignores the fact that there were trees in Cuxham hedges, which probably provided some of the fuel needs, thus reducing the P imported. The basic point is that P concentration in wood is low.

Turning now to potassium, rates of its release by weathering at eleven sites in Europe and United States ranged from 0.5 to 17 kg/ha/yr; only one site had a rate below 1. Potassium's higher rate of weathering over phosphorus is because many rocks contain higher concentrations of K than P. These rates suggest that weathering in most soils would be releasing K fast enough to balance the deficit of 0.36–0.72 that occurred at Cuxham. As with P, there remain two uncertainties, input of K in firewood and loss in leaching. The concentration of K in wood is much higher than P (Table 5), and an estimate of the input in the same way as for P gives an input in ash of 0.8 kg K/ha/yr. We are not aware of any relevant measurements of K leaching rate from unfertilized fields, but the K⁺ ion is less mobile in soil than the nitrate ion. To a first approximation, gain in firewood and loss by leaching may be viewed as balancing each other. It is unlikely that they could alter our conclusion that the potassium deficit was probably balanced by natural inputs.

There are thus two important differences between phosphorus and potassium relating to inputs: potassium is about ten times as concentrated in hay and firewood, and its release from rock by weathering is about ten times as fast. So although the losses in produce of K from Cuxham were slightly greater than of P, our prediction is that the available pool of K in the soil would not decrease year by year, whereas the pool of P probably would decrease.

²⁸ Newman, 'Phosphorus inputs'; T E Crews *et al.*, 'Changes in soil phosphorus fractions and ecosystem dynamics across a long chronosequence in Hawaii', *Ecology*, 76, 1995, pp 1407–24.

²⁹ H Tiessen, ed, *Phosphorus in the Global Environment*, Chichester, 1995, pp 186–88.

³⁰ *Forest Products Yearbook*, United Nations Food and Agriculture Organization, Rome, 1987, p xlvii.

³¹ About 110 people just before the Black Death: Harvey, *Medieval Village*.

V

If our conclusion is correct that the phosphorus status of the soil was declining year by year, did this result in declining crop yields? The Cuxham accounts provide yield data for many of the years over a period of about half a century. However, for most of the crops the yields per acre can be calculated accurately only for the period when areas sown were reported in measured acres, which started in 1318. From then until the Black Death provides few years in which to see any clear trend, taking into account the wide fluctuations from year to year. However, for wheat the time can be extended. From 1318 to 1347 the total area sown on each field was almost always the same – $93\frac{1}{4}$ acres on the West Field, $88\frac{1}{4}$ on the South Field and 87 or $87\frac{1}{2}$ on the North Field. Since a whole field was sown with wheat each year, and we know which field, it is reasonable to assume that these areas applied to wheat before 1318. In this way yields per acre can be calculated for wheat for most years from 1298 onwards. Figure 1 shows the yields up to 1348. Values after that are not used, since they may have been affected by the disruption caused by the Black Death. The yields varied widely. The lowest were about 11 bushels per acre in 1316 and 1319, during a period of very wet summers.³² In contrast, there were several years when the yields exceeded 20 bushels per acre. In spite of this large scatter, there is a clear downward trend during the fifty years. The straight line is the best fit calculated by linear regression; its slope is statistically significant (probability < 0.05).³³ This decline was not caused by a decrease in the amount of seed sown; in fact the amount of wheat seed sown per acre increased during the period.

So the yield expressed as yield ratio (grain harvested/grain sown) also declined during this period (statistically significant at probability = 0.001).

For the other crops we can use the yield ratio over the whole fifty-year period, or bushels per acre for 1319–1347. The yield of dredge declined significantly with time according to both criteria; peas showed a downward trend, but it was statistically significant only by yield ratio; and barley and oats showed no significant change with time according to either criterion. It is surprising that neither barley nor oats showed a clear trend, when a mixture of the two, dredge, did. The overall conclusion is that some crops showed a declining trend of yield, others did not, but no crop showed an increase during this period.

As explained earlier, in many soils the store of 'available' phosphorus is large, so the declining phosphorus status of the soil would affect crop growth only slowly. As an example, if available P in the Cuxham soil was in the range 100–150 kg/ha (as reported from long-unfertilized fields elsewhere),³⁴ and declined at 0.5 kg/ha/yr (see Table 9) then it would be exhausted in 200–300 years. This is similar to the time-scale of wheat yield decline shown in Figure 1. Such a slow decline in soil fertility and yield would not be noticed by a fourteenth-century farmer within his lifetime, given the large yield fluctuations from one year to the next; but over the time-scale of a century or more it could be extremely important. Of course, crop yields did not in fact continue to decline until they reached zero in the sixteenth or seventeenth century. If agricultural methods had continued unchanged, the declining yields would have resulted in reduced annual nutrient removals in crops, so that inputs and losses would gradually have come more into balance. In reality

³² Lamb, *Climate*, p 195.

³³ Linear regression was calculated using the Minitab statistical computer package. Linear regression is explained in most standard statistical text-books, for example, R C Campbell, *Statistics for Biologists*, 3rd ed, 1989.

³⁴ A E Johnston and P R Poulton, 'Fields on the Exhaustion Land, 1852–1975', *Rothamsted Annual Report for 1976*, pt 2, 1977, pp 53–83.

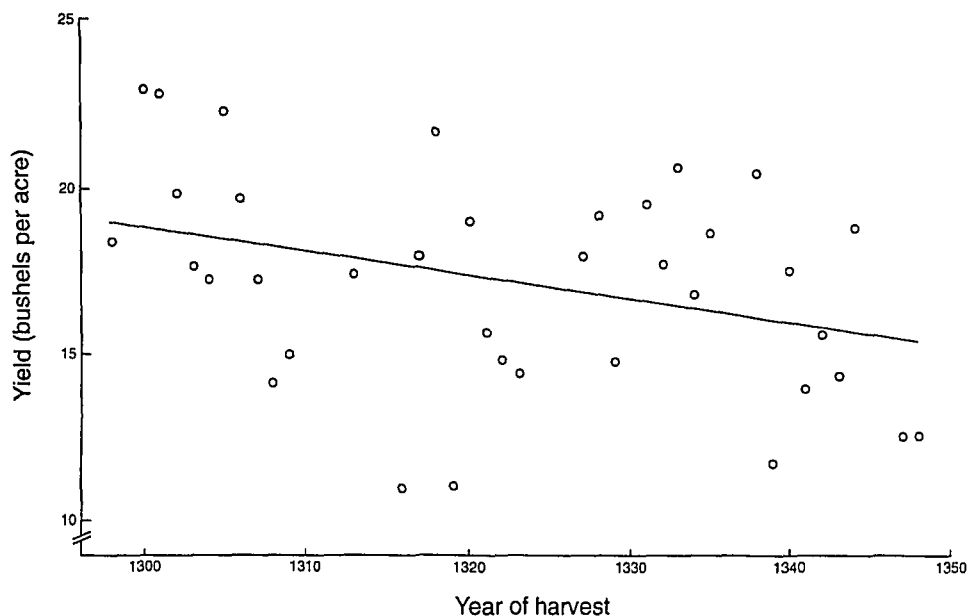


FIGURE 1

Yield of wheat per acre at Cuxham, including tithe, for each year from 1298 to 1348 for which data are available. (The line is the best fit calculated by linear regression.)

agriculture changed greatly after the Black Death, at Cuxham and elsewhere. Changes that would have helped to restore nutrient balance include a higher ratio of pasture area to arable area, with a consequent lower removal of phosphorus in crop harvest per input by weathering; and less produce exported from the farm, for example because of reduced population of towns. Significantly, deliveries of produce from Cuxham to Merton College ceased soon after 1349.

Our nutrient balance calculations are for one manorial demesne. It is relevant to ask how typical Cuxham was among demesnes of its period. A high proportion of the vill was cropland, relatively little was pasture and meadow (Table 1). This was true also for many other vills in the English midlands at that time. The hay brought to Cuxham from other vills allowed it to benefit from nutrient inputs to their meadows; Cuxham's non-crop area was thus effectively increased, but still not enough to

cure the phosphorus deficit. In contrast, a vill with a high proportion of pastureland and meadow, or access to much common rough grazing, could have a markedly different nutrient balance, because all those areas could contribute to nutrient input. Such farming systems did occur at this time, particularly around the margins of England.³⁵

Campbell, Galloway, Keene and Murphy have compiled data from about 200 demesnes in central and south-eastern England.³⁶ The data from each are for a few years, between 1288 and 1315. Table 10 compares means of these 200 demesnes with Cuxham. At Cuxham about half the sown area each year was wheat, as was normal for vills operating the three-field system; the average for the 200 demesnes was pulled down by those

³⁵ H S A Fox, 'Some ecological dimensions of medieval field systems', in K Biddick, ed, *Archaeological Approaches to Medieval Europe*, Western Michigan University, Kalamazoo, 1984, pp 119-58.

³⁶ Campbell et al, *A Medieval Capital*.

TABLE 10
Comparison between Cuxham (mean 1320-1340) and the mean of about 200 manorial demesnes in central and south-eastern England (1288-1315)

Crop	Area sown (percentage of total area sown)		Yield ^a (bushels/acre)		Exported from farm (percentage of (yield + import)) ^b	
	Cuxham	200 demesnes	Cuxham	200 demesnes ^c	Cuxham	200 demesnes
Wheat	49.8	32.9	17.3	10.5-11.6	73	55
Oats	29.7	30.3	14.0	12.2-12.8	18	28
Barley	3.0	11.1	21.5	17.2-17.6	48	37
Dredge	10.7	6.7	16.1	14.7-16.0	36	44
Peas	6.8	9.2	11.8	10.2-12.8		
Beans						
Vetch						

^a Yield includes seed and tithe.

^b Percentage exported counts tithe as an export.

^c Calculated in two alternative ways.

operating the two-field system. The yield per acre was higher than average at Cuxham for wheat, oats and barley, though not for dredge or peas. However, yields varied widely from one manor to another, and some had yields as high as Cuxham. For example, the mean yields (including tithe) of some Norfolk demesnes during 1325-49 were wheat 17.3 bushels per acre, oats 16.7, barley 19.1, similar to those at Cuxham.³⁷ So Cuxham may be considered as within the range of demesne production of its time. Nevertheless, we should bear in mind that Cuxham had a high proportion of its area as cropland, it had a high yield of wheat, and a high proportion of that was exported: Cuxham was primarily a wheat-exporting demesne.

Our calculations apply to the demesne only, and this is clearly a limitation. We have no basis for calculating nutrient balances for the remainder of the parish area, cultivated by tenants. There would be nutrient transfer between the demesne and the other parts. Some of this would be through people, especially tenants who worked part time on the demesne and

were paid in kind. This uncertainty should lie within the range of the two alternative figures given for each element (for example, Table 7, bottom line). Animals could also transfer nutrients, for example when demesne and tenants' animals grazed on the fallow. We cannot put a figure on how much this could have altered the nutrient balance of the demesne. A fundamental problem in the agricultural history of the Middle Ages is shortage of information about peasant cultivation.

In the final nutrient balances (Tables 8 and 9), much greater uncertainty attaches to the inputs than to the losses. Some readers may wonder why we have made no measurements on the soil at Cuxham. The answer is that the soil must have been so much altered by twentieth-century farming that any measurements made now would not be relevant to the Middle Ages. For example, rates of nitrogen fixation would probably be very different now. Measuring rates of release of P and K by weathering involves considerable technical difficulties, and could not be carried out at Cuxham, with present methods. So the rates of input we have used are, we believe, the best available.

³⁷ Campbell, 'Land, labour, livestock and productivity trends'.

VI

Our conclusion on the nutrient balance of Cuxham in the early fourteenth century is that phosphorus losses were probably not balanced by inputs, potassium losses probably were balanced by inputs, and for nitrogen we cannot say with any confidence. Clearly some uncertainty attaches to these conclusions. However, this paper does make a contribution to answering the question of our title, did soil fertility decline in medieval England. Decline of even one essential element would sooner or later result in reduced plant growth and crop yield. So we are predicting that soil fertility did decline. It would be very desirable to have nutrient balances for other places, and we hope that this paper will encourage and help other people to make such calculations.

This paper has drawn attention to phosphorus as a possible key element in maintenance of crop yields before the era of bag fertilizer. In ecologists' jargon, nitrogen

has a relatively open cycle, phosphorus a much more closed cycle, with potassium intermediate. This means that a system (for example, a farm) is likely to have large natural inputs and losses of N each year, but only small natural inputs and losses of P. This in turn means that removal of P in crops harvested is potentially a serious upset to the natural cycle, because there is little opportunity for it to be made good by natural inputs. We suggest that the possible importance of soil phosphorus as a limitation on pre-nineteenth-century farming deserves further study. As a hypothesis for future testing, we suggest that phosphorus may have played a crucial role in determining what crop yields could be sustained long-term, and also how much of the produce could be exported to towns, and hence how many people could live in towns. Viewed in this light, phosphorus may have played a key role in limiting the whole social and economic development of Europe.